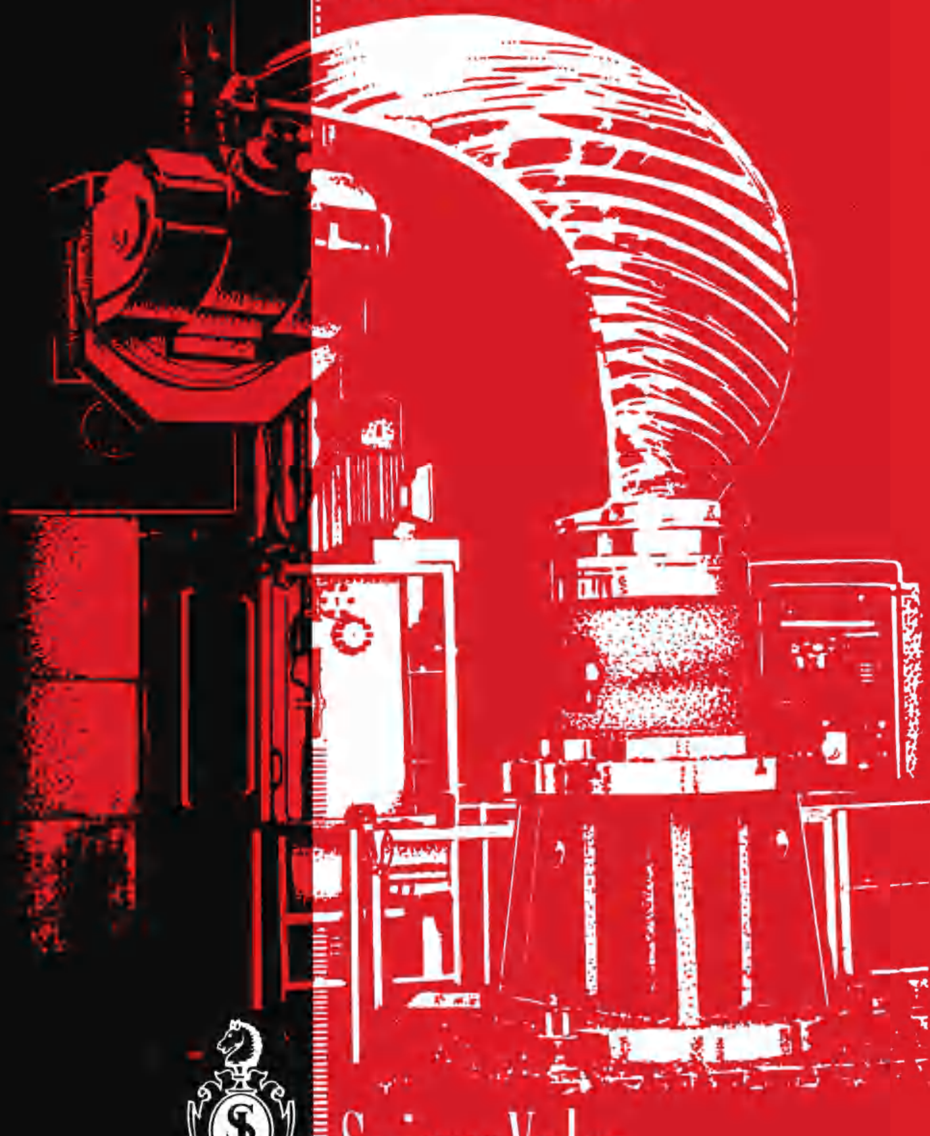
CNC MACHINING TECHNOLOGY

Graham T. Smith



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Graham T. Smith
Technology Research Centre, Southampton Institute,
City Campus, East Park Terrace, Southampton SO9 4WW,
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Cover illustration: Ch.5, Fig.36. The complete machining of an impeller, by utilisation of a 5-axis horizontal machining centre in conjunction with a high-level programming language. [Courtesy of Scharmann Machine Ltd.]

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To my grandfather
Mr T.W. Chandler
who encouraged me
to take an interest
in all things

*ΣΟΦΟΣ ΑΝΗΡ Ο ΕΞ ΙΔΙΑΣ
ΠΕΙΡΑΣ ΔΙΔΑΣΚΟΜΕΝΟΣ
ΣΟΦΟΤΑΤΟΣ ΔΕ Ο ΕΚ
ΤΗΣ ΤΩΝ ΑΛΛΩΝ*

Translation:

*A wise man learns from
experience and an even
wiser man from the
experience of others*

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Contents

Preface

This book has been written as a result of the favourable comments made about its companion volume over the years: *Advanced Machining – The Handbook of Cutting Technology*, published jointly by IFS and Springer-Verlag, in 1989. It follows a similar and successful format and considers possibly the most prolific metalcutting machine tools used by industry today: turning and machining centres. First, in the opening chapter we will consider how these machine tools have evolved and developed to their current level of sophistication, try to explain how such equipment is constructed, and discuss the various elements necessary to ensure quality workpieces occur. Furthermore, this chapter will help those not too familiar with this technology to gain an insight into the operating mechanisms. Chapter 2 is especially important as a thorough working knowledge of the latest cutting tool technology is crucial if we are to capitalise upon the potential productive capacity offered by such machines. It has been written to complement and not to supersede the information given in the previous book; the same could also be said about chapter 3, on cutting fluids.

Obviously, an important consideration for any machine tool is how we are to restrain and locate the workpiece in the correct orientation and with the minimum of set-up time. With this in mind, chapter 4, on workholding technology, was included. However, it is by no means meant to be an exhaustive account of this important and often misunderstood technological application.

Chapter 5, on CNC programming, has been written in conjunction with a major European supplier of controllers, so that the reader gains a more consistent and in-depth understanding of the logic used to program such machines. The chapter is by no means a comprehensive appraisal of the subject of programming, more an indication of how, why and where to program specific features of a part and build them up into complete programs.

Finally, chapter 6 considers the method by which a company justifies the purchase of either cells or systems and illustrates why simulation exercises are essential if a company is to gain a clear understanding of these complex and associated technologies in a real-time simulated environment, prior to a full implementation and commissioning of the plant. Communication protocols and networking topologies are discussed, however, I have refrained from mentioning the latest and somewhat controversial research activities of "neural networks" and "fuzzy logic", as they have still to make an impact in a "workshop hardened" environment – being just at the development stage. In the closing pages, I have mentioned the important activities underway in many machine tool companies concerning high-speed machining developments and the drive towards ultra-high accuracy/precision. These developments are being forced upon the machine tool builders by a market which requires higher stock removal rates per kilowatt of power drawn by spindles and the associated benefits, together with greater and greater accuracy as companies work at the current limits of the process capabilities of today's machine tools.

A list of company addresses is given so that more in-depth information can be gained by the reader. Lastly, my final thoughts are to you, the reader, as this book has taken three years to write – with frequent up-dates to sections as topics have changed during the writing – I hope you will have found it of use and I would be pleased to hear your thoughts on the book as a whole, or in part.

Graham T. Smith
West End
Southampton

Acknowledgements

A book such as this, leaning heavily upon the current trends in machine tool and peripheral technologies, relies strongly upon the support it obtains from industrial companies around the World. With this in mind, I would like to express my gratitude to a whole host of companies, too numerous to mention here individually, listed at the back of the book. However, I would like to single out several people who have given of themselves and their companies. First and foremost, I would like to extend my sincere thanks to my wife, Brenda, who has typed and corrected the manuscript throughout, and secondly to the late Grahame Wheatley of Cincinnati Cimcool and to Paul Jackson, for allowing me to use their information on cutting fluids – the book is considerably better for their help. Ron Ansell of Cincinnati Milacron and W.H. Fletcher have provided me with considerable photographic and literature support and the same can be said for Tony Rose of Gildermeister (UK) Ltd. Peter Martindale of Scharmann Machine Ltd and Les Pratt of Yamazaki Mazak also gave of their time and themselves freely in supplying photographs and literature whenever asked, which was much appreciated.

Once again I must thank Bill Kennedy of Kennametal Inc. and Paul Brohan of Sandvik Coromant for their support, along with many other cutting tool companies. This is also true for the many people at Siemens, G.E. Fanuc and other CNC controller companies. For the Greek translation I would like to thank Vassilios Gatselos.

I would like to express my thanks to my publishers who have given me time and space to write this book, in particular Nick Pinfield, Linda Schofield and Lynda Mangiavacchi.

Chapter 1
The Development and Design of CNC Machine Tools

1.1 Historical Perspective – the Early Development of Numerically Controlled Machine Tools

The highly sophisticated CNC machine tools of today, in the vast and diverse range found throughout the field of manufacturing processing, started from very humble beginnings in a number of the major industrialized countries. Some of the earliest research and development work in this field was completed in the USA and a mention will be made of the UK's contribution to this numerical control development.

A major problem occurred just after the Second World War, in that progress in all areas of military and commercial development had been so rapid that the levels of automation and accuracy required by the modern industrialized world could not be attained from the labour intensive machines in use at that time. The question was how to overcome the disadvantages of conventional plant and current manning levels. It is generally acknowledged that the earliest work into numerical control was the study commissioned in 1947 by the US government. The study's conclusion was that the metal cutting industry throughout the entire country could not cope with the demands of the American Air Force, let alone the rest of industry! As a direct result of the survey, the US Air Force contracted the Parsons Corporation to see if they could develop a flexible, dynamic, manufacturing system which would maximise productivity. The Massachusetts Institute of Technology (MIT) was sub-contracted into this research and development by the Parsons Corporation, during the period 1949–1951, and jointly they developed the first control system which could be adapted to a wide range of machine tools. The Cincinnati Machine Tool Company converted one of their standard 28 inch "Hydro-Tel" milling machines to a three-axis "automatic" milling machine for this contract, having removed the contouring equipment. This machine made use of a servo-mechanism for the drive system on the axes, which controlled the table positioning, cross-slide and spindle head. The machine can be classified as the first truly three axis continuous path machine tool and it was able to generate a required shape, or curve, by simultaneous slideway motions, if necessary.

At about the same time as these American advances in machine tool control were taking place, Alfred Herbert Limited in the United Kingdom had their first NC machine tool operating, although Ferranti Limited produced a more reliable continuous path control system which became available in 1956. Over the next few years in both the USA and Europe, further development work occurred. These early numerical control developments were principally for the aerospace industry, where it was necessary to cut complex geometric shapes such as airframe components and turbine blades. In parallel with this development of sophisticated control systems for aerospace requirements, a point-to-point controller was developed for more general machining applications. These less sophisticated point-to-point machines were considerably cheaper than their more complex continuous path cousins and were used when only positional accuracy was necessary. As an example of point-to-point motion on a machine tool for drilling operations, the typical movement might be: fast traverse of the workpiece under the drill's spindle and after drilling the hole, another rapid move takes place to the next hole's position – after retraction of the drill, of course. The rapid motion of the slideways could be achieved by each axis in a sequential and independent manner, or simultaneously, if a separate control was utilised for each axis. The former method of table travel was less costly, whereas the latter was faster in operation. With these early point-to-point machines the path taken between two points was generally unimportant, but it was essential to avoid any backlash in the system to obtain the required degree of positional accuracy and so it was necessary that the approach direction to the next point was always the same. The earliest examples of these cheaper point-to-point machines usually did not use recirculating ball screws; this meant that the motions would be sluggish, and slideways would inevitably suffer from backlash, but more will be said about this topic later in the chapter.

The early NC machines were, in the main, based upon a modified milling machine, with this concept of control being utilised on turning, punching, grinding and a whole host of other machine tools later. Towards the end of the 1950s, hydrostatic slideways were often incorporated for machine tools of higher precision, which to some extent overcame the stiction problem associated with conventional slideway response, whilst the technique of averaging-out slideway inaccuracy brought about a much increased precision in the machine tool and improved their control characteristics.

The concept of the "machining centre" was the product of this early work, as it allowed the machine to manufacture a range of components using a wide variety of machining processes at a single set-up, without transfer of workpieces to other machine tools. A machining centre differed conceptually in its design from that of a milling machine, in that the cutting tools could be changed automatically by the transfer mechanism, or selector, from the magazine to spindle, or vice versa. In this manner, the automatic tool changing feature enabled the machining centre to productively and efficiently machine a range of components, by replacing old tools for new, or preselecting the next cutter whilst the current machining process is in cycle.

In the mid 1960s, a UK company, Molins, introduced their unique "System 24" which was meant to represent the ability of a system to machine for 24 hours per day. It could be thought of as a "machining complex" which allowed a series of NC single-purpose machine tools to be linked by a computerised conveyor system. This conveyor allowed the workpieces to be palletised and then directed to each machine tool as necessary. This was an early, but admirable, attempt at a form of Flexible Manufacturing System concept, but was unfortunately doomed to failure. Its principal weakness was that only a small proportion of component varieties could be machined at any instant and that even fewer workpieces required the same operations to be performed on them. These factors meant that the utilisation level was low, coupled to the fact that the machine tools were expensive and allowed frequent production "bottlenecks" of work-in-progress to arise, which further slowed down the whole operation.

The early to mid-1970s was a time of revolutionary advancement in the area of machine tool controller development, when the term computerised numerical control (CNC) became a reality. This "new" breed of controllers gave a company the ability to change workpiece geometries, together with programs, easily with the minimum of development and lead time, allowing it to be economically viable to machine small batches, or even one-offs successfully. The dream of allowing a computerised numerical controller the flexibility and ease of program editing in a production environment became a reality when two related factors occurred. These were:

the development of integrated circuits, which reduced electronic circuit size, giving better maintenance and allowing more standardisation of design;

that general purpose computers were reduced in size coupled to the fact that their cost of production had fallen considerably.

The multiple benefits of cheaper electronics with greater reliability have resulted in the CNC fitted to the machine tools of today, with their power and sophistication progressing considerably in the last few years, allowing an almost artificial intelligence (AI) to the latest systems. Over the years, the machine tool builders have produced a large diversity in the range of applications of CNC and just some of these developments will be reviewed in chapter 5.

With any capital cost item, such as a CNC machine tool, it is necessary for a company to undergo a feasibility study in order to ascertain whether the purchase of new plant is necessary and can be justified over a relatively short pay-back period. These thoughts and other crucial decisions will be the subject of the next section which is concerned with the economic justification for CNC.

1.2 The Economics of CNC

1.2.1 The Importance of a Feasibility Study

It is normal for a company to embark on a feasibility study prior to the purchase of any capital equipment such as a CNC machine tool. This study fulfils many functions, such as determining the capacity and power required together with its configuration – horizontal/vertical spindle for a machining centre, or flat, or slant bed for a turning centre. Many other features must also be detailed in the study, encompassing such factors as the number of axes required and whether the machine tool should be loaded manually, by robot, or using pallets. An exhaustive list is drawn up of all the relevant points to be noted and others that at first glance seem rather esoteric, but will affect the ability of the company to manufacture its products. It has been shown time and again that many mistakes have been made in the past when companies rush into the purchase of new equipment without considering all of the problems, not only of the machine tool itself, but of the manning and training requirements together with its effect on the rest of the shop's productive capability. Often the fact that an advanced, highly productive machine is now present in the shop could affect the harmonious flow of production, causing bottlenecks later, when the purpose of purchasing the machine was to overcome those problems at an earlier production stage. Machine tools have even been purchased in the past without due regard for the components they must manufacture, or without correct assessment of future work. This latter point is not often considered, as many companies are all too concerned with today's production problems rather than those of the future. Taking this theme a little further, in a volatile market a feasibility study should perceive not only the short and medium term productivity goals, but also the long term ones, as it is often the long term trends of productive capability which are the most important if a company is to amortise their costs. When highly sophisticated plant such as an FMS is required, it can be several years from its original conception before this is a reality on the shop floor, and a company's production demands may have changed considerably in the mean time. If, for any reason, the wrong machine/s has/have been purchased, or more likely, something has been overlooked during the feasibility study, then the "knock-on effect" of this poor judgement is that it will have cost the company dearly and, at the very least, any future study will be looked on by the upper management with disdain and scepticism.

A company should plan and discuss their products and systems to be implemented in the future with an eye on the production equipment of the present. This is very relevant, as any responsible production engineering company will invest in manufacturing equipment which has reached a reliable level of maturity, yet at the same time allow for further growth over a foreseeable time, and in such a manner, maintain and strengthen the competitiveness of the enterprise. Fig. 1.1 graphically illustrates the relationship between product maturity and level of utilisation of production technology today. In recent years, the labour overheads have reached almost the same level as the direct labour costs and this has meant that methods employed using conventional production have clearly slipped into an "ageing phase". This is also true, to a certain extent, for NC technology, as this has shifted from maturity to a particular level of ageing and in the medium term, will offer no further competitive opportunities. Obviously, planned investments must embrace the growth area technologies

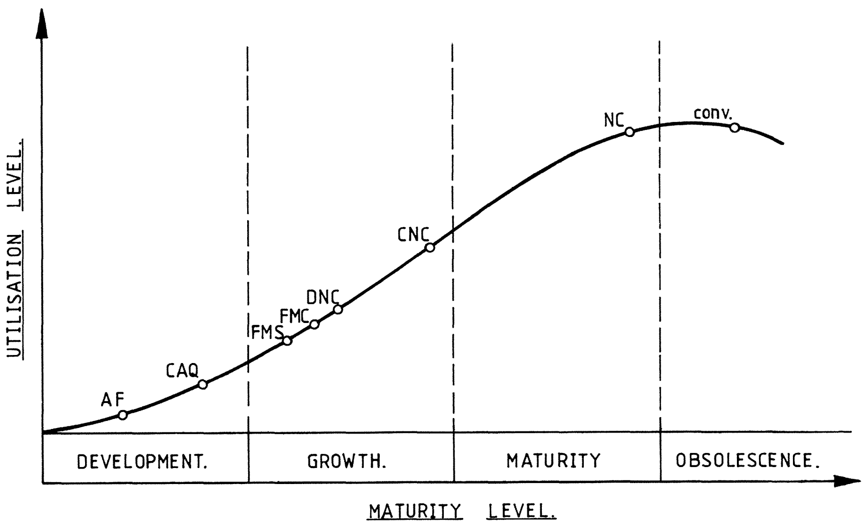


Fig. 1.1. The degree of maturity and utilisation of manufacturing techniques currently on offer. conv., conventional manufacture; NC, numerical controlled manufacture; CNC, computerised NC manufacture; DNC, distributed numerical control (note: not direct numerical control in this context); FMC, flexible manufacturing cell; FMS, flexible manufacturing system; CAQ, computer-integrated quality control; AF, automated factory. [Courtesy of Scharmann Machine Ltd.]

(Fig. 1.1), but these sophisticated technologies – although they create conditions for optimum utilisation of the plant – mean that capital equipment is more costly to purchase. Whenever high cost equipment is purchased it is usually the intention of a company to maximise their financial outlay by reducing the pay-back period to a minimum, using second and possibly a third shift. This strategy has the effect of lowering the hourly machine rate drastically, or to put it another way, these systems are over-compensated by more intensive utilisation, so that despite the higher amount invested, a better utilisation and in most cases higher machine performance will achieve a reduction in costs.

In the high technology-orientated former West Germany, a recent survey concluded that only about 12% of the machine tools installed were less than 5 years old. That is to say, many conventional machines are still actually in use and must be supplemented, or replaced in successive small steps by replacement and/or expansion investments. Continuing this theme, of current average age of the machine tool compared with its utilisation level, it can be seen (Fig. 1.2) that it is precisely in this area that the largest amount of manoeuvring space for entrepreneurial decisions occurs. In the early 1980s, a review regarding machine tool utilisation was conducted and the results showed that on average only approximately 700–800 hours per annum were spent actually doing "cutting" work. If one refers this to the theoretically available annual loading time for the machine tool of 364 × 24 hours per day, this time will represent approximately 8% and this is shown in Fig. 1.2. This graph also attempts to show the individual blocks of time which cannot be used for actual production and it illustrates just how little influence any small idle time improvements

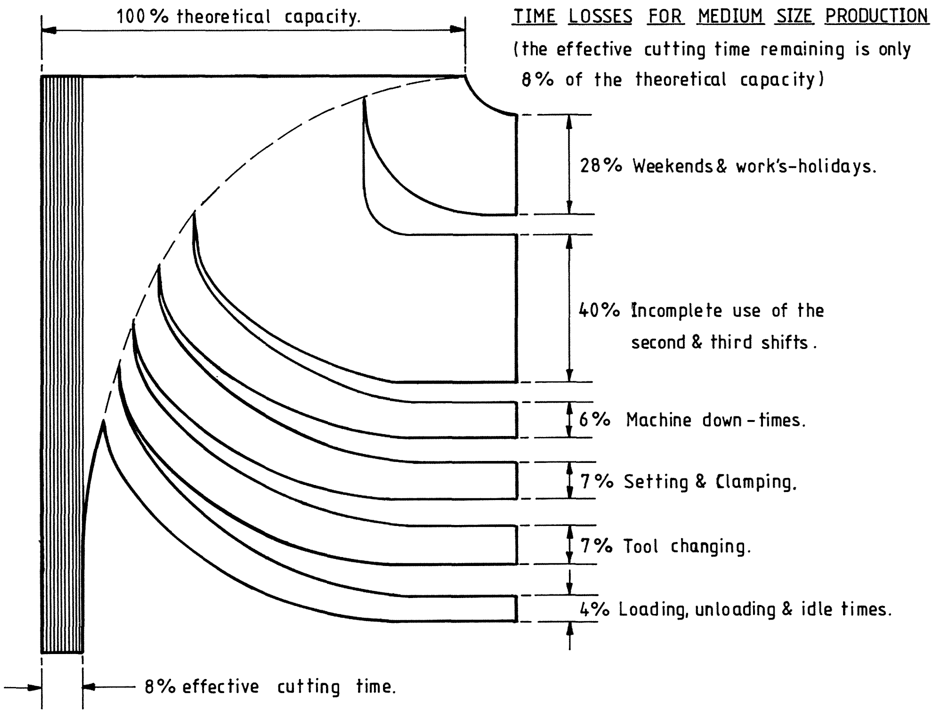


Fig. 1.2. Time loss constituents in medium batch manufacture. [Courtesy of Scharmann Machine Ltd.]

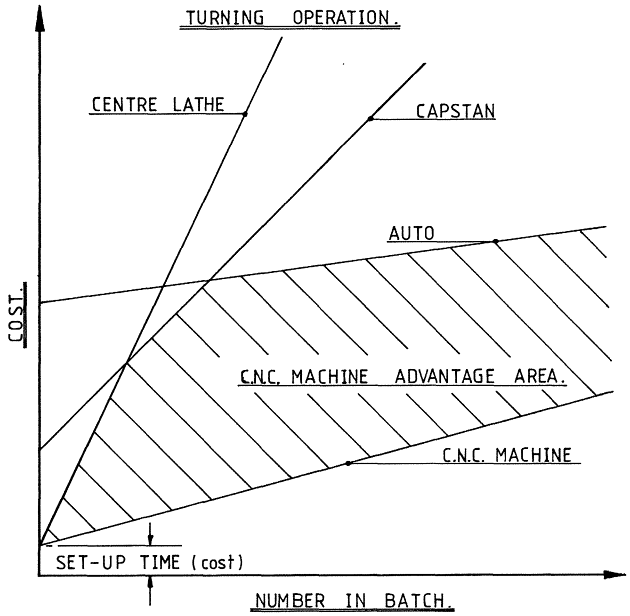


Fig. 1.3. Cost comparison against batch size. This shows clearly the advantage of using a CNC machine.

will achieve on the machine, when compared with the enormous potential of incomplete utilisation. Obviously, improvements during the last 20 years in the cutting capability of machine tools and their performance have shown increases averaging 500% and further drastic savings of time have been achieved in the area of idle times – where higher rapid traverse rates and automatic tool and workpiece-changing equipment have been developed. It nevertheless remains a fact, that even though these are impressive productivity gains, they are a "drop in the ocean" when seen from the overall view of the plant utilisation throughout the year.

So far we have been concerned with the likely problems that face a company embarked on a feasibility study for the purchase of new equipment. Let us now discuss the advantages to be gained from the purchase of the "correct" plant. One of the main purposes in using a CNC machine tool is to increase the productive throughput with this equipment – but this, as Fig. 1.2 has shown, can only be effective when the other time-loss constituents have been minimised. Although high volume production can occur using CNC equipment, it is not alone in this area and under certain conditions can be surpassed by using more conventional technologies, such as, single and multi-spindle lathes, or plug board machine tools, as illustrated in Fig. 1.3. However, even here most of these controllers are now being sold with CNC. The major feature of a CNC machine tool is its ability to cut down drastically the lead times for similar components manufactured by a different plant (as depicted in Fig. 1.4) and this has meant that an economic batch size is one! Even complex double-curvature component geometries can be quickly and successfully programmed by a trained employee using on- or off-line programming methods, but more will be said about this in chapter 5. The real advance in machine tool design and monitoring systems has meant that accuracy and repeatability of a component's dimensional characteristics can be confidently predicted, thus time and again uniform work results.

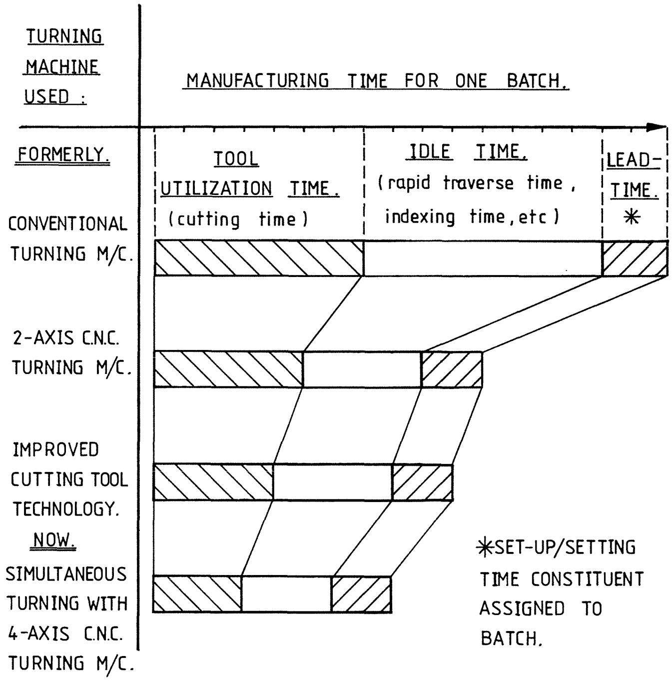


Fig. 1.4. To illustrate how cycle times have reduced with advancing CNC turning technology. [Courtesy of Gildemeister (UK) Ltd.]

This repeatability has the added bonus of reducing inspection, assembly and fitting costs by the virtual elimination of re-work and scrap. Storage of the part program and its retrieval also has the effect of decreasing the lead times over the more conventional manufacturing methods still further. As a consequence of this feature, the skill level is retained by the company and does not leave when the employee moves on, or retires. Other indirect, but crucial advantages accrue through the application of CNC technology and include: the precise processing of changes to the part with the minimum of disruption of production, improved planning and scheduling results, repeat orders are easily undertaken, plus many more attractive benefits. The results of these improvements of reduced tooling requirements and inventories together with the administration benefits can be summarised graphically by the simple profit and loss statement against time, shown in Fig. 1.5. Any machine tool is only making money when it is cutting material (Fig. 1.6) and it is important to maximise this fact by improving the machine's utilisation over second/third shifts and by other non-productive machining time advances, as clearly indicated in Fig. 1.2.

This section has tried to show that positive advantages occur when a company embraces the current CNC technology, but only, hopefully, after an exhaustive feasibility study. Let us now consider how and why CNC machine tools are designed and constructed and then go on to look at their systems of machine control.

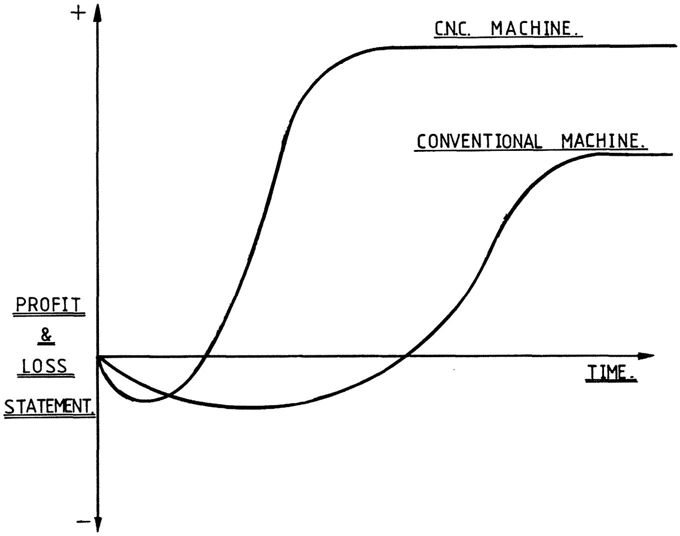


Fig. 1.5. Tooling lead-in time for a new product. NB: There is a definite period of loss before the product reaches the market and using CNC the "cross-over" comes sooner and profit is higher.

1.3 The Design and Construction of CNC Machine Tools

With the development of CNC machine tools from the earlier NC machines, this meant that they were able to impart a degree of flexibility into programming and more particularly editing. These controllers mean that program input and editing has drastically reduced lead-times, making the acceptance of CNC technology to a whole host of machine tools a more attractive proposition. Together with the great advances in CNC electronic developments, the major machine tool casting designs have also been rationalised and in many cases designed around "modular concepts". More will be said on this topic later in this chapter.

1.3.1 Developments in the Design and Cast Structure of the Machine Tool

The structure of a machine tool must fulfil several requirements if it is to allow an accurate and efficient cutting action to take place. The primary requirements for any CNC machine are that the structure should be: torsionally rigid, thermally stable and have adequate vibration damping capacity, in conjunction with precision and accuracy to the moving elements. Torsional rigidity is required to overcome the flexures that result from forces generated by the cutting action. The structure must be thermally stable to overcome the heat generated – not so much by the cutting action, but more particularly as a result of heat generated by bearings, motors and ballscrews, which might otherwise distort the structure through differential expansion/contraction. This factor of thermal drift is becoming a major problem for machine tools when used close to their process capability and in themselves can be the cause of scrap occurring. Any machine tool must dampen the vibrations set up by the cutting action quickly,

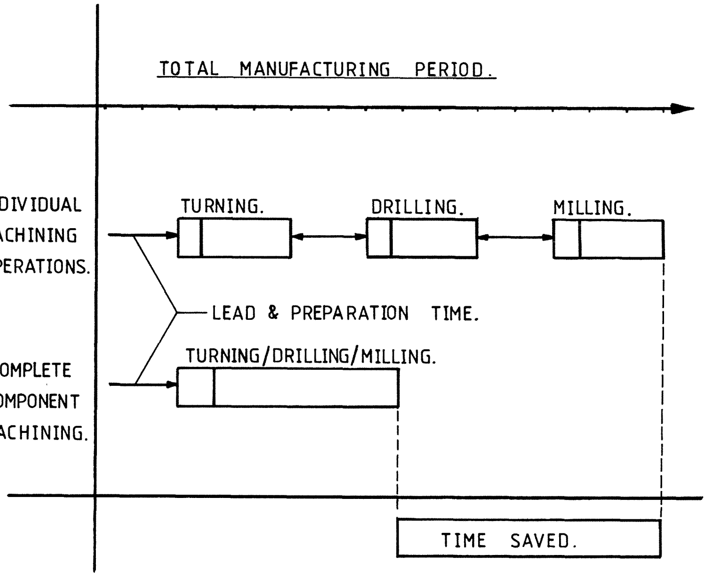


Fig. 1.6. The turning centre with driven tooling considerably reduces work-in-progress, compared with conventional manufacturing methods. [Courtesy of Gildemeister (UK) Ltd.]

otherwise they will have a disastrous effect on the tool life and on the workpiece surface finish generated.

The secondary requirements of the machine tool structure are that the workpiece and tooling are easily accessible to the operator, so that care is taken by the designers to allow ease of access to a machine, which in turn reduces operator fatigue, a major factor attributed to scrap workpieces. Until recently, all of the larger parts of a machine tool's structure were built using cast iron, although some companies have produced partially steel fabricated (welded) with cast iron assemblies fitted into them. Some years ago concrete was employed instead of the welded bases; but although it has been shown to give excellent results, only a few companies have chosen this route. In fact several machine tool builders having tried the welded/cast structures for a number of years, have reverted back to their original cast iron castings because of their superior ability to dampen the tendency for self-exciting vibrations which can attend the machining operation. It should be stated that all machine tool elements have both static and dynamic vibrations present, but the cast iron structures have shown superior vibration damping capacity to the partially welded and cast versions and are less prone to flex under the higher forces generated by the latest cutting tool materials and higher powered drive motors used of late. The very latest material to be used is "Granitan" which is a mixture of crushed granite and a thermosetting mixture to cure and bond it together; this is cold-set and has very high thermal stability, whilst offering much greater damping capacity over cast iron.

If vibration were the only problem when machining then this could easily be remedied, but, the cutting action induces high forces within the cast structure and if it is not robust enough to withstand them, then it may twist and distort slightly promoting poor geometrical and dimensional characteristics to the workpiece. In order to minimise the torsional and distortion problem, a rib, or box-like structure is usually

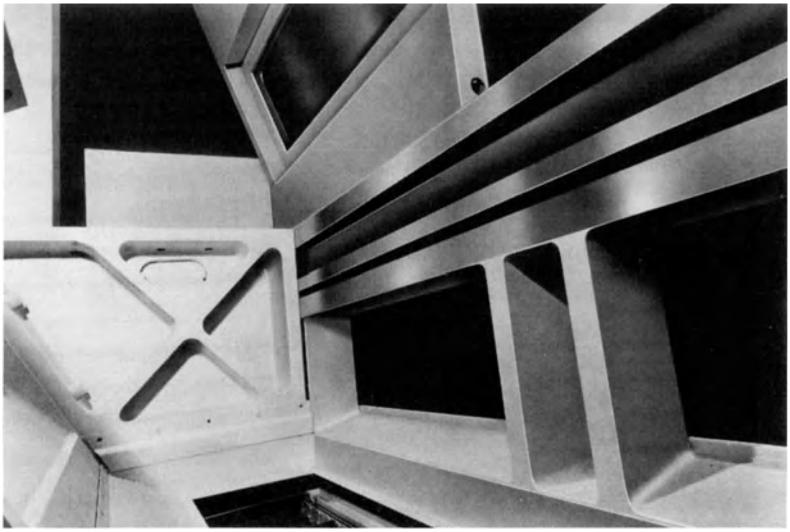


Fig. 1.7. The rib and boxlike construction of the castings. [Courtesy of Cincinnati Milacron.]

employed on the casting as shown in Fig. 1.7. With the advent of unattended machining which CNC allows, the structure of machine tools could be radically changed giving better access and easier swarf removal. Typically, the slant bed on turning centres has evolved which allows for these problems to be more-or-less overcome and is considered superior to the flat bed construction found on conventional lathes. When the lathe bed is slanted, tooling can be more easily reached by the operator, as is true in the case for the workpiece. Swarf build-up has always been a problem area when cutting certain materials and this has been completely overcome in turning using a vertical bed – which is often protected completely by shrouds from the swarf. When cutting long, stringy materials, the use of chip breakers allows the swarf to drop freely away from the cutting region to the bottom of the bed where it is disposed of efficiently.

Recently, many machine tool structures have become rationalised designs and are based upon the "modular concept" philosophy. This "modular" design (Fig. 1.8) allows the machine tool builder the opportunity to standardise certain features over a range of machine tools, benefiting the manufacturer and consumer alike in reducing the development and purchase costs whilst allowing more attention to be given to each "module" in the machine. The same column, or table, may be common to a variety of machines and this trend may be seen across the whole product range of a machine tool company in certain instances. A typical modular concept philosophy can be appreciated throughout the design of the major component parts shown in Fig. 1.9.

A critically important feature of any CNC machine tool is the accuracy/precision of the bedways which provide a datum from where all subsequent workpiece accuracy emanates. This feature must be rigorously assessed as, if inaccuracies are present in the base casting, as other axes are added this accumulation will compound the problem of workpiece inaccuracy. Fig. 1.10 shows nicely the slant bed Z axis, with the X axis assembly mounted in-situ and it can be appreciated that a single large casting is used for the bed with the bearing areas spaced widely apart for extra stability to minimise flexure – which is an important feature to note when purchasing a new CNC

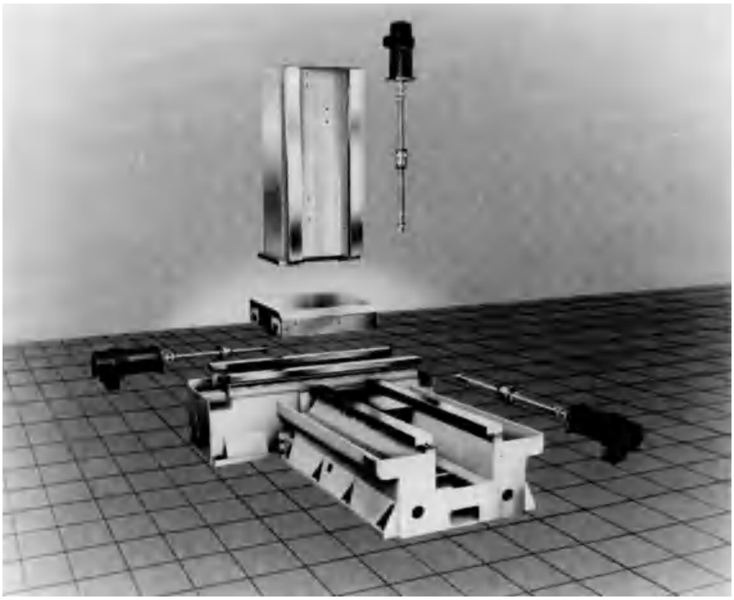


Fig. 1.8. The modular construction of machining centres. [Courtesy of Cincinnati Milacron.]

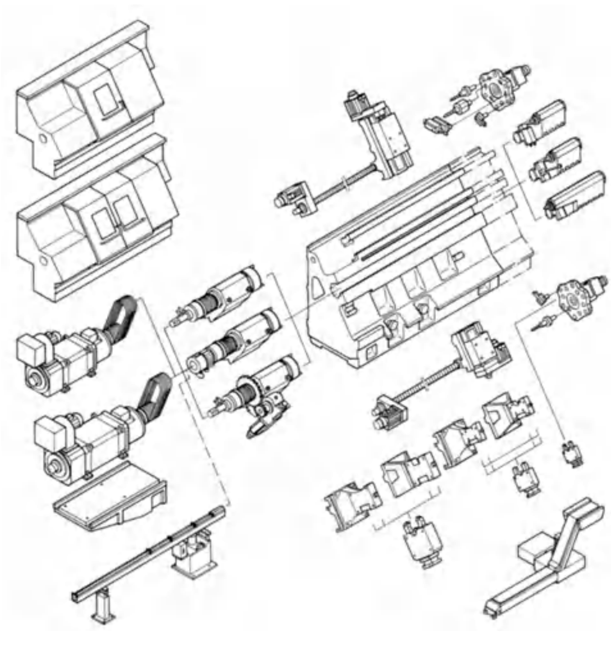


Fig. 1.9. The optional equipment and modular concept for a turning centre. [Courtesy of Gildemeister (UK) Ltd.]

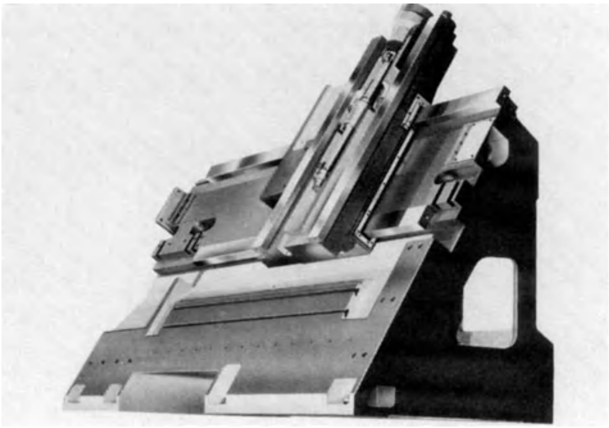


Fig. 1.10. Partial assembly of a turning centre's slideways. [Courtesy of Cincinnati Milacron.]

machine tool. Bedways have always been hardened in the past by using an induction hardening technique, or similar methods, but a more common feature now is to bolt fully hardened steel "ways" directly onto the casting. In particular, in recent years, the major advancements have been in increasing slideway response and overcoming the stiction problem which is present in most conventional bedway designs. As rapid speeds on machine tools have increased to 30 m/min recently, it was imperative that stiction was minimised by reducing the coefficient of friction levels considerably. Slideways are often given treatment such as "stick-free" coating – typically "Turcite". This minimises the "stick-slip" effect and has tended to be used on the lighter cast machine tool structures. When heavy workpiece loads are to be coped with, then hydrostatic slideways are the only choice, as these "oiled" solutions are the only viable alternative on extra large machine tools. With many of the machine tools carrying intermediate loads, a different solution is on offer to the machine tool designer and this utilises the so-called "frictionless" systems. A typical linear bearing assembly has a combination of either rollers or needle rollers assembled into hardened guides and bolted onto the casting and these run the whole length of the axis travel. When the axis travel is particularly long or loads are higher, then the "Tychoway" system might be used (Fig. 1.11). This assembly is in the form of continuous rollers which are situated in the moving members and they bear onto the fixed member either directly, when the surface is hardened, or onto a hardened strip let into the casting's bearing faces.

1.3.2 The Recirculating Ballscrew

Almost without exception, when the machine tool's slideway requires motion, this is transmitted via an assembly known as a "recirculating ballscrew". Fig. 1.12 shows a partially cut-away diagram of just one type of ballscrew assembly mechanism. The assembly shown in Fig. 1.12 has the flanged nut attached to the moving member and the screw to the "fixed" casting. Thus any rotational movement of the screw will displace the moving member's slideway in the desired direction. These recirculating ballscrew designs can have ball cages of internal or external return, but all of them are based upon the Ogival or "Gothic arch" principle. This geometry ensures that a point

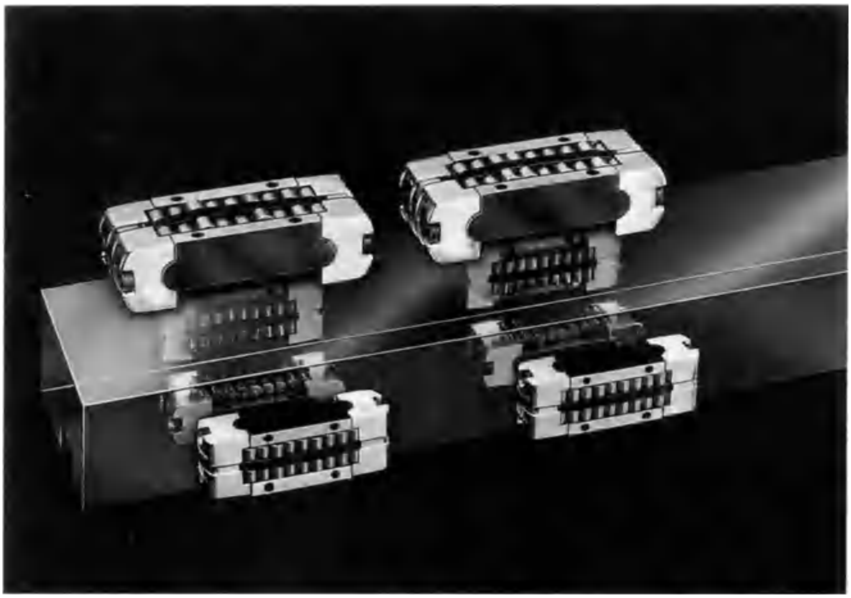


Fig. 1.11. "Tychoways" situated strategically along the hardened way of a machine tool for efficient transmission of loads and motions. [Courtesy of Cincinnati Milacron.]

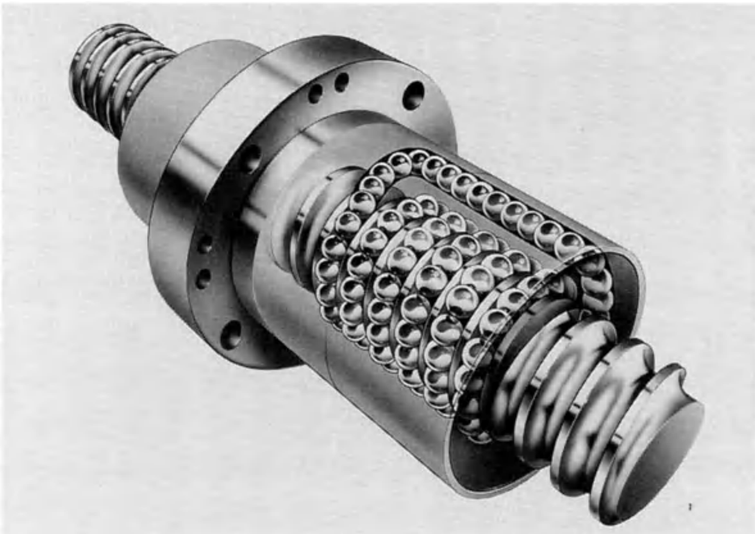


Fig. 1.12. A typical arrangement of a recirculating ballscrew assembly for efficient transmission of motion of slideways without "backlash". [Courtesy of Cincinnati Milacron.]

contact occurs between the ball, its nut and the screw, giving low friction with over 90% efficiencies. With the ultra-fast "rapid" motions of some of the latest CNC machine tools being around 30 m/min, some ballscrew assembles are of the two-start Ogival type and are needed to cope with such high translations of motion. As expected, the accuracies of such ballscrews are high, in the region of 0.005 mm over 300 mm being possible and on large machines these ballscrews may be of considerable length with high values of stiffness, up to 2000 N/μm.

The traditional Acme thread used on conventional machine tools has efficiencies ranging from 20% to 30%, but although this is significant, it is not the main reason why ballscrew assemblies have superseded them. The real reason for their universal acceptance by machine tool builders, is that they can be pre-loaded in-situ and in such a manner overcome any backlash which might otherwise be present in "normal" thread assemblies. Ballscrew assemblies vary in their method of achieving zero-backlash and are available as either single, or twin-nut designs with such features as vernier adjustments in the more expensive designs for accurate pre-loading level adjustments. These vernier systems can be precisely set to the required pre-load level, whereas the other ballscrew systems require a ground spacer to be fitted between the two flanged nuts. These hardened and ground ballscrew assemblies require little, if any maintenance during their working lives once "torqued-up" and set. Every ballscrew, however accurately ground it is, will have errors in its pitch present. This inaccuracy is removed upon laser calibration at the final assembly stage when alignment errors are assessed and these pitch errors are fed into the machine control unit at precisely displaced intervals (Fig. 1.13). This means that despite pitch inaccuracies occurring, the controller adjusts – in other words, compensates for – the slideway position to eliminate this error and move the axis to the command position given by the CNC program.

1.3.3 Drive Motor Advances

Complementary and in situ with the ballscrews are the main motor drives which are usually of several types:

stepper motors (these will be discussed in section 1.4.1)
DC motors
AC motors
digital drives

The power of DC motors has increased the metal cutting capability of CNC machine tools in a similar manner to that of advances in the cutting tool materials available and their geometries over the last few years. In 1900 a turning operation on a bar of steel 100 mm in diameter and 500 mm long would have taken about 105 min. By 1970, owing mainly to cutting tool improvements, the time taken to machine a bar of the same dimensions was down to 1.2 min. Today, a time of half the 1970 value is possible, with the added bonus that if a facing-off operation is required on a bar, a constant surface speed could be used. With DC motors, the trend at present is to use Thyristor/Triac controls to be fitted to machine tools. Asynchronous motors with variac controls which were fitted to the older machine tools could only achieve a speed range of 1:4. By using gearboxes the range could be enlarged to over 10 speed ranges in a geometric progression. The problem with the older system was that even with the highest speed selected, the range was not great enough to optimise the new speeds required by the latest cutting tools and to obtain a constant surface speed requirement. DC motors allow the advantages of higher speeds available with a better ratio between the lowest and highest speeds and this simplifies the gearbox requirements, whilst their high torque characteristics enable them to turn large diameter bars at low surface speeds.

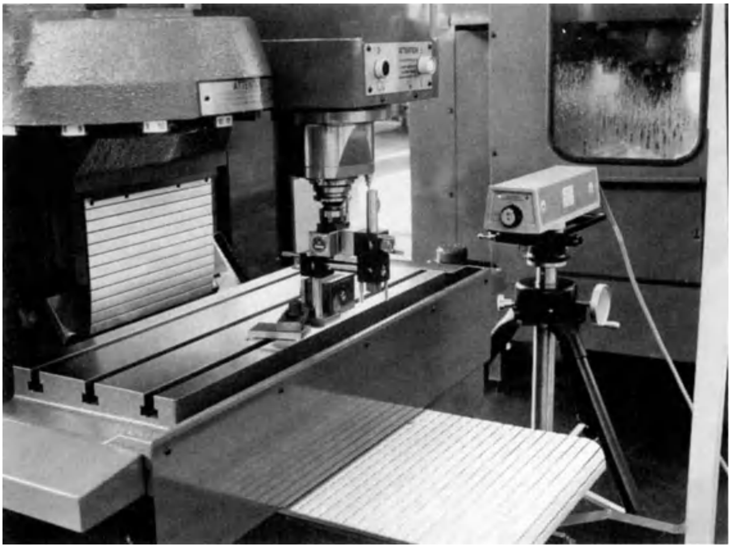
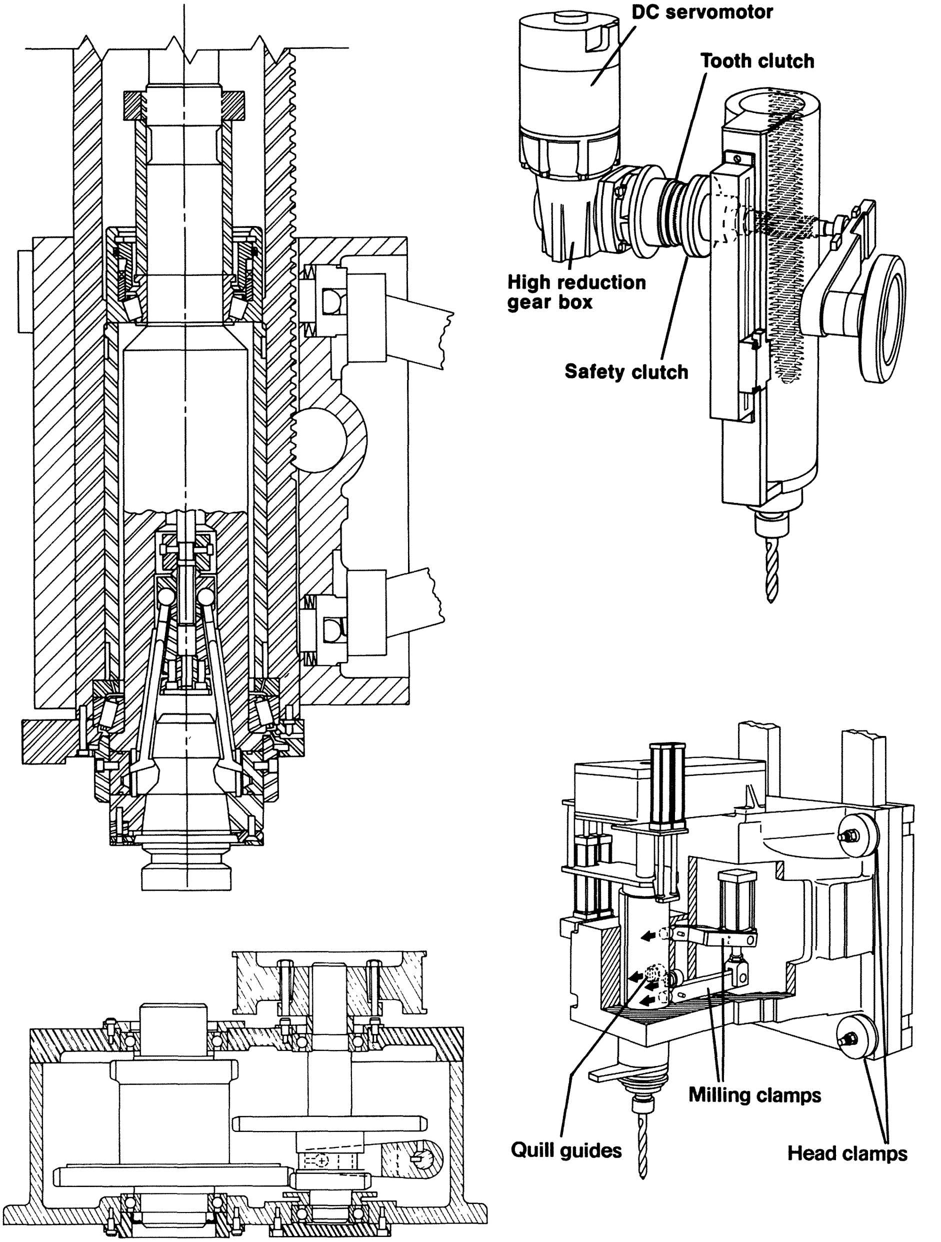


Fig. 1.13. The final test area, prior to alignment testing (laser calibration assessment). Each machine tool is run continuously to check both electrical and mechanical performance before acceptance. [Courtesy of Bridgeport Machine Tools.]

Metal removal rates under constant conditions of cutting speed, depth of cut and feedrate, will keep the cutting forces constant, so that when the bar diameter is increased the torque increases accordingly – hence the need for the high torque at low speed. Rapid advances have occurred with high-power control technology and this has meant that a reappraisal of DC motors for CNC machine tools has taken place.

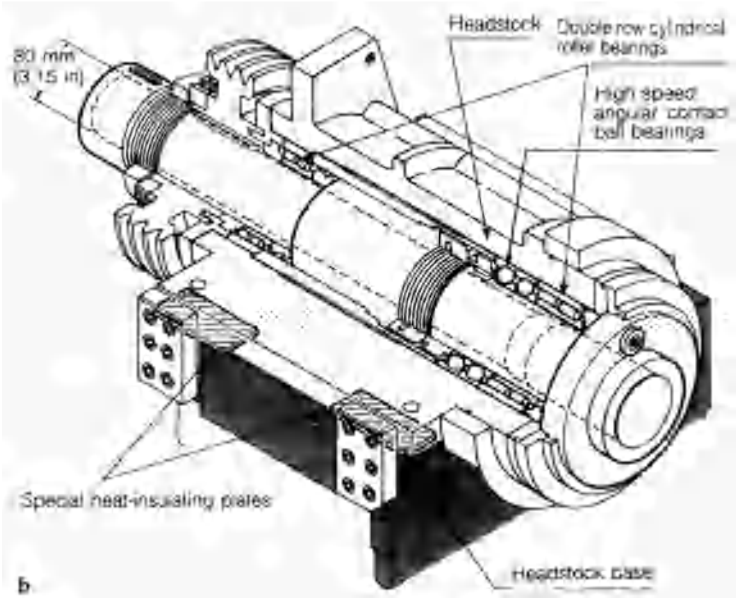
The advantages of using AC induction motors over other types is that they tend to be more reliable and easily maintained, yet are less costly than most other motors. Obtaining rotation reversal of direction is simple with these three-phase AC motors and it is possible using pole-change motors to obtain four speeds in arithmetic progression such as: 350, 700, 1400, and 2800 rev/min, or similar. AC motors are not usually used for driving the main spindle directly – apart from the pole-change motors, as expensive and specialised electrical equipment is needed to provide high power with accurate stepless variable speeds. Whenever there is a need to drive the main spindle directly, it is usual to utilise a mechanical variable speed unit in order to obtain spindle speed variation. By 1984, it became possible to produce speed control and variation of AC motors, by frequency variation of the electrical supply; this resulted in a more general adoption of the AC induction motor by industry.

Recently, digital drives have become an important addition to machine tools, particularly with the advent of machines requiring ultra-high speed spindle rotations and more importantly rapid feedrates in two, or three dimensions. Such drives have very fast response times and are ideal for minimising the "servo-lag" problems associated with high speed cutting operations, "data-starvation" – causing problems on part geometries and the tendency for cutter vibration, together with improved cutter accelerations/decelerations. However, this will be discussed in more detail in the following chapters.



a

Fig. 1.14. a A typical spindle system for a machining centre. (i) A large diameter spindle rides in tapered roller bearings in a quill which is chrome plated and ground for smooth motion and long wear. Tapered roller bearings have 6 times more stiffness than ball bearings to provide a net 50% increase in milling rigidity. At speeds above 1400 r.p.m., the bearing preload is automatically reduced by 30% to assure cool operation and long life. (ii), (iii) Quill guides provide accurate z-axis tracking. Milling clamps are automatically energised during the milling cycle. (iv) The DC spindle drive motor is blower cooled. Filters are easily inspected.



b The construction of a turning centre headstock. The headstock is designed to minimise the effects of thermal distortion in order to provide high accuracy over extended periods of continuous operation. The symmetrical spindle housing is separated from the machine bed by a special insulation plate so that any heat generated by operation will not displace the spindle centre. In order to supply the rigidity required for heavy duty cutting, the spindle is supported by double row cylindrical roller bearings and combined angular contact ball bearings at the front, and double row cylindrical roller bearings at the rear. [**a** Courtesy of DSG/Monarch; **b** Courtesy of Yamazaki Mazak Corporation.]

1.3.4 Headstock and Main Spindle Design

Probably the most important element in the complex build-up of CNC machine tools is the main spindle on a machining centre or CNC mill, or the headstock on a turning centre or lathe. The crucial element of its design and subsequent assembly directly affects the workpiece quality. Fig. 1.14a shows a simplified diagram of a typical machining centre spindle system, illustrating the attendant shafts, bearings and gears, being of robust construction. Often the main spindle is refrigerated or the oil supply is kept at constant temperature in order to minimise the effects of thermal expansion. Figure 1.14b shows a typical advanced turning centre headstock spindle assembly with its sophisticated arrangement of bearings and heat resistant material strategically positioned to act as a "heat sink" to minimise the thermal growth and possible distortion of the headstock assembly. If any growth due to thermal effects occurs in the headstock its design should allow it to "grow" axially, thus minimising the effect on workpiece accuracy.

1.3.5 Auxiliary Equipment Fitted to Turning Centres

An important element on any turning centre when turning between centres, is the design and adaptability of the tailstock and the ability to remove it from the cutting zone when it is not required. Tailstocks tend to be of either the solid, partially programmable, or fully programmable varieties, with increasing versatility being with the latter type. If tailstocks are of the solid casting type then their use is rather limited to supporting the workpiece only and some simple machining operations during the CNC program, whereas the partially programmable type can be "latched-up" to the centre-line for work support between centres, or used for drilling etc., if mechanically attached to the cross-slide, which is a provision most machine tool companies offer. Figure 1.15 shows a partially programmable tailstock in the "latch-up" position supporting a workpiece whilst locked in position on the lathe bed. By far the most universal variety is the fully programmable tailstock which offers all the features of the partially programmable version, but in addition has a continuous feed control of the barrel enabling a range of hole generating processes to be achieved totally independent of the cross-slide operation. The barrel's oil pressure can be adjusted by a hydraulic restrictor to give a variation in clamping force to the component; this is necessary because small diameter work would distort or deflect otherwise.

The problem of rough turning operations is the nature and volume of swarf generated during cutting the workpieces under production conditions. The former problem of continuous swarf can be minimised by using chip-breakers on the cutting tools (more will be said on this topic in chapter 2) whereas the volume of swarf would build up to unacceptable levels and interfere with the cutting process if not removed. By supplying a swarf conveyor on a turning centre, the swarf can be deposited in a container well away from the cutting region. There are several varieties of design of swarf conveyors, ranging from the most common chain-type to the rotating spiral

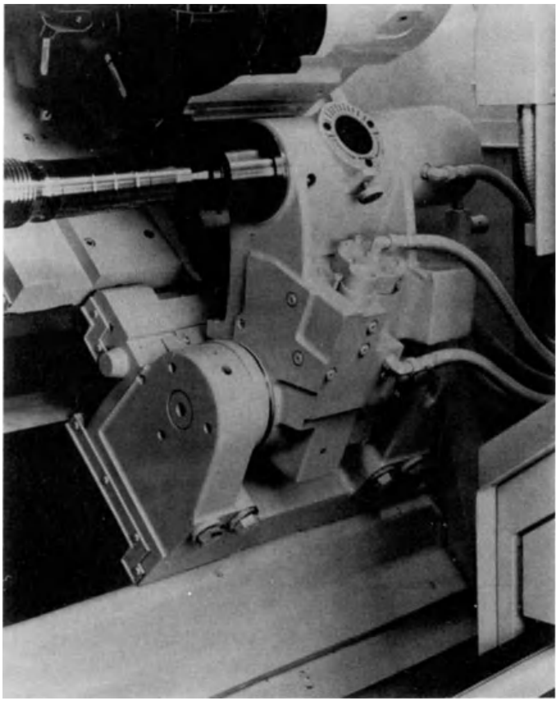
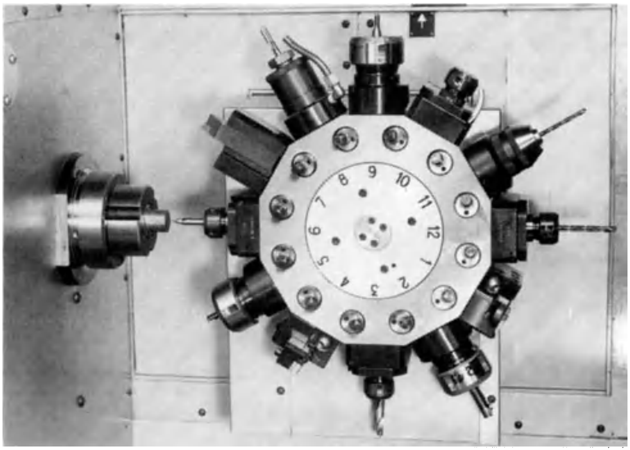


Fig. 1.15. A partially programmable tailstock supporting a long workpiece in the "latch-up" position. It can be "latched-down" (lowered) when not required. [Courtesy of Cincinnati Milacron.]

a



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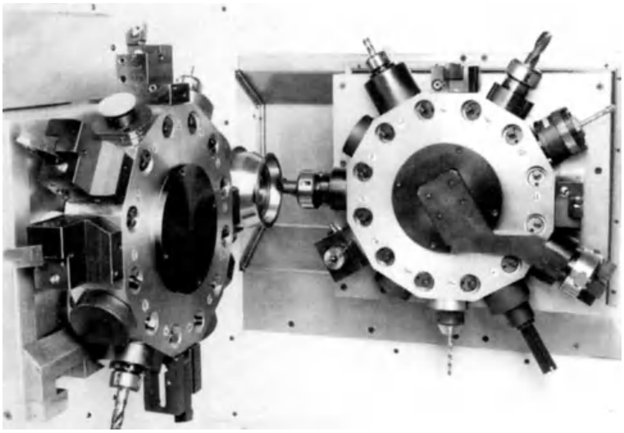
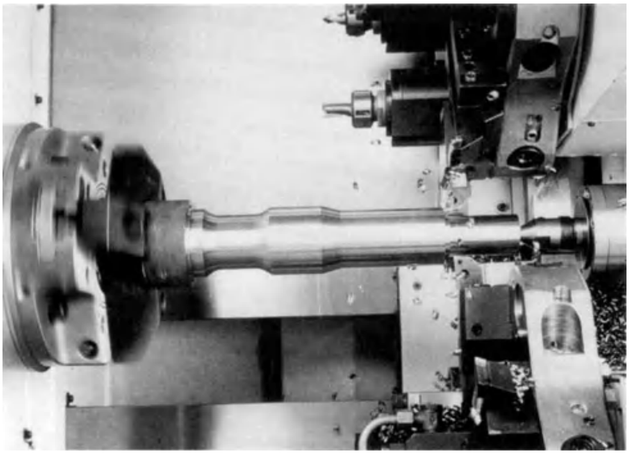


Fig. 1.16. Turret configurations. **a** 2-axis, driven/conventional tooling. **b** 4-axis, twin turret with driven/ conventional tooling. [Courtesy of Gildemeister (UK) Ltd.]

versions, but they all achieve the desired effect of removing unwanted swarf from the machine.

Automatic and programmable tool changing mechanisms are an essential feature on any turning centre and usually of the indexable turret variety typified by Fig. 1.16. The two-axis version is normally a single type whilst the four-axis configuration has the ability to machine several features on the same component, typically roughing and finishing operations – known as "balanced turning" (Fig. 1.17a), or individual features on the same component such as turning and boring (Fig. 1.17b), or to machine dimensions on separate components, when an auxiliary spindle is present. To give the turning centre even more versatility it is possible for most machine tool companies to offer machines with a "driven/live spindle" to most, or all, of the turret positions if required. This allows the programmer to specify drilling or milling operations on the component using a rotating tool station (Fig. 1.18). This useful feature of powered tooling requires at the very least, some form of indexing control to the headstock

a



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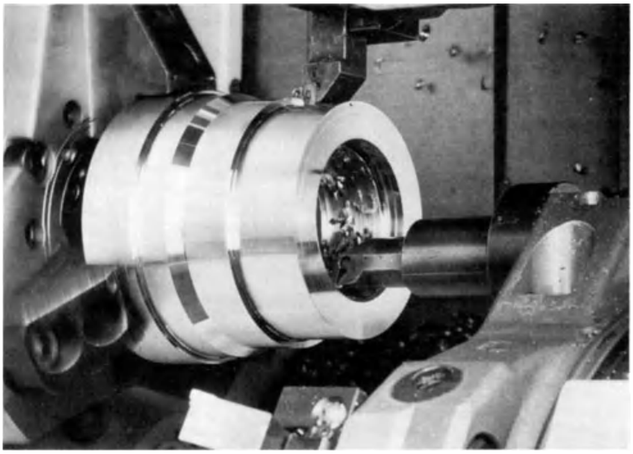


Fig. 1.17. a "Balanced turning" produces fast stock removal, or different features to be machined simultaneously. **b** Twin turrets allow versatility, i.e. to turn and bore simultaneously. [Courtesy of Gildemeister (UK) Ltd.]

spindle, allowing such features as: flats, slots, and splines, etc., to be machined on prismatic parts. The indexing "C-axis" will clamp the headstock spindle at the required angle via a "shot-pin" which positively locates into an index plate slot, then the feature to be milled, drilled, or tapped etc., can be accomplished with a degree of accuracy and constraint.

For completely universal machining capabilities on a turning centre using the so-called "one-hit" cutting capabilities in just one set-up, the machine tool needs to be equipped with a fully programmable "C-axis" control to the headstock spindle coupled to a "driven tooling" facility (Fig. 1.19). By using such a combination of full "C-axis" control and "live tooling", this will, in one sense, negate the need for using, say, a machining centre to complete the part. "One-hit machining" has several major economic benefits:

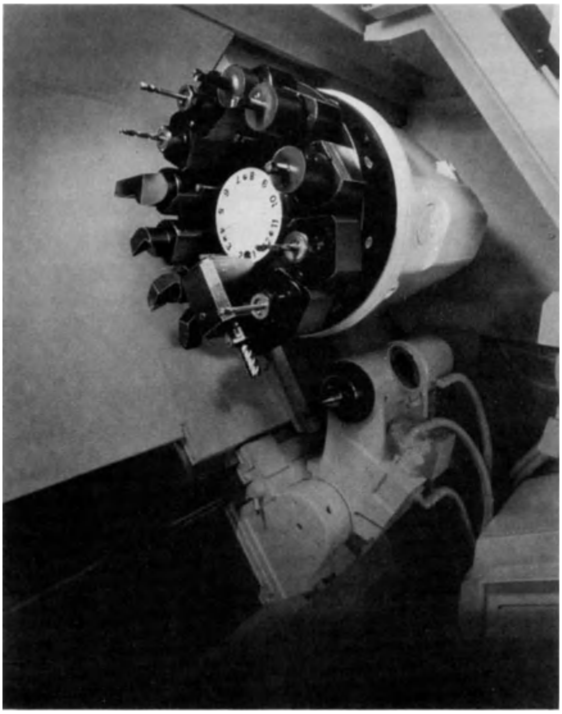


Fig. 1.18. A "driven tooling" facility will increase a turning centre's versatility to machine a range of prismatic parts. [Courtesy of Cincinnati Milacron.]

it reduces capital outlay on a second machine tool
it significantly cuts down work-in-progress times
it increases the range of component parts to be machined by the turning centre
it improves the overall machine tool efficiency by increasing the productive cutting time
higher quality parts result as the turning centre completes the parts at one set-up on the machine
it uses less floor space, therefore only one machine tool is necessary, rather than two

NB: Although a turning centre with "driven tooling" has such versatility and the ability to cut a large universal range of products, it is not cheap to purchase initially but has the advantage that its pay-back period is considerably reduced and offers better utilisation than the more "simple" turning centres. Figure 1.20 shows just some of a whole host of cutting tool configurations of the "live tooling" variety which can be held in the tool turret and this increases the machining capabilities of turning centres considerably.

Obviously a turning centre is only making money as it cuts metal; this means that delays in the supply of workpiece material will have serious consequences on the efficiency and overall productive capability of the machine tool. To minimise any non-productive time that would otherwise accrue, automatic bar-feeders housing wrought bars can be supplied to the machine (Fig. 1.21) and these feed lengths of material

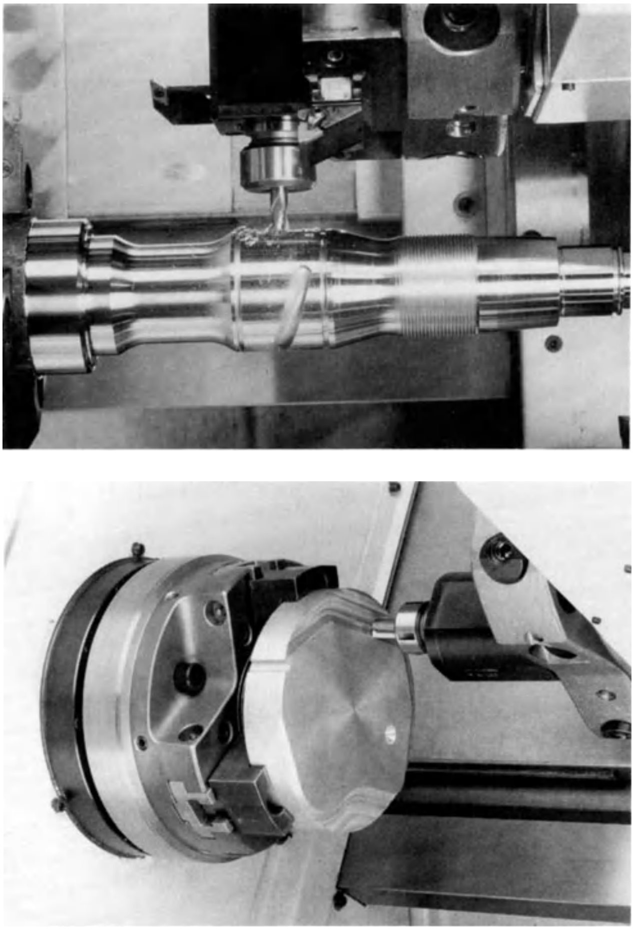


Fig. 1.19. To show just some of the cutting capabilities when a fully programmable "C-axis" headstock spindle, utilising a "driven tooling" facility is available. [Courtesy of Gildemeister (UK) Ltd.]

through the headstock spindle for the manufacture of parts. Some bar-feeders are of quite sophisticated design with "silent-running" capabilities; these also allow new lengths of bar stock to replenish the bar-feeder when the previous one has been consumed. When automatic bar length loading accessories are present, then an untended machining condition is possible with large batch runs.

When it is necessary to machine either long workpieces or those requiring support whilst either centre-drilling or boring, then a very useful accessory is the programmable steady. The programmable steady (Fig. 1.22) supports the part in order to eliminate the effects of the cutting force and its subsequent displacement of the work during machining operations – this would be a particular problem whenever it is necessary to completely machine a long, thin bar along its entire length. Steadies are usually of two types, those:

with a separate motion along the bedway of the turning centre,
fixed onto the turning centre turret (as shown in Fig. 1.22).

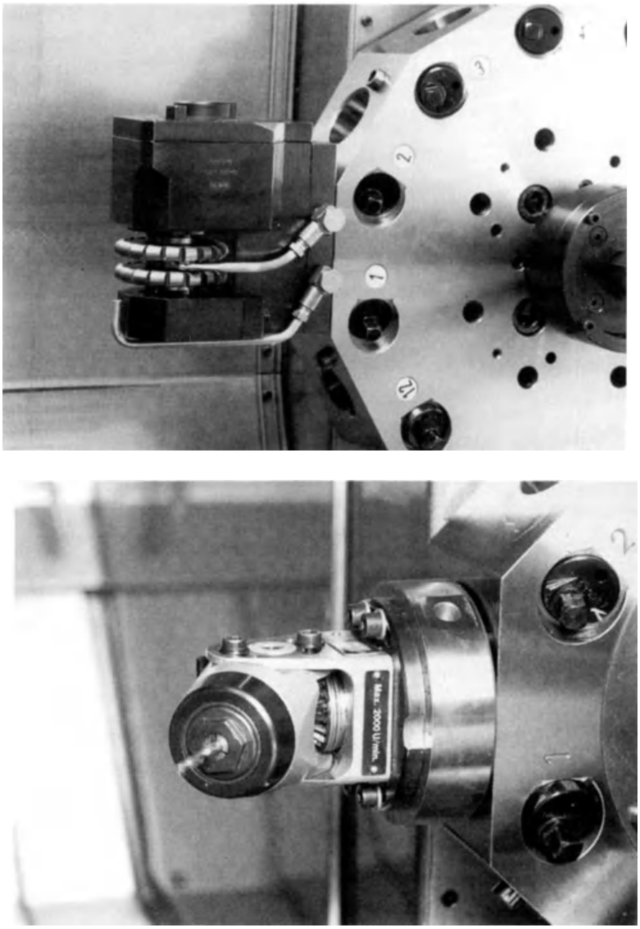


Fig. 1.20. "Driven tooling" configurations can be quite sophisticated, ranging from (*above*) straddle milling to (*below*) adjustable angled heads on a turning centre turrets. [Courtesy Gildemeister (UK) Ltd.]

In either case, the rolling element supports are positioned on adjustable fingers which automatically open, or close, according to the diameter to be supported.

In order to minimise the damage to the completed workpiece an automatic part-catcher is a useful addition to a turning centre. Part-catchers come in a variety of designs and have different methods for catching the workpieces. As the surface finish is often a criterion used in assessing the part quality, then any damage to its surface once machined will obviously affect the quality attributes on the drawing and may lead to the workpiece being scrapped. Therefore the part-catcher should collect the workpiece and deposit it into a receptacle and avoid damage to the finished part by gently guiding the components to their respective parts bins.

To complete this over-simplified and brief view of just some of the auxiliary equipment offered by machine tool companies on turning centres, it is worth returning once again to some other interesting tooling configurations available today. Fig. 1.23 illustrates a synchronised dual turret mechanism that has been partially cut away to

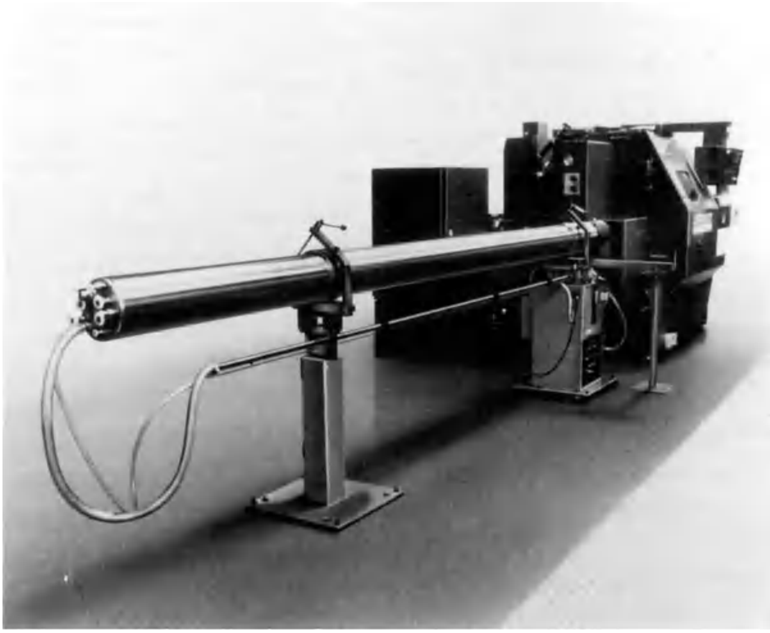


Fig. 1.21. A "silent running" automatic bar-feeder for uninterrupted production of parts. [Courtesy of Cincinnati Milacron.]

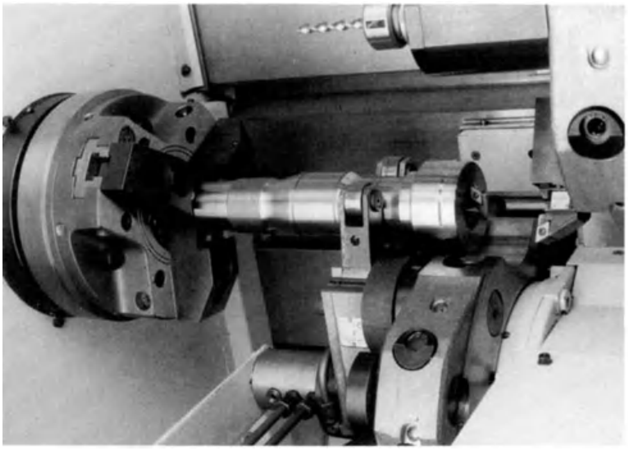


Fig. 1.22. A programmable steady for long workpiece support. [Courtesy of Gildemeister (UK) Ltd.]

show the internal constructional details of its assembly. As can be appreciated from the photograph, the external tooling is held in the lower drum turret whereas the internal tooling is located on the larger turret. This design considerably increases the versatility and range of cutting tools available for component production. The final tool holding mechanism, shown in Fig. 1.24, utilises an automatic tool delivery system to the turning centre via a gantry robot. This type of tooling arrangement decreases

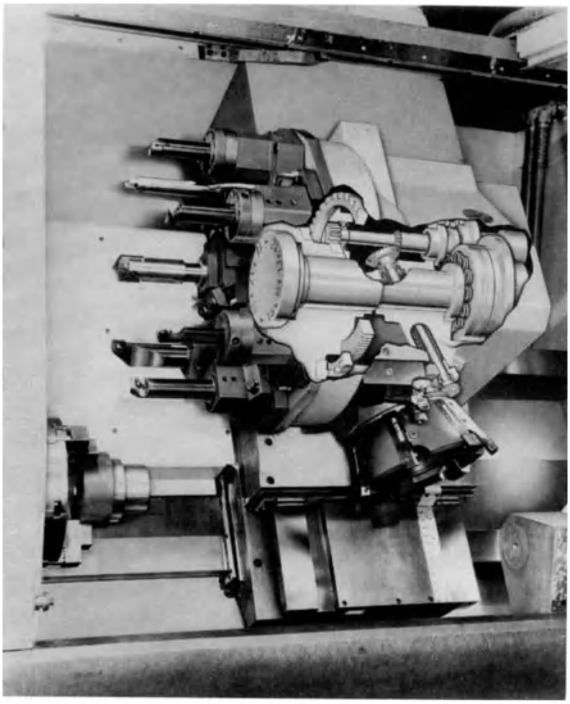


Fig. 1.23. Synchronised dual turret mechanism. [Courtesy of Cincinnati Milacron.]

the amount of tooling held on the turning centre at any instant and allows "sister-tooling" concept (this means a duplication of much-used tooling) to be incorporated, whilst a large tool library is held in the buffer-store of a chain-type holder. The versatility of tooling configurations is increased phenomenally by such mechanisms and they are often incorporated into Flexible Manufacturing Systems, but are not unusual in the larger "stand-alone" turning centre applications and auxiliary equipment.

1.3.6 Tooling Mechanisms and Auxiliary Equipment Used on Machining Centres

As with turning centre tool-carrying configurations, machining centres are just as diverse, ranging from relatively simple geneva-mechanisms for turret indexing with a small tooling complement, to highly complex and sophisticated tool storage and delivery methods. Typical of the drum-type of tooling carousels is the one shown in Fig. 1.25, where a large machining centre is fitted with twin rotary carousels holding a considerable tooling inventory. The tool transfer mechanism is situated above the machine's horizontal spindle and can extract tools from both magazines by pre-selecting the next tool to be used whilst cutting continues. These tool magazines are bi-directional, meaning that the quickest time for indexing the carousel results from it taking the shortest route to the tool-change position. Tool pre-selection in such a manner means that the non-productive idle-times are reduced to a minimum. A different approach to tool storage is shown in Fig. 1.26, where the chain-type of

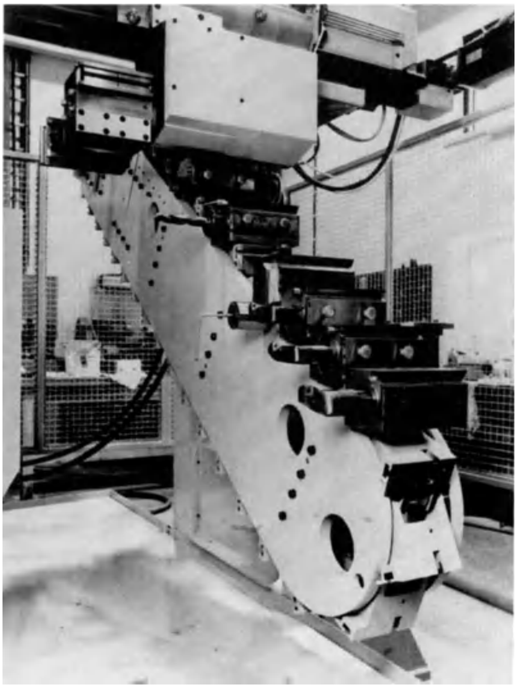


Fig. 1.24. Automatic toolchanger for a turning centre using a gantry robot. [Courtesy of SMG Co. Ltd.]

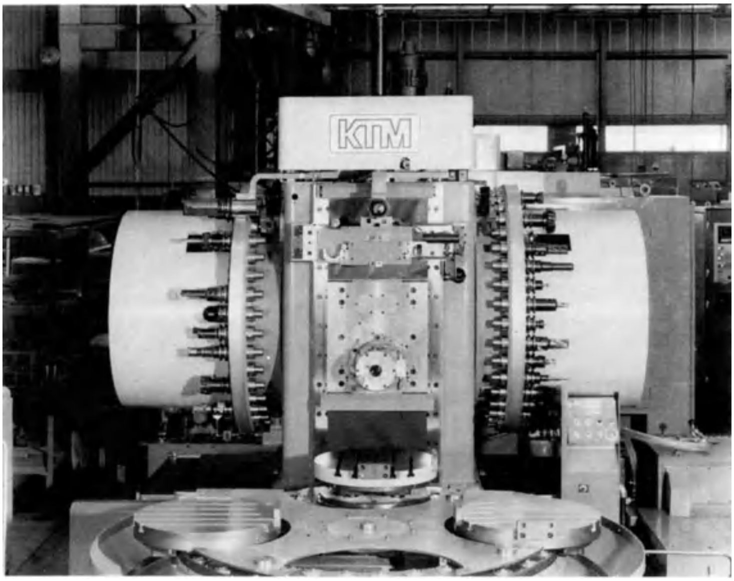


Fig. 1.25. Twin rotary carousels on a palletised horizontal machining centre. [Courtesy of FMT Ltd.]

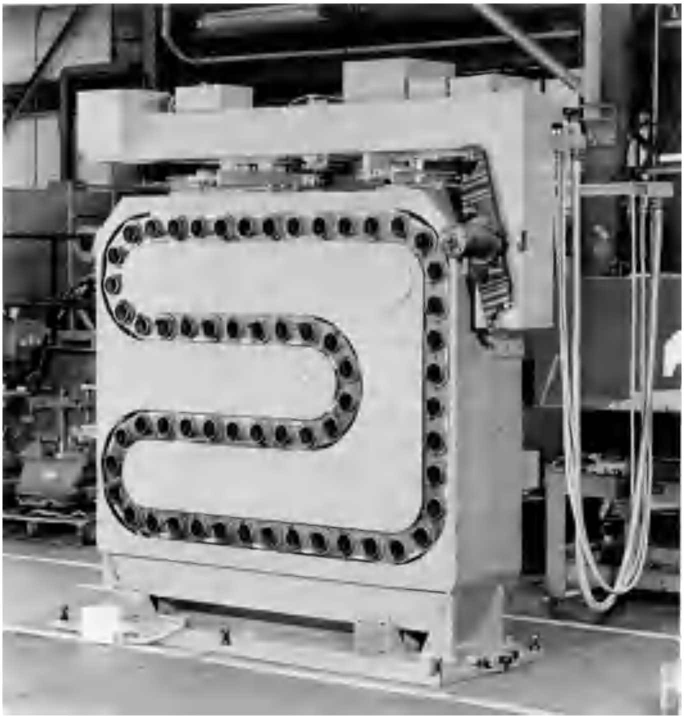


Fig. 1.26. A 60 tool capacity chain-type magazine for a machining centre. [Courtesy of FMT Ltd.]

magazine is depicted. This type of tooling configuration lends itself nicely to the "banking of magazines". With the "banking" approach to tool storage, the inventory of tools held can be increased by positioning side-by-side similar tool magazines allowing the capacities to be increased in steps of 60. Thus with only one magazine 60 tools can be held, with two 120 tools may be carried, with three "banks" 180 tools can be used on the machining centre. Obviously there is a finite limit to how many magazines can be "banked" for each machine tool and when a greater capacity is required this means using a different approach to tool delivery. More will be said on this topic in chapter 6. Yet another chain-type method of tool carrying is that shown in Fig. 1.27, where two magazines of tools are situated above and below one another and this application also lends itself to the "banking" technique, up to a maximum of three banks – giving a total of 270 tools. As can be appreciated by observing the photograph, the range of tooling carried by such magazines is immense. The tooling inventory ranges from: small drills and endmills, to multi-spindle drilling heads, special-purpose tooling and large side-and-face cutters mounted upon stub arbors, to tool-sensing probes (i.e. touch-trigger probes). Clearly, when large diameter tools are held in their respective tool pockets, then the adjacent pocket either side of this tool must be left empty to avoid them fouling one another. This fact can be appreciated by looking at the large diameter face mill shown in the bottom left-hand position of the lower magazine in Fig. 1.27 and at other positions in the photograph. Whenever a large tooling load is to be carried by a magazine it is important to "balance" the loads within it, by situating the heavy tools evenly throughout the tool pockets as this

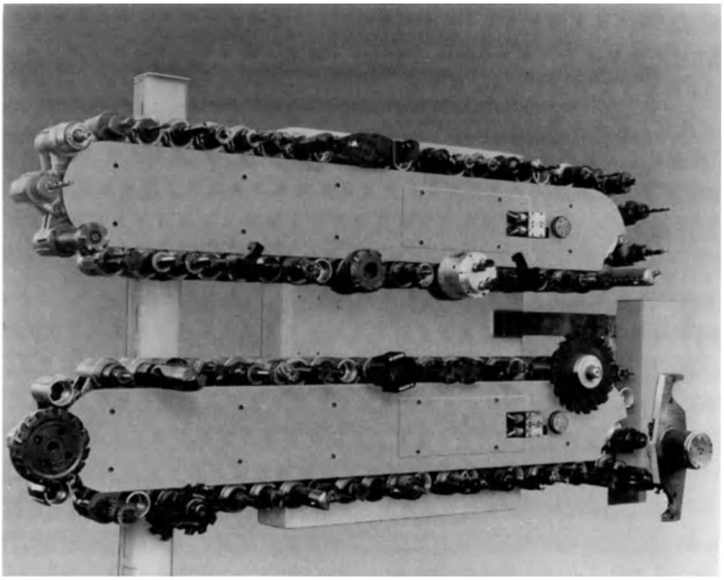


Fig. 1.27. A 90 tool capacity auto-toolchanger magazine (chain-type). [Courtesy of Cincinnati Milacron.]

ensures that an out-of-balance effect is not created in any particular area of the chain. This approach to "balanced" tool loading within the magazine can be appreciated from Fig. 1.27 where the large tool masses are distributed throughout each chain. If out-of-balanced tooling occurs there is a tendency for high inertial effects to be present within the chain and this may lead to premature seizure of the chains or tools jamming.

When a really large scale tooling capacity is needed – often in an FMS environment, rather than with the large "stand-alone" machining centres, then the "hive" tooling approach is often used. This simply consists of "racking" the tools in a storage unit and using a tool transfer mechanism to deliver them to the machine tool. This "hive" method allows a high density of tooling to be achieved in a relatively small floor area.

It has been shown in the previous comments and photographs that great importance is given to the tool change mechanism, as this will directly affect the non-productive idle times during the manufacture of a part. In order to achieve efficient tool transfer the tool changer has recently been the subject of intensive design changes by the machine tool manufacturers. Typical of a large-scale tooling complement with a heavy-duty tool change mechanism is the one illustrated in Fig. 1.28, where the whole assembly can be appreciated. This assembly will form the basis of an explanation in a step-by-step manner of the actual tool changing sequence (Fig. 1.29). In Fig. 1.29a, whilst the machine tool continues performing the cutting operations, the magazine is rotated by the shortest route until the required pocket appears at the tool change position – in this case a twist drill will be the next tool chosen. The machining is completed and the double tool change arm removes the drill from the pocket (Fig. 1.29b) and slides down to the position where tool changing can begin and whilst this is occurring the magazine rotates to the empty pocket which is ready to receive the slot drill. In Fig. 1.29c the photograph shows how the double tool change arm has swung through 90° and gripped the slot drill in the machine's spindle. The double

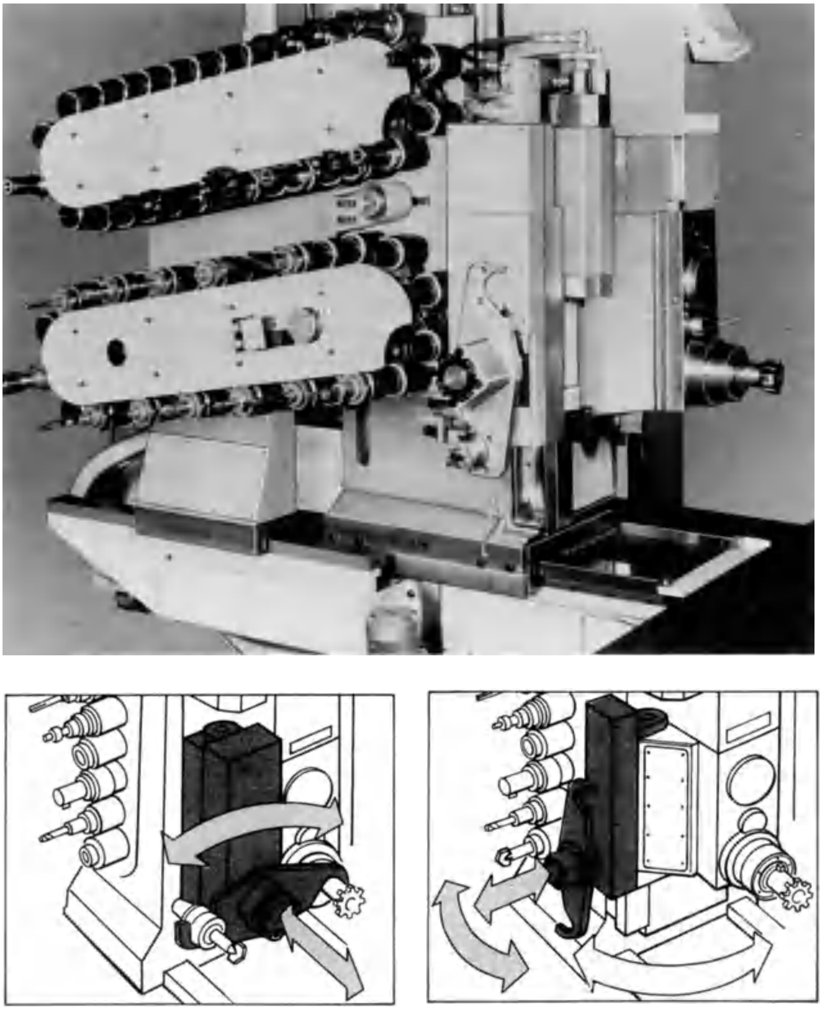
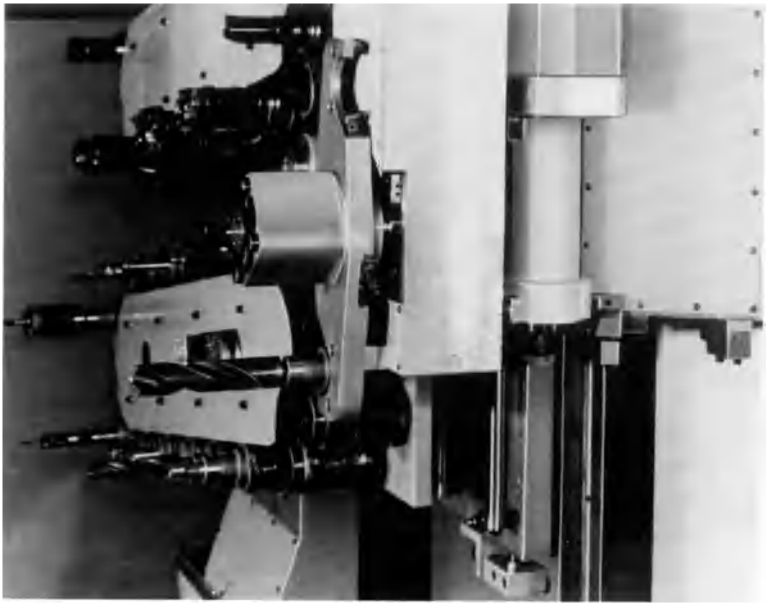
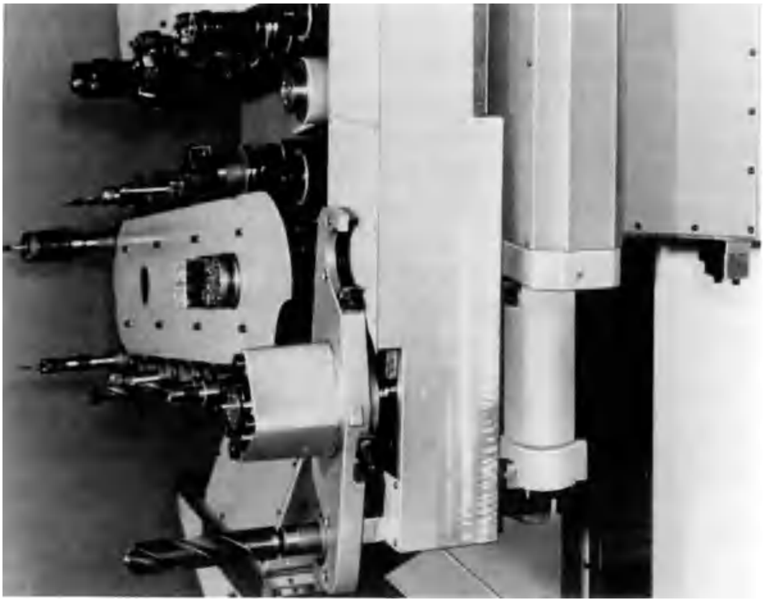


Fig. 1.28. Automatic toolchange using a double-ended index arm. The diagrams show the tool index arm movements. [Courtesy of Cincinnati Milacron.]

arm then indexes through 180°, after the hydraulic draw-bar has released the pull stud on the tool adapter and lifted clear of the spindle nose (Fig. 1.29d). It places the twist drill into the spindle nose, then it is free to withdraw from the vicinity swinging back to the tool chain to place the slot drill into its correct pocket, so that cutting can recommence. Several points should be made before we dismiss this tool changer from our thoughts. During the removal of the slot drill from the spindle nose by the hydraulic draw-bar, once disengaged from the pull-stud on the tapered tool adapter it has an air-blast through from the back of the tapered seating face. This blast of air removes any debris situated in the vicinity of the spindle nose and continues until the new tool is firmly seated in the spindle taper. This continuous air-blast will also clean the new tool of any debris which it might have picked up, allowing a positive seating in the spindle nose.

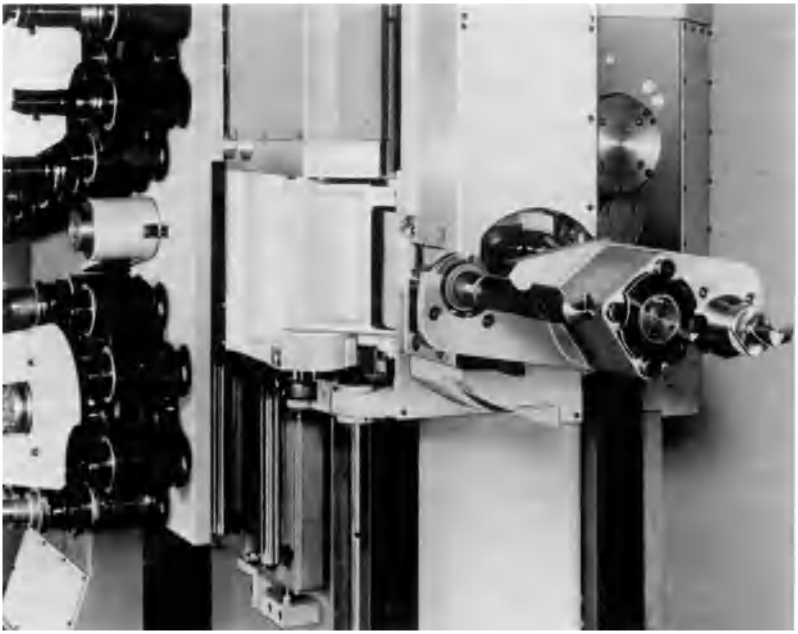


a



b

Fig. 1.29. **a** Whilst machining continues, the tool is found in the magazine (twist drill). **b** The double arm removes the drill from the pocket and the magazine rotates to the empty pocket ready to receive the slot drill (in spindle). **c** The double arm unit swings through 90° and grips the slot drill. **d** The double arm indexes through 180°, placing the drill in the spindle. It then withdraws and puts the tool in the pocket and machining recommences.



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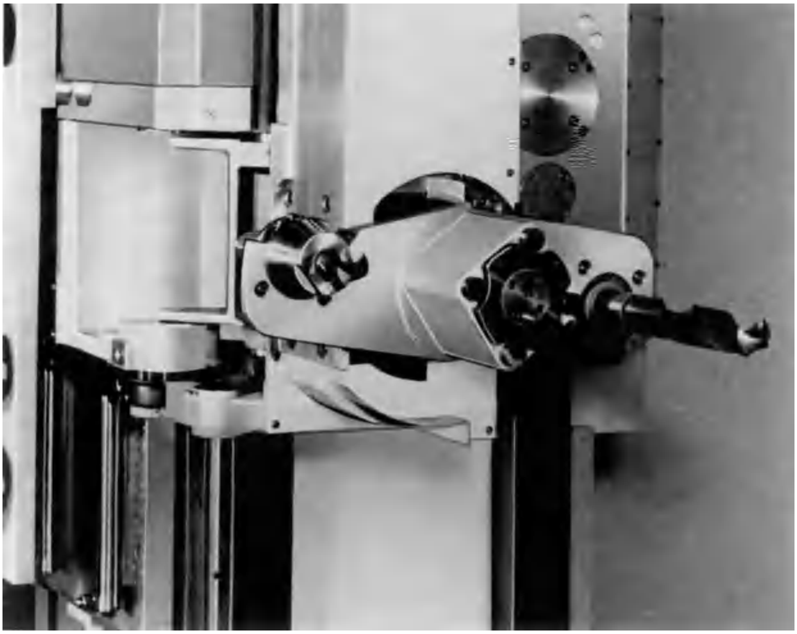


d

A tool-changing sequence similar to the one described in Fig. 1.29 would have a cut-to-cut time approaching 20 s and is reasonably slow compared to some of the latest versions offered. This is not meant as a criticism as these heavy-duty systems, and tool loads of necessity would suffer from inertial effects if there were great increases in speed. However, some of the lighter-duty machine tools with smaller tooling capacities and light tool loads can literally be swung over the Z-axis of the machine's spindle and the cutter. It is then positioned in its correct pocket by a downward slideway motion of the Z-axis, in the case of a vertical machining centre. The axis travel is then reversed and the magazine is rotated until the new tool is below the Z-axis and this tool is picked up by the movement downwards of the Z-axis slideway and when it is clear of the magazine the whole tool carousel will swing out of the way. This tool change mechanism has fewer moving parts than most conventional systems and relies on the fast up and downward motions of the Z-axis. It can typically change tools in less than 2 s, giving a cut-to-cut time of 4–5 s. Many tool changers utilise pneumatic arms for the relative motions of tool changing and it is essential to have an adequate air supply in order to minimise pressure drops which can jam the tool change mechanism during cutter removal. If tool change arms become stuck, then there is a recovery sequence of button-pressing, but the whole problem may be minimised by having enough air available to meet the demands from all other areas of the machine shop.

Special purpose auxiliary tooling equipment is available for machining centres and sophisticated and highly adaptable numerically controlled u-axis programmable milling heads can be fitted, for the machining of complex part geometries. Angled and swivel heads allow the machine tool to cut surfaces not readily accessible to the normal tooling. This means that an extra break-down and resetting of the work-holding equipment is reduced, as would be the non-productive idle times. Multi-spindle drilling and tapping heads, on the other hand, give the programmer the ability to drill, tap, counterbore, etc., a series of holes in just one Z-axis motion of the slideway. This has the affect of drastically reducing the machining time for a similar part produced using conventional machining technology and becomes a useful cost-effective addition to any medium-to-large term batch production.

1.4 Principles of Control

When the early machine tools were designed there was an obvious emphasis on manual operation with the slide positioning being controlled by human involvement. To achieve this level of control "men" used their "sensors" – eyes and ears – whilst the central processing unit – the brain together with servos (arms and legs) – allowed them to control machine tools by communication of all these interrelated functions using the central nervous system. Until the advent of micro-electronics this method for machine control was the best system of universal adaptability available, but it suffered from serious shortcomings:

a period of lengthy training was required for the craftsman
people can easily become distracted
a person's performance is dependent upon their physical/mental condition
their efficiency is inversely proportional to time
their speed of operation is limited

If these obvious disadvantages could be overcome using the latest CNC technology, how should it be developed? At the heart of any computerised machine tool is the machine control unit (MCU); this is the connection between the programmer and the machine tool. If a part program is written with/without the use of computer assistance, it must be produced in a suitable medium for conversion by the MCU into machine motions via electrical, or hydraulic servo-mechanisms. During the early 1950s the numerical control units tended to be bulky, whilst today's CNC utilises the latest microprocessor technology. The early NC systems were "hard-wired" – meaning that functions such as interpolation, tape format, positioning methods of slideways and others, were determined by the electronic elements built into the MCU. Purchasers of early NC machinery had to specify whether they wanted the equipment to function in an absolute, or incremental format and so on, as this considerably affected the cost of the MCU. The advantages gained by having a large range of programming options had to be weighed against a healthy cost penalty.

By the early 1970s electronics had become more sophisticated so that complete mini-computers were being fitted to CNC machine tools; this meant that the previous "hard-wired" options were now contained within the software package. As a result of these software options, greater flexibility of programming was possible utilising computer logic for specifying commands in absolute, incremental and polar coordinates, etc., making them infinitely more capable, but at no real extra cost. Other bonuses directly related to computer usage included the ability to be programmed at a later date using different tape formats, as these are within the computer logic at its time of original manufacture. When one considers the CNC designed MCU, it can be readily appreciated that the "soft-wired" controllers are significantly different from their older "hard-wired" cousins and have an "executive program" allowing the controller to "think" as either a turning or machining centre. The company building the CNC will load an "executive program" into it and the machine tool company will modify it to suit their requirements. In this manner the machine tool builder will use a portion of the memory for such features as: interface logic, tool changer control and so on, to give the controller the ability to be used in a specific type of machine tool.

The latest CNCs are incredibly sophisticated using a visual display of programming parameters on the cathode ray tube (CRT), similar to a TV screen. However, the real difference lies in the fact that the screen is often a multi-function type and can display the full operational and parametric data together with screen graphics; more is mentioned on this topic later when considering CNC programming and types of controllers currently available. Together with the functions concerned with actually running the program, other necessary functions that are also displayed include: diagnostic maintenance backup and trouble-shooting guidance together with many other features that may be displayed on CRT.

Any CNC has an internal memory store for keeping and listing a library of previously proven part programs and until recently these were volatile in nature. This meant that if there was no battery-backup when the machine was shut down then all the programs were lost. This was obviously undesirable, therefore non-volatile "bubble" memories have overcome the problem associated with saving the "hard-copy" punched paper or magnetic tapes as they are often termed. These "bubble" memories refer to the method of charging (ionising) particles to give the "sense" of memory. The "bubble" memories can maintain and retain the part program in their memory for many years without use and degrade very slowly. They can be "refreshed" if called into the active memory area and then restored, if necessary, at any time. The main draw-back with storing programs that are not used very often, is that the available memory is soon exhausted and it is usually more profitable under these conditions to save any infrequently used programs in "hard-copy format". Recently, some CNC systems have been up-graded to 32-bit microprocessor hardware, allowing a degree of artificial intelligence (AI) to be used to overcome and enhance the programming of parts, but more will said about this feature later when we consider part-programming techniques.

1.4.1 Machine Tool Control Systems

Slideway positional control systems may be classified into three different groups, these are:

an open-loop system
a closed-loop system, with indirect measurement
a closed-loop system using direct measurement

Considering each system in turn and illustrating their mode of operation and control using simple block diagrams will be the theme discussed next.

An Open-loop System (Fig. 1.30a)

Open-looped systems by definition do not use any form of feedback control and as such neither the slide movement nor its velocity is monitored. With such a system, the motor will simply drive the slideway to the desired position by means of a pulse count electrically generated. A command signal is sent to the stepping motor and it assumes that when the required count of pulses has occurred, the machine slide has moved a certain distance. As no form of slideway monitoring system is present, this method of control is relatively cheap to construct; however its real draw-back is that any errors that are present will obviously accumulate. As mentioned above, these open-loop systems for slideway motion and control rely on stepping motors and their method of operation will be mentioned later in this chapter.

A Closed-loop System with Indirect Measurement (Fig. 1.30b)

Any closed-loop system has two extra elements that are not present on open-loop systems. These are the measuring system and its comparator. The measuring head is attached to the ballscrew assembly, so that as it is rotated by the energised drive servo the head will begin to monitor the angular displacement then compare it with the value required by the comparator, using a feedback signal. The command/feedback signalling occurs continuously. If the slide movements are compared with an open-loop system, then the whole action seems to be much more "controlled" giving a feeling of a higher degree of precision to the system. One problem associated with this indirect feedback control system, is that it is prone to suffer from "torque effects". These effects are a result of minute twisting of the ballscrew as heavy cuts are taken and this problem cannot be monitored – and hence controlled – by the comparator, thus a small error can occur in dimensional accuracy of the part.

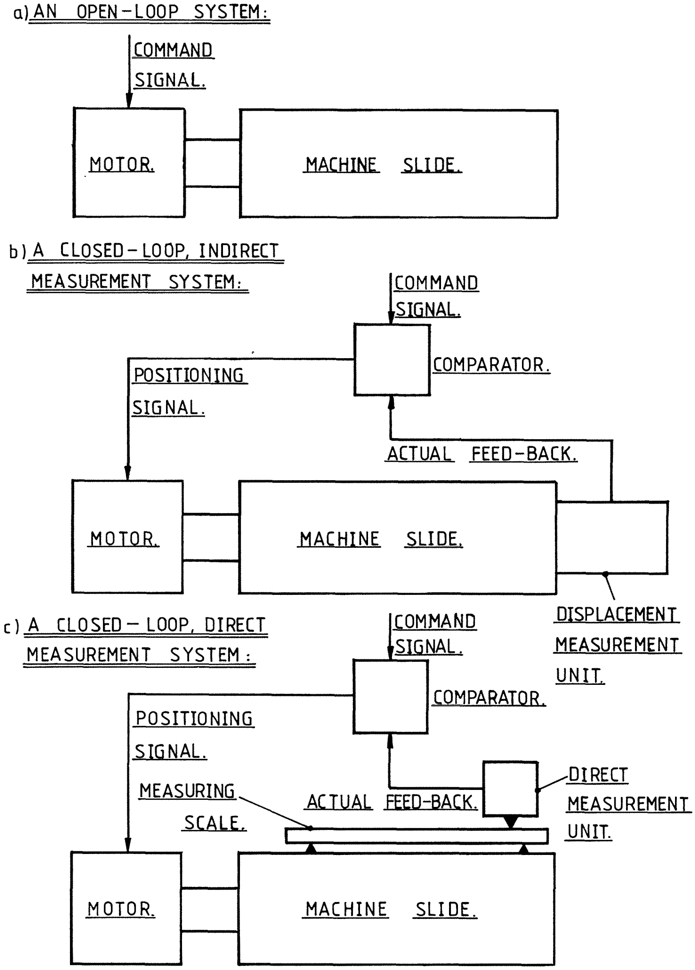


Fig. 1.30. Typical control systems. [Courtesy of Sandvik (UK) Ltd.]

A Closed-loop System Using Direct Measurement (Fig. 1.30c)

Systems using a direct measurement closed-loop can be thought of as an almost "ideal" method of control, as they measure the slideway position directly and hence the workpiece. To obtain measurement of the slideway movements the linear measuring scales are mounted along the length of each slideway. As with the indirect feedback system, the same comparator principle is used, but because the measuring scale runs the length of the axis travel it improves slideway determination and higher positional accuracy results, without the effects of torque reactions affecting the readings. Invariably, linear scales are a costly option which most machine tool builders offer and they are becoming more popular as the demand for higher accuracy components drives the pace for better quality products by the consumer. Linear scales need protection from the machining environment, but offer elimination from backlash, pitch error in the ballscrew and torsional effects.

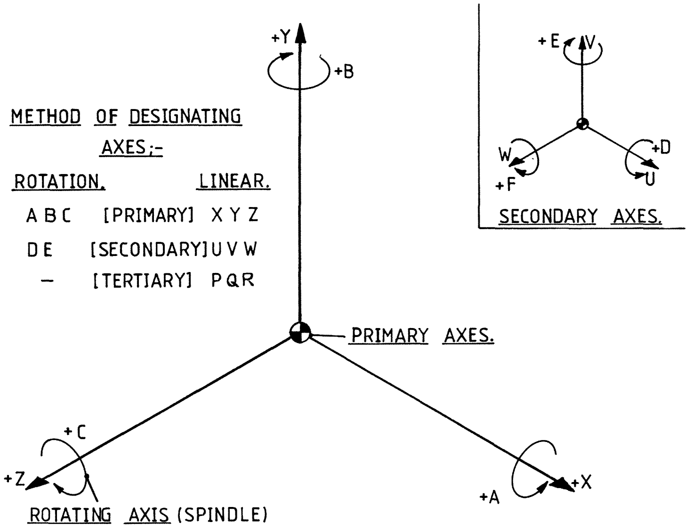


Fig. 1.31. Designation of the machine axes.

NB: to a certain extent the pitch error can be compensated for, once the machine has been calibrated. Calibration to eliminate the errors occurs by programming a laser interferometer to take account of the slideway pitch errors in the ballscrew. Thus as the program for the machining of the part occurs, minute slideway adjustment of its position is undertaken keeping a higher precision than the ballscrew would otherwise suggest.

1.4.2 The Designation of Machine Tool Axes

The BS3635 Part 1: 1972 and the German VDI proposal 3255 have identified CNC machine tool axes with the following three-dimensional mathematical system: X, Y and Z using upper case letters. The direction of movement along each axis is denoted by a plus (+) or minus (−) sign, from an established datum. Together with the primary axis designations, there is rotational notation around each linear axis and this is specified by A, B and C in upper case.

These linear and rotational motions are illustrated in Fig. 1.31; however, a number of rules are observed when considering motional kinematics:

coordinates are perpendicular with respect to each other and primarily refer to the workpiece, with the direction of the machine tool motion being derived from them

for all machining phases such as workpiece swivelling, the coordinate system is retained

following the mathematical direction of rotation, the angles should be stated clockwise from the datum – looking in the positive direction

the origin of the coordinate can be positioned outside, or inside, the workpiece and with care in the axes selection, only positive coordinates will result. The alternative would be a mixture of positive and negative coordinates, which might add to confusion when programming.

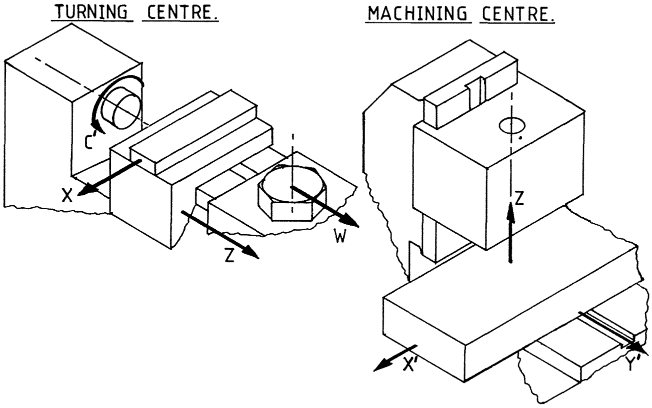


Fig. 1.32. Machining axes designation as applied to machine.

When one considers the methods for axes identification on turning and machining centres (Fig. 1.32), we note that in both cases the rotating axis is always Z. So in the case of a lathe or turning centre, the workpiece rotates, whereas on a mill or machining centre it is the cutter. On a turning centre the next principal axis is the X and two others are shown, the workpiece rotation C′ – that is counterclockwise, with C being clockwise rotation, and when the machine tool is fitted with a secondary turret, the notation is W. The secondary axes system U, V and W is independent and parallel to the primary axes X, Y and Z respectively, as shown in Fig. 1.31. A third, or tertiary, linear motion with the axes recognition of P, Q and R is again parallel to and independent of X, Y and Z which can also occur. Thus the secondary linear motions are those nearest to their parallel and independent primary axis respectively, whilst the tertiary axes are obviously farthest away.

The characters D, E and F are normally used to designate secondary angular/rotational motion either parallel to A, B and C, or about special axes. To confuse us even more, D may be associated with a tertiary feed function and E a secondary feed function!

When axes designations are assigned, it is assumed that the cutter moves in relation to the workpiece. We know that this is not always true and on many machines the workpiece moves relative to the cutter, which means that the workpiece moves in the opposite direction to the tool. Under such circumstances, it has been stated that each axis should be designated by a prime mark (dash). In Fig. 1.32, the milling application shows this notation, namely X′ and Y′. All of this seems rather complicated, but fear not, the programmer need not be too concerned with prime designations. If one considers that the X axis moves to the right along a plane of the workpiece, when facing that plane, with Y moving up and Z moving out, this simplifies things considerably. So, if the cutter moves over the workpiece, or vice versa, this possible confusion becomes of minor consequence. The main concern is to obtain the correct finished geometry on the workpiece and to achieve this aim, the programmer must know the machine type and its basic axes designations. To put it another way, the programmer needs to know which axis is, for example, say, the Y, and what is the plus direction, and which is the minus, and this is so for each linear and rotary axis.

Just to complete the intricate picture of axes designations, if a multi-spindle machining centre was to be used: motions, or axes that are parallel to and "slaved" to the principal axis, are designated as follows: the principal axis is Z, and say the two "slave" spindles would be Z2 and Z3 respectively. This would be true for a gantry mill with three spindles working in unison on a profiling application.

1.4.3 The Positional Control Modes Used on CNC Machine Tools

Other than classifying machine tools by their cutting processes, it is also possible to distinguish them by the method used for positional control of the slideway motions. Broadly speaking, there are three main positional control categories used in classifying all CNC machine tools:

point-to-point
straight-line (or paraxial as it is sometimes known)
continuous path control

These methods of positional control systems will now be briefly reviewed.

Point-to-Point Controlled Machines (Fig. 1.33a)

The applications of point-to-point machines might be to either drill and tap, or be used in a punch-pressing operation. The system works on the principle that once the command signal has moved the slides to a particular point – usually a fixed set of cartesian coordinates – then the table is clamped and the cutter begins machining. The manner in which the cutter is positioned over the next feature to be machined is irrelevant and can be seen by the cutter path in Fig. 1.33a. At first glance, it looks as though a random cutter path occurs to the next feature, but this is not the case. In fact, the controller works on the following principle (see Fig. 1.33a): if the cutter can move in a straight line it will, as shown by positions 1 and 2 in the diagram. However, when the next hole is after hole position number 5, then the motion is for both axes to move simultaneously at rapid speed. Thus the approximate angle of 45° occurs until one of the coordinates is reached. This causes one axis to cease moving and motion occurs along one axis until the final position is reached.

NB: All movements are undertaken at full speed.

The requirements of the controller are relatively unsophisticated, with a fast response to the slideway motion produced through needle roller, or linear bearing types, or indeed using air bearings, as the loads are low.

Straight Line, or Paraxial Control (Fig. 1.33b)

If a milling operation is the requirement from one feature to the next, then there is usually a feedrate associated with this movement. Therefore the previous point-to-point method of control would be useless, as each axis must be monitored continuously under full control. Paraxial control was a system developed quite early on, which gave machine tools better control and adaptability than the point-to-point variety. However, to the author's knowledge, there is no machine tool company that solely offers this type of positioning facility nowadays.

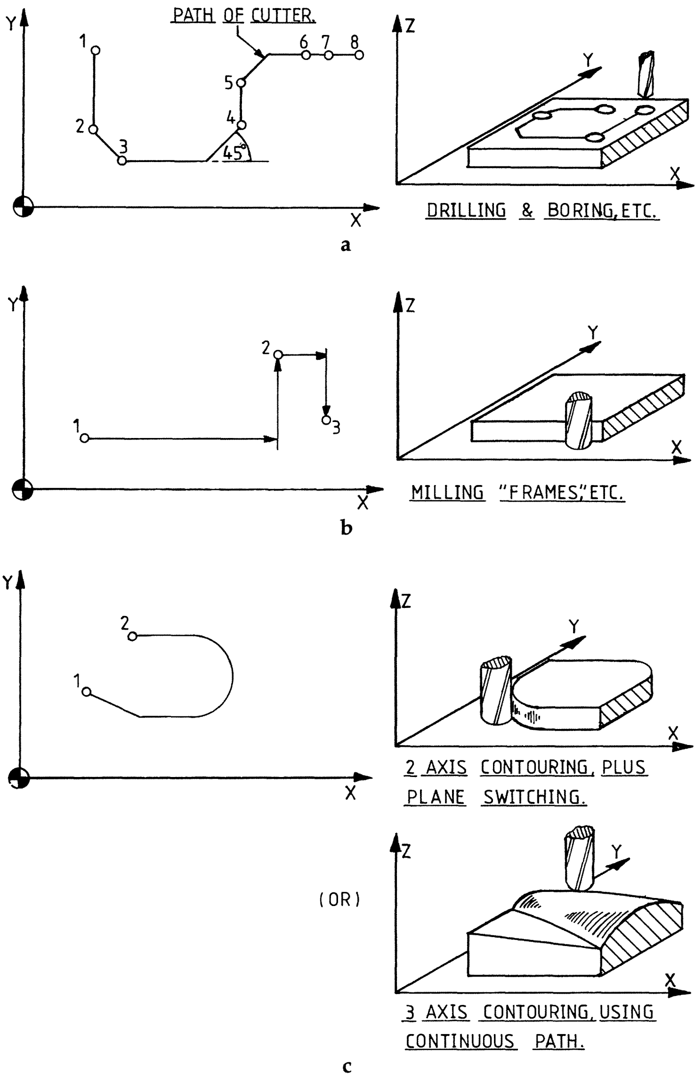


Fig. 1.33. Various types of control modes. **a** Point-to-point control. **b** Straight line or paraxial control. **c** Continuous path control.

Continuous Path Control (Fig. 1.33c)

Contouring systems such as the continuous path type are by far the most common types in use today. They have synchronised drives for feeding, providing an accuracy of positioning anywhere within the "work envelope". These universal controls can be used for point-to-point positioning and can rapidly vector from one coordinate to the next; they can also be fed in a straight-line motion or be used for contour feeding applications. When contouring, the tool's position must be continuously controlled and this means that the controller must frequently change the relationships of the linear motions of two or more axes in order to generate a contoured profile on the workpiece. The control path must have an interpolator, so that it can calculate continuous path positions until the target point is reached. To illustrate the requirements of such a contouring operation, if we consider that a contour is to be machined on a turning centre, then to discriminate between one point and the next on the X/Z plane, then the rectilinear movements must maintain an X:Z path ratio with a speed control that governs the feed drives in the exact synchronised ratio of fx:fz, for the shape to be successfully produced on the workpiece.

On most machining centres, they use two and a half axes for continuous path control, where two axes are used for circular and one for linear interpolation when machining three-dimensional (3D) shapes of reasonable complexity. If, however, a "true" 3D or multi-path milling control is required, then a more sophisticated machine tool is usually desirable. Mention should be made of the fact that even when controlling only two and a half axes, if the information has been post-processed on a CAD/CAM work station, then intricate 3D shapes can be successfully machined, but more will be said on this topic later.

It has been mentioned that when we are controlling axes an interpolator is used; so what are these interpolation methods and how do they differ? This will be the subject considered under the next section, where most of the popular interpolation methods will be reviewed.

1.4.4 Interpolating Methods on Machine Tools for Control of the Cutter Path

In a strict mathematical sense, if we know where the coordinates of two points are in space, then as long as we define any position between these points we are "interpolating" and this is what a control system tries to achieve. There are many techniques used for the interpolation of the cutter path that have been developed over the years, with some of them losing favour of late. The principal interpolation techniques used are:

linear interpolation
circular interpolation
parabolic interpolation
helical interpolation
cubic interpolation
involute interpolation

The first four have been shown schematically in Fig. 1.34 and a brief review of each type will now be considered.

Linear Interpolation (Fig. 1.34a)

As its name implies, this method produces programmed points connected by straight lines, whether this distance is close or far apart. Motion can be achieved in any number of axes simultaneously. As an example of this, if we consider a machining centre's axes configuration, it can produce linear interpolation on the X, Y and Z axes for spatial point movement and B and C for rotating motions. Thus, on a 5-axes machine tool it would be incrementing feeds at differing rates to allow for contour machining to be undertaken.

When a contour is to be machined using linear interpolation, then the higher the number of individual points present, the closer this approximation is to a true curve

(Fig. 1.34a). To achieve this feat, the controller requires a high data processing ability and using such methods it is possible to theoretically control the cutter path around any complex shape, notwithstanding the geometrical limitations of the cutter orientation to the workpiece. A major problem with using this interpolation method, is that when contour machining, the part programs tend to be of vast block length. Incidentally, this was one of the major reasons for the demise of NC punched paper tape as a storage medium for complex contours. This point brings us nicely to a consideration of the reasons why circular and parabolic interpolation have become popular, in particular the former technique.

Circular Interpolation (Fig. 1.34b)

Interpolation using circular motion control is the next order of CNC movement and has become a standard feature on most machine tools today. Principally, its obvious use is in the machining of circles, or portions of circles – or their approximations. Minimal data is needed to generate the necessary circular motions. Normally, all that is required are the arc centre coordinates and the end points of the arc, together with the circle radius to complete the programming as well as the direction of cutter movement around the feature. On most machine control units (MCU), the circular interpolation requires that the circle span be broken down to a single pulse output of approximately 0.0005 mm. This output is termed the "pulse weight", however, most systems resolve to 0.001 mm. Automatically, the interpolator will compute enough of these "pulses" to describe the circular cut, then the controlling signals will be generated progressing the tool's path along this feature. Hence, the cutter path around a circular arc will be within plus or minus one "pulse".

Circular interpolation may only be used on two axes planes at any instant and will not interpolate on all three simultaneously. By utilising a series of arcs, a free-form shape may be closely approximated using fewer data points, giving a truer profile than by linear interpolation.

Parabolic Interpolation (Fig. 1.34c)

Interpolation by parabolic means is an even higher order than the others mentioned so far and has been almost exclusively used by the automotive industry in the past, for the manufacture of free-form shapes. To define the curve using parabolic interpolation, three points are needed: two end points and a mid point (Fig. 1.34c), as a parabola has a "unique" focus. This technique defines a curved profile with better than 50:1 fewer programming points than by linear interpolation. The major disadvantage of parabolic interpolation, when compared against the linear method, is that to program a shape with this technique a more specialised programming language is necessary and for this reason it has lately fallen out of favour. The latest CNCs offering circular interpolation have vastly higher computing power than was previously available, allowing free-form shapes to be machined and this is another reason for the decline of parabolic interpolation.

Helical Interpolation (Fig. 1.34d)

Owing to the fact that many operations previously machined on the turning centres can now be undertaken on machining centres has meant that a new form of inter-

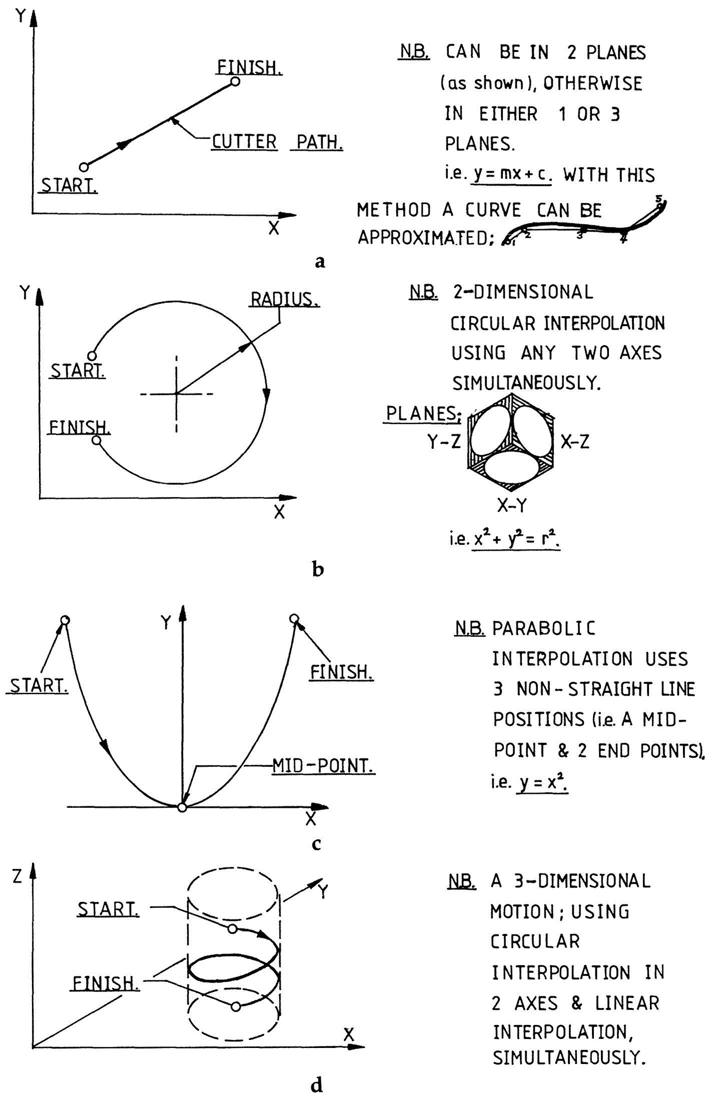


Fig. 1.34. Interpolation methods. **a** Linear interpolation. **b** Circular interpolation. **c** Parabolic interpolation. **d** Helical interpolation.

polation has been developed. Helical interpolation allows programmers to exploit these new capabilities, giving them the ability to mill internal and external threads. Helical interpolation utilises two axes providing circular interpolation whilst simultaneously providing linear interpolation in the third axis (Fig. 1.34d). This helical interpolation feature allows single or multi-start threads to be generated on the workpiece successfully.

Cubic Interpolation

In a similar manner to parabolic interpolation, the main users for this technique are the automotive and aerospace industries, where it is often required to machine free-form component geometries, but even here, there are only a limited number of users. Using cubic interpolation, that is the ability to produce a third degree curve, gives the programmer the ability to generate complex profiles with a small number of data inputs. It describes curves accurately and allows for the smooth blending of one curve to another without geometric discontinuities. The programmer uses customised software when describing free-form shapes and does not have to write cubic interpolation executive routines.

Involute Interpolation

Recently, the introduction of involute interpolation has been found on some CNCs. This technique allows the programmer to specify gear tooth forms based upon an involute form, to be quickly and accurately defined using just a few data inputs.

General note: When considering the variety of interpolation techniques available then the following observations based on the part geometry to be machined can be made. If the profile is:

a straight line – use linear interpolation
a circle – use circular interpolation
a helix – use helical interpolation

if none of these, use linear interpolation – to approximate the curve, but never allow the cutter path to deviate more than the component's tolerance.

1.5 Measuring Systems for Machine Tool Path Determination

To determine the slideway position of each axis of a machine tool, an electronic measuring device is required and this monitors and compares the present position with the command position for every movement of the axis. Various criteria must be considered by the machine tool builder when selecting a suitable measuring system, such as: the accuracy and precision, its reliability, the length of total traverse and the expected maximum velocity of the slideway motion, together with the cost of fitting such a system. To compound the problem, there is no specific measuring device used throughout industry, and by way of illustrating this point, it is possible to select either a closed or open-loop system with rotary or linear monitoring, which may have either direct or indirect feedback using an analogue or digital signalling method. As such a choice is available to the designer for axis monitoring systems, then each type has certain advantages and, of course, limitations. However, as so many methods of monitoring the slideways exist, only some of the common systems will be discussed.

1.5.1 The Stepping Motor (Fig. 1.35)

A common method of assessing the rotational displacement of the ballscrew on the lower cost machine tools is by way of drive by the stepping motor. This open-loop device does not monitor the axis position, but relies for its accuracy on discrete steps that the rotor can be rotated through in order to achieve the desired linear displacement via the ballscrew rotation. To describe the types of stepper motors available

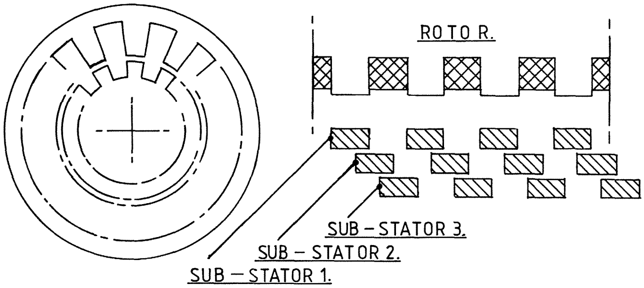


Fig. 1.35. The principle of the stepping motor.

would need considerable space, so only a simplistic view of its operation will be given. As a rule, stepper motors fall into two categories: the permanent magnet motors, and variable reluctance motors, but there are hybrid constructions which feature some of the functions of each type.

Basically, the stepper motor utilises the well-known principle that unlike poles attract; if one assumes that the rotor and stator were made to appear like toothed wheels (Fig. 1.35), with the general convention being for the external teeth on the rotor and the internal teeth on the stator. With this approach, if we consider that the alternative teeth are magnetised as either a "north" or "south" pole, this means that the corresponding pole on the rotor will be attracted to the opposite pole in the stator. Assuming now that we turn the stator, this would also turn the rotor, but naturally the stator is not physically turned as it is the fixed part of the motor, although it is possible to turn it electrically.

Normally a number of sub-stators are used to make up the total stator, with each sub-stator being displaced from the next one by a "step" of 5°–10°. If the sub-stator is now sequentially energised – that is one after the other – the rotor is attracted to the next pole and so on. So as the poles are displaced a definite distance, the motor is said to "step". Most stepper motors use 3 or 4 sub-stators, so that once the last one has been energised, the cycle recommences at the first. Whenever the stator is energised in the reverse direction, this causes the motor to run backwards. In this manner, it is possible to convert digital signals directly into a defined distance, enabling an open-loop CNC motion to be achieved.

1.5.2 Indirect and Direct Methods of Control of the Slideways

It is worth restating that there are two basic methods of controlling the slideway position prior to describing in detail closed-loop systems: indirect and direct techniques. Fig. 1.36 schematically illustrates the two methods of monitoring slideway position. The indirect method utilises the ballscrew for positioning, whilst the slideway positional measurement is the linear distance travelled, which is monitored and subsequently fed to the computer controlling the axis. Alternatively, the direct method of slideway measurement uses a long, permanent scale fixed between the machine's non-moving casting and the reading head to the moving slideway. A major bonus of such a system is that the slide measurement does not rely on the ballscrew accuracy and the presence of possible backlash, or indeed, the motor drive for positional accuracy. These advantages of backlash and torque reaction elimination occur with

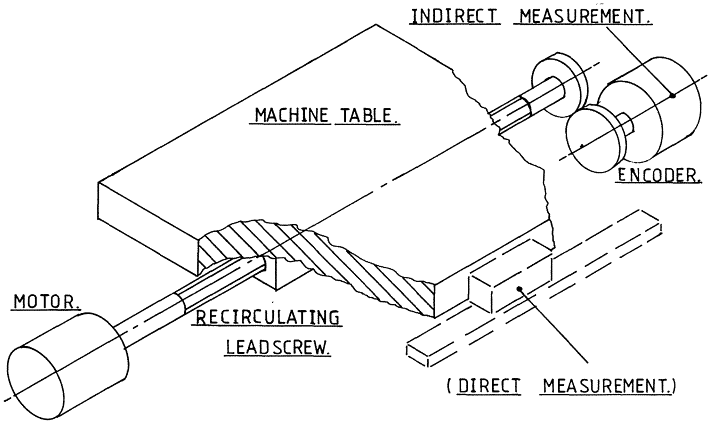


Fig. 1.36. Indirect and direct measurement.

direct measuring techniques, although they are present during heavy cuts with the indirect methods and as such the "direct" methods give greater determination and precision of slideway positioning. It should be noted that "Abbe's principle of alignment" is still not complied with, owing to the fact that the table ballscrew drive and the measuring position of the fixed scale are not coincident. Abbe's alignment principle states that "the measuring plane and the measuring position should be coincident", whereas in reality there is an offset between the cutter path and its measurement plane, which might cause errors to be induced during cutting operations.

Analogue and Digital Measurement

Earlier it was stated that there are two types of measuring principles: analogue and digital. The analogue system implies that a signal such as an electrical voltage magnitude will represent a physical axis position, or to say it another way, we use the physical variable of distance to represent a voltage. A specific slide displacement will be "analogous" with an induced voltage; for example: 15 V equals 150 mm travel of the slideway from its datum. Conversely, the digital measurement technique is usually a pulse counting device, which counts the discrete pulses that are being generated by a direction sensing grating as the axis moves. These digital systems will now be considered in more detail.

Digital Measuring Systems

A digital device can be either of linear or rotary configuration, with two main principles used:

photo-electrical systems
inductive scanning methods

It is worth mentioning that inductive scanning techniques are not used on CNC machine tools, because they have a relatively large resolution which excludes them from the precision applications of this nature.

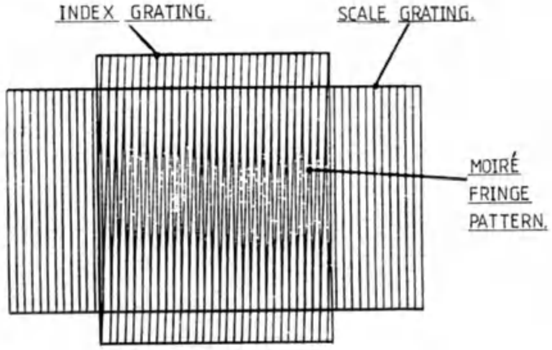


Fig. 1.37. The principle of optical measurement based upon Moiré fringes.

By way of introducing digital systems, the photo-electric slideway positioning technique will be reviewed initially, using a lamp or fibre optic unit together with photocells and some form of grating, and then some other methods will be briefly considered.

The Principle of the Optic Grating

The optical grating principle is based upon the well known "Moiré fringe effect" and is shown in Fig. 1.37. Optical gratings may be made from glass, or a reflective strip onto which is marked, or photo-etched a series of parallel lines closely and uniformly spaced together. Effectively, the same equally spaced lines occur on both the index and scale gratings. The long fixed scale grating extends over the length of the machine tool's axis travel, with a short index grating overlaying it, being held in a reading head. The lines of both gratings are set at a small angular displacement to each other. This causes an interference effect between them at the intersection of the lines. This pattern is termed a Moiré fringe.

In practice, when the slideway is moved the lines on the two scales are displaced and, as a result, the fringe pattern travels at right angles across them, with their direction of movement being dependent on the plus or minus direction of the slideway, as shown in Fig. 1.38. A dark fringe pattern is produced across the width of the grating and moves in the sequence shown in the illustrations. Now, if a collimating beam of light is placed either through the glass gratings, or reflected from it – depending on the system used – then a change in the light intensity occurs as a result of the fringe pattern motion being of sinusoidal form. Photo-electric cells are strategically positioned to detect this fringe pattern, converting it from light energy into electrical energy – pulses. These pulses are counted, relating to the number of lines displaced on the scale grating as it passes through the reading head. If the line pitches are known precisely, then the slideway displacement can be monitored. The reader should gain an appreciation of this phenomenon by a practical demonstration using two hair combs, with one placed over the other – but at an angle to it. Whilst holding one still, to represent the fixed grating and moving the other, to indicate displacement of motion over the index grating, a fringe pattern can be crudely shown to move upwards or downwards depending whether motion is to the right or left hand. This shows the basic effect of a Moiré fringe operating principle.

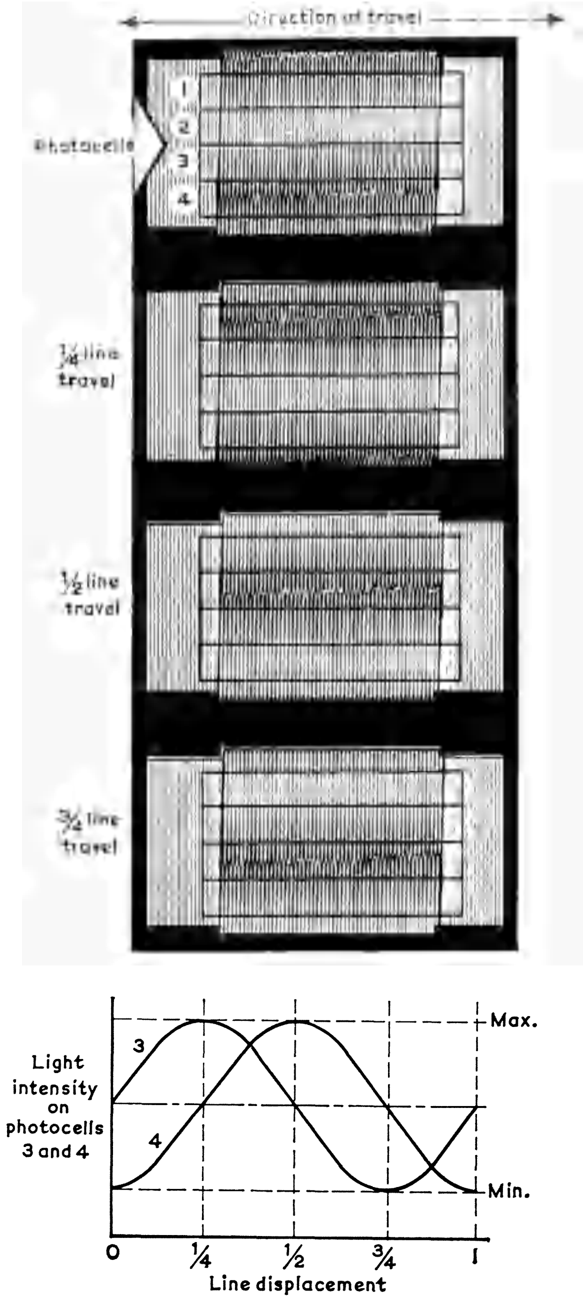


Fig. 1.38. Four-phase fringe system with resultant waveforms. [Courtesy of Ferranti Ltd.]

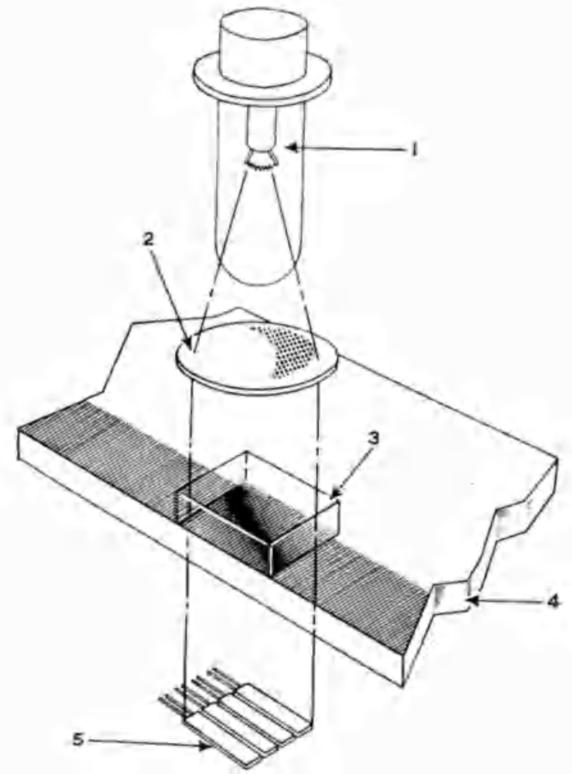


Fig. 1.39. Optical arrangement used with line and space transmission gratings. 1, exciter lamp; 2, collimating lens; 3, index grating; 4, scale grating; 5, photocell strips. [Courtesy of Ferranti Ltd.]

In order to gain some degree of discrimination from one fringe to the next, four photo-cells are usually spaced across the grating's width. As a result, four pulses per cycle occur, with each pulse representing 0.005 mm if the pitch of the gratings is 0.02 mm. The sense of slideway direction can be obtained, by registering the order in which each photo-cell is energised. Each axis when in motion produces generated pulses, and an electronic decimal counting device sums them up, adding or subtracting them from their various slideway displacement directions. All axes can be set to zero at any convenient position and a comparator unit compares the actual slide position with the command position and if a difference occurs, corrective action by the servo-drive system results.

Typical arrangements of the optics and their respective Moiré fringe assemblies are shown in Figs. 1.39 and 1.40, for glass and reflective gratings, respectively. These optical configurations are perfectly acceptable for lower accuracy machine tools, but if high precision continuous control is required, then a more complex arrangement is necessary. The upper diagram in Fig. 1.41 illustrates the previously mentioned incremental mode type, whereas in the lower diagram the sophisticated high accuracy approach for continuous path CNC uses more tracks to detect movement, with the distance quanta doubling for every extra track added. In Fig. 1.42 an enlarged version of this absolute scale method can be seen, using this "V-scanning" principle as it is

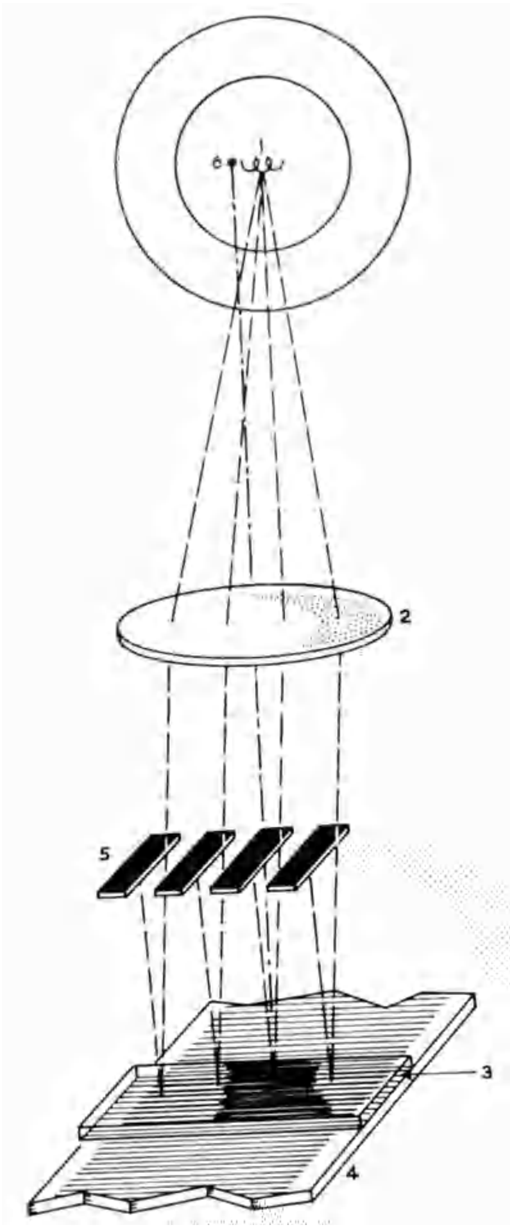


Fig. 1.40. Optical arrangement used with reflecting gratings. 1, filament; 2, collimating lens; 3, index grating; 4, scale grating; 5, strip-silicon photocells. [Courtesy of Ferranti Ltd.]

often termed. It is worth discussing how and why this arrangement improves the accuracy of slideway positioning of machine tools over the previous systems mentioned so far. Any CNC machine tool uses binary coded decimals – numerical control, with the top diagram in Fig. 1.42 schematically illustrating a binary signal stretched

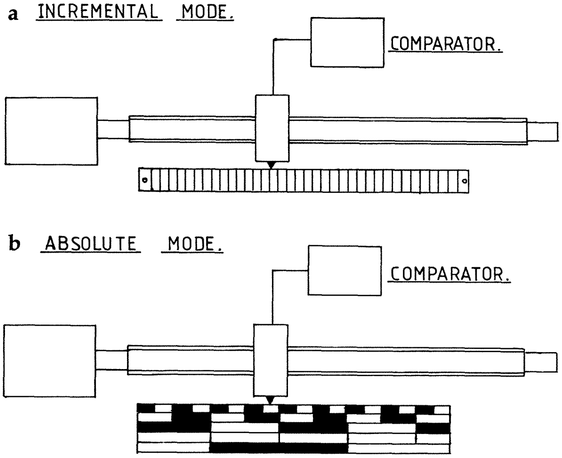


Fig. 1.41. Modes of measurement. **a** Incremental mode. **b** Absolute mode.

out for the slideway length in longitudinal tracks. When the slide is moved, a binary signal is produced and can be analysed, allowing the exact position of an axis to be established. A problem arises with this technique in that the photo-diodes cannot be exactly positioned so that all tracks are "switched" at the same time, leading to the likelihood of faults in the reader system. The problem is overcome by using a "grey-code" switch track and a V-form reader. The photo-diodes are arranged in the V-form with the finest track using a single photo-cell, whilst other tracks have two photo-cells positioned such that they are in the middle of the respective distance quanta producing the so-called V-form. This configuration offers the advantage that only the finest track needs to be very accurate, meaning that its calibration is much easier to achieve.

There is a wide range of rotary and linear monitoring systems available to the machine tool builder.

Analogue Measuring Systems

A brief discussion of analogue systems was given earlier in this section and they can be either rotary or linear measuring devices. The principle of operation of analogue devices is that an inductance of an applied reference alternating current occurs from a stator to a rotor, or vice versa, when of the rotary variety. The latter system known as a "Resolver" will be mentioned first, and its cousin, the linear resolver known as the "Inductosyn", will complete this review of analogue techniques.

The Resolver (Fig. 1.43)

The operational procedure of the resolver is that if the rotor is lined up with the stator, then the induced voltage is at a maximum and when the rotor is at 90° to the stator, the voltage induced becomes a minimum. By counting the number of times the voltage reaches zero, it is possible to determine how many times the resolver has

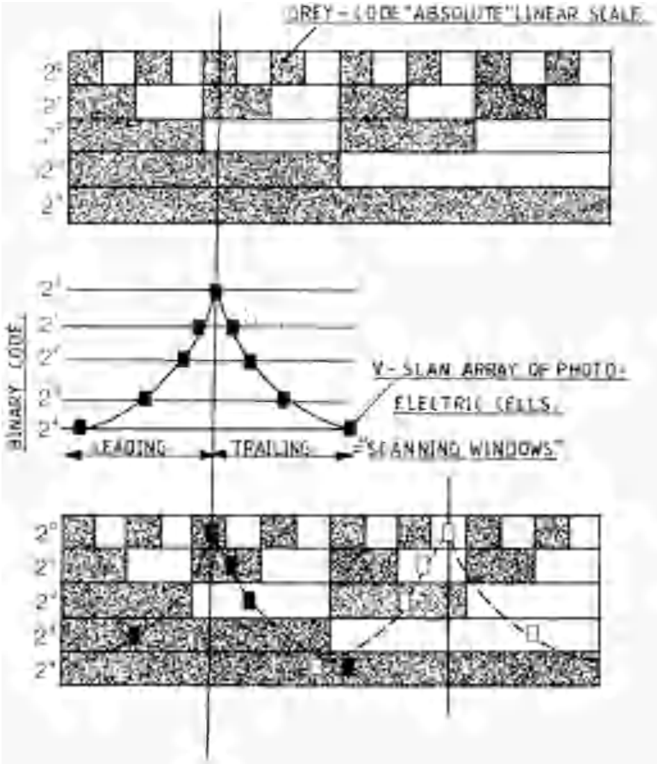


Fig. 1.42. V-scanning.

turned and this being connected to the ballscrew assembly, determines the table's position. A further feature of the resolver is that the phase is altered so that at each zero mode there is a phase shift of 180°. By using the commonly practised two-phase secondary winding technique where each winding is displaced at 90° to the other, then the phase displacement and amplitude are "resolved" into their respective sine and cosine components and can be analysed for slide displacement. A typical resolver has a slideway resolution of 0.01 mm.

The Inductosyn (Fig. 1.44)

An inductosyn is simply a resolver that has been "straightened out". The system uses a printed circuit winding that is etched onto a carrier board and fixed to the length of each axis of the machine tool. The winding carries a reference AC voltage with a frequency of 1–20 Hz. Superimposed over the winding running the length of the slideway travel, is a short slider. This slider has etched onto its surface two windings that are displaced electrically at 90° to each other. The resulting induced signal is "resolved" in the same manner as the previous analogue method discussed for the resolver.

A typical resolution of the inductosyn is 0.0025 mm and like the optical grating system discussed earlier, it finds many applications on CNC machine tools. A general

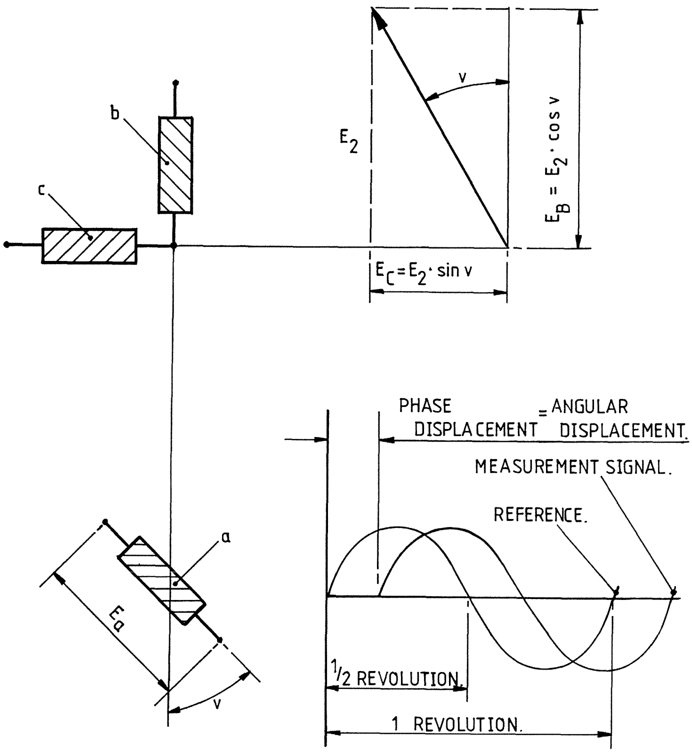


Fig. 1.43. The principle of a resolver.

assembly partially cut away is shown for slideway monitoring in Fig. 1.45 and a rotary application for a fourth axis on a horizontal machining centre in Fig. 1.46.

The Laser (Fig. 1.47)

The laser offers the ultimate in position monitoring devices presently attainable, but is still under development at the time of writing. However, it cannot be long before such systems are adopted by machine tool companies for ultra-high precision work. It offers the major benefits in a high resolution, direct reading, closed-loop and linear control system for slideway positioning. To monitor the slideways, a stabilised laser interferometer, coupled to customised optics, together with an electronics and software package, produces the high resolution required and should be available in the future. A data transfer rate equal to the laser reference frequency can be achieved.

A typical laser arrangement of an expected 3-axis closed-loop control on a machine tool is shown in Fig. 1.47. The stabilised helium–neon continuous wave two-frequency laser head sends out a beam which is bent, split and reflected around the machine tool axes and then back to a receiver unit, closing the loop.

There are several major advantages with such systems apart from the high resolution of around 10 μm, including the much sought after ability to compensate auto-

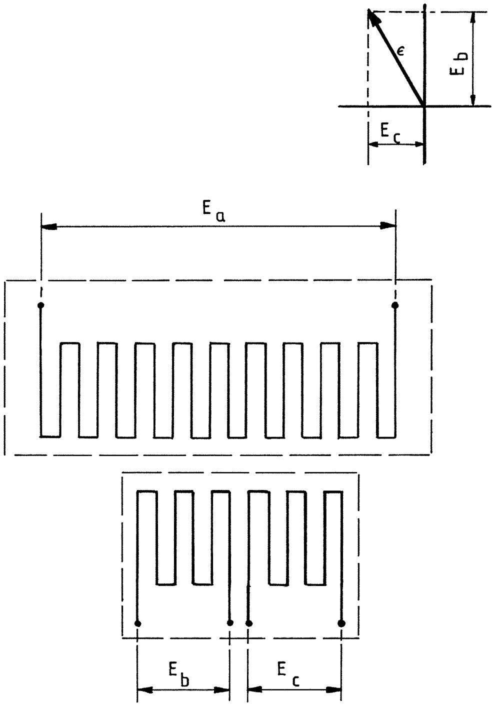


Fig. 1.44. The principle of an inductosyn.

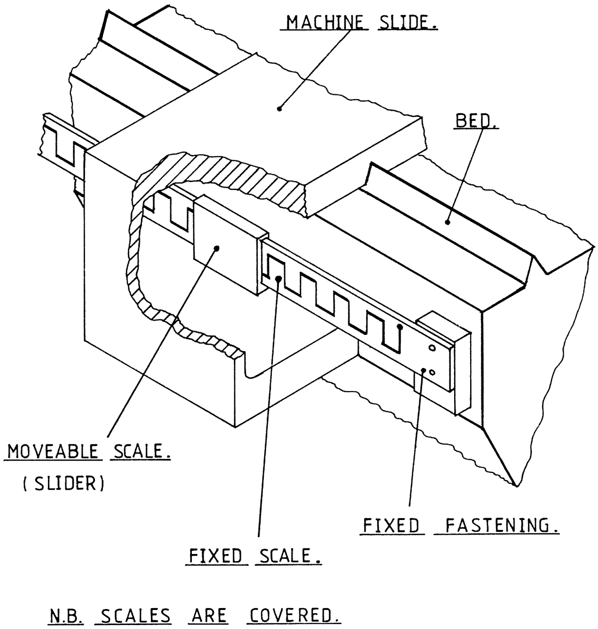


Fig. 1.45. A linear inductosyn. NB: scales are covered.

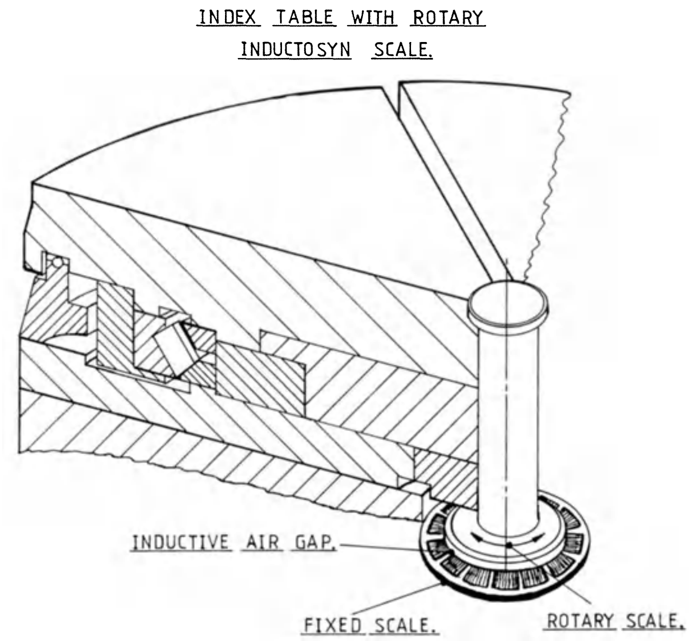


Fig. 1.46. An application of a rotary inductosyn.

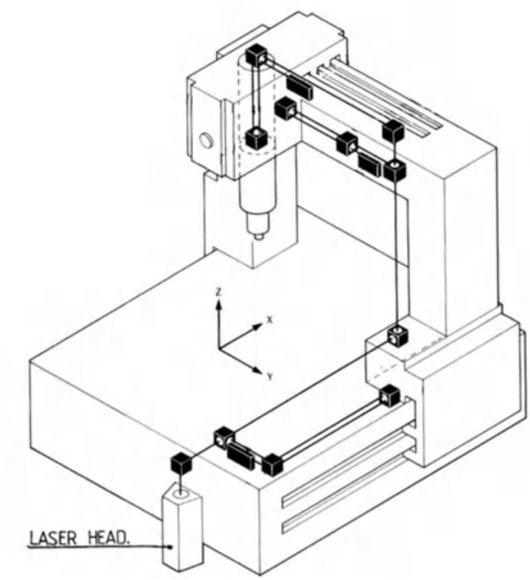


Fig. 1.47. Closed-loop position monitoring using ultra-precise linear interferometers/laser. [Courtesy of Habn & Kolb (GB) Ltd.]

matically for ambient temperature changes, humidity and air pressure, which is a major problem in most machine shops.

1.6 A Review of Typical CNC Machine Tool Configurations

This section is not meant to be an exhaustive account of all the available machine tools utilising CNC; that would require a book on its own. However, the comments and photographs will be confined to reviewing turning centres and CNC lathe configurations and then go on to briefly describe machining centres and CNC mills that are currently available.

Let us begin the review by looking at probably the most popular turning centre configuration currently available and shown in Fig. 1.48. This slant bed turning centre has a 2-axis controlled turret holding a dozen or so tools in its turret. This allows both right- and left-hand tooling to be situated in the outer ring of tool pockets, with the inner ring being used in the main for hole-making operations: drilling, boring and tapping. A partially programmable tailstock is a standard feature which can be latched up/down to provide workpiece support, using centres. The tailstock's barrel can be programmed to move in and out with a hydraulic pressure regulator controlling the barrel's pressure requirements. This feature is important whenever long, slender workpieces require centre support to avoid them buckling or distorting under the hydraulic pressure application. However, the barrel is not feed programmable for drilling, but it can be used in such a manner if physically connected to the cross-slide and a Z axis motion is programmed with the tailstock latched up. The cast iron slant

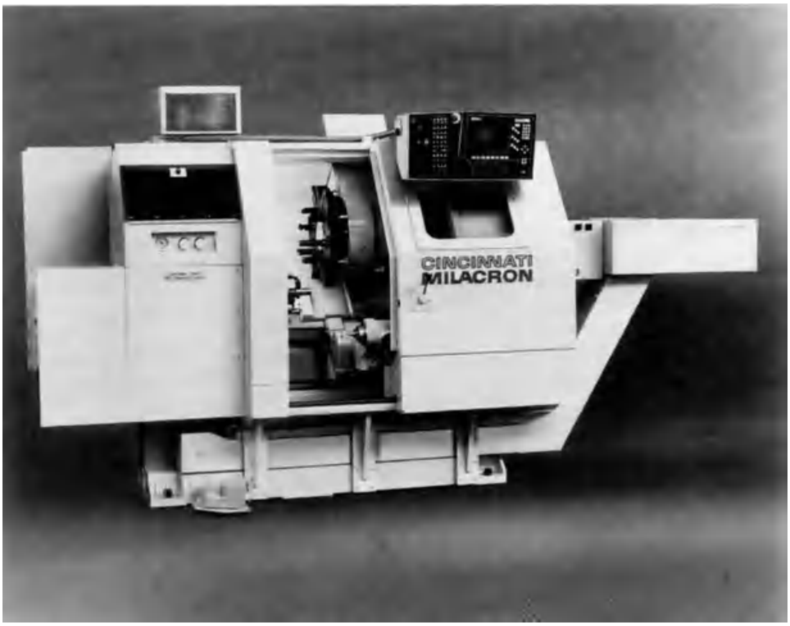


Fig. 1.48. A 2-axis turning centre with programmable tailstock. [Courtesy of Cincinnati Milacron.]

bed drops swarf into the tray and is carried away by the continuous chain-type swarf conveyor to a receptacle. The CNC has full colour graphics capability, displayed on a large CRT.

A more sophisticated derivative of the previous turning centre is a twin turret 4-axis machine tool (Cincinnati Milacron, Cinturn 8 C, Series 1408, CNC Chucking Centre), but in this case without a tailstock fitted. The CNC has been up-rated allowing the full control of 4-axes, but in this case in a rather unique manner. When programming the part only the X and Z axes of the top turret need be considered and where appropriate the U and W axes of the bottom one can be used to perform simultaneously machining operations such as "balanced turning" where necessary. This feature gives a 4-axes turning centre the ability to manufacture parts much faster, thereby improving the overall productivity considerably (see Fig. 1.4). As well as the "balanced turning" operations on long diameters, useful operations using, say, one tool turret for external and the other one for internal work can be accommodated easily. The penalty for such turning flexibility is obviously a much more expensive capital outlay to purchase these machine tools. As with the previous 2-axis machine, a swarf conveyor is a standard feature and essential when such high stock removal rates are possible. It is worth mentioning that programming this 4-axis machine requires the programmer to be concerned with only two primary axes, X and Z, as the secondary motions of U and W are taken care of by the CNC, including collision protection – which is a rather unique programming aid.

If even greater flexibility and increased productivity is required from a turning centre, then the levels of sophistication of machine tool axes configurations can be increased immensely. Probably one of the most sophisticated turning centres available is the Gildemeister (UK) Ltd, GT 50, featuring twin turrets and twin spindles (Figs. 4.11 and 4.12) – fully programmable with the ability to use "driven tooling" for the machining of prismatic features on turned components. Incidentally, both of the previous turning centres discussed can be operated with driven tools – milling, drilling and tapping operations from their turrets if so ordered in such a configuration from the machine tool builder. It is very easy to see that a considerable number of axes may be controlled through the CNC and seven to nine axes are not unusual nowadays. The unique feature of having a twin spindle facility is that the main headstock and chuck is used for all "normal" "chucking" operations. The opposing co-axial spindle (Fig. 4.11) can slide down the bed once features to be machined by the headstock are completed by the top turret and grip the component in synchronised rotation whilst the workpiece is still rotating. This allows the component to be withdrawn, or supported whilst parted-off prior to withdrawal enabling "back turning operations" to be completed on the rear of the workpiece by the lower turret (Fig. 4.12). Whilst the "backface" machining operations are under way, the front facing top turret begins simultaneous machining of the next workpiece so that two components are being machined at the same instant of time. Such universal applications do not come cheap, but have expanded manufacturing abilities offering great savings in productivity and if the company has the throughput of work to justify this level of capital expenditure, then pay-back periods are significantly reduced. The control console of this advanced turning centre has remarkably few switches and buttons present to confuse the programmer/operator and the sophisticated and customised software is where the "intelligence" of the CNC machine resides. It is interesting to note that even this degree of advanced turning centre control is not the highest level available, as on some machines the jaws, or even the whole chucks can be automatically (Fig. 4.27) changed allowing much greater workholding flexibility and this is without even considering the automatic tool and workpiece sensing devices, yet to be reviewed.

Yet another derivative of the turning centre theme so far discussed is the configuration used in the Pittler Petra, where a front loading arm will load workpieces onto twin spindles after removing the previously machined parts. Different components can be manufactured simultaneously by both of the independent slideways offering considerable versatility. When higher production dictates this type of automatic machine work loading, then greater volumetric throughput can be machined on identical parts at the same time, as two can be produced in the time it takes to manufacture one. Once again, a short slant bed is incorporated for each turret, and naturally a swarf conveyor is an essential item in view of the volume of swarf produced. Part delivery can be automatically achieved through the use of workpiece conveyors or gantry loading systems, whichever is applicable to the company's needs.

Whenever there is a call for ultra-precise components and particularly of highly accurate surface finishes, then a totally different CNC turning philosophy must be adopted (see Fig. 6.27). To obtain the ultimate surface finishes produced by single-point tooling, demands a machine tool with exceedingly high r.p.m. to cope with the speeds necessary, using natural diamond turning tools, together with much greater rigidity, and even more important is the high vibration damping capabilities required when using mono-crystalline diamonds. These capabilities are essential in order to minimise cleavage of the natural diamond tooling cutting edges whilst machining parts at high speed. As a result of the specialised cutting edges needed for this type of machining, the tooling and its fixturing tend to be relatively simple in concept. The CNC diamond turning lathes can machine complex geometric parts as well as relatively simple part geometries with exceptionally fine feedrates, offering superb surface finishes. A degree of automation can be incorporated into such machines by using bar-feeders, or automatic part loading facilities coupled to automatic chucks. Often these machine tools have unusual work holding facilities utilising, for example, vacuum chucks and faceplates and other such methods.

This brief review of CNC turning machine tool applications would not be complete without a mention of the vertical lathe illustrated in Fig. 1.49. Often such specialised turning machines are used to manufacture large squat and irregular-shaped components which may offer out-of-balance problems, or workholding difficulties on conventional turning machines. Typical of such products manufactured are volutes, or gear crushing rings which are made from exotic materials which are exceedingly difficult to machine. As machine tool rigidity is of prime importance on these machines, with their portal construction being a typical feature, the requirement is for good torque–low speed power characteristics with high volume production being of secondary importance in this case. Tooling needs as a result, tend to be of simple, but robust construction and fine feedrates can be programmed. Owing to the relatively long cycle times necessary for machining exotic materials, or if rotating out-of-balance loads, the low volume production which results dictates manual rather than automatic loading of workpieces. Once again, a simple and strong, but effective method of part clamping is considered to be of prime importance here.

The diversity of machining centre and milling machine configurations available to the would-be purchaser is vast and depending upon the part complexity, size and volume produced, there is a range of machines on offer. The horizontal machining centre shown in Fig. 1.50 is typical of its genre, offering 4-axis control, 3 linear and one rotary for pallet/workpiece rotation. An automatic pallet changer with eight pallets is incorporated with the adaptability of workpiece fixturing and component diversity being displayed. The photograph shows a range of fixtures on each pallet, such as: cubes, tombstones, or special-purpose varieties allowing the wide variety of components to be accommodated from small to large dimensions. It is possible to tool-

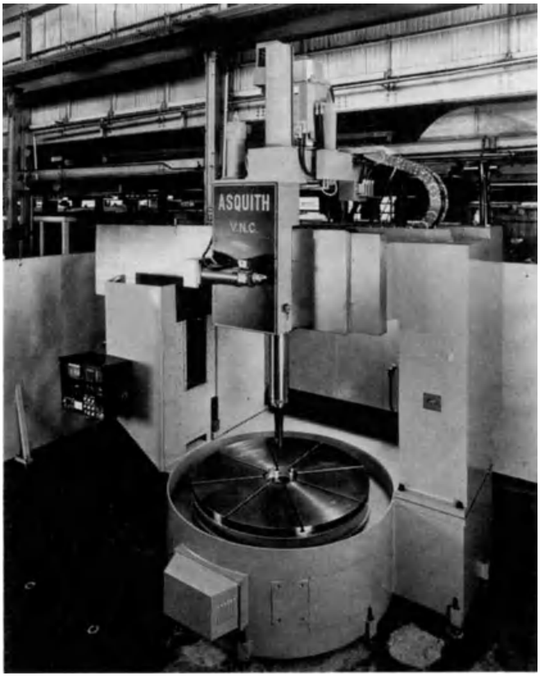


Fig. 1.49. A CNC vertical turning lathe. [Courtesy of Asquith 81.]

up a fixture to carry many small components on each pallet and this gives a degree of medium-volume production to such machines. Obviously features such as swarf conveyors, adaptive control and tool and workpiece monitoring systems can be incorporated, together with further "tool banks" when appropriate.

The CNC has to be quite sophisticated in order to cope with all the likely permutations of component piece-part programs that need to be stored in the memory. Not only does the controller need a part scheduling ability, it also requires further controls to orchestrate the relative auxiliary devices included on the machine, typically, a pallet recognition system, tool management and magazine handling together with touch-trigger probing software and adaptive control through some form of torque controlled machining (TCM) capability. These aspects offering a degree of intelligence into the machine tool will be the theme of further discussion later in chapter 2.

A popular machining centre often used in Flexible Manufacturing Cells or Systems, is the 4-pallet horizontal machining centre illustrated in Fig. 1.51. Obviously large machining centres of this type offer great flexibility in the ability to cope with a diverse range of parts. A key feature with such machine tools is the crucial areas of part fixturing and cutting tool management, if the benefits from such a costly machine tool are to be realised. The machine has a sophisticated CNC necessary to carry out not only the part programs, but tool and machine monitoring through sensors, for example: adaptive control, tool breakage detection, and workpiece probing, coupled to thermal drift compensation devices and refrigerated spindle assemblies, plus many more techniques desirable in the "stand-alone" machine, or ones used in the unattended machining environment. Machine tools having the likelihood that they will be used in

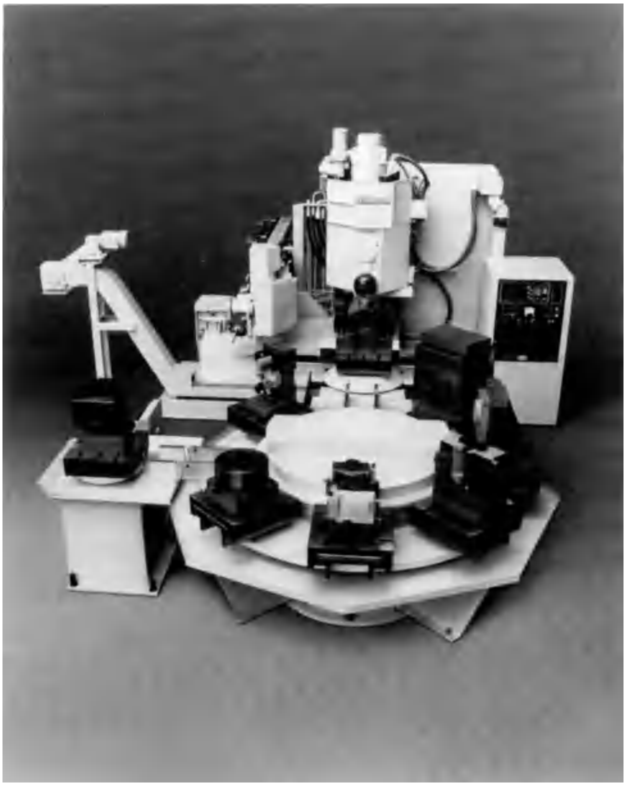


Fig. 1.50. A machining centre (horizontal) with rotary pallet changer. [Courtesy of Cincinnati Milacron.]

Fig. 1.51. A large 4-pallet machining centre (horizontal) with 4-axis control. [Courtesy of FMT Ltd.]

a variety of "stand-alone" or automated configurations of necessity must be built around a "modular principle" previously discussed; this ensures that part delivery can be universally accommodated through: rail-guided vehicles, AGVs, gantry robots, or universal 6-axis robots. Not only can a host of part delivery systems be interfaced to these machine tools, but table sizes and weight capacities can be changed to suit the customer together with the "working envelopes" as necessary.

All CNC machine tools do not of necessity have to be highly complex and sophisticated equipment as described in Fig. 1.51. There is a good case for CNC control principles to be adopted whenever it is necessary to machine large components using the gantry or portal type of machine tools. Invariably these gantry milling machines have simpler CNCs from the point of view of auxiliary software options, such as tool management and part scheduling abilities, but concentrate on the software enhancements needed to machine divergent part geometries likely to be encountered by such machines. Typical of these larger scale machine tools is the one pictured in Fig. 1.52 where a custom-built machine tool is manufactured to cater for the large flat-type of components, but at relatively low volume production rates. Once again, these machines can be purpose built to the customer's requirements and as a result can be considerably larger than the one shown in the photograph. This machine tool (Fig. 1.52) does not have automated tool changing abilities as speed of manufacture is not the dominant criterion, moreover the ability to machine large components, or small to medium-sized batches at one set-up, is its main function. However, automated tool changing can be supplied and it then becomes a large capacity machining centre.

The next machine tool to be considered in our review highlights a different approach to piece-part production, giving it the ability to manufacture free-form shapes typically to be found in the aerospace and automotive industries, rather than the more usual prismatic part geometries mostly catered for in less sophisticated machines. This machine (Fig. 1.53) is a five-axis twin pallet vertical machining centre offering two

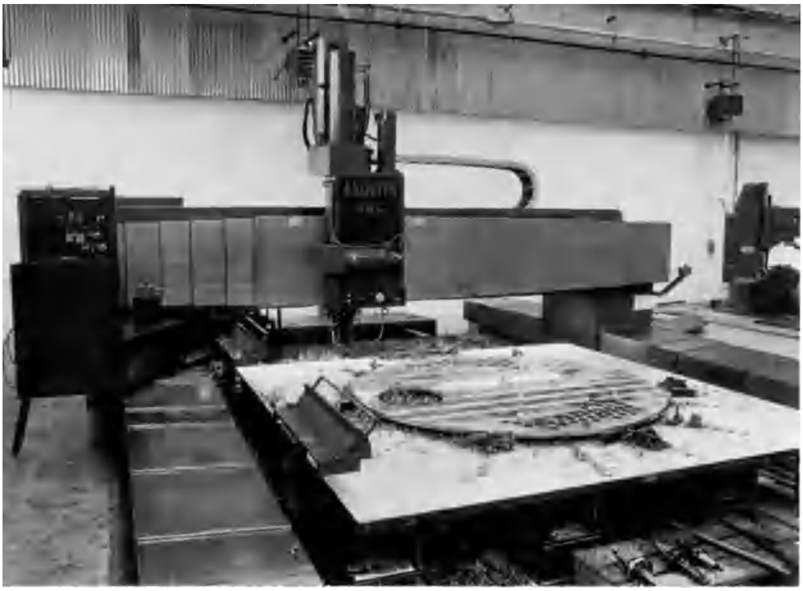


Fig. 1.52. A moving gantry vertical milling machine. [Courtesy of Asquith 81.]

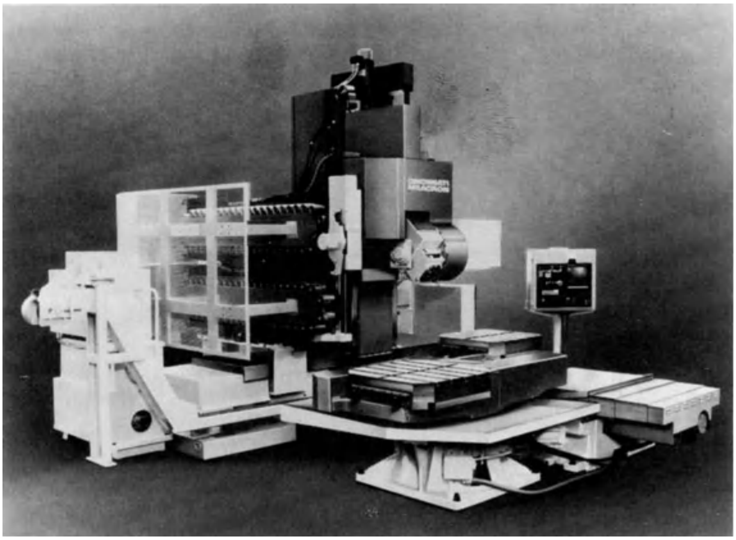


Fig. 1.53. A large 5-axis twin-pallet machining centre. [Courtesy of Cincinnati Milacron.]

linear axes to the table, a rotary pallet motion, with a linear motion to the column and a rotary axis to the tool head assembly. Such range control over a greater number of axes allows the cutter orientation to the workpiece to be continually monitored and changed, giving it the capability to present the cutter normal to the surface which is a requirement when machining many complex geometrical components. As expected on such a universally adaptable machine tool, the tool library is of large potential capacity, and can be extended to even greater size if necessary. These machine tools may be custom-built, but are expensive. As before, swarf conveyors and the usual health monitoring equipment for tool and machine protection can be supplied if appropriate and the CNC in this case is quite a sophisticated device.

By way of a comparison with the large-scale CNC milling machine depicted in Fig. 1.52, the more compact fixed table travelling gantry CNC mill shown in Fig. 1.54 is a more popular alternative. This machine is more easily automated; tool changing and axis speeds are less restricted owing to smaller inertial and momentum constraints. A swarf conveyor is supplied on this machine tool and full slideway protection from swarf and debris is incorporated into its design. This slideway protection is an important feature whenever high-speed routing heads are fitted as swarf volume and velocities are very high. Often these gantry/portal machine tools require hydrostatic bearings for the table, owing to the large weight capacities that can be held on tables, as separation pressure between conventional slideways would cause problems for the smooth CNC linear motions normally required.

To complete this appreciation of just a few of the diverse range of CNC machine tools available today, a 6-axis vertical CNC machining centre is illustrated in Fig. 1.55. The table in this case has two linear and one rotational axes present, whereas the column offers one linear motion with two rotary motions to the main spindle assembly. This amount of control over linear and rotational axes truly allows the cutter to machine highly complex free-form geometries to parts as depicted in the photograph. These machine tools can be programmed directly through the CNC, or more typically

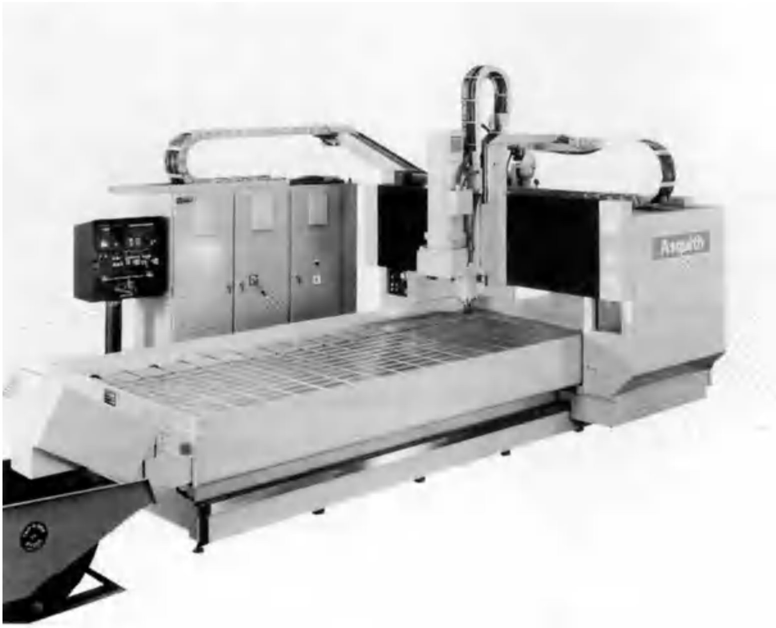


Fig. 1.54. A fixed table travelling gantry milling machine. [Courtesy of Asquith 81.]

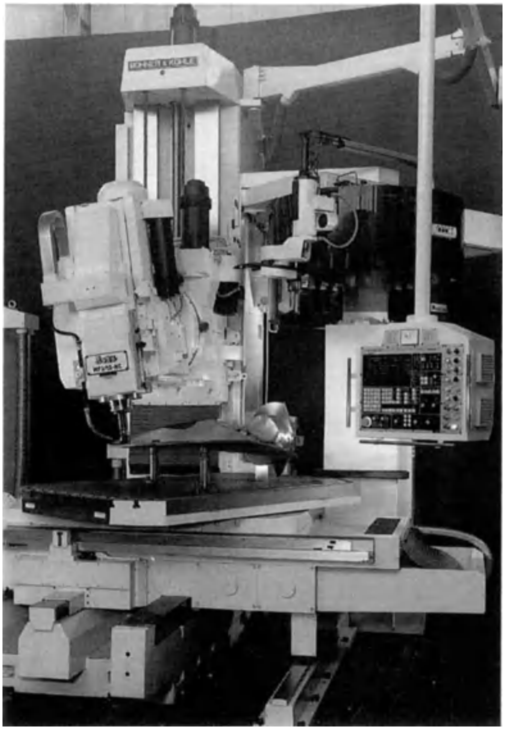


Fig. 1.55. A 6-axis machining centre cutting a complex curved component. [Courtesy of Bohner & Kohle.]

nowadays, a direct numerical control (DNC) link is established to the machine tool from a CAD/CAM workstation. As with most of the previous machine tools mentioned, this machine, as shown, can be supplied with/without tool magazines and automatic tool changing equipment as necessary. All of these photographs showing unguarded machine tools are more usually purchased fully guarded when high metal removal rates are a major requirement for operator protection.

The metal cutting machine tools described in this chapter are of no practical use if they are not "tooled-up" with the latest efficient and productive cutting tools. The following chapter discusses the correct tooling philosophy to be adopted, as well as many other important tooling considerations demanded by any competitive manufacturing company today.

Chapter 2
Cutting Tool Technology

2.1 Introduction

If one compares the sectors of the materials and metallurgical industries, the cutting tool industry can be considered as small. However, it is vital, owing to the fact that even with the great advance in materials technology, these materials are of no practical use unless they can be economically fabricated into useful shapes. As it is generally accepted that around 10% of all metal produced is converted into swarf, machining remains the most common fabrication method.

Using the latest cutting tool materials, today's machine tools can be driven up to cutting speeds of 1000 m/min with feedrates approaching 1 m/min. Depths of cut can also be used over greater ranges than previously, and vary from 0.1 mm for fine finishing operations, with up to 1 cm or more for heavy roughing cuts.

Tooling plays a significant role in the productive throughput of the machine tools in a factory and if due attention is not given to this technology, even the most up to date machine will not realise its full potential; but more important than this is the fact that it will not be economical and competitive. To take this point a stage further, a well "tooled-up" turning or machining centre of moderate size and sophistication will be more productive than a highly expensive large machine with dubious vintage tooling. Regardless of cost, a machine tool is only earning money when it is cutting material, so make sure the best possible tooling has been purchased.

2.2 Tooling – the Key to Prompt, Productive Operations

Prior to the purchase of a new machine tool, or indeed for a reappraisal of the tooling requirements for an established machine within the plant, the cutting tools should also be assessed and thereby available when the machine is ready to work. Typically, a good tooling package will cost no more that 5% of the cost of, say, a turning centre, but is usually considerably more expensive when milling applications are required. These tooling costs will obviously depend on the manufacturer's requirements and as an example of this, if a large manufacturer's production needs are only for a single part, or family of parts, then it is unlikely that a wide range of tooling is necessary. Conversely, when perhaps a jobbing shop specifies its tooling requirements, then it is normal to suppose that a diverse range of parts will be manufactured, needing a wider range of tools. Often tooling manufacturers will sell tooling packages for specific machine tools, but as they are meant for universal usage they are rarely exactly right for a given application. This means that the manufacturer of parts will have to supplement the tooling inventory to make the parts they need, and as a result some of the tools in the package become redundant.

The first step when "tooling-up" a new machine does not involve the tooling at all – it is an exercise in data collection. Initially, this means determining the complete specification for the machine tool, including supposedly inconsequential data such as the address and telephone numbers of the machine tool builder, the local representative for the builder, work-holding companies, etc., as they can prove to be invaluable later. The next step is organisation of the data about parts to be manufactured and this requires a detailed survey of the engineering piece-part drawings, which allows parts to be categorised or grouped by size, material, operations to be carried out, surface finish requirements, tolerances, and so on. One of the main advantages this gives to the manufacturing engineer is to allow the collected knowledge to be gathered together in one place which focuses thoughts on what the machine tool has to do, and as such, enables the tooling engineer to initiate a tooling program for the expected production requirements.

2.3 Basic Guidance in Determining a Tooling Set-up

Any tooling decisions should begin with the insert choice and not the holders, as these are the key to productive throughput, so with this in mind, the first choice to be made should be to consider the insert size. A reasonable indication when selecting the size of the insert can be established from the spindle power rating and this in turn will help to determine the insert geometry, which will also affect the expected volume of material which may be removed.

An example of the material removal rate may be appreciated if one considers the case of only light roughing and finishing on a relatively large machine; this would not warrant the use of, say, 20 mm inserts. Another important factor when determining the insert geometry would be the material from which the part is made and data on this point can be sought from the guidelines established by cutting tool manufacturers; more will be said about this aspect later in the chapter. The choice of insert shape is important, as it will affect its ability to cut the contour and also affect its strength. Not only must the insert shape enable the part geometry to be cut, it also has a considerable influence on the number of parts that can be made per cutting edge. Take for example a triangular shaped insert: it has fewer cutting edges than a square insert shape, for a similar price, but more importantly the square-shaped insert is stronger and gives more parts per edge, which has the twin benefit of reducing down-time, giving greater economies. As a by-line to this fact, most companies operating turning machines usually require milling facilities, so that any left-over turning square-sided inserts can as often as not be used in the milling operations, thereby improving cutting economies still further.

Once the major factors of insert selection have been established, our attention can be turned to toolholder selection, which usually starts with three basic rules:

part contours will determine the correct tool style for the job

insert must have an adequate cutting-edge length

holder shank or adaptor must fit the machine

The details on the tool holders can usually be found in a tooling company's catalogues, or by contacting the machine tool salesman, but occasionally the information is not available and this may often be the case with turning tool holders. So, in order to determine the "hand" of the holder, here are some general guidelines:

when turrets are located in front of, or below the spindle centreline, using a clockwise rotation of the spindle, use right-hand toolholders

if turrets are located behind or above the spindle centreline, with the spindle rotation clockwise, use right-hand toolholders, but they are mounted upside down

when turrets are located behind or above the spindle centreline, with the normal spindle rotation anti-clockwise, use left-hand holders

NB: When this type of machine tool is used with the spindle reversed (clockwise), a drop-head style holder is used when cutting threads; i.e. right-hand, from the tailstock to the headstock.

The toolholder style must be determined from the part requirements, with checks on clearances on the part and over the moving elements of the machine tool transfer – in the case of machining centres and turret indexing on turning centres this latter point must be considered when dealing with drills and boring bars.

Once the information has been organised, it is now possible to go through the "NC Tooling Checklist", so that we can list the styles required and fill in the details on shank sizes. This "checklist" will obviously not include all of the tools needed, but represents those most commonly used during production. Finally, the "checklist" is gone through and all the inserts and hardware are listed, providing at least one backup (i.e. "sister tool") for each holder. The expected production levels and budget consideration will determine the number of inserts of hardware required, but it is usual to begin with moderate quantities as, if, for some reason, different grades or geometries are needed then it becomes easier to make a substitution.

Having introduced the fact that care must be taken when choosing cutting tools and their associated equipment, it is worth describing in more detail the considerations which have influenced our choice, starting with a review of the materials for inserts and solid tooling.

2.4 Cutting Tool Materials

It has often been said that in view of the stringent and complex demands required of cutting tool materials, an ideal material should exhibit the hardness of a diamond, the toughness of high-speed steel, together with the chemical inertness of alumina. The problem is that no tool fulfils all of these criteria, but may achieve excellent results in one or other of these desirable qualities. As a result, a wide range of cutting tool materials occurs which, to a greater or lesser extent, can be used in conjunction with a variety of materials to be cut. In this review let us firstly consider a material which has been used for cutting tools for some considerable time, namely high-speed steel, and although its use for turning operations is perhaps limited, it is still used predominantly for small diameter drilling operations in highly productive environments.

2.4.1 High-speed Steel

If slower speed machining operations occur, then high-speed steel can be employed in large quantities, particularly for small diameter endmills, slot drills, twist drills, etc., and some form tools, where perhaps the grinding of carbide would be uneconomic. In recent years, the high-speed steel tool life has been extended through coating techniques such as chemical or physical vapour deposition methods, and more will be said on this topic shortly.

2.4.2 Cemented Carbide

Undoubtedly the most widely used general purpose cutting tool material is cemented tungsten carbide, catering for up to 70% of cutting tools for swarf generation. It is predominantly found as small indexable inserts, ranging in size from very small boring inserts around 4–20 mm across for the larger rough turning inserts, which are about 5 mm thick. These inserts are mechanically clamped to a tool shank, or tool head – in the case of modular quick-change tooling – and can be indexed as their name suggests, once an edge is worn with good repeatability of location in their holders.

In effect, cemented carbide is a hard transition metal carbide ranging from 60% to 95% bonded to a more ductile metal such as cobalt. The carbides vary, ranging from tungsten carbide having hexagonal structure, to a solid solution of titanium, tantalum and niobium carbides having a NaCl structure. Tungsten carbide will not dissolve any of the transition metal carbides; however, it can dissolve with those carbides forming a solid solution. The powder metallurgy processing route is used to produce cemented carbide products and because they melt at very high temperatures, there is a means of reducing tungsten powder using hydrogen from chemically purified ore. By manipulating the processing conditions of reduction, the grain size can be controlled and altered as necessary. Typical tungsten carbide grain sizes are in the range 0.4–7 µm. At a further processing stage, precise control over the grain size can be achieved, principally through additions of fine cobalt and then wet milling the constituents, making a final powder, whilst adding a lubricant which aids when consolidation (pressing to shape) occurs. Once milled, the powder can be spray dried giving a free-flowing spherical powder aggregate and this can be subsequently pressed to shape. Sintering is the next operation, which usually occurs at 1500 °C in a vacuum and this reduces porosity from 50% in the pressed compact, to less than 0.01% by volume in the final product. The low porosity is the result of liquid being present during sintering, with the extent of wetting being dependent on the molten binder metal dissolving to produce a pore-free product having a good cohesion between this binder and the hard particles. Most of the iron-group metals can be "wetted" by tungsten carbide, forming sintered cemented carbide offering excellent mechanical integrity. However, those desirable properties which enable tungsten carbide to be tough and easily sintered, will cause it to readily dissolve in the iron and are known as "straight" cemented carbide grades. These grades contain just cobalt and tungsten carbide, so are used predominantly to machine cast iron only, as the chips fracture easily and will not remain in contact with the insert, reducing the likelihood of wear by dissolution. Steel machining, on the other hand, requires quantities of alternative carbides like titanium or tantulum carbides, being less soluble in heated steel, although even these "mixed" grades will wear by dissolution of the tool material in the chip and can limit its machining life at high speeds.

Dissolution of the tool material in the chip can be overcome by the development of grades which have been based on titanium carbide, or nitride, together with a nickel–cobalt alloy binder. These tool materials can be used in both turning and milling applications at moderate to high speed and now account for up to 15% of all the inserts used in Japan today. For general machining applications, their reduced toughness makes them less suitable, as the feeds and induced tool stresses are higher. Another approach to combating dissolution of the tool material in the chip is to coat the cemented carbide substrate, but before we discuss this popular method, it is worth reviewing how carbide grades are classified.

If one considers the number of permutations of substrate materials, coatings and geometrical shapes available in cemented carbide inserts from cutting tool companies, then they seem infinite. To overcome this problem and present a standardised classification system ISO guidelines have been produced: *Classification of Carbides According to Use,* which has been well received and adopted by most industrial countries.

Under this system carbides are grouped by an alphanumeric classification, designated by three main groups – P, K, and M (Fig. 2.1):

P represents their use with long-chipping materials such as steel, etc.

K represents their use with short-chipping materials typified by cast iron and so on

M is considered to be best applied to intermediate applications, represented by: steel castings, malleable cast irons and similar

Each main classification of insert grade is further sub-divided into a numerical scale, 01–50. The higher the number of the sub-group, the greater the toughness – but at the expense of hardness and, of course, wear resistance. However, this can be partially remedied by the latest "coated" grades which can be supplied with a tough core and an abrasive resistant coating, combining good shock resistance and lower wear rates.

Normally the K-group has high quantities of tungsten carbide present, giving greater wear resistance, whilst minimising flank wear when machining cast iron. If crater wear is likely, then changing to other grades is the only answer. The P-group of inserts usually contain titanium; tantulum and niobium carbide may overcome crater wear at high machining rates, as combined with tungsten carbide they provide higher hardness at elevated temperatures.

With the tooling manufacturers recently improving their grades of carbide, it is now possible to use them over wider ranges of materials and this has the twin benefits of improving the bulk order quantities by the users, whilst enabling them to rationalise their stock and gain greater advantage and knowledge from their use.

2.4.3 Coating Cemented Carbides

Rather quaintly, the idea of introducing a very thin coating onto a carbide cutting tool originated with the Swiss Watch Research Institute, using the chemical vapour deposition (CVD) technique. So what is CVD and how does it coat the cutting tools? Let us consider this coating technique and then go on to review an alternative method of coating – physical vapour deposition (PVD).

COLOUR DISTINCTION.	DESIGNATION.	MATERIAL TO BE MACHINED.	APPLICATION.
BLUE.	P01	Steel, steel castings.	Finish turning & boring, small chip section, dimensional accuracy & vibration – free.
	P10	Steel, steel castings.	Turning, milling, threading, with small–to – medium chip sections.
	P20	Steel, steel castings, Malleable cast iron with long chips.	Turning, milling, with medium chip sections.
	P30	Steel, steel castings, Malleable cast iron with long chips.	Turning, milling, planing, with medium–to – large chip sections.
	P40	Steel, Steel castings with sand inclusions & cavities.	Turning, planing, slotting, with large chip sections & under unfavourable conditions.
	P50	Steel, steel castings of medium or low strength, with sand inclusions & cavities.	Turning, planing, slotting, demanding large cutting angles under adverse conditions.
YELLOW.	M10	Steel, steel castings, Manganese steel, Grey cast iron & alloy cast iron.	Turning using small–to – medium chip sections.
	M20	Steel, steel castings, Austenitic or Manganese steel & Grey cast iron.	Turning, milling with medium chip sections.
	M30	Steel, steel castings, Austenitic steel, Grey cast iron & high–temperature – resistant alloys.	Turning, milling, planing with medium – to – large chip sections.
	M40	Mild free–cutting steel, low tensile steel, non–ferrous metals & light alloys.	Turning & parting – off.
RED.	K01	Chilled castings, high silicon – aluminium alloys, Copper alloys, abrasive plastics & ceramics.	Turning, finish – turning, milling & boring.
	K10	Short – chipping cast irons, hardened steel, silicon – aluminium alloys, Copper alloys, plastic, glass & rubber.	Turning, milling, boring, drilling & broaching.
	K20	Chilled cast iron, non – ferrous alloys of; Copper, Brass & Aluminium.	Turning, milling, planing, boring & broaching.
	K30	Grey cast iron of low hardness, low–strength steel & compressed wood.	Turning, milling, planing, slotting demanding large cutting angles under adverse conditions.
	K40	Non – ferrous metals, hard & soft woods.	Turning, milling, planing, slotting demanding large cutting angles under adverse conditions.

DIRECTION OF INCREASE IN CHARACTERISTIC:–	
CUT.	CARBIDE.
INCREASING SPEED.	WEAR RESISTANT.
INCREASING FEED.	TOUGHNESS.

Fig. 2.1. Carbide insert classification according to use.

The process of chemical vapour deposition of cutting tools is carried out in controlled atmospheres and temperatures in the range 950°–1050 °C. Essentially, the process consists of a commercial CVD reactor with the tools to be hard-coated being positioned on trays as depicted by Fig. 2.2a. Prior to coating the insert it is normal to obtain a good surface finish and a radius to the edges, normally around 0.1 mm, as if the radius is too sharp it will not support the coating and when too large the edge is dulled and will not cut correctly. These inserts have their trays staged one above the other, being of precoated graphite and loaded onto a central gas distribution column (tree). Graphite is most commonly used as it is inexpensive compared to stainless steel or nickel-based alloy shelving, and it has the benefit of good compressive strength at elevated temperatures. The "tree" loaded with inserts to be coated is placed inside a retort of the CVD reactor (Fig. 2.2b). Tools are heated in an inert atmosphere until the coating temperature is reached and the coating cycle is initiated by the introduction of titanium tetrachloride ($TiCl_4$) together with methane (CH_4) into the reactor. The $TiCl_4$ is a vapour and is transported into the reactor via a hydrogen carrier gas, whereas CH_4 is introduced directly. The chemical reaction in forming the surface coating process of TiC is:

$$TiCl_4 + CH_4 \rightarrow TiC + 4HCl$$

The HCl gas is a by-product of the process and is discharged from the reactor into a scrubber where it is neutralised. If a titanium nitride is to be coated onto the inserts, then the previously used methane is substituted by a nitrogen/hydrogen gas mixture. So, when a multi-coated charge of inserts is required, it is completed in the same cycle, firstly by depositing TiC using methane and then depositing TiN using a nitrogen/hydrogen gas mixture.

As the TiN and TiC are deposited onto the inserts, they nucleate and grow on the carbides present, with the coating process taking in all about 14 h – 3 h for heat up, 4 h for coating and 7 h for cooling. The thickness of the coating is a function of the reactant concentration – the flow rates of the various gaseous constituents, the coating temperature and the time soaking at temperature. Carbide tooling will not soften under this coating process and no further treatment is required after CVD processing, but for high-speed tooling – in the main, small drills and taps – owing to the coating temperature being above its tempering temperature, it is necessary to harden the tooling afterwards. This process of CVD is carried out in a vacuum together with a protective atmosphere, in order to minimise oxidation of the CVD deposited coatings.

The alternative to the CVD process is the physical vapour deposition (PVD) coating process, with the principal differences between them being the temperatures at which coating is achieved and the mechanism required in transferring the coating to the tooling. There are three differing methods for coating by PVD currently practised:

reactive sputtering
reactive ion plating
arc evaporation

For all these techniques, TiN coating is formed by reacting the free titanium ions with nitrogen away from the insert's surface, then relying on physical methods to transport the coating onto the surface of each insert.

The oldest method of applying coatings is by PVD sputtering; this utilises a high voltage which is positioned between the inserts (anode) and a titanium target (cathode). The target is bombarded with an inert gas, generally argon, which frees the titanium ions allowing them to react with nitrogen, forming TiN. The positively charged anode

a

b

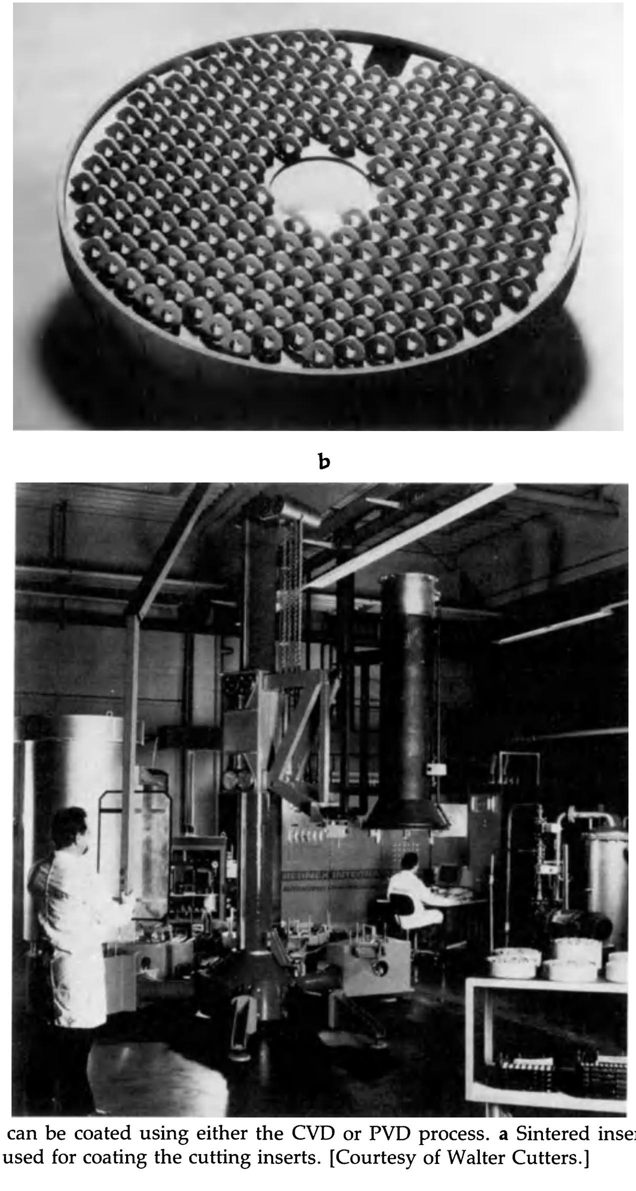


Fig. 2.2. Inserts can be coated using either the CVD or PVD process. **a** Sintered inserts prior to multi-coating. **b** Plant used for coating the cutting inserts. [Courtesy of Walter Cutters.]

(inserts) attracts the TiN. The second technique, ion plating, relies on titanium ionisation using an electron beam to meet the target, which forms a molten pool of titanium. Vaporised titanium reacts with the nitrogen and an electrical potential accelerates it towards the tooling/inserts. Arc evaporation is the third method of achieving coatings on inserts; it utilises a controlled arc which vaporises the metal directly onto the inserts from the solid. It should be said that all of these PVD coating techniques are "line-of-sight" processes and in order to obtain a uniform coating on the tooling with the required thickness and coverage, the parts must be rotated whilst coated. All of these PVD processes are undertaken in a vacuum of 260°–485 °C, as the substrate heating will enhance the coating adhesion.

Recently, an exotic process, shock-induced dissolution of carbon-rich plasmas has created amorphous diamond coatings in the electrical industry in particular, but may eventually be used as a coating process on tooling.

To conclude this review of CVD/PVD coating techniques, it is worth mentioning that each process offers the cutting tool manufacturers a range of surface coating conditions which can be exploited to obtain different cutting objectives. If we consider each process in turn, the CVD process, as mentioned earlier in this section, requires the inserts to be honed and chamfered prior to coating as there is a degradation of the substrate forming a brittle eta-phase which becomes detrimental at corners as a result of the high temperatures employed. This promotes some problems for milling insert coating, but may be minimised by careful control of the processing parameters. However, if problems do occur, then the lower temperatures of the PVD process overcome them and result in a good edge sharpness with minimum distortion to tooling. The PVD coating technique was not popular at first, owing to the false belief that these coatings do not adhere to the insert substrate; not only is the edge retention better, the coated surface by PVD methods is much smoother and appears as shallow-dimpled with a finer grain size than the blocky-grained appearance of the CVD process. Smoother surfaces reduce the problems of thermal cracking leading to edge chipping and premature failure, whilst improving the resistance to repeated mechanical and thermal stresses minimising interface friction and resulting in lower flank wear.

A typical multi-layered coating of the insert's surface can be seen in Fig. 2.3, where the substrate can have up to thirteen coatings, giving a very exotic surface metallurgy which truly enhances cutting performance. In general CVD coatings are thicker than PVD techniques and are 6–9 μm, whereas PVD coatings are 1–3 μm. Obviously, any multi-coated insert will be more expensive than the uncoated cemented carbides –

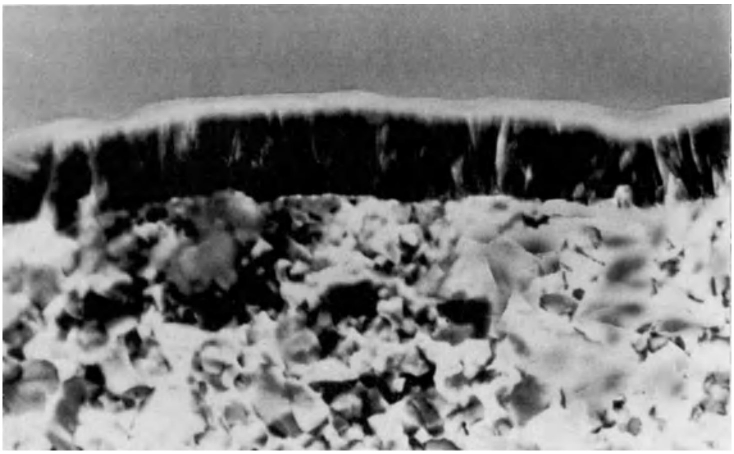


Fig. 2.3. A carbide insert clearly showing the metallurgical composition and construction of the tin deposited layer on the tungsten carbide substrate. This could have a very complex metallurgy with up to 13 coatings produced by either the PVD or CVD process. [Courtesy of Walter Cutters.]

owing to the lengthy processing time and capital equipment required, but buying them is not a false economy as the number of parts per edge is much greater than the uncoated inserts and more than makes up for this extra expenditure.

Another material which has been available for some time, but through new mixtures and processing routes is now firmly gaining popularity by the end users, is ceramic-based material and this will now be considered.

2.4.4 Ceramic-based Materials

Ceramic materials can be considered to be the oldest cutting tool materials. Stone-age man used broken flints to cut and work with and these are ceramics. The first modern-day industrial applications of ceramics occurred in the 1940s and they had the potential of retaining their hardness at high temperature, yet were chemically inert to steels. This has allowed them to exploit the high cutting speeds obtainable on the latest machine tools, without deformation and dissolution wear processes which would otherwise limit their tool life. The main problem with this class of cutting tool material is that they lack the toughness and resistance to both mechanical and thermal shock. So, a limitation in their usage occurs and only stable machining can be utilised, thus interrupted cutting is disastrous for pure ceramic tooling, which has meant that their popularity has been limited.

The recent advance in popularity of powerful and rigid CNC machine tools means that wider applications of ceramic cutting tool materials have been evident. Coupled to the advances in machine tool design are the significant developments in ceramic materials themselves. Today, there are three grades of ceramic tool materials available:

1. "Pure" ceramic – the traditional tool material has been aluminium oxide – alumina, which is coloured white, and is manufactured by cold pressing powder in dies and subsequent sintering to fuse alumina particles together and decrease the porosity; they are sometimes termed "pure oxide", or a " cold-pressed ceramic". The major disadvantage of such ceramics is their low thermal conductivity, making them highly susceptible to thermal shock, and these effects become more pronounced with shorter cycle times, variable depths of cut, and higher machining speeds. Additions of zirconia increase toughness of these "pure" grades greatly.
2. "Black" or "mixed" ceramics overcome the thermal shock problem encountered with the "pure" grade and by additions of titanium carbide to alumina causes them to turn black. However, mixed ceramics do not sinter as easily as pure alumina, so require "hot pressing" of the powder, which obviously limits shape production of these inserts. Recently, by additions of titanium nitride, the thermal shock resistance has improved still further and the resulting inserts from cold pressing and sintering become "brown" or "chocolate" in colour, so the terms "black"/"hot pressed" become irrelevant. Thus the preferred term is "mixed ceramics", which in addition to having better thermal shock resistance are also harder and retain this hardness at higher temperatures, allowing them to be used for machining harder steels and cast irons, where the combinations of greater cutting forces, together with higher interface temperatures, would produce surface deformation in "pure" ceramics.
3. "Sialon" ceramic tooling was initially developed by Lucas under the trade name "Syalon" and is based on silicon nitride, which has a very low coefficient of thermal expansion. This low expansion rate reduces the stresses between the hotter and cooler parts of the insert during cutting, giving greater shock resis-

tance. However, it is difficult to sinter this grade to full density, but by substituting some of the silicon and nitrogen by aluminium and oxygen, the "sialon" (the name represents the chemical symbols of the constituent elements) can be successfully processed, giving equally good thermal shock resistance, but with the twin benefits of being cold pressed and more easily sintered. A notable elemental addition which further aids sintering performance is yttria and during sintering the silica (SiO_2) on the surface of the silicon nitride particles reacts with the yttria (Y_2O_3), forming a liquid. A reaction takes place between the silicon nitride and this liquid forming "sialon" which forms a glass upon cooling. So, depending on the relative proportions of the reactants, the "sialon" formed may have an atomic arrangement of:

(i) beta silicon nitride
(ii) alpha silicon nitride

So it is more than possible to have a very complex metallurgy occurring, having both "beta" and "alpha" "sialons" present. Thus the "beta" metallurgy is $Si_{6\cdot Z}$ AlzOz$N_{8\cdot Z}$ where "Z" represents the degree of substitution of silicon and nitrogen by aluminium and oxygen, whereas the "alpha" "sialons" are represented by $Mx(Si,Al)_{12}$ $(O,N)_{16}$ where "M" is the metal atom such as yttrium. All of this sounds rather confusing, but basically the "sialon" microstructure consists of a crystalline nitride phase held in a glassy, or partially crystallised, matrix. These crystalline grains may be either "beta" "sialon" or a mixture of "alpha" and "beta", but generally as the "alpha" phase increases, the hardness of the "sialon" increases, giving a greater "hot hardness" to the insert. Probably the greatest benefit is gained by the substantial improvement in toughness which can now rival that of cemented carbide of equal hardness. The major limitation with these "sialons" is that they cannot be used to satisfactorily machine steels, owing to their poor performance in resisting solution wear; however, they are outstanding for machining cast irons and nickel-based alloys, but even here a direct competitor is the "mixed" ceramic based on alumina, with 25% additions of silicon carbide "whiskers" within the substrate of the insert.

It should be stated again that the ceramic-based materials are intrinsically brittle and in the context of intended machining, typified by flexible manufacturing cells and systems, cemented carbide offers greater security of cutting performance rather than the dubious benefit of simply being able to machine parts at higher speeds.

2.4.5 "Super-hard" Materials

Polycrystalline diamond (PCD) and cubic boron nitride (CBN) are second only to natural diamond in their hardness and in many ways can be considered to be very similar, in that both share the same cubic crystallographic structure and exhibit a high thermal conductivity. However, they have profound differences in properties. Diamond is prone to graphitisation and oxidises easily in air, whilst reacting with ferrous workpieces. Conversely, CBN is stable at high temperatures both when machining ferrous workpieces and in air. Owing to these fundamental differences in properties, there is a divergence in the basic application areas for diamond and CBN.

Diamond machining applications tend to be for the non-ferrous and non-metallic materials such as aluminium alloys, brass, wood composites, abrasive plastics, glass and ceramics, as well as for machining tungsten carbide. Cubic boron nitride is used for machining ferrous materials, typically tool steels, hard white irons, surface hardened steels, grey cast irons and a few hard-facing alloys.

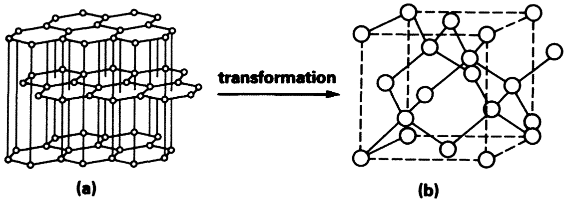


Fig. 2.4. Polycrystalline diamond (PCD) development. **a** The hexagonal arrangement of atoms in graphite. **b** The cubic arrangement of atoms in diamond. [Courtesy of Debeers PLC.]

Let us now take a closer look at how the synthesis of the single crystals of diamond and CBN occur, by firstly considering diamonds. Most diamonds used for industrial applications today are made synthetically by subjecting carbon, in the form of graphite, to high temperatures and pressures. In graphite, the carbon atoms are arranged in a hexagonal layered structure (Fig. 2.4a) and when subjected to heat and pressure application they can be transformed into cubic diamond structure (Fig. 2.4b). This transformation does not easily occur and temperatures in excess of 2000 °C and pressures of 6 GPa are necessary for this conversion to take place.

Cubic boron nitride is an amalgamation of boron and nitrogen which are two elements positioned either side of carbon in the Periodic Table, from which it is possible to form a compound: boron nitride. This compound exhibits a hexagonal, graphite-like structure with approximately equal numbers of boron and nitrogen atoms arranged alternately. Like graphite, this compound of hexagonal boron nitride is a slippery, friable substance. Just as the hexagonal carbon (graphite) can be transformed into cubic carbon (diamond), so can hexagonal boron nitride be turned into cubic boron nitride.

The reason why PCD is not used on ferrous components is that under the temperatures and pressures sustained during metal cutting, the diamond has a tendency to revert back to graphite in a few seconds, making it impossible, in practice, to use. CBN is synthesised in a similar fashion to that of synthetic diamond (PCD) and at similar cost. It is not as hard as PCD, and is less reactive with ferrous metals, but can revert to its softer hexagonal form and oxidise in air above 1000 °C. For this reason it is not used for machining hardened alloy steels and the other materials listed above, and is now superseding rough grinding operations on many "hard-metal turning" applications. PCD has been found considerably superior to other cutting tool materials when dealing with machining highly abrasive metals such as the high silicon content aluminiums. Even though PCD/CBN costs approximately fifty times more than cemented carbide (per cutting edge) the tool life is vastly superior and in the correct circumstances more than recoups the extra cost.

So far we have discussed these ultra-hard materials, but in what form are they purchased and how are they applied to the current cutting tool problems found in industry? There is a range of ultra-hard cutting inserts in the form of tungsten carbide backed blanks and smaller shapes which are wire-eroded from the larger-sized blanks, then mounted in holders, or indeed used as complete circular cutting tools. When heavy rough machining of hard ferrous materials in the range 45–65 HRC, a solid rather than a carbide-backed insert is preferable. Typically these CBN inserts find special applications in machining the Ni-hard, or high chromium irons used in the roll, pump and crushing industries. These irregular cast component designs have high toughness and wear resistance and cause many problems with alternative tool materials. The CBN inserts cope with it admirably, giving longer tool life combined with increased productivity, via increased cutting speeds (up to eight times greater than carbide tooling), which more than compensates for the increased costs of tooling. Other areas where great benefits have accrued are in the machining of grey cast irons, where it has been reported that the tool life has increased by twenty to thirty times that of ceramic tooling, but this grey cast iron should retain a fully pearlitic microstructure, as, if there are large areas of free ferrite, rapid tool wear would result. When a situation arises where the clamped cutting inserts are unsuitable, it is possible to use the alternative brazed versions. With these brazeable types, one side of the cutting insert has a metal skin bonded to it, which enables the "hard irons" to be bored, grooved, and threaded.

If we now consider the applications for PCD cutting tool materials, they can be classified into:

PCD with the particles sintered together using cobalt, as a solvent/catalyst
PCD with the particles bonded together using a ceramic second phase

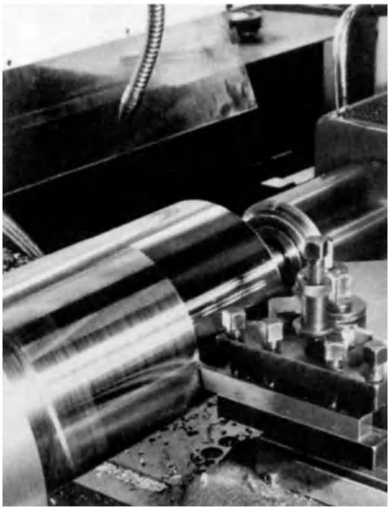
In the main, the former cobalt sintered type is most dominant in the cutting tool industry and applications of these will be briefly considered. As mentioned earlier in this section, the main benefits of using PCD are when there is a requirement to machine the highly abrasive non-metallic/ferrous materials in use today. However, there is another area of application where these PCD materials have shown themselves to be excellent alternatives to natural diamonds, and that is where the surface finish is of prime importance. So, to cope with these different situations, various grades of PCD have been developed, using different particle sizes of diamond. In all the machining applications where PCD has superseded other cutting tool materials, the tool lives can be extended 50–200 times that of the carbide alternatives.

Apart from turning and milling applications of PCD inserts, drilling is gaining in popularity, particularly for the larger twist drills used in hole-making operations in abrasive non-metallic materials. In this situation the insert is made in the form of a standard PCD blank "sandwiched" between metallic backing layers, permitting it to be brazed and held on both sides. This is often known as a "microdrill". It is recommended that the body of these drills is made of tungsten carbide, and a shank of this composition has greater wear resistance against abrasive swarf than other materials, whilst offering a thermal expansion compatible with that of PCD.

To complete this review of these "super-hard" cutting tool materials, Fig. 2.5 shows just a small proportion of the cutting tool applications of both CBN and PCD inserts. Let us now consider the effects of tool geometry on CNC machining applications in turning and milling.

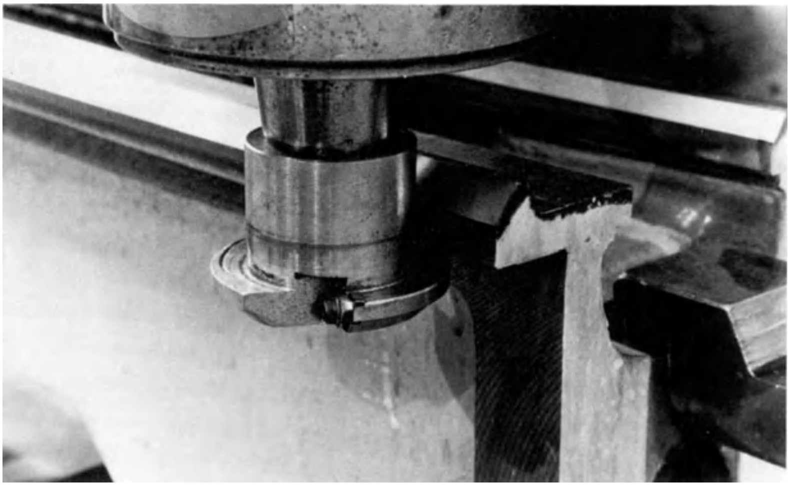
2.5 Insert Cutting Tool Geometries and their Selection

There is a large choice of tool materials to cater for a wide range of workpiece materials. Where the qualities expected from a tool vary from hot-hardness, toughness, resistance to oxidation, thermal shock, and a lack of affinity between the tool



a

b



c

Fig. 2.5. Machining applications are many and varied using ultra-hard cutting tool materials like PCD and CBN. **a** PCD turning copper printing rolls. **b** PCD boring alloy engine support struts. **c** CBN fly-cutting induction hardened cast iron lathe beds. [Courtesy of Debeers PLC.]

and workpiece, they are also dependent on the mutually inclusive relationship between the cutting speed, feedrate and tool life. To obtain the desired effect of an overall increase in production, a judicious selection of the above criteria must be coupled with an appreciation of the tool geometries necessary to optimise efficient cutting conditions. The greatest stock removal rate does not always increase production throughput, if the work-in-progress slows everything down and this is further compounded by using very expensive tooling. Often, a modest increase in cutting efficiency and less expensive tooling creates a harmonious productive flow through the shop. So speed is not always the desired criterion; it is the author's view that the number of parts obtained per cutting edge is of much greater significance in creating overall production efficiency. Increases in parts per edge tool life give many real benefits ranging from more predictable cutting conditions, less power consumption and reduced stresses in the component and work-holding devices, meaning that part quality is enhanced. If production "bottlenecks" are avoided and an efficient work-in-progress system is used within a company, any losses sustained in the speed of the workpiece manufacture is more than made up by these efficiencies.

If we return to the selection of insert geometry and consider the "pros and cons" of using either single-sided or double-sided inserts, prior to a more in-depth discussion of tool geometries, then positive advantages can be gained, in both cases, if the correct selection procedure is applied. A single-sided cutting insert, whether it is used for milling or turning, has much greater strength and rigidity than its double-sided equivalent, giving extended tool life, and is often the recommended insert for roughing cuts, where higher stock removal rates are demanded. Set against this is the fact that only half the cutting edges are present when compared with the double-edged versions. These offer more edges and may be the answer for lighter cuts or softer materials, but even here the advantages gained are dubious. The time taken in tool preparation – changing tips and tool presetting – must be put against lost production, regardless of whether "sister" tooling – exact duplicates in the tool turret/magazine are present – as an extra cost is implied in increasing the work in tool preparation. Although an important part of insert geometry selection, we will discuss this no further, but will go on to consider firstly turning and then milling geometry relationships.

2.5.1 Turning Geometries Using Indexable Inserts

The variation in insert geometry in turning operations is diverse and a wide range of rake angles, plan approach angles, nose radii and insert shapes can be obtained and just some are shown in Fig. 2.6. The method of clamping these inserts is subject to a range of securing techniques, such as levers, pins, clamps, etc., and for a given torque offer greater clamping/locking effort.

The tool angles are fixed and determined from manufacture, and the workpiece's shape, the machine's capacity and its condition, together with the part material are the determining factors in the correct selection of the tool and its insert. The cutting process in influenced by the tool angles and a distinction occurs between the positive (Fig. 2.6a) and negative inserts (Fig. 2.6b). A positive cutting rake offers an easy cutting edge and also reduces the power requirements, with there being little danger in workpiece bending and a reduced tendency towards vibrations. On the other hand, a negative insert can be obtained with twice as many cutting edges, although needing greater power output from the machine. Generally, plain negative inserts are used for rough machining operations, or for short-chipping work materials, or both. Certainly, a negative rake will strengthen the cutting edge, but induces heavier cutting forces during machining. Positive inserts, in general, are best adopted for turning slender workpieces, or wherever there is a risk of vibration on the lower powered machines.

The back rake angle may also be obtained in a positive (Fig. 2.6c) or negative geometry (Fig. 2.6d). Where interrupted cutting conditions exist, such as when turning, eccentrically, with keyways, or splines, etc., shock-loading of the insert is present, and it requires tools with negative back rake (Fig. 2.6d) in order to preserve

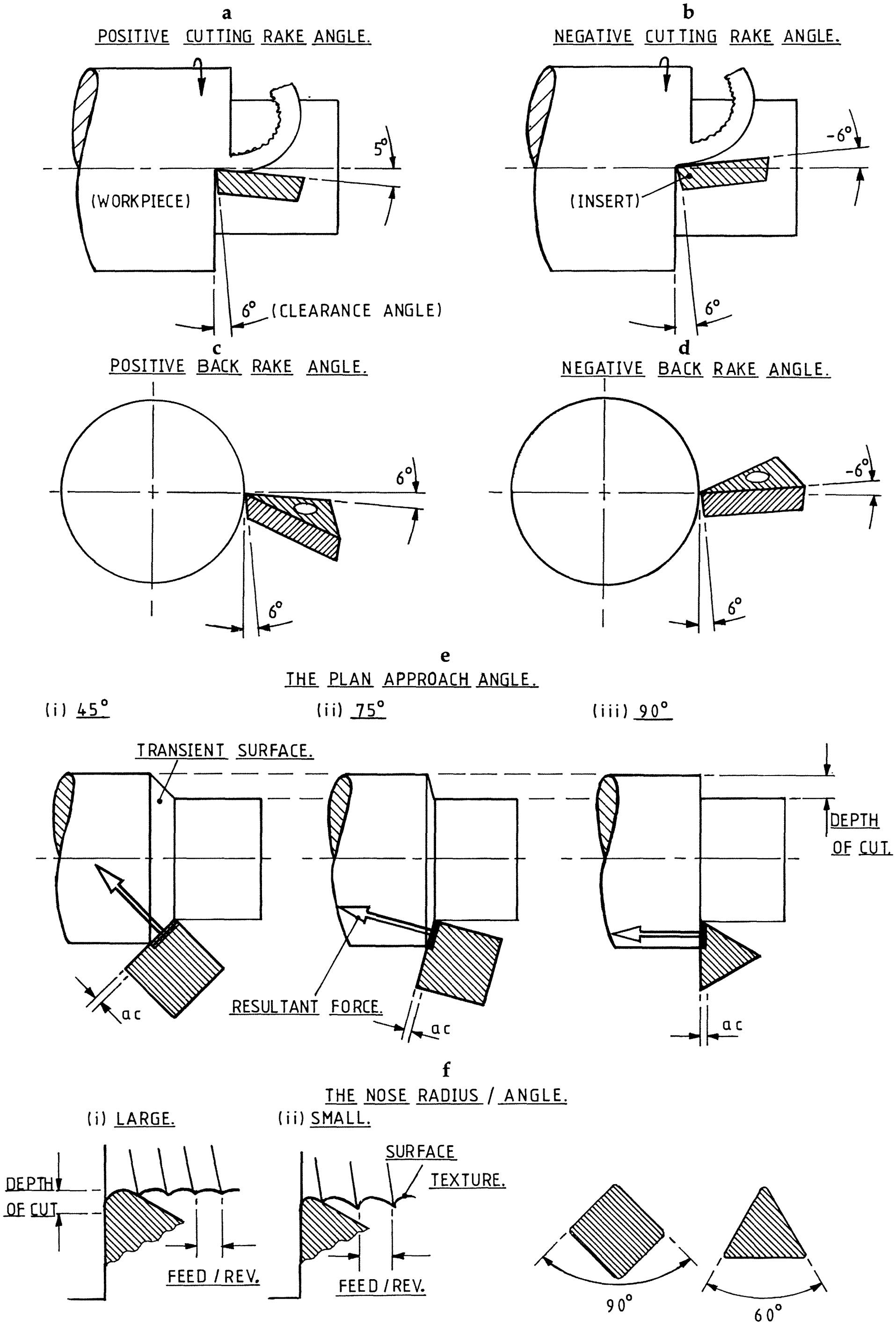


Fig. 2.6. The insert geometry in turning operations.

the point of the cutting edge from these impact stresses. Another feature of the back rake is that it will influence the chip flow direction. The effect of this negative back rake is to force the chips towards the workpiece, which might roughen its surface, but the positive back rake allows the chips to be lead away from the work surface. Using the pin-type clamping arrangement gives the insert a wider variety of chip flow characteristics than other methods, allowing special chip breaker geometries to be sintered into the insert.

By manipulating the turning insert's clearance angle with respect to the workpiece, this has several important ramifications on its temperature, edge life, and workpiece surface finish. The size of this clearance angle will have an influence on the time it takes to reach a certain wear land on the insert and using a small clearance angle will mean that the quantity of insert material needing to be worn down during cutting to reach specific land width is smaller than if a larger clearance angle had been used. If a larger clearance angle is used this produces a weaker edge, in the same manner as when a large rake angle is utilised. Large insert clearances increasingly involve the risk of the edge breaking down and failing before the calculated wear land has been reached. If weak workpieces must be machined using a rather unstable tool set-up, then the danger of vibration can be eliminated by setting the tool marginally above the workpiece's centre and in so doing, offering a smaller clearance angle.

In general, the cutting forces are hardly affected by the insert's clearance angle, but the rapid wear which takes place when the insert clearance is too small will increase the cutting force to some extent.

Of some significance in any turning operation is the influence during machining of the setting, or plan approach angle (Fig. 2.6e). When a 45° large plan approach angle is used (Fig. 2.6e), then the chips tend to be thick, but this can be lessened by the 75° or even further, 90° plan approaches. The large plan approach angles increase the radial force component considerably, owing to the oblique cutting geometry, which will affect the machining of slender shafts, whereas orthogonal cutting using 90° inserts, means that rigid tools, workpieces and work-holding devices are necessary.

The size of the tool nose radius has a big influence on the surface finish produced on the part (Fig. 2.6f) and the larger this radius, the more even the surface. When too large a radius is used it can produce vibration. The determining factor when establishing the feedrate to be utilised is the nose radius and as a rule you should not use a larger feed than 80% of the nose radius.

2.5.2 Chipbreaking

One of the least understood areas of cutting is the influence of efficient chipbreaking in the satisfactory production of parts by the general engineering population as a whole – with a few notable exceptions. It is crucially important to obtain in all machining operations the correct chipbreaking ability, as badly controlled swarf can cause problems. The chipbreaker affects the chipbreaking ability and is also influenced by other factors such as the feedrate and depth of cut. If the depth of cut produced continuous ribbon-like swarf using a low feedrate in the first instance, then by increasing the feedrate, this will improve chipbreaking if part geometry and surface finish will allow.

Assuming that a separate chipbreaker is present above the insert, then its distance from the cutting edge – known as the chipbreaker width – will, together with its height, determine the chip's shape. If too large a width and/or too low a chipbreaker are present, then this produces long, continuous chips. Conversely, when the width is small and/or too high, chipbreaking occurs, but it might produce chip clogging which will inevitably cause the cutting edge to fail. If an efficient chipbreaker is present then the swarf is broken into relatively short, unconnected parts which are easily disposed of by swarf conveyors. It is usual to grind chipbreakers onto brazed carbide tips, or those made from high speed steel, but there is a real risk that the brazed tools may have cracks present, caused by stresses produced whilst grinding takes place. If this is not the case, then the grinding stresses may cause premature edge failure. There is limited potential to be gained from the regrinding of brazed tools, meaning that when carried out, it results in higher resharpening and tool costs.

The whole problem of grinding the cutting edge and the subsequent chipbreaker is eliminated by using indexable inserts – of the pin-type clamping arrangement – which are by far the most prevalent today. With modern inserts, the chipbreaker is "sintered in" with quite complex chip grooves, or dimpled (embossed) surfaces, to artificially break the chips. Some of the latest chipbreaker designs – produced on CAD/CAM equipment – have "sintered-in" different chipbreaker actions for varying depths of cut. So, at small cut depths, chipbreakers close to the edge break the chips, whereas if depth of cut is increased, the influence of other chipbreakers further in the insert's body will promote automatic chipbreaking. In fact the whole subject of chipbreaking is quite complex and only a superficial treatment is possible here. If a greater knowledge is required then most leading tooling manufacturers offer seminars on this and other tooling related subjects.

Some of the factors influencing the selection of the correct geometry and cutting action in milling operations are discussed in the following section.

2.5.3 Milling Geometries Using Indexable Inserts

Prior to a discussion about the pros and cons of selecting different inserts, it is worth restating the obvious – that the workpiece, machine, fixturing and milling cutter must all be examined in terms of the rigidity of the set-up. More will be mentioned on cutter rigidity later, but for now let us consider the factors which influence our decision to select cutters based on the following reasons:

peripheral or face milling
axial and radial rake angles
approach (entering) angles

In the case of peripheral milling operations, a basic distinction to be made is the direction from which the workpiece is approached by the cutter. When the milling cutter rotates with the direction of feed of the workpiece, we call this climb or down-cut milling (Fig. 2.7a); alternatively, if the milling cutter rotates against the workpiece feed it is termed conventional, or up-cut milling (Fig. 2.7b). In either case the cutting action is best illustrated when side-and-face milling, as shown in Fig. 2.7a,b. Considering down-cut milling initially, we can appreciate that the insert begins the cut directly, which in turn produces impact stresses which avoids the "gliding effect" associated with up-cutting milling operations. The direction of the cutting forces is such that they are directed away from the machine table and hence the work, whereas the opposite is true in up-cut milling. In appreciating the criteria which must be met in down-cut milling, we can see that some form of backlash elimination must be present in order to avoid the workpiece being "snatched" into the cutter. In fact, the pre-loaded ballscrews used on CNC milling machine tools offer this protection to the cutter/workpiece. The relationship between the inserts and cutting depth must be

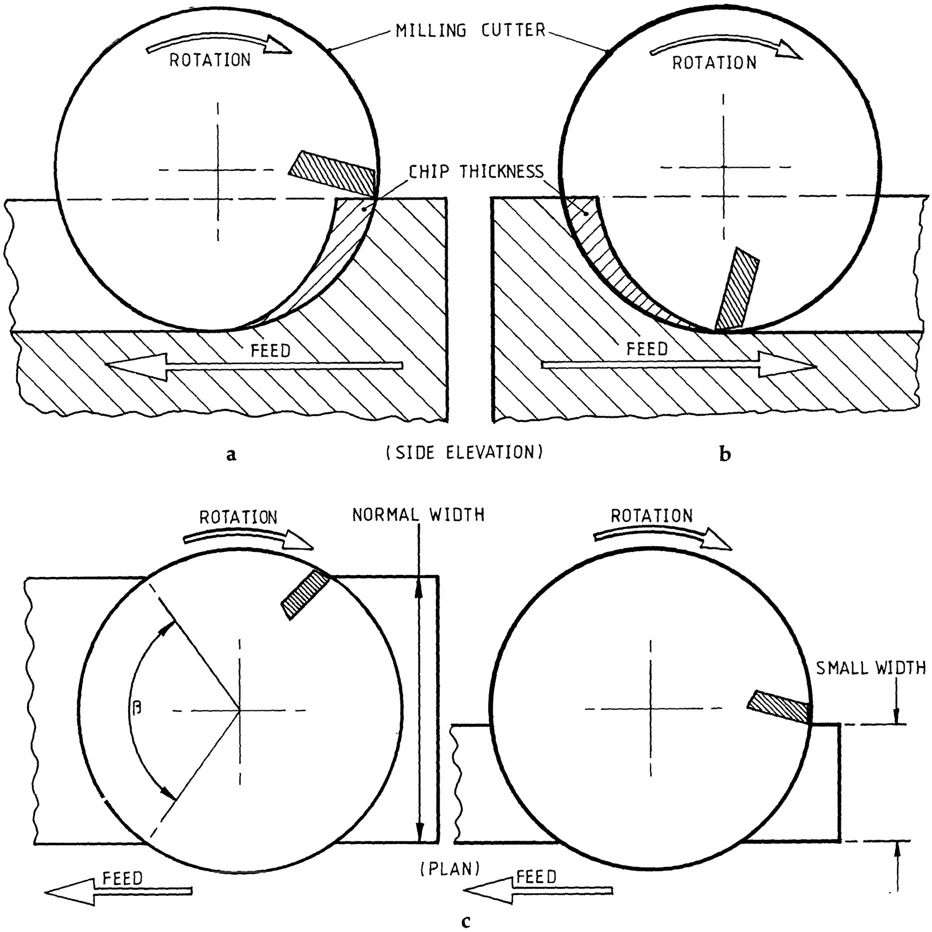


Fig. 2.7. Typical milling techniques adopted for either peripheral (**a**, **b**) or face milling (**c**) operations. **a** Climb- or down-milling. **b** Conventional or up-milling. **c** The effect of workpiece width on the cutter's performance. NB: Use a cutter diameter 30% larger (at least) than the width of engagement.

such that at least one insert must be in cut at any time and when this factor has been satisfied, down-cut milling is the preferred method of cutting and an added bonus is that the surface finish improves along with a drop in spindle power.

However, it is sometimes the case that the up-cut method must be employed and this technique has the chip thickness increasing from zero to a maximum during the cut (Fig. 2.7b). Prior to the insert actually cutting the workpiece, some burnishing of the part occurs as it "glides" over the previously machined surface. This action tends to separate the cutter and workpiece and can influence the surface finish somewhat. These are some of the factors affecting peripheral milling operations; let us move on to consider face milling operations.

For maximum efficiency a face mill should be engaged in the workpiece by about two-thirds of the cutter diameter, as depicted in Fig. 2.7c (left), where in this case the cutter is positioned symmetrically to the work, initially, then the climb milling action is illustrated, which requires a ratio of cutter-to-width that will favourably ensure an acceptable entry angle into the work. So, at the point of entry into the workpiece, the cutting edge takes an acceptable bite. If it is uncertain whether the machine tool has enough power to operate the cutter under this ratio, it may be advisable to divide the cut into two, or more, passes to maintain the width-to-cutter ratio as closely as possible.

Before continuing to discuss choosing the correct insert densities and rigidity demanded in productive machining using the latest milling cutters, it is worth reviewing the geometrical relationships which exist between the insert and its respective holder and its influence on the workpiece. This cutter insert geometry is an important aspect of face mill design and the main features to be considered are shown in Fig. 2.8a, where three major insert inclinations occur:

axial rake

radial rake

lead, or approach angle, with combinations of at least two inclinations being present in today's cutters.

Therefore the insert's cutting edge can be positioned relative to both the radial and axial planes and may be either positive, negative, or neutral rakes. In general the neutral rake is rarely used in either plane, owing to the entire cutting edge impacting simultaneously on the workpiece, and will be ignored from now on. A combination of the radial and axial rakes determines the shear angle with three basic combinations available:

negative radial and axial (Fig. 2.8b)

positive radial and axial (Fig. 2.8c)

negative radial, positive axial (Fig. 2.8d)

We will consider each combination individually, beginning with the double negative insert geometry (Fig. 2.8b), as this is traditionally the "start point" in selecting a face mill for roughing steels and cast irons when power and rigidity are adequate. This double negative insert design gives the strongest combination for the cutting edges and can withstand greater chip loads and higher forces than when using other designs. Of course, we should remember that the increased cutting forces generated by such geometry will consume more spindle power, requiring greater machine, workpiece and fixturing rigidity in order to productively utilise its true benefits. Additionally such double negative tooling has less favourable shearing mechanisms, resulting in generally poor workpiece surface finishes.

The converse of this insert geometry is that offered by the double positive insert cutters (Fig. 2.8c), where the most efficient cutting occurs, owing to the improved shear angles present, for although they are not as strong as the double negative types, they have greatly reduced entry impact loads and cutting forces present. These benefits make them the logical choice on older and less rigid machine tools, or if the spindle power is rather limited. Using the double positive geometry, the peripheral edge in both the radial and axial planes leads the insert through the workpiece and in so doing, creates a true shearing action. With such high shear cutters, they are the obvious choice for any non-ferrous materials, or indeed, if the soft and gummy stainless steels must be cut.

Lastly, we will consider the compromise of these extreme geometries, namely the negative radial, positive axial insert inclinations shown in Fig. 2.8d. This design offers the advantages of both the previously discussed types, where the negative radial rake

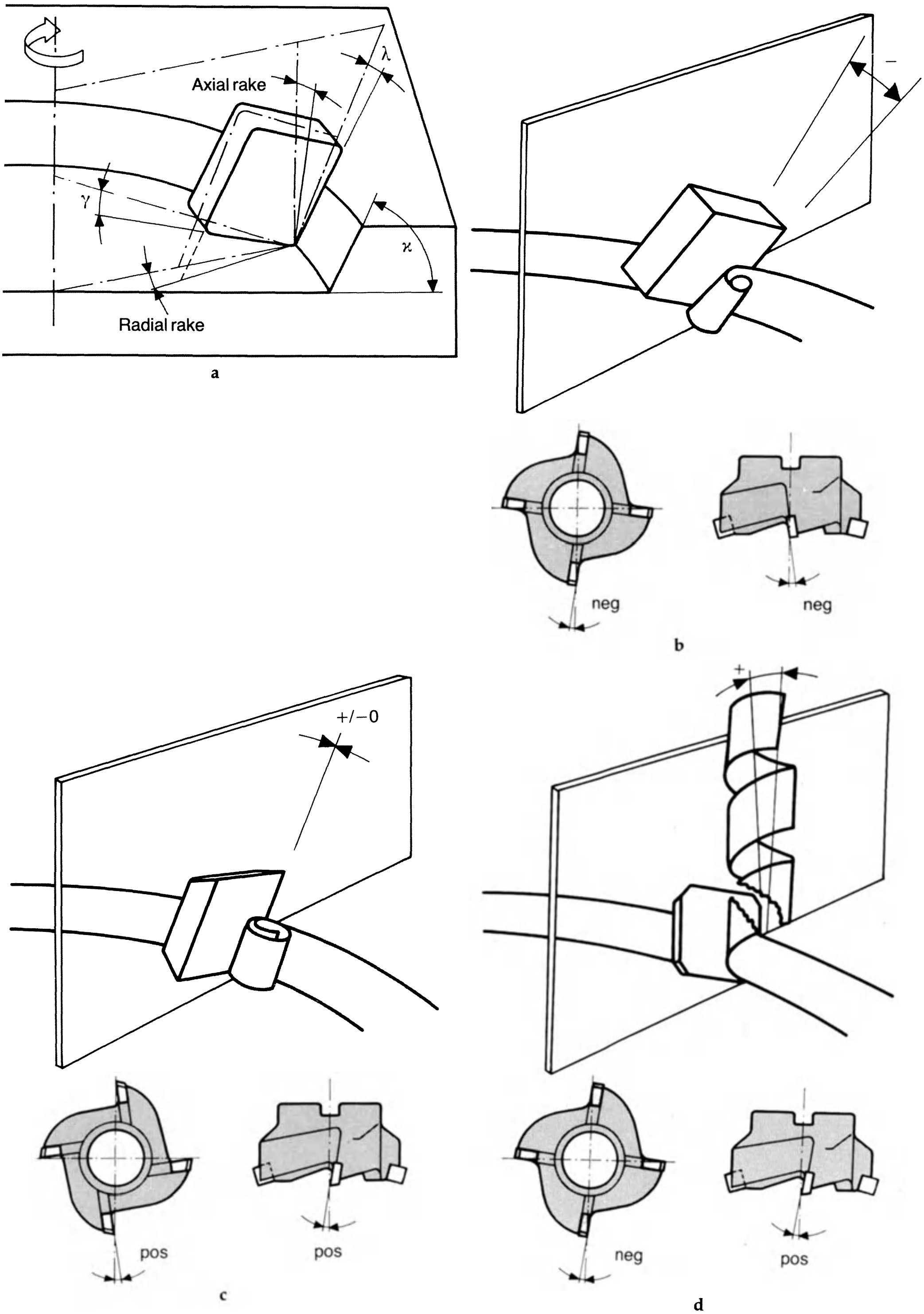


Fig. 2.8. Cutter insert geometry and terminology in milling operations. **a** Cutter insert geometry. **b** Negative/negative. **c** Positive/positive. **d** Negative/positive. NB: The angle of inclination of the insert generally termed "plan approach angle" and denoted by the Greek letter λ, has a significant effect on

provides a strong cutting edge, whilst the positive rake creates the shearing action. The axial rake determines the direction of chip flow and as this type of cutter has a positive axial plane, the chips are directed up and away – termed evacuated, or exhausted – from the workpiece. This is an important point, as it prevents the recutting of chips still in situ on the machined surface, taking away with them the heat that would otherwise be present on the surface and from the cutting edge.

Finally, the last insert geometric inclination can be considered, termed the approach, or entering angle, denoted by the Greek letter lambda (λ) as depicted in Fig. 2.8a. The favoured inclination angles are 90°, 75° and 45°. The 45° lead insert, for example, will reduce the chip thickness by around 30% for an advance per tooth, allowing increased feedrates at a given chip load, resulting in improved stock removal rates. Another function of the entering angle is that it allows the cutter to enter and exit the cut more smoothly and in so doing, reduces the shock loading on the inserts. A problem with any small approach angle is that when machining brittle materials, edge breakout (often termed "frittering") occurs. Under these conditions it is advisable to increase the lead angle, giving a gradual exit from the workpiece and in so doing, lowering the radial force on the material's transient surface. If we increase the entering angle to reduce the radial pressure, this leads to greater axial pressure, which may result in the machined surface being deflected if it has a thin cross-sectional area, or is poorly supported. Obviously, when a square-shouldered step is required on the part, then the 90° approach angle cutter is the only choice, but if general machining conditions are to be employed, then a 75° entering angle is a good compromise cutter. A few more points are worth making before we leave this topic of insert inclinations: when the spindle head bearings are slightly worn, greater machine consistency arises from using large approach angles as they provide axial pressure on the bearings and this higher thrust force minimises the "play", assuming that the part geometry is not affected by this high inclination angle. Finally, the 90° approach angle inserts – owing to the sudden impact loads on the workpiece – tend to be very noisy at higher depths of the cut and obviously will not last as long as the greater entering angle inserts.

To complete this resumé on milling cutters, the last choice to be made when considering the cutting action of the inserts is the cutter density. This insert density must be such that it allows the chip to form properly and clear the cut. If inadequate chip space is provided in the chip gullet, then "chip jamming" may occur, which could lead to insert edge breakage or damage to the workpiece. It is always advisable to note that at least one insert should be in cut at all times, as failure to do so could cause severe pounding to the insert's edge, leading to a damaged cutter and excessive wear on the machine tool. Coarse pitched inserts in the cutter body with one to one and a half inserts per 25 mm of diameter, provide a large chip gullet space and are recommended when machining soft materials producing continuous chips, or in wider cuts with long insert engagement. The finer pitched insert tooling with about four to five inserts per 25 mm of diameter are recommended if insert engagement is a problem. The finer pitching allows more than one insert edge to be in cut all the time – even on very thin cross-sectional areas – and are normally chosen when high-temperature alloys and hard steels with light chip loads must be machined. As the chips are smaller, then less gullet space is necessary, allowing increased cutter density to be used.

The final comments in this section on milling cutters are reserved for an appreciation of the effect of cutter rigidity and its expected deflection during a machining operation. A cutter's performance and its tool life are substantially affected by the workpiece's accuracy and surface finish. If the cutter, through lack of rigidity, takes a pounding, then bending and vibrating during cutting occur and the machine's wear life is severely affected, regardless of whether it is a large, or small machine. There are many factors which affect rigidity during cutting, such as the basic machine's design, its drive mechanism, bearing positions, spindle size, length of overhang, and also the workpiece and its fixturing. Assuming that all the above factors are adequate, then the only other variable is the basic structure of the cutter in affecting its rigidity. There are inherent differences in the tool rigidity between face mills and slot drills being more rigid than, say, end mills, boring bars, or tooling on extension arbors. The cutting tool geometry will also influence tooling rigidity, as a negative rake and large entering angled insert cutter require more rigidity than a positive raked 90° insert. Furthermore, greater rigidity is demanded of a cemented carbide cutter over an HSS cutter composition.

When a cutter is not very rigid, for whatever reason, this influences its deflection, which in turn affects the part quality. A tool's resistance to deflection is determined by its diameter, length, shape, and material composition. If we ignore the cutter and material and confine our discussion to its length and diameter, we can see that the deflection is inversely proportional to the fourth power of the cutter diameter and it is directly proportional to the cube of the length. More simply stated, the deflection reduces by four-fold relative to an increase in the tool's diameter and will reduce three-fold by a reduction in length. Thus, by increasing the cutter's diameter or reducing the length, this improves deflection in the first instance. If this is not possible, then improving the cutter's stiffness by utilising better tool adaptors, rather than the less attractive alternative of decreasing tool force through lowering the feeds or speeds, is a better choice. Any would-be purchaser of milling, or indeed turning tools, should look closely at the rigidity offered by the cutter body as this will have a great influence on its subsequent cutting performance.

This completes the milling cutter review and we will now consider the influence that the chip thickness plays in turning and milling operations.

2.5.4 The Effect of Chip Thickness in Milling and Turning Operations

Most cutting edges lead a short but hectic life and under favourable conditions live to see a great chip volume pass by. Under abusive machining conditions, a much less impressive chip volume yield results. In all these cases the chip thickness is of crucial significance: with a turning operation the theoretical chip thickness will equal the feed per revolution, multiplied by the sine of the setting angle, as depicted in Fig. 2.9a. Therefore, as long as the cutting edge is in constant engagement, this will result in an equally thick chip passing over the rake surface, but, owing to plastic deformation, the chip will be slightly thicker than its calculated value.

If we now consider the case of milling, the theoretical chip thickness is also dependent on the setting angle and the feedrate (Fig. 2.9b), and this is only true for the chip section that is formed by an axial plane through the cutter's centre, in the direction of the feed. So, on both sides of this section (Fig. 2.9b), the chip thickness is reduced until it becomes zero at the points where lines in the feed direction touch the periphery of the milling cutter. Obviously, this pre-supposes that there is engagement by the milling cutter over its full diameter, which, for example, is the case when milling a slot in wrought stock using an end mill. Under these machining conditions, as the milling cutter's tooth enters into engagement, it must start by cutting a chip thickness that is less than the tumbling radius of the edge. An analogy of this difficulty facing the tooth would be like trying to peel an orange with a cucumber! Clearly, no cutting takes place until enough pressure has been generated between the

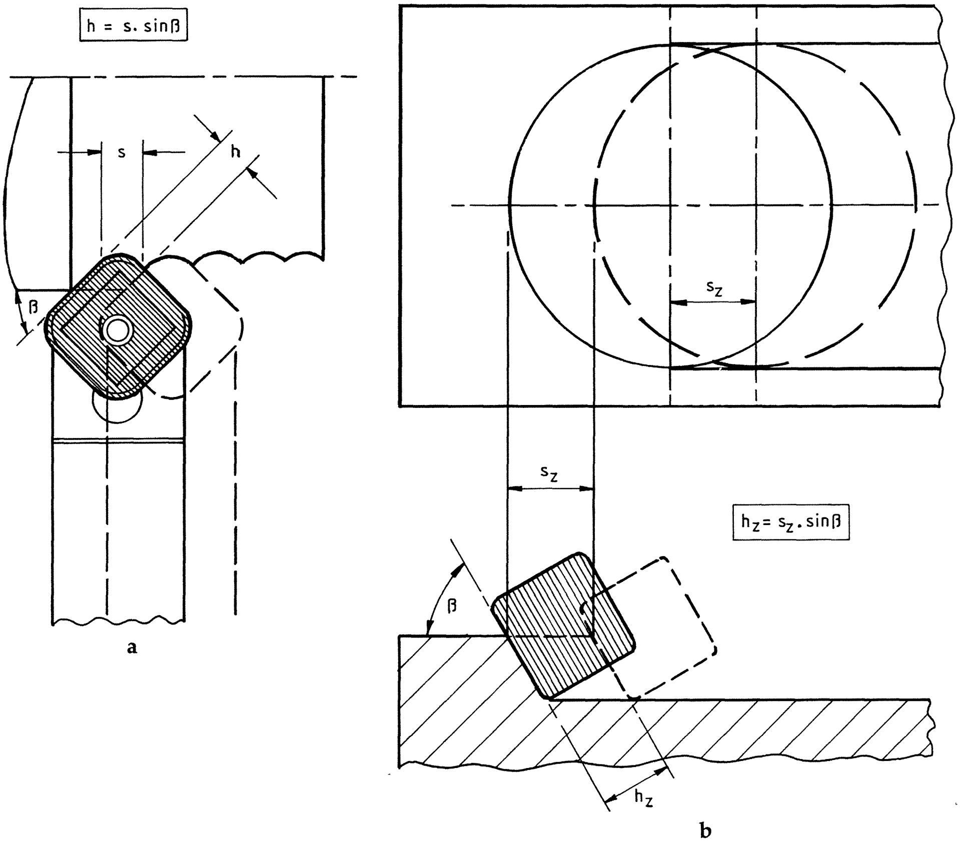


Fig. 2.9. Chip thickness in **a** turning and **b** milling operations. [Courtesy of Seco.]

tooth's edge and the workpiece. Once this level has been reached the edge will begin to penetrate into the material to form a chip. Therefore, during this burnishing phase, when sliding and rubbing occurs on the workpiece's surface, unproductive wear on the tool takes place. Fortunately, this unacceptable condition is of shorter duration than might be appreciated from the description given here. Owing to the action of milling operations (as against turning) it is impossible to offer the cutting edges ideal working conditions.

When cutting a slot using an end mill, the unfavourable starting phase – already described and which affects the milling teeth at each revolution – cannot be avoided. It is appreciated that if we have a good edge sharpness this would make workpiece penetration easier. This is obviously desirable, if it can be combined with sufficient edge strength, reducing edge breakage, chipping, and crumbling, which would otherwise seriously shorten the tool's life.

2.6 Cutting Tool Diversity – a Review

So far we have been mainly concerned with the implications of different turning and milling cutter geometries in the machining operation. Little has been said about the vast range of cutting applications, and indeed tooling, used on both turning and machining centres that are currently available to the user. In many cases, companies are oblivious to the potential productive capabilities of recent advances in cutting technology, let alone how to optimise these cutters for higher productive throughput. This section is simply intended to review just a few of these cutting tools to give an appreciation of the reasons why this latest tooling can enhance and save the companies' profits, which must surely be at the heart of any true manufacturing engineer.

Any large cutting tool company has a vast range of cutters and services it can offer to its customers, ranging from milling, drilling, turning, work-holding devices, up to tool monitoring equipment and transportation equipment of considerable sophistication. These companies invest heavily in order to produce tooling to the highest productive quality and it might be worth pausing to consider the reader's company's tooling inventory to see if it matches this level of sophistication? If the answer to this question is "yes", then assuming it is utilised in an efficient manner, a company can be considered as one of those enlightened ones which are probably at the forefront of cutting capability. However, if the answer is "maybe", or still worse, "no", then assuming it has reasonable machine tools in its workshop, it is missing a competitive edge that its competition can exploit to the full.

As an example of how cutting advances have progressed in recent years, only a short time ago ball-nosed cutters were invariably purchased in high-speed steel, whereas nowadays a typical ball-nose has inserts situated strategically along its periphery and nose, offering high stock removal rates obtainable in a range of sophisticated metallurgies and coating treatments, similar to the one shown in Fig. 2.10. Not only are these cutters very robust and easily able to withstand the forces generated by high stock removal, they can be simply and quickly reset for cutting a range of materials whilst still offering optimum geometries and tool life.

Another example of the development of traditional milling cutter designs, incorporating the very latest inserted-toothed cutting configurations whilst offering interchangeable ends, is the "porcupine" cutter shown in Fig. 2.11, being based upon the older solid end mill design with helical fluting. This cutter, however, is far removed from its outdated high-speed steel predecessor and allows for quick and precise interchangeable ends to not only vary its overall length, but to replace the worn section of the cutter, which inevitably occurs after a busy life, avoiding a total cutter body replacement. The inserts, chip gullets and cutting tool materials are designed and developed with one thought in mind – high stock removal and swarf evacuation, with an extended tool life, offering acceptable roughing surface finishes to the workpiece. This type of cutter is becoming an industry standard for a whole host of cutter diameters and lengths, when slots, corners, profiles, and some facing work is required to be roughed out.

In the last few years a new concept in turning cutting technology has been introduced which has major implications on the current cutting tool philosophy utilised by most companies. Instead of using a range of expensive tooling in the tool turrets and then having to index them for different operations, which wastes productive cutting time and costs more in a higher tooling inventory, the new groove-turning system has been developed. This unique cutting system using only a few tools (for face-grooving

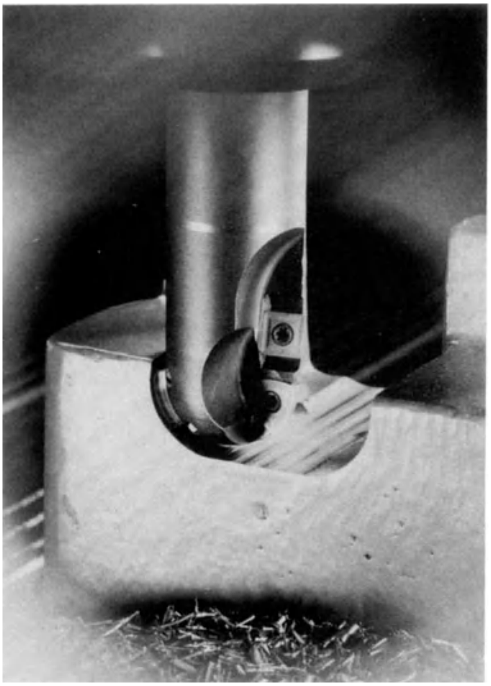


Fig. 2.10. A ball-nosed cutter with inserts positioned such that a swept volume occurs upon rotation. A wide range of materials can be machined simply by changing the grade of insert, which is true to a certain extent for all inserted-toothed cutters. [Courtesy of Walter Cutters.]

and groove-turning) allows complex part geometries to be machined with the minimum of tools, making it simpler to program and increasing part throughput considerably. In order to make this concept possible, total chip control is necessary and this relies on the fact that chips which are stressed during chip forming are easily broken with minimal energy consumption and part deflection. To obtain good chip control characteristics the geometry across the rake face is exceedingly complex. When considering chip control designs, two main types occur:

chipbreakers
chipformers

The most recent types – chipformers – are distinguished still further by subdivisions into those that cut and form a chip and those that mostly form once it is cut. However, a requirement of any chip-control cutting tool is to produce chips that do not inhibit normal production or impair part finishes. If we consider the original chipbreaker designs, these only tend to break it, or others simply narrow the chip. Although some designs can achieve both breakage and chip narrowing, they only work over a small range and are sensitive to changes in feeds, part diameters, and different materials. An ideal chipbreaker design should narrow and form the chip over a range of cutting conditions, in an energy-efficient way. In this manner, chips are easy to dispose of, and compact and safe to handle. The major advantage in narrowing the chip is that it freely emerges from its groove and in this sense it reduces

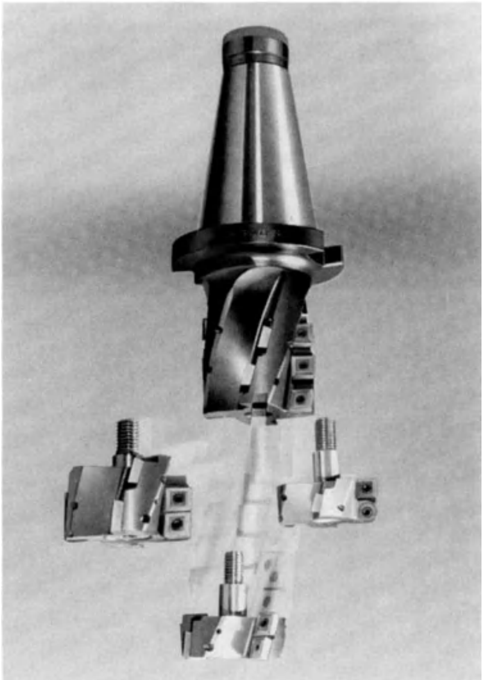


Fig. 2.11. An inserted-toothed end mill, known as a "porcupine cutter", with interchangeable ends as they are prone to damage in use. This also allows the cutter length to be modified. Notice how the strategic placement of the inserts on the cutter's periphery allows cutting along the whole length of the effective cutter per revolution. [Courtesy of Walter Cutters.]

the contact friction whilst simultaneously improving the cut surface finish. Any chipbreaker works by mechanically bending the chip until it meets an obstruction, which forces it to quickly change direction, or by chip flowing it into a deflector groove. The main disadvantage with such methods is that the tools are subject to material variations and changes in cutting parameters – the latter influences the bending radius of the chip. Therefore, if chip bending is not at an optimum, then poor chipbreaking results, but even when conditions are correct, the rhythmic breaking of chips can influence chatter in the tool and inhibit productivity at higher speeds.

To overcome these problems of chip control using chipbreaker designs, the chipformer was designed and developed to a highly sophisticated level in these new groove-turning tooling systems. In this case, the front cutting edge alternates as follows: negative–positive–negative–positive–negative rakes, producing coiled chips whilst plunging. If the tool is fed laterally as in diameter turning operations, the chipformer becomes a raised-land chipbreaker and in this form produces chips of the "6" and "9" shapes, which are directed away from the workpiece to break on the insert's side. This total chip control allows the cutting edge to groove, turn (right or left), face groove and recess, part off and thread, with just a few tools; all of which means that programming is simplified, as is set-up time, and drastic reductions in cycle times accrue. Other benefits are that fewer burrs and blend marks occur with up to 14% reduction in power requirements over traditional methods, with less part deflection.

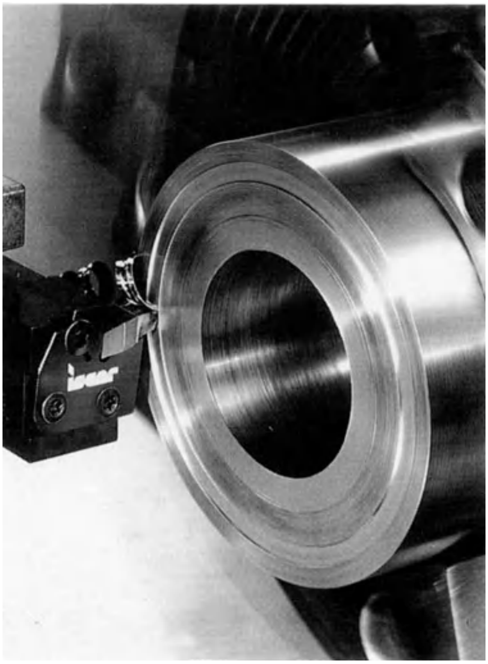
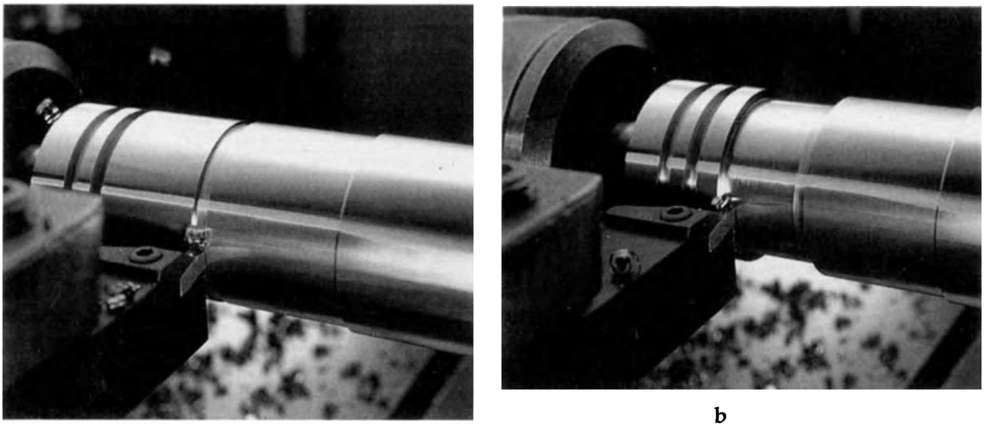


Fig. 2.12. A face-grooving operation using a sophisticated insert geometry for good chip control. [Courtesy of Iscar Tools.]

Obviously, photographs cannot show the dynamic cutting capabilities of such chipforming technology, but an appreciation of the face-grooving and the groove-turning tools can be gleaned from Figs. 2.12 and 2.13 respectively. Of particular interest in these photographs are the chip flow characterstics and the generated surface finish, in conjunction with the high stock removal rates shown by the depths of cut obtained using such inserts.

Whenever large bosses or holes are produced on milled components, a feature often required is a thread which, because of its diameter, rules out the use of taps and their associated tapping heads. Under these conditions, the only real alternative is to thread mill the feature – if we ignore thread turning, as this requires another set-up. In order to mill a thread on a machining centre, it must be equipped with a helical interpolation facility (see chapter 1). Prior to it being machined the "correct" diameter must be circular interpolated on the hole, or boss, as necessary. Figure. 2.14 shows an efficient thread milling cutter.

Thread milling requires the cutter to obtain the smoothest entry into the workpiece and in so doing it avoids thread errors, so it is usual to "arc" in and out of the cut. The position at which the "arc" begins to feed is chosen by considering the cycle time, which, for a large diameter internal thread, can be long. Another important point to remember, is that the smoothness of the entry to the cut depends on the arc radius, with a small radius giving a more severe entry than a larger one. As a useful guideline, when thread milling, the arc radius which is programmed is not less than the diameter of the cutter used. Also, to avoid the possibility of "thread thinning", on



a

b

Fig. 2.13. This shows the advantages of using a cutting insert with a "plunge-and-run" capability. **a** The groove is "plunged" to depth at the true position for the start of the diameter to be turned. **b** The turned diameter is generated at full depth of cut and with high metal removal rate. [Courtesy of Iscar Tools.]

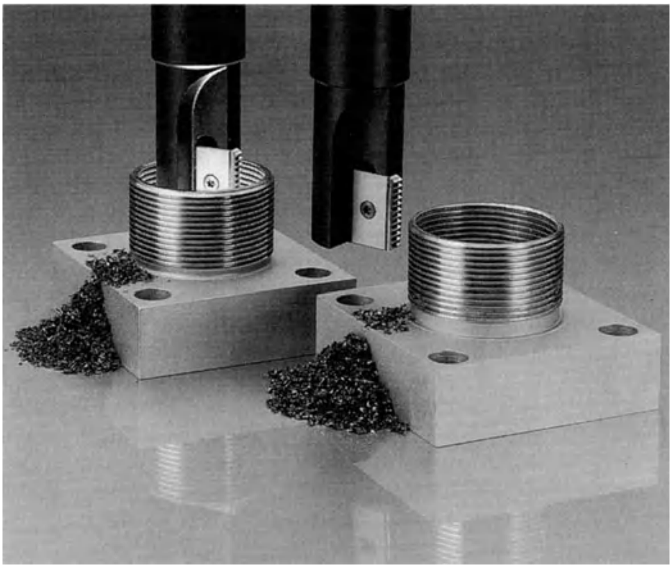


Fig. 2.14. External and internal thread milling. [Courtesy of Seco.]

entry of the workpiece, it is usual to move the Z axis during the "arc-in" block. This simultaneous linear and rotary motion reproduces the tool path to the correct helix, just prior to helical interpolation of the thread. What has been said about internal threads is also true for external ones. Owing to the short time in which the cutter is in contact with the workpiece, the cutting speeds can be increased to that of normal carbide milling operations. Feedrates are generally 0.05–0.15 mm per revolution and are principally controlled by the surface finish requirements of the part and the rigidity of the set-up.

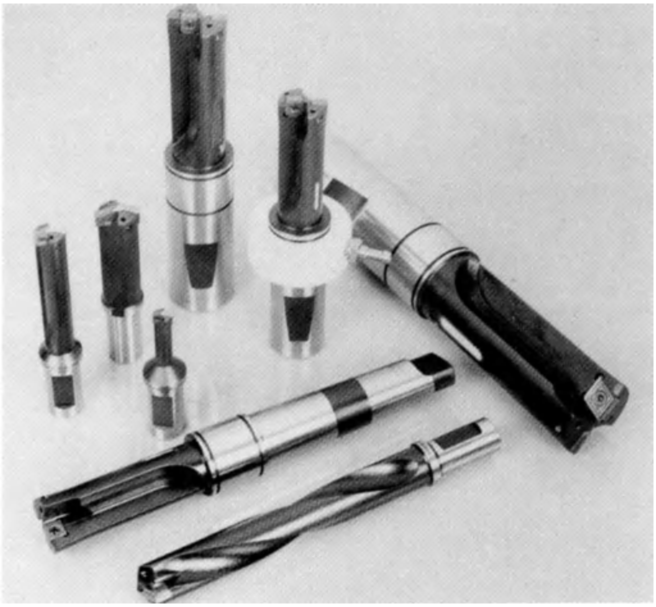
If the thread milling cutter is to cut an internal thread, its centre-line path is shorter than the actual path of the insert as it cuts the diameter. Therefore, because these two path lengths differ, the effective feedrate for the insert is considerably higher than that of the tool centre – which is the point at which any programmed feedrate is effective. The opposite, of course, is true for any external thread milling operations, but both of these points can be ignored when programming the tool using radius compensation, and in so doing, avoiding laborious calculations. Of a different order of magnitude is the thread milling of tapers, as these involve programming true involutes needing a "high-level" language (parametrics) which some machines offer, or an involute interpolation capability within the CNC, otherwise a CAD/CAM solution is necessary.

Turning threads on CNC lathes or turning centres utilises, in the main, two types of single-toothed cutters: full-profile or V-profile designs. When using full-profile cutters, several advantages occur, in that the tooling inventories are reduced and the workpiece diameter does not have to be cut to the exact diameter, as the insert will skim off the excess material on its final pass along the workpiece. Other benefits are that these inserts' points need not be overly pointed and so the total depth of cut is attained in fewer passes as the full depth is cut, whilst ensuring that its thread form is correct and no deeper than necessary, which results in stronger threads. The multi-tooth designs have the second tooth cutting deeper than the leading one and the third, when present, deeper than the second, with only the last tooth being of full form. With both the previous full-form and V-profile designs a range of programming feeds can be employed, but using the multi-toothed inserts the radial (plunge) method should be used; however, more will be said later, in the chapters on programming cutters and workpiece profiles.

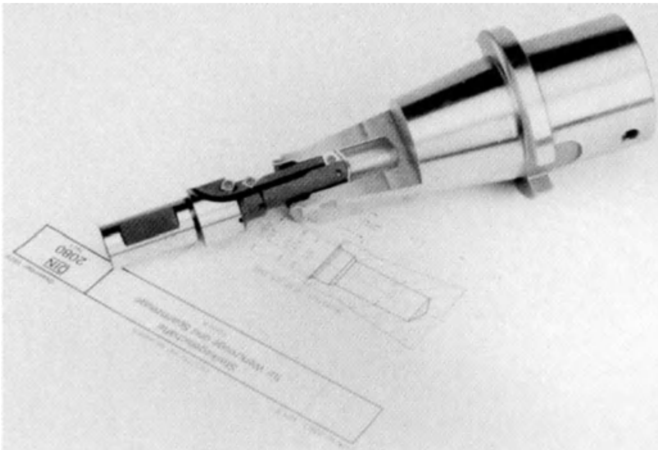
The technology of thread turning operations for internal, external, single and multi-start and tapered threads is beyond the scope of this review, together with chip formation effects and inclination of inserts and their respective geometries. A companion book in this series is recommended to the reader, giving a more comprehensive account of a whole range of cutting technologies and operations possible on CNC machine tools. Similarly, such topics as boring, trepanning and parting off, amongst other techniques are discussed under the title *Advanced Machining – the Handbook of Cutting Technology.*

Without question, the greatest amount of time spent in the production of parts is in hole-making operations, so a review of these techniques is in order, with by far the most popular longer technique being indexable-insert drilling. It is well known that these drills can cure many hole-making problems, eliminating cutting edge regrinding, raising penetration rates, improving size control, increasing productivity and thereby lowering the cost per hole, when compared with conventional solid drills. A typical range of indexable-insert and spade drills is displayed in Fig. 2.15a, but whichever drill is chosen, it is designed to cut at its best under specific conditions. To make the correct choice from the vast range of drills available requires a number of interdependent factors to be considered:

the workpiece configuration and its material composition
the hole's dimension and the number of holes to be drilled
tooling cost
chip control
availability of coolant



a



b

Fig. 2.15. **a** A small complement of the range and diversity of indexable-insert drills obtainable. **b** A spade drill in situ in a partially sectioned component. [Courtesy of Stellram Ltd.]

These factors must be considered when making the choice between the two drill types and may be thought of as an "educated" decision.

If one tries to match the parts to the tooling, one of the first steps is to define the working conditions of the drill to that of the workpiece. As an example of this strategy, an indexable-insert drill with tungsten carbide cutting edges is chosen if cutting at high speeds using low feedrates is required. Conversely, a high-speed steel spade drill is at its most productive when used at low speeds with high feedrates. This tells us that the indexable-insert drills are best when machining steels and their alloys, or cast irons; whereas spade drills (Fig. 2.15b) perform better on work-hardening materials and high-temperature alloys. Spade drills are also used when drilling through laminated materials. The indexable-insert drill produces a disk as it breaks out of the workpiece, therefore, in a laminated material, or parts that are "stacked", a slug/disk is pushed into the next layer causing pressure and heat which will damage both workpiece and drill alike. Yet more problems arise for the indexable-insert drill when drilling holes in workpieces with uneven surfaces, parting lines, or at an entry angle other than at 90° to the surface – with some notable exceptions; if feed is kept low a workpiece inclination up to 80° can be accommodated.

The surface preparation of the workpiece will influence the choice of drill type, as a spade drill is preferred if a hole is semi-finished, precast, or premachined. This is because an indexable-insert drill needs to drill into the "solid" and its action is self-centring, thus it does not require pilot holes to be drilled. If it is used in a pre-drilled hole the drill will create side pressures, causing it to bind in the hole, which may lead to its destruction, in the worst case. Spade drills, furthermore, may begin drilling without special surface preparations and only encounter problems when used in conjunction with the less-rigid longer holders. Under these conditions the drill blade may "jump", or "walk" when it has to cope with surface imperfections. Even this problem may be overcome if a short holder with the same type of drill blade is used to start the hole. These spade drills (Fig. 2.15b) are not self-centring, but the indexable-insert drills are subject to deflection. As a result of this effect, the drill's rigidity is influenced by the workpiece fixturing and the type and condition of the machine tool and are usually termed short-hole drills. If the operation requires a hole deeper than three times the drill's diameter, a spade drill is preferred. Hole accuracy will also influence our choice of drills and generally indexable-insert drills can be made to cut both under and over size, by off-setting the drill in non-rotating tooling which typifies most turning operations.

An important factor in any machining operation – hole drilling being a typical example – is the tooling cost and its influence in choosing the right tool for the job. Knowing that our indexable-insert drill can produce holes four times faster than its equivalent spade drill is not the only criterion that should be assessed, as its productivity needs to be set against a specific diameter, as well as the cost of the drill and its insert. When a lot of holes of a particular diameter are required, the saving from increased productivity will multiply, so that the drill's cost can be divided into the number of holes. When the holes required are few in number, a spade-blade holder of the same diameter may prove more cost effective. Yet another benefit of using the spade drill technique in hole production may be gained by its hole-sizing flexibility, through changing various blade diameters in just one holder including special points and flat-bottom drills, producing some degree of tooling rationalisation. Another feature worth mentioning is that depending on the hole size and its frequency of production run, blade resharpening might prove to be economical; resharpened drills can also have their diameters changed, offering a diameter range across a spectrum of hole sizes.

The true benefits gained from any modern tooling, as typified by a drilling operation, may only be optimised by suiting the workpiece tooling to the machine tool. The factors affecting the machine tool's ability to cut efficiently are its rigidity, spindle power, along with its alignment accuracy. As an example of this last point, if the machine has a degree of misalignment, this can cause indexable-insert failure in rotating tooling on either a machining centre, or on "live/driven" tooling on turning centres. Spindle power is yet another consideration, as an indexable-insert drill requires greater power, yet develops similar thrust force levels as encountered using either twist, or spade drills. When inadequate spindle power occurs, the cutting parameters must be adjusted, meaning that the productivity gains of indexable-insert drills will not be realised over spade drills. Another feature of limited spindle power is that it determines the maximum hole diameter which can be drilled.

The last decision which will influence our choice of drills is the ability of each drill type to control the chips produced. Proper chip control is essential and is a crucial feature when there are tight clearances in the hole-drilling operations. Control of chips is to a greater extent influenced by the speeds and feeds chosen, and together with other metal cutting operations, increasing the feedrate will tighten the chips, whilst reducing the feed opens up the chip. For drilling operations to be efficient the chips should be small enough to prevent the drill from binding in the hole. If the feedrate is too high, the tool forces become too high, which in turn may break the inserts. To achieve the correct balance between an increased tool life whilst maintaining the maximum productivity, the accepted procedure is to adjust the cutting speed to give the maximum penetration rate once the correct feedrate has been determined.

Before dismissing the tooling used for drilling from our thoughts, some mention should be made of the influence that coolant plays during any machining operations such as drilling, although a chapter specifically on this topic occurs later in the book. When using indexable-insert drills, the best results are obtained when the coolant is directed through the drill (see Fig. 2.15a). The delivery rate and pressure should be adequate to flush out the chips, whilst minimising the heat effects, with higher pressures being necessary for horizontal, rather than vertical drilling operations. When deep-hole drilling is required, it may be necessary to provide compressed-air to the coolant line to allow for adequate chip removal, particularly in vertically drilled holes.

To complete this brief review of the diversity found in cutting tool technology of the "solid" tooling types, and before we consider the methods and advantages to be gained from using modular quick-change tooling, a mention should be made of the so-called "special engineered" tools used in the manufacture of specific part geometries. As their name implies, these tools are custom-built for specific tooling problems, or when greater productivity can be made from their use – assuming that an adequate pay-back results from their costly manufacture. One-off tooling of this type (Fig. 2.16) can range from simple insert orientations to machine a desired feature, to highly complex and elaborate cutters that can machine a number of part features simultaneously.

2.7 Modular Quick-change Tooling

The modular tooling concept has brought an amazing versatility to a whole range of machine tools and not just the CNC versions. This tooling is used on stand-alone CNC turning centres and lathes, machining centres and CNC mills, as well as for flexible machining cells and systems, even on multi-spindle automatics. In all cases, such sophisticated tooling, whether changed manually or automatically, will have the effect of decreasing tool changing times and easing set-up procedures, whilst minimising non-productive idle times. If these and other benefits accrue, how do such

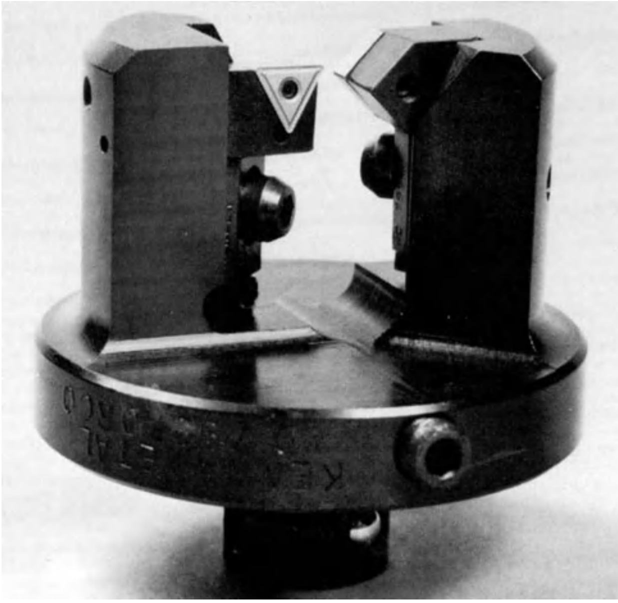


Fig. 2.16. A special engineered tool. [Courtesy of Kennametal (UK).]

tools operate and in what manner are they designed in order to achieve these desirable features? These thoughts will be considered in the following review of such tooling, but before we begin, it is worth mentioning the findings of the "Machine Tool Task Force Survey" of the early 1980s by the US government. It came to light that in the medium-sized companies surveyed, typical machine tools were only productively cutting for around 11% of the time. The non-productive time was taken up by such activities as unloading and loading (6%), changing tools (10%), setting up and gauging (10%), equipment failure (8%), with by far the worst utilisation being the incomplete use of shifts (55%). The survey also highlighted that times related to cutting tools, tool changing, set-up and gauging times were around 20% of the availability of the machine tool's time. If a company can reduce these non-productive operations significantly, then its overall machine tool utilisation will be markedly improved and offer greater overall productivity. It is for these reasons that the modular quick-change tooling has been developed and has become a popular concept with many companies.

The first machine tools to benefit from this modular tooling approach were turning centres and CNC lathes, but it can be usefully employed on conventional lathes as well. In principle, there are two systems available and they can be categorised as:

cutting unit systems
tool adaptor systems

The systems vary in their basic approach to quick-change tooling and in general are modified for use on turning, or machining centres, but prior to a review on cutting unit systems, it is worth reviewing the newest variant in the quick-change modular tooling family. Probably the latest modular quick-change tooling system to come onto the market is the one shown in Fig. 2.17. It is known as "Capto", which is derived from the Italian: "I hold firmly"; this coupling device between the holder and the cutting unit is the amalgamation of a self-holding taper and a three-lobed polygon. A tapered polygon is an extremely difficult geometric shape to manufacture for both male and female couplings, but offers a robust and precision coupling allowing high torques to be absorbed for both rotating and stationary tooling. Although this is the latest coupling device by the manufacturer, their earlier cutting unit couplings are still used by many companies and continue to be manufactured offering an alternative modular system, which will now be discussed. The well-established pioneering work in this field was that of the cutting unit systems (Fig. 2.18) which are usually referred to as "block tooling". This method is designed around a replaceable clubhead, held in

Fig. 2.17. The latest in modular quick-change tooling concepts: "Capto" (from the Italian "I hold firmly") based upon a tapered polygon coupling. The length of the taper and the precision contact surfaces of the Coromant Capto result in low surface pressures. This means long tool life and great repetitive accuracy. The stress curves lack peaks, avoiding the risk of vibrations or deformation. [Courtesy of Sandvik (UK) Ltd.]

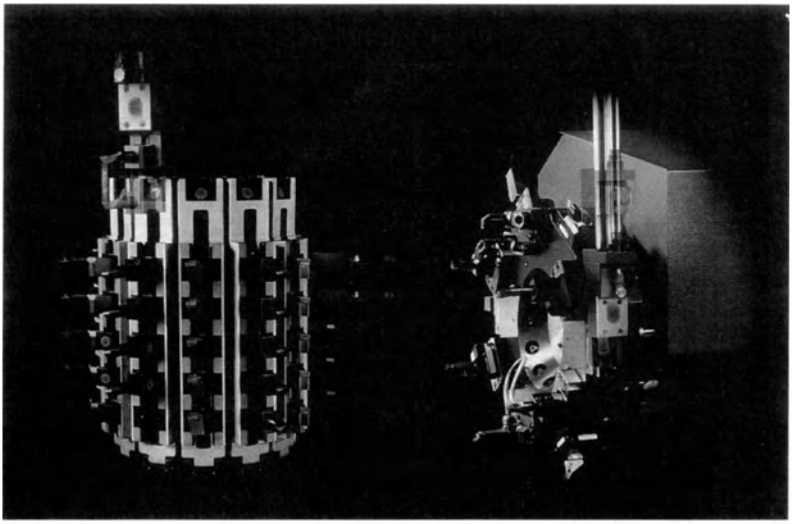


Fig. 2.18. The load/unload facility of an automatic block tooling arrangement for a turning centre turret (right) from/to the tool drum storage magazine (left). This reserve of tooling in the drum increases the machine tool's cutting capability and flexibility for unmanned machining considerably. [Courtesy of Sandvik (UK) Ltd.]

a square-shanked toolholder. Such a coupling offers a radial repeatability to within ±0.002 mm, with a clamping force of 25 kN to ensure that the generated forces during cutting operations do not deflect the tool. The application of the clamping force can be manual, semi-automatic, or fully automatic (as depicted in Fig. 2.18). Such systems of the fully automated kind require considerable financial outlay and by their very nature must offer an unmanned capability for "lights-out" machining operations for a third shift, as well as faster cut-to-cut times. In a simple scenario, under modest tooling demands, it has been shown that productivity over a year can be improved by up to 18 full working days by the adoption of this quick-change modular approach to tooling. Not only can the tooling be universally applied to unmanned machining operations, it can also be tracked and its cutting condition and parameters be modified whilst in use. This technique is often referred to as an "intelligent" or "tagged" tooling, although this approach to tool management will be expounded later in the chapter.

The second category of the modular quick-change tooling in use is that of the tool adaptor systems shown in Fig. 2.19. Here we can see the lock-up arrangement of the adaptor and the cutting unit with the draw rod exerting a pulling force of nearly 9000 N. This results in a clamping force of over 30 000 N, through a leverage offering a 3.5:1 mechanical advantage. A short self-holding taper of the "Morse" kind precisely locates the two male and female parts offering a repeatability of:

axial tolerance ± 0.0025 m
radial tolerance ± 0.0025 mm
cutting edge height ± 0.025 mm

Even with tangential cutting loads of 12 000 N, these modular tools offer the required resistance to deflection necessary and under such circumstances will deflect less than 0.005 mm.

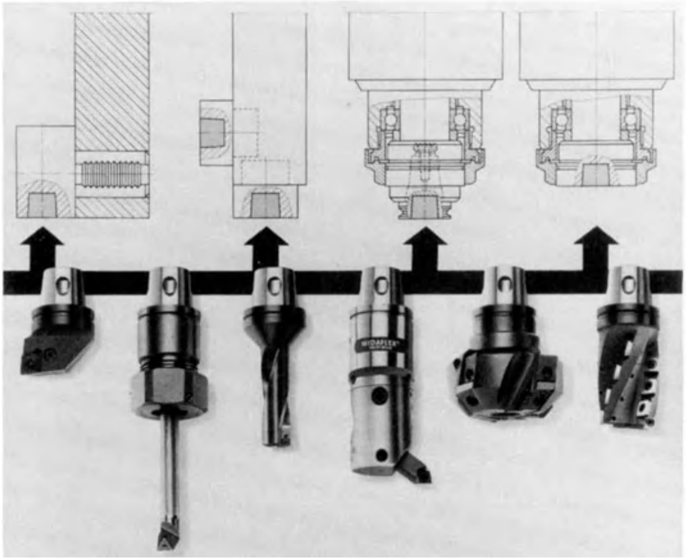


Fig. 2.19. A universal cutting adaptor for modular quick-change tooling. [Courtesy of Kruppwidia.]

Fig. 2.20. The modular quick-change tooling for rotating tools on a machining centre or "driven" tooling on a turning centre. [Courtesy of Kennametal (UK).]

Fig. 2.20 shows a range of cutting units which can fit the universal adaptor for rotating tooling as used in milling, drilling, boring, etc., whilst the non-rotating cutters can be fitted to a turning centre turret (Fig. 2.21) either manually, or automatically. Both photographs show the manual method of tool clamping, which simply needs a short turn of the key to lock the cutting unit into its adaptor quickly and efficiently. It

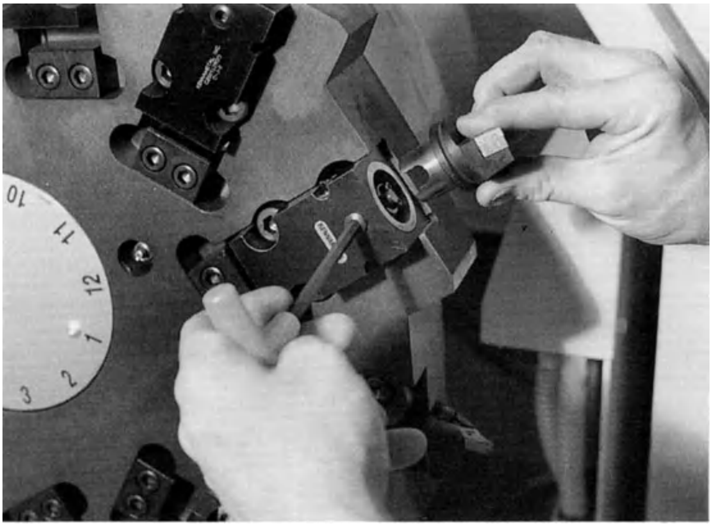


Fig. 2.21. These manual modular quick-change tooling units can be easily retrofitted to end-user's machines like the turning centre pictured. [Courtesy of Kennametal (UK).]

is worth stating that such cutting units are very compact in their design and utilise very little floor space, either by each machine tool, or by the storage facility, such as a magazine, and need minimal effort to load into turrets or spindles.

Yet another approach to the lock-up sequence and design of these tool adaptor systems is that shown in Fig. 2.22. The Hirth gear-tooth coupling offers a high accuracy of positioning, with an almost perfect transmission of torque whilst cutting. Clamping consists of insertion of the cutting unit into the adaptor – but these need not be too precise, as the location and clamping is by means of an axial movement of the draw-bar. This draw-bar can be manually or automatically moved by using a torque motor, with the Hirth coupling firmly locking both male and female assemblies together. As with all these modular-quick-change tools, they may be internal or external design, or right- or left-hand. The face and diametral grooving cutting units shown in Fig. 2.22 can be of different "hands" in order to achieve universal grooving applications on the parts.

A problem associated with any CNC machining or turning centre is that only a finite amount of tooling can be stored and this is further compounded when the "sister tooling" concept is operated. In order to overcome the limitation of tool storage space an automatic tool changing mechanism for the modular quick-change tooling can be incorporated onto the machine. Such auxiliary equipment offers the following benefits:

increasing the machine's productivity times

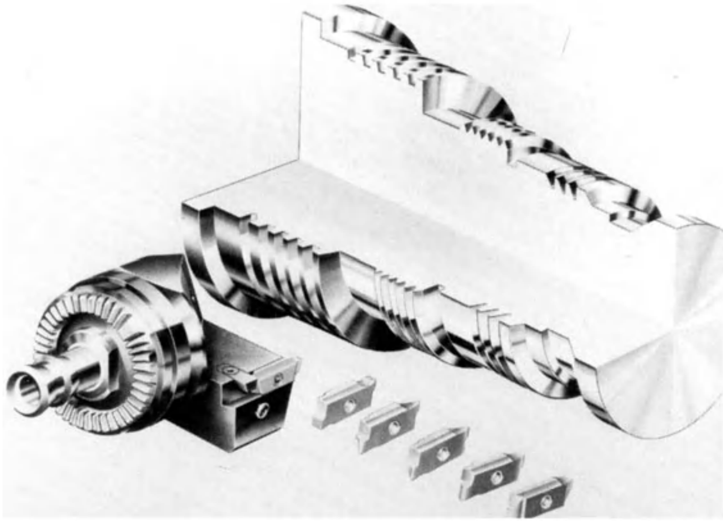
reducing the time for changing worn tooling

the tool-changing unit delivers new tools to the machine automatically

provides storage for the cutting units and those returned automatically from the machine tool

easy integration of this equipment to the machine tool

a



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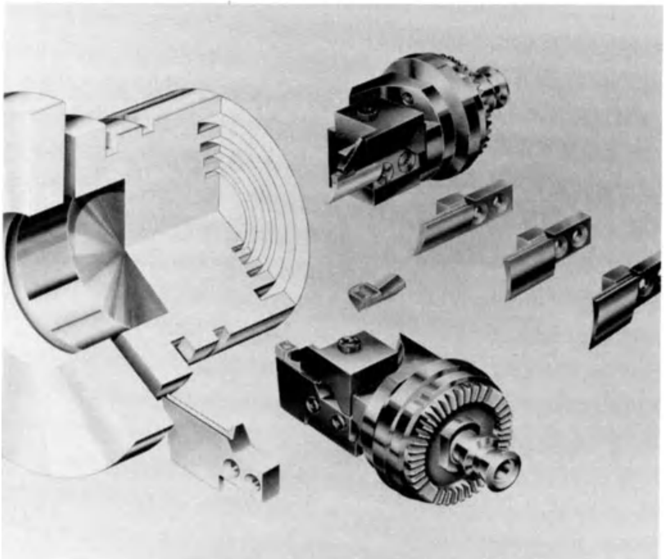


Fig. 2.22. **a** Grooving operations on diameters using a modular quick-change tooling system with a Hirth coupling adaptor. **b** Face and diametral grooving operations together with parting-off can be achieved with the minimum of tool holders. [Courtesy of Walter Cutters.]

such systems cover a large range of tooling sizes and are suitable for most machining operations

These automatic tool-changing mechanisms which enhance the tool-carrying capacity of the machine tools, offer an almost unlimited and seemingly inexhaustible supply of cutting tools to each machine, but at the cost of a high capital outlay. As such, these sophisticated systems can only be really justified when a high diversity of parts is to be encountered in the day-to-day running, or when a continuous utilisation of the plant is expected.

As one would expect from running such a vast tool library, a major problem would exist in tool tracking and identification (on-line tool management) but a solution to this problem has been found and operated successfully for a number of years. Such systems for tool recognition are often termed either "intelligent" or "tagged" tooling, as described earlier. When we consider that in a large-scale FMS, with the tool delivery being from just one source – such as a "tool highway" to the various machine tools – the simple logistics of tracking and identification of the tooling would be at best difficult, but more likely, impossible. Therefore, a range of secure tool recognition systems has been developed and the "intelligent" tooling concept is utilised widely in a diverse range of manufacturing companies today.

"Intelligent/tagged" tooling carries, in a coded form, discrete information within the cutting units and it might range from tool offsets, insert geometry, tool life expectancy, cutting data and an identification code which ensures that the correct tool has been selected and inserted into the machine tool's spindle or turret – as the case may be. Such "intelligent" microchip memories are conveniently located on the cutting tool in the form of small integrated circuits which might have dimensions of 12 mm diameter by 4 mm in length. The hybrid miniaturised circuits on small semiconductor chips can contain up to 1024 bits of information – enough for the most complex and demanding applications. The operation of such microchip capsules embedded into the tools, can be classified into several configurations and types:

contact varieties which may be further sub-divided into "read-only" or "read/write"

non-contact, also in the same sub-divisions

Lately many companies have been favouring the latter type and particularly the "read/write" variety. This technique of data transfer to the machine tool's controller senses and reads the previously input tooling data across an air gap, by electrical induction transmission, or similar methods. Such data reading and transmission takes less than 300 ms, with the memory chip being of a non-volatile type (i.e. does not require battery back-up to maintain the memory). Fig. 2.23 shows how such information is processed onto each chip and then into the tool data file. Such information is written onto the chip by a special computer which may be linked to other peripheral devices within the company's computerised tool management system – more will be said on this topic later in the chapter – or to CAD/CAM, MRPI and II systems, etc., in a full Computer Integrated Manufacturing facility. These facilities are becoming increasingly common. This information might be passed along a local area network (LAN) through the RS232/422 port, or similar, which links a variety of software packages together. However, at the other extreme, a simple direct link might be established to a specific stand-alone machine tool. Having such memory capabilities within these programmable chips will increase the possible tool-code combinations into billions of permutations, so that they become almost inexhaustible. Any chip exposed to an oil-ladened atmosphere and the harsh environment of cutting must have a high memory stability.

The non-contact read/write programmable tool identification systems are very tolerant for misalignment of the reading head and can operate successful data transmissions over greater distances that 8 mm with a misalignment of ±5 mm, whilst travelling at a relative motion of 600 mm/s. To gain an appreciation of how such intelligent/tagged tooling is incorporated onto modular quick-change tooling, Fig. 2.24

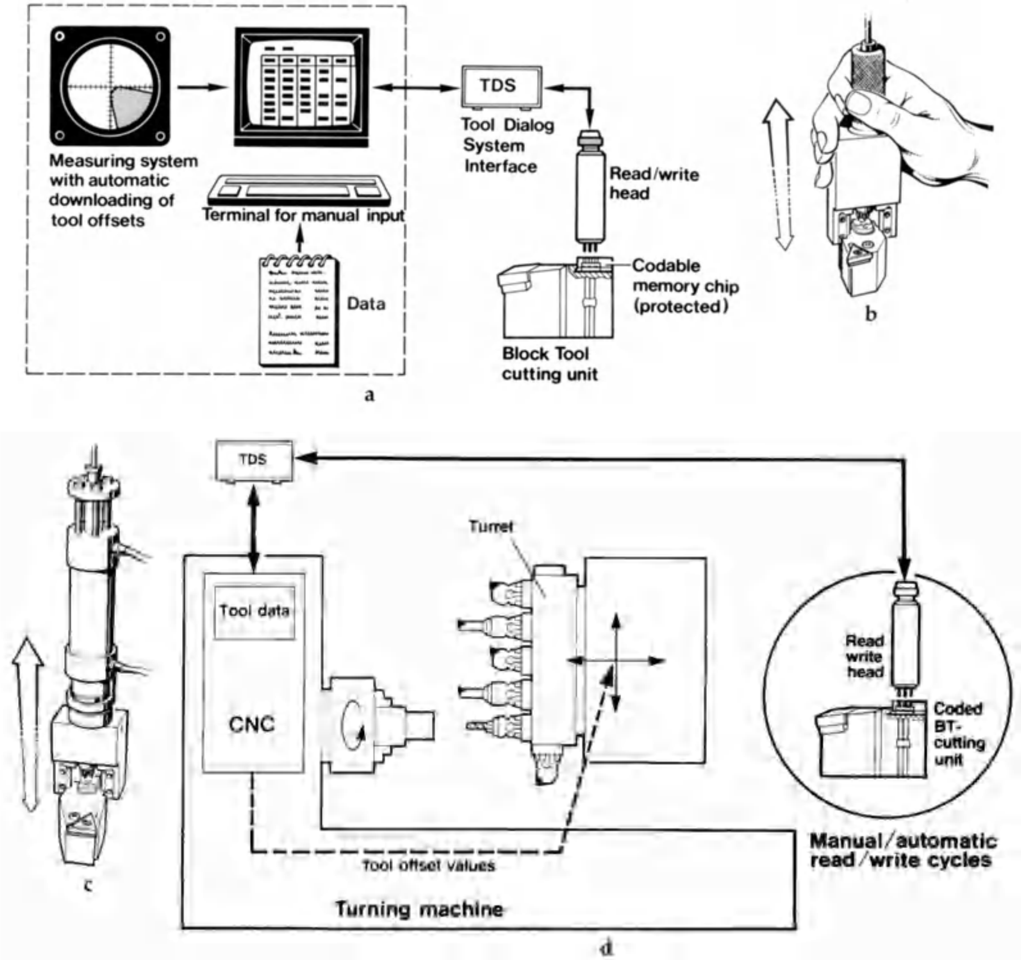


Fig. 2.23. Tool data processing using modular quick-change tooling on a turning centre via the "intelligent/tagged" tool concept. **a** Scheme of tool data input/output during tool preparation. Offsets are automatically downloaded. Tooling and other required data are entered manually and can be freely edited. Any simple data already existing in the memory chip can be overwritten or retained as required. **b** During tool preparation all data is written into (input) or read from the chip using a simple read/write assembly. **c** In the machine an automated assembly reads from and writes to each tool data carrier in the magazine. **d** Scheme of CNC turning machine showing two-way tool data exchange between tool and CNC. An automated read cycle at the tool magazine is performed each time a tool is loaded, to update the CNC's tool data file. Automated tool data processing eliminates offset and tool changing errors. [Courtesy of Sandvik (UK) Ltd.]

shows some of the clubheads with their 5-pin contacts of the read/write variety shown diagrammatically in Fig. 2.23.

Much more could be said about the two-way dialogue that occurs between the CNC and such memory chips, both prior to and after the cutting operation, where G01 feed function is monitored and the cutting tool life is decremented accordingly, or indeed on the whole modular quick-change tooling concept, but space will not permit further

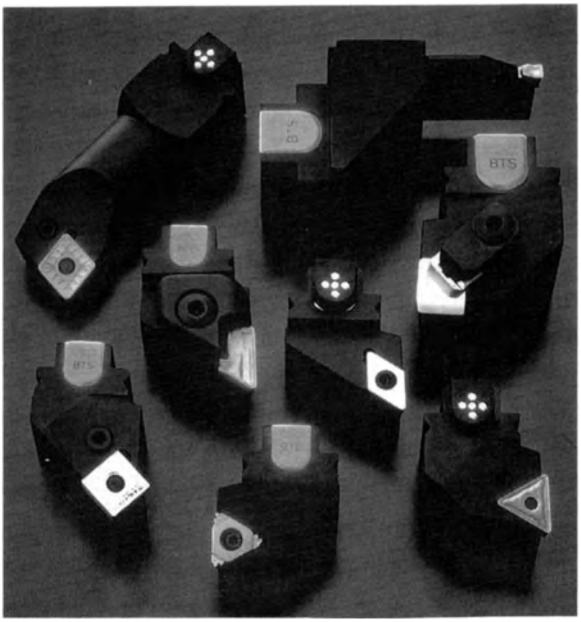


Fig. 2.24. A range of modular quick-change "block'" tooling illustrating "intelligent/tagged" programmable clubheads clearly discernible by the five contact pins amongst standard units. [Courtesy of Sandvik (UK) Ltd.]

explanation. If a company, or individual, requires further information, then the manufacturers of such systems should be consulted, or alternatively, a more in-depth review appears in the companion volume to this book.

2.8 Tool and Workpiece Monitoring Systems

Regardless of whether a machine is in a Flexible Manufacturing System, or indeed in a stand-alone situation, when it is unmanned, or at best minimally manned, a variety of problems must be overcome if such machine tools are to function correctly. When an operator is present he has the ability to:

monitor the condition of the cutting tool
replace defective or worn tooling by interrupting the cutting cycle
determine the quality of the workpiece whilst machining takes place
modify speeds and feeds as necessary during machining
respond to any unusual cutting conditions that might be seen or heard during part manufacture

2.8.1 Tool Monitoring Systems

When unmanned machining takes place, the monitoring system will need to provide a degree of "artificial intelligence" necessary to duplicate the experience provided by a fully skilled operator with instinctive reactions. The tool-related monitoring functions dutifully carried out by an operator whilst manufacturing parts on such machines may be classified under the following headings:

monitoring tool life and cutting conditions
breakage detection
tool offset measurement
tool identification

Tool identification and offset measurement were discussed in section 2.7, but this is by no means the only way of establishing tool offset data and identification, as we shall see a little later on. However, let us confine our thoughts to the means of monitoring and controlling the tool life and breakage detection.

Whenever cutting tools are engaged in the manufacture of parts there is an interaction between the workpiece, chips and tool, causing tool wear. It is essential that any worn tools (at a pre-determined level of wear) must be replaced before their predicted failure occurs. During unmanned machining, tool sensing is necessary in order to establish the extent of wear and activate a tool change so as to optimise its useful life. In recent years, a variety of sensing techniques have been developed and are classified into two distinct groups:

direct sensing methods, which include
- (a) the measurement of electrical resistance
- (b) techniques based on radiography
- (c) dimensional changes in workpiece via measurement, or alternatively, the distance from the tool post to the part

indirect sensing methods, covering methods based on temperature, vibration, sound, acoustic emission and force measurement, which can be measured directly or by torque, current, and power measurements

It should be said that many of the methods listed above have proved to be satisfactory in the laboratory, but few have been "workshop hardened" for industrial applications. The tool monitoring systems available of late tend to be classified into three groups, as those involving:

recording machining time
tool breakage detection devices
touch-trigger probing

The latter method is reviewed later in the chapter but for now we will concentrate on the methods used to protect the tool and hence workpiece from the vagaries of the cutting process, whilst offering numerous other advantages during cutting. The simplest device to be used for tool wear prediction is the former method and is offered by numerous machine tool companies. It focuses on the estimation of the machining time which has elapsed whilst cutting components. The permitted tool life is determined by software within the controller, which can be specified according to the tool and workpiece combinations and cutter geometries, together with other related factors. The operation of such systems is simple: during cutting, when the feed functions for both circular and linear interpolations are monitored, the controller accumulates data on the actual time employed. Once this time has reached a prescribed level a "worn tool" alarm is triggered and the tool is changed as soon as it is safe to do so. In this manner cutting life is optimised, but the approach to such techniques is based on steady-state machining and it can be influenced by unexpected, interrupted and abusive cutting conditions, which can be considered a draw-back, but this solution to tool wear control is a relatively cheap option and as such cannot be severely criticised.

A more sophisticated method of tool breakage detection based on the indirect approach to sensing, using adaptive control techniques has been around for some time. In the early days it was an adaptive control optimisation (ACO) system which was developed using a form of in-process measurement to assess such factors as tool wear rates, spindle deflection and vibration. It suffered from poor sensitivity in monitoring tool wear in a productive environment and was plagued with troublesome sensing methods. Lately, the adaptive control constraint (ACC) technique has proved to be most popular and is simpler in design and use, whilst costing considerably less. These "feed-only" systems, as they are sometimes referred to, are still quite complex and have unique sensory circuits and computation methods for establishing the net torque during cutting and comparing the monitored value to a preset torque limit. They are often known as torque-controlled machining (TCM) systems. To have such systems present is a boon on any machine tool, with the costs of such options being of the order of 5% of the total machine's cost. A machining centre application (Fig. 2.25) and a turning centre application (Fig. 2.26) are illustrated schematically and the benefits they accrue to the optimisation of any cutting process are listed.

An obvious problem associated with any torque-controlled machining monitor, is that if insufficient torque is developed – in the case of small drills, taps and milling cutters on machining centres, or small diameter workpieces on turning centres – then when they are under approximately 10 mm diameter, lack of torque makes them obsolete. To overcome this problem and alleviate such "blind spots" in the machining of critical features in this size zone for cutters, a further monitoring system is available which complements TCM monitors and is known as acoustic emission (AE). In principle, the acoustic emission technique is shown in Fig. 2.27 and has a variety of sources for the generation of sound waves during the cutting process (Fig. 2.27b). The AE signals generated are filtered out, so that only the ultrasonic waves released by the generation of high-frequency elastic stress waves – whilst cutting – are sensed, owing to the rapid release of strain energy which is caused by such factors as material deformation, fracture, and metallurgical phase changes. In order to monitor the AE signal, it is usual to use piezoelectric sensors which detect the AE amplitude showing a rising tendency (often termed "tare") just as the tool is about to break (Fig. 2.28). It is quite straightforward to separate out the AE signal from extraneous noises generated by the machine tool, owing to the very high frequency of this signal. These fast-response piezoelectric sensors require the minimum of power input and are characterised by their high resolution and sensitivity. The electrical signal produced is proportional to the measured value and can be amplified for machine tool control. In principle AE active sensors utilise the piezoelectric effect, in which electrical charges are formed on the surfaces of particular crystals such as quartz, tourmaline, etc, when they are subjected to mechanical stress. The reciprocal piezoelectric effect is the reverse of this process and is used to power quartz clocks and watches, by deforming the crystal by an electrical charge. The mechanical deformation of the direct piezoelectric sensors used on machine tools produces electrical charges with virtually no delays and as a result can be used in high-speed machining operations, or when

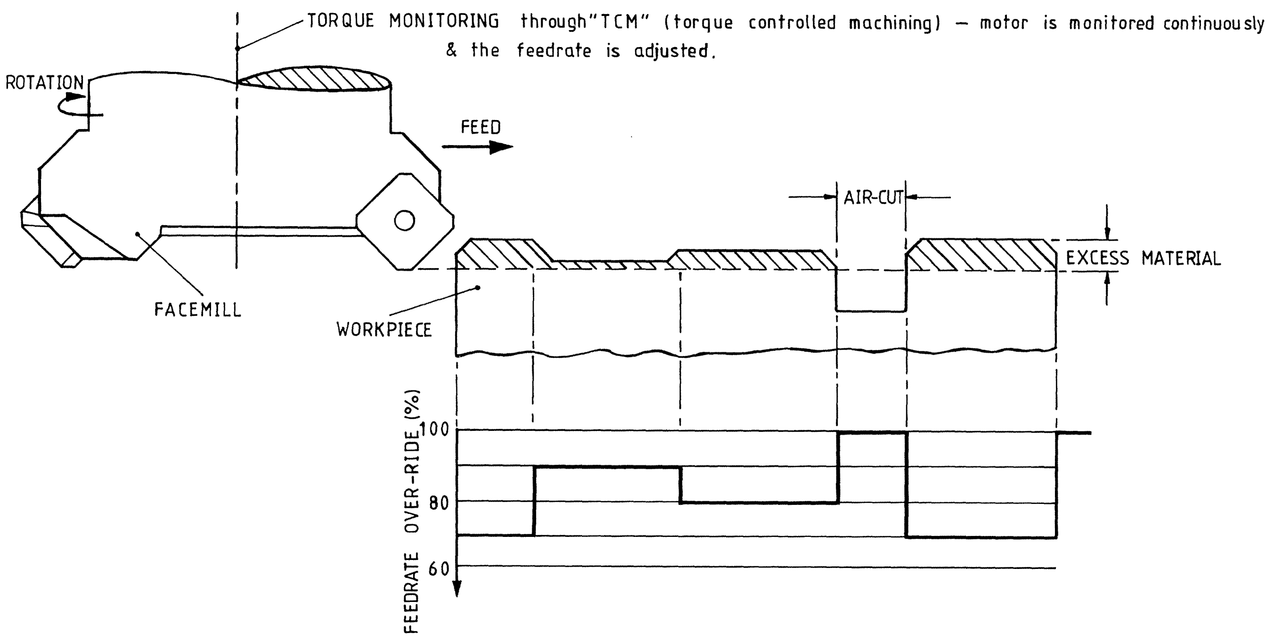


Fig. 2.25. Advantages of adaptive control when milling: optimised feedrates avoid tool damage; extended tool life; higher production rates; reduced intervention by operator; faster set-up times; reduced tool breakage.

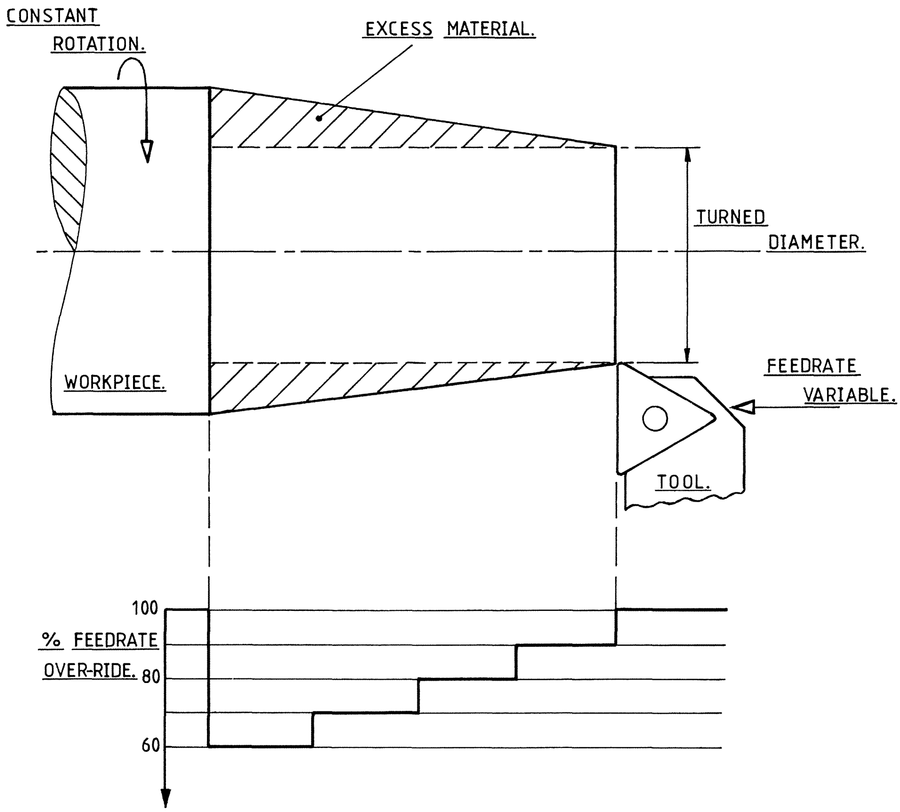


Fig. 2.26. Adaptive control in turning operations.

instantaneous response to a broken-tool signal is required in order to shut down the feed, or rapid motions of the machine, to prevent costly further damage.

A typical tool condition sensor may be used to monitor in-process worn and broken cutting tools on turning centres. It utilises the three-axis cutting tool information-feed, radial and tangential, as input data which is then processed by proprietary software to detect the occurrence of tool breakage, or wear. It is a self-contained system which is self-tuning, allowing it to operate without the necessity of a trial, or tuning cut and, as such, needs minimal operator setup. The system output signals are defined in the following way:

worn tool: indicates a significant change in the cutting performance – due to wear of the cutting edge and may be adjusted for the level at which the tool is declared worn

broken tool: indicates either a break, or a significant chip in the insert's edge

collision: indicates a significant and abnormal force level applied to the tool due to a collision, mis-chucked part, or other error condition

The principle of operation of such systems results from the characteristic changes in the cutting force signals which accompany tool failure and may clearly be discerned from normal cutting. These systems use advanced algorithms that are based on

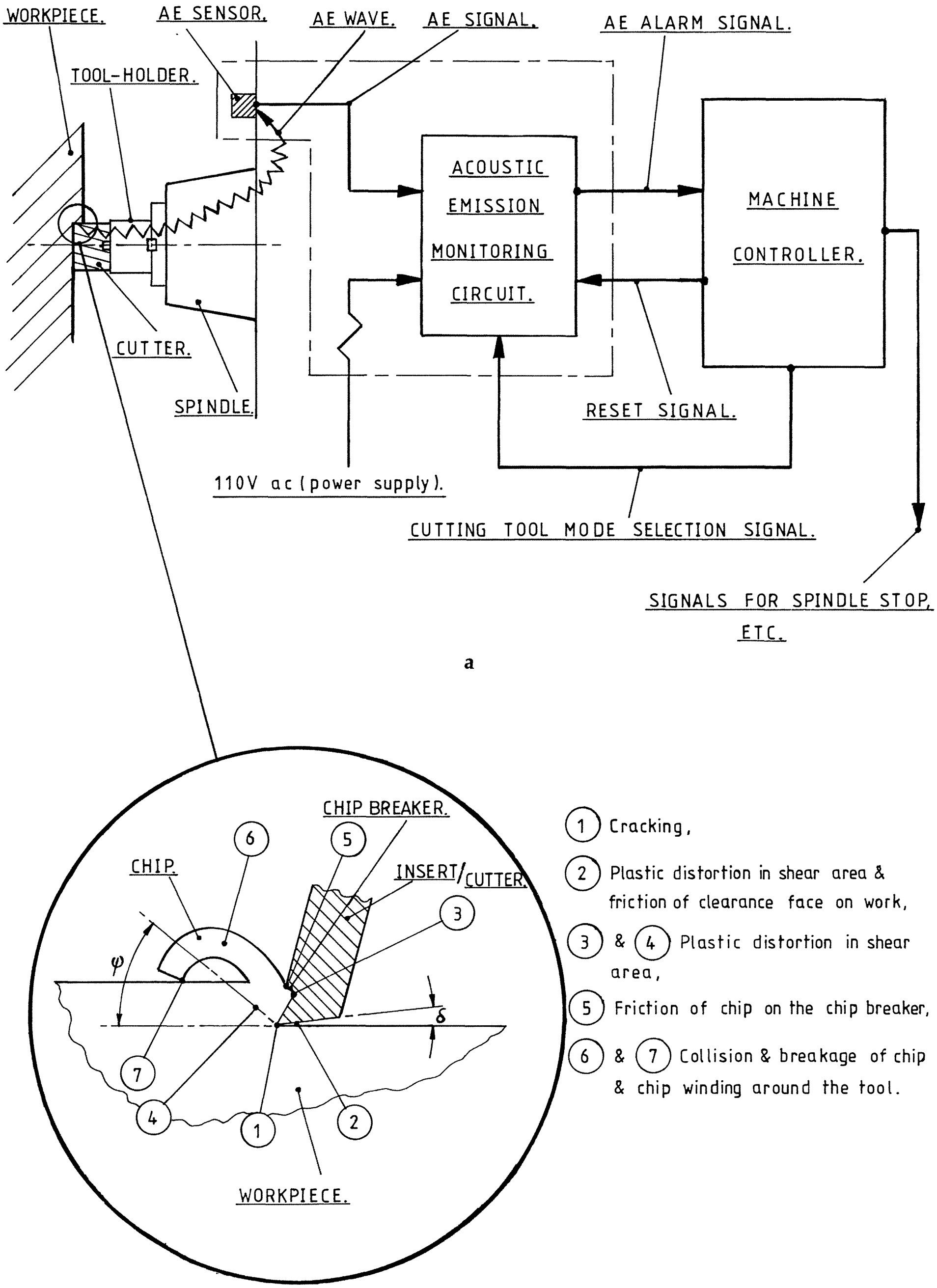


Fig. 2.27. **a** The application of acoustic emission to a horizontal machining centre. **b** Possible sources of acoustic emission during machining.

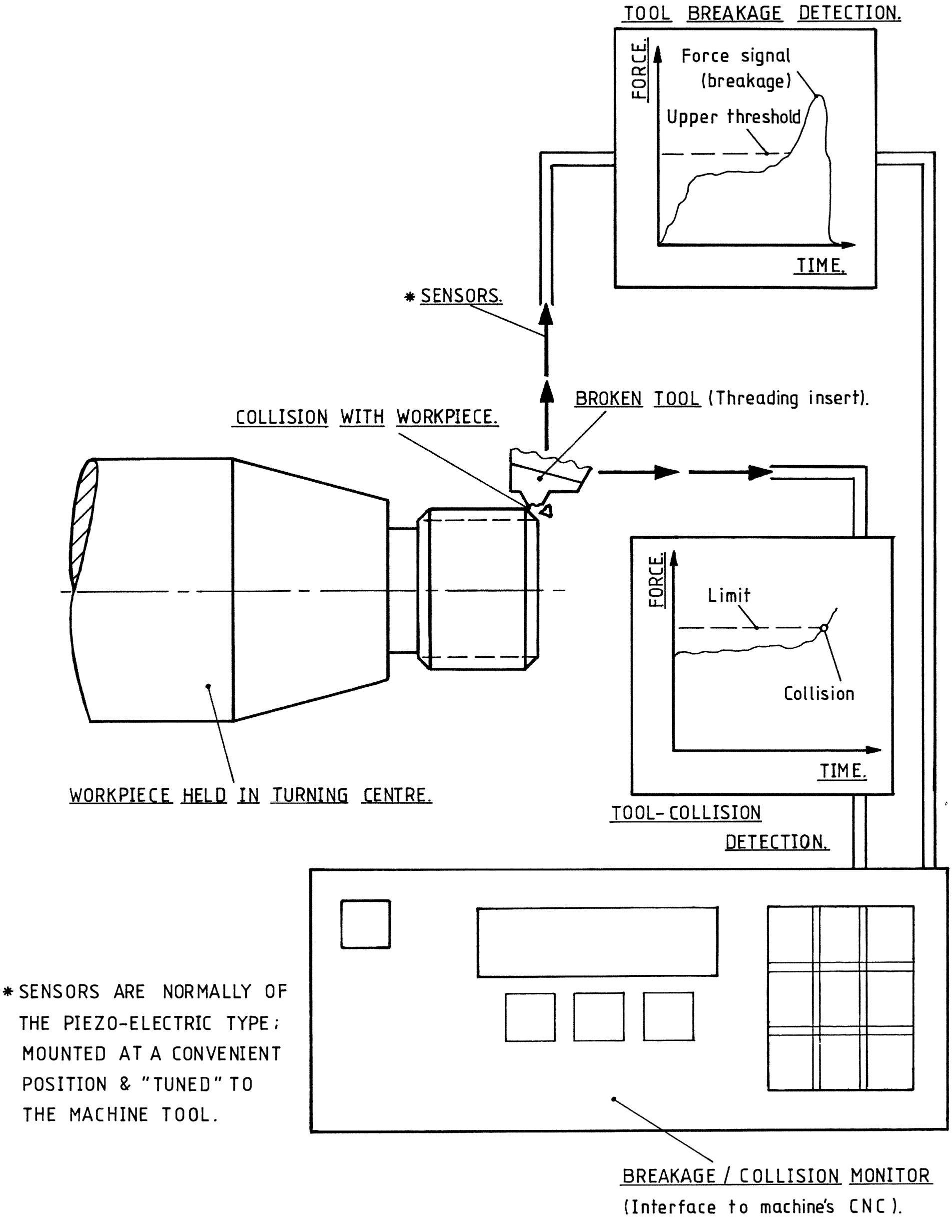


Fig. 2.28. A typical monitoring system used on a turning centre for unmanned machining in an FMS environment.

metalcutting experience by the tool builders over many years and detect the characteristic changes resulting from tool failure. Such systems utilise yet further algorithms for the detection of wear, breakage and collision, providing separate outputs to the machine tool for each occurrence.

Any tool breakage tends to be both sudden and catastrophic, and is characterised by distinct changes in the force signals. Typical signals (as depicted in Fig. 2.28) showing the force signal characterised by breakage, are detected using "pattern recognition" techniques. These real-time force signal events show key parameters which are assessed in terms of significant spikes and sudden changes in force levels. When such an event occurs, it is recognised as a characteristic, say, of a broken tool pattern – based on "prior experience", which is incorporated within the software and a "broken tool" signal is generated. A user of such systems can select the worn tool variable over a range from level one, for finishing cuts, to level ten, for heavy roughing.

One might ask the question, "Why do we need so much sophisticated tool and subsequent machine protection in stand-alone or FMS environment?". The answer to this can be found by considering the consequences of not providing such monitoring equipment: in a recent German survey it was determined that a typical collision resulted in around £7500 worth of damage to the machine tool. This is exacerbated by the staggering statistics that for all tool collisions, 72% were the direct result of operator error, whilst only 26% were traced to faults in the electrical systems, with 2% of all faults unclassified. These results clearly show the advantages of incorporating tool/machine protection devices for a relatively small capital cost. If advantages can be gained, or protection provided by tool monitoring, there must be similar benefits from utilising workpiece gauging and inspection monitoring techniques, and this will be the theme of the following section.

2.8.2 Workpiece Monitoring Systems

If, for the moment, we ignore the methods used in detecting parts destined to be machined in an FMS by loading the workpieces onto pallets, and train our thoughts into the problems and methods of assessing parts in semi – or automated – manufacturing facilities, then four principal methods have been devised in the establishment of workpiece quality:

post and near inspection
on-machine gauging
in-process gauging
deterministic metrology

In Fig. 2.29, these systems have been categorised for an FMS environment, but they are equally true for stand-alone machine tools where some form of "real-time" adjustment and control of part quality is desired. Let us briefly review each system in turn and in this way gain an appreciation of the philosophy behind each technique for assessing part quality.

Most of the post- or near-inspection workpiece gauging systems that are currently available offer the twin benefits of establishing the correct dimensional characteristics for each part feature – as dictated in the part program, whilst correcting the tool offset table, or modifying the program for tool wear – depending on how the discrete software has been written. Near-machine gauging systems overcome the main limitation of in-cycle gauging, using up small proportions of non-productive cycle time, but in themselves offer a few substantial problems – the workpiece is inspected historically, that is, after it has been "broken-down" from setup and, as its name implies, inspects the parts at a later time, meaning that the following part quality itself may need adjustment. The "closed-loop" inspection function offered by such systems

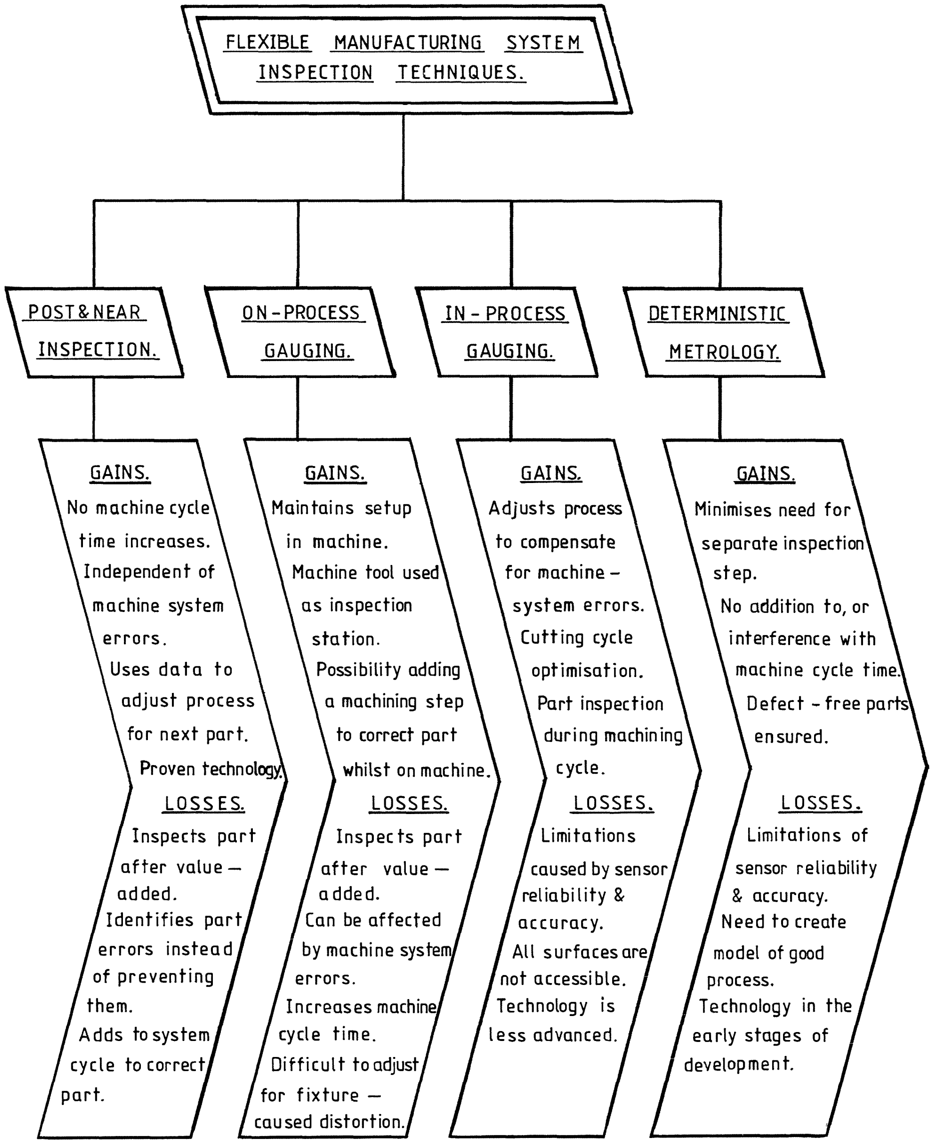


Fig. 2.29. Techniques applied to flexible manufacturing systems to maintain the quality of parts by different metrological methods and their advantages and limitations. [Courtesy of the FMS Magazine.]

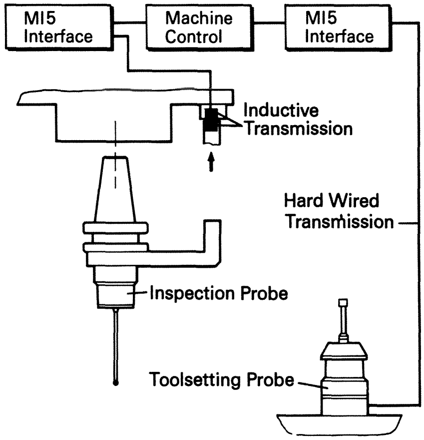
can be used for 100% inspection or be based on a statistical sampling scheme which is found to be satisfactory and might be determined by batch size, complexity of part, predicted tool wear and processing time, or indeed, on other more urgent assessment criteria. As its name implies, these near-gauging stations tend to be strategically positioned close to (or as a built-on piece of hardware) the machine tool. It is a popular method, particularly for components produced on turning centres where the part is transported – by a robot, or when part volume or batch sizes are smaller, manually – to an independent receiver gauge station. This receiver gauge can inspect either single, or multiple features simultaneously, based on the critical dimensional requirements for the workpiece. The results obtained can be fed back to the CNC where adjustments are made to the machine – as suggested earlier, normally within specific limits by the closed-loop function. Not only can an almost "real-time" adjustment of part quality be maintained, but reports can be automatically written from the statistically processed data and be incorporated into a total quality management function within the organisation, through suitable customised software.

The major limitation of any of these contacting inspection techniques in the workshop is that they are highly influenced by the vagaries of workshop condition environments: ambient temperature changes, workpiece temperature variations, dust, debris, and oil-ladened atmospheres, etc. In order to overcome this flaw in such systems, these near-gauging facilities can be enclosed in some form of environmental protection. If a non-contact laser receiver gauge is used, it overcomes these problems and the processing speed is considerably increased. However, they can only be used for the inspection of symmetrical parts, such as those produced in turning operations. However, there is no real substitute for a true metrological inspection facility.

In order to improve the on- or near-inspection determination, but without involving complete post-inspection or time-consuming activities, a hybrid of each type has been proposed. This technique is usually known as "footprinting". Errors are compensated by establishing a so-called "footprint": first, the near, or completed, part is inspected in the near- or on-gauging equipment for its dimensional features considered to be of critical importance. It is then transported manually, or automatically, to a coordinate measuring machine, or to a measuring robot (this latter version is faster but less accurate than the CMM), where its actual dimensions are correcly established. If, as expected, there is a dimensional difference between the two metrological assessments, then a correction for this discrepancy is incorporated into the controller to overcome any dimensional workpiece errors. This method of "footprinting" is not widely adopted, as it suffers from a few operating limitations, not the least of which being the extra time associated with increased inspection and its additional expense. If a prudent use of statistical sampling is used, then a full inspection of part quality need not be too prohibitive, but some delays in obtaining up-dating information may occur; this is in one sense affected by the part cycle time more than any other characteristic.

Probably the most important technique in establishing part quality is that of "on-process gauging", which is sometimes wrongly termed "in-process gauging", which will be considered shortly. With on-process workpiece gauging methods, the touch-trigger probing technique is without question the most popular inspection method. Such a gauging system is shown diagrammatically in Fig. 2.30, where a machining centre application is illustrated; also highlighted in this diagram is the cutting tool setting probe which more often than not is an option fitted to such machines. Machine tool companies offer customised software enabling these contacting touch-trigger probes to fulfil a number of functions, such as: to align the fixtures through interrogating their position relative to the machine and program coordinates, alignment of workpiece so that they conform to the established coordinates in the program, and when fitted with toolsetting probes the cutter offsets can be established in the tool table, or their data updated, together with the ability to detect broken tooling.

It might be expected that when using touch-trigger probing on either machining or turning centres, this might tie up valuable productive cycle time and further increase the cost, but in reality this is not the case, just the opposite in fact occurs (Fig. 2.31). By using "probing" for both tool and workpiece setup, real savings in terms of



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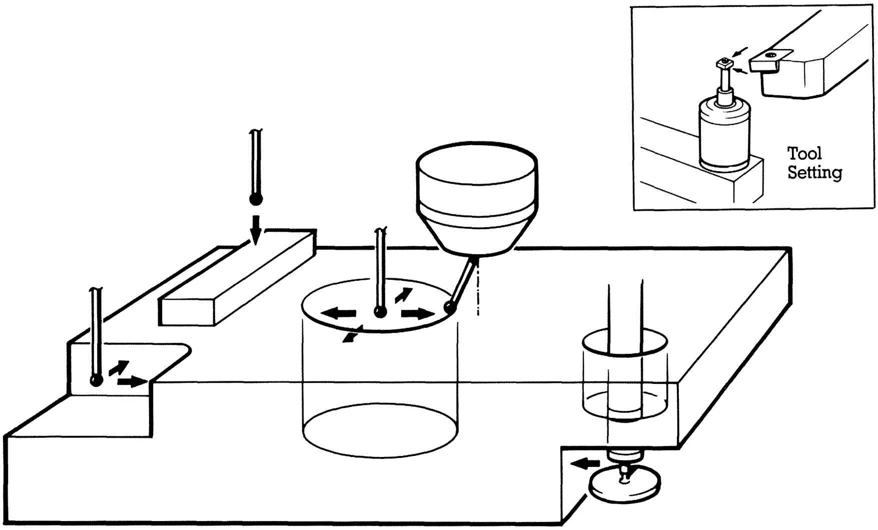

b

production occur, as the resulting time is drastically reduced for individual parts or batches. It is not necessary to probe every dimension on every part machined, as a reasonable statistical sampling plan can be incorporated and, in any case, only critical part features need to be assessed. The quality is further enhanced by the fact that the flank wear on the tool increases during a batch of parts being manufactured and frequent tool offset updating occurs so that when a prescribed limit has been reached the tool is exchanged for its "sister tool". This updating occurs despite the fact that the in-cycle feed function might be monitoring tool life and will over-ride this data, as the wear in the case of the toolsetting probe measurements is the actual case, rather than the theoretically calculated values from data sheets.

The in-process gauging of parts is well known in grinding applications of cylindrical parts. It is based on controlling the process during machining, by measuring its

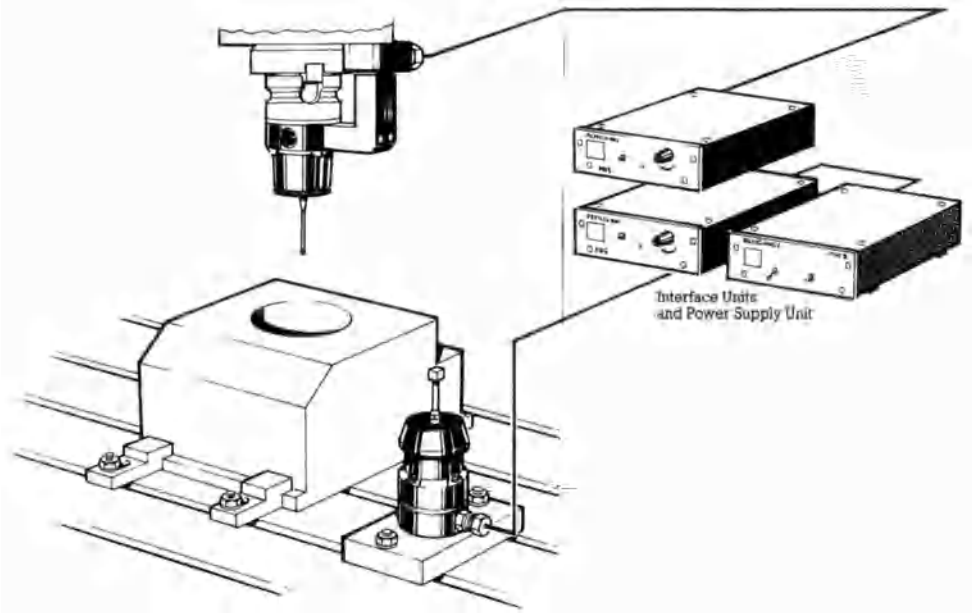

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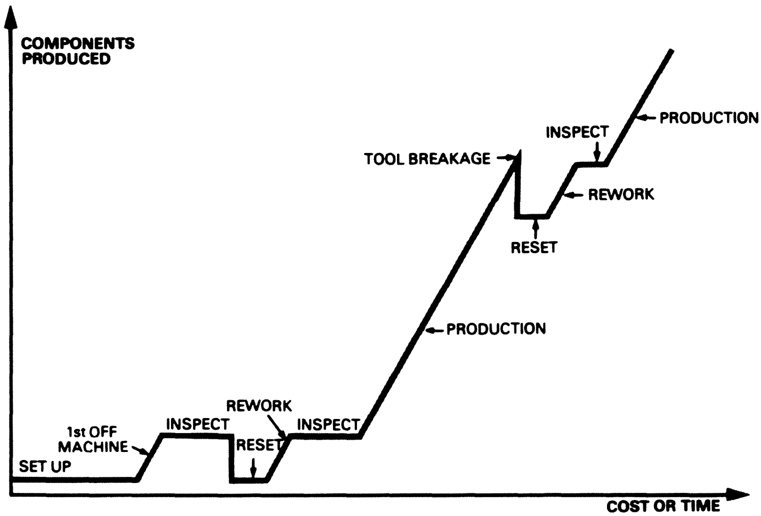
Fig. 2.30. In-machine gauging using touch-trigger probes in milling/machining centres. It has applications for: fixture alignment; workpiece interrogation of critical dimensions; tool presetting and tool offset updating; tool breakage detection. **a** Typical machining centre arrangement. **b** In-cycle gauging. **c** Typical "hardwired" inductive transmission application on a vertical machine tool (optical transmission is used when the quill can move independently using infrared coded messages, up to a distance of 4 m). [Courtesy of Renishaw Metrology Ltd.]

dimensional characteristics and utilising this information through a feed-back loop to control the process. This information is provided in continuous data – as the part is measured whilst being cut – and in this manner the workpiece quality is assured through a series of limits for the part tolerances, having been preset in the controller's memory. In a similar manner to the "match grinding" approach, the machined part can be assessed against a "master" and in this way further part dimensional security is assured. It might be possible to have a form of in-process gauging in a turning operation where symmetrical parts occur, but it would be difficult to achieve in the case of prismatic parts produced in either machining centres, or on turning centres with driven tooling and "C-axis" facilities. Even if it is employed, the contacting probe technique would not be really applicable, owing to the hostile environment of swarf and to a lesser extent, coolant problems. This might be overcome by using non-contact in-process gauging for workpiece assessment, but even here–when video cameras or laser techniques have been used, problems arise in determining edge recognition of dimensional features caused by coolant or swarf interference. However, further work is being undertaken in research facilities into these and other problems. If they can be overcome and the equipment can be suitably "workshop hardened", then the real-time in-process assessment, in turning operations particularly, becomes a reality.

The final and probably the most controversial method of workpiece assessment during machining is that known as "deterministic metrology". The basic idea in this method of part dimensional assessment is the need to predict the errors in the



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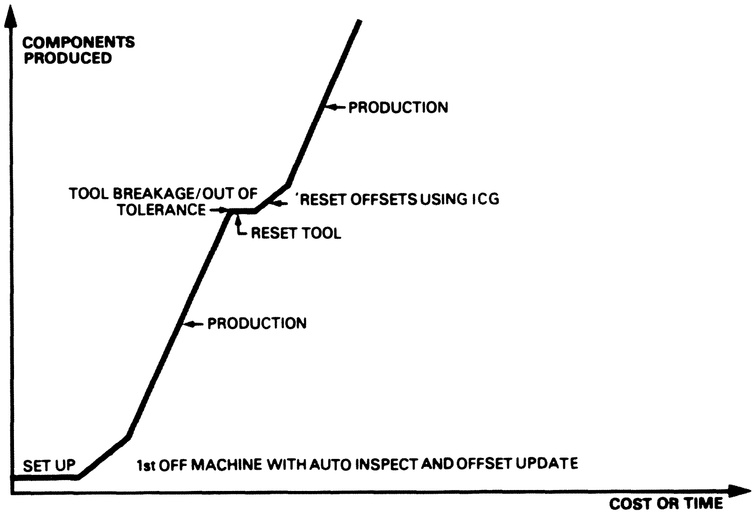
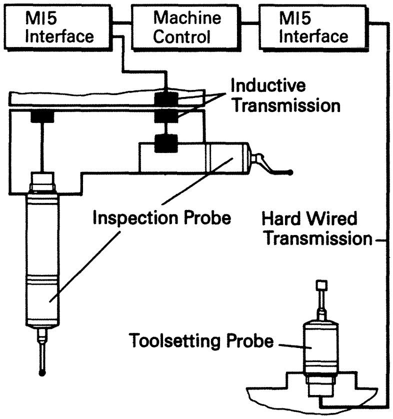


b

machining process and the corrective actions necessary to anticipate these errors in a real-time sense, and in so doing, correct them. In any machining process the objective is to cut a good workpiece and in this way eliminate the need for further inspection. In order to achieve this aim, the deterministic metrology technique provides a detailed mathematical model in which the error-producing parameters–namely the effects and interactions – are accurately described and in such a way a good part is machined every time. The major problem to overcome is not the complex mathematical algorithms which must be constructed, but determining and, more importantly, predicting which, why, and how errors occur.



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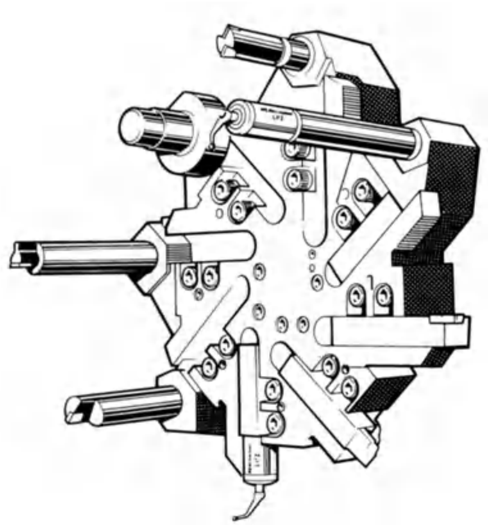

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Fig. 2.31. a Conventional use of NC. **b** NC machining with in-cycle gauging. **c** Typical lathe arrangement. **d** Turning centre tool turret with touch-trigger probing.

Although not strictly just a workpiece monitoring system, the "datalogger" can be used to monitor the part and compare its measurements to set statistical standards and use this data to compensate the process for tool wear, as necessary, before it affects the quality of the workpiece. In this manner, it virtually eliminates costly part rejections and the productivity losses resulting from tool wear. Another feature of this system is that it can keep track of invaluable information such as the number of parts manufactured so far, compensation performed, part and compensation tolerances, together with part sizes, allowing the information to be displayed on either the console, or fed to a printer. Equipment such as this needs to be "workshop-hardened" – being oil tight and robust, whilst allowing a full programming ability through the keyboard, with the advantage of locking the controls for added security, but giving access to the run-time controls whilst operational. System connections are through two RS232 outputs, which may have their outputs transmitted to a remote location such as a cell control area, or conveniently displayed for an operator. These "dataloggers" can accept information from a wide variety of sources such as the linear variable differential transformers (LVDT) in a receiver gauge, from optical sensors or digital logic and mechanical switches.

The outputs from these "dataloggers" can be used to drive up to four types of compensation mechanisms, such as:

stepper motors for fixed increments
analogue motors for infinitely variable adjustments
CNC offset controls for fixed increment adjustments
contact closures for signalling operators

Having so many different output results allows their selection and combination to produce the best results for a given application range. A typical system will allow up to 256 inputs and outputs from one unit, giving it complete versatility when manipulating a constant flow of data which needs to be logged for future reference, or used to control the process of part manufacture.

The field of cutting tool technology is considerably greater in depth and scope than discussed so far in the chapter and to gain a much better appreciation of all the applications and interactions in this field requires more space than available here. For more comprehensive information see *Advanced Machining*. However, one crucial area needs to be expounded before finally leaving this important subject: namely the field of "tool management" which holds the "key" to effective production in manufacturing departments, whether they are run with conventional machine tools, or the highly complex and up-to-data FMSs which are becoming vital to many companies' survival needs in the late twentieth century. So it is with these thoughts in mind that space has been provided for this last section on "tool management".

2.9 Tool Management

2.9.1 The Effect of "Just-in-Time (JIT) Manufacture in the Workshop and its Influence on Tool Management

The philosophy of using JIT to reduce the stockholdings is becoming very popular of late, but in practice, it is difficult to apply the idea uniformly. Often JIT has been seen as just another new contract between the purchasing department and the vendor, but in reality it must permeate through the whole chain of manufacture and supply, if it is to work.

If we view the affects of a JIT approach from the machine shop manager's point of view, then three separate applications arise:

the shop's output to the customer of machined parts must be maintained
the operational logistics of day-to-day running of their own manufacturing department needs to be consistent and harmonious in operation

the purchase of raw materials and consumables from suppliers must be predictable and consistently in line with the manufacturing schedule

Customers' demands are usually for smaller batches with a predictable throughput time, often associated with higher quality assurance standards. Recently, big strides have been made in manufacturing departments by the application of MRPII, Production Control software, and more effective use of CNC machine tools. So, in order to achieve the full benefits of such technology, it is important to remember that if only a threefold improvement occurs, a company might not be truly competitive when it might be possible to gain a tenfold increase!

CNC technology simplifies the logistics of manufacture as it combines several operations at one set-up and in so doing reduces the process stages and queues, whilst increasing cutting ability and subsequent part quality. As we have seen in chapter 1, most machine tool utilisation in batch production is poor and output might easily be doubled or trebled, if an improvement in the support infrastructure results through the internal application of JIT. Basically, this is requirement planning (MRPII) but technology improvements together with organisational changes are necessary as the installation of basic software is not the sole answer to this problem. In order to increase the effectiveness of machine tool utilisation, a good place to start is by studying the requirements of the shop's small batch production. Rather complex calculations can be made to find the economic batch quantity, but usually it can be broken down into set-up time, machine setting time, plus any advanced preparations specific to this batch. With most operations involving batch machining, the machine's set-up time for each batch tends to be too long, as all the preparation work is done in real-time at the machine. Ways of minimising this lost production time will be discussed in chapter 4. However, let us continue on this theme for the moment and consider that most of the setter's work on the machine tool might be actually better spent away from the machine prior to cutting the parts. Machine tool utilisation can be drastically improved with the correct hard- and software as set-up times can be reduced to around one minute, as we shall see later in the relevant chapter. This particular technology has seen very little implementation in most workshops, but should really be the focus of attention for companies trying to improve their machine tool utilisation, as the competition will certainly be looking at this area now.

In recent years, a great effort has been made to ensure that work material arrives at each machine on time, but often there is a defeatist tradition when it comes to a material's specification. Machine tool setters will often adapt the process to cope with raw material variation between batches, with the disastrous consequence that this time becomes built into MRP for the set-up cost. In order to achieve consistent raw material, the checking of its specification must be pushed back up the supply chain as the machining process should not need to be adapted. Consistency in the specification of the material can be achieved by proper liaison with the supplier and using single-sourcing.

JIT can be improved by the production of setting instructions and part programs in advance and off-line, where they may be fully proven-out using simulation of the cutting process, workholding methods, and so on. This can be easily and speedily achieved using CAD/CAM integration to transfer the geometry and may be considered a profitable first step, but the choice of tools, methods, and process data are just as important. Data files for tooling, workholding, settings, times, and feeds and speeds, need to be systematically used whilst obtaining the feedback of experience from the shop floor in a progressive manner to improve the cutting times, accuracy and quality. These activities may be considered as part of process planning and when carried out centrally within the company, offer tremendous scope using computerised aids.

A great area for improvement in machine tool up-time can be found if one attacks the traditional down-time activities associated with finding, servicing, and measuring tools at the batch set-up on the machine. It is much better and quicker if these activities have been previously carried out away from the machine tool by a trained specialist in a properly equipped central preparation area. Hopefully, companies are beginning to realise this fact: until recently it had been long neglected by management. Great benefits can be accrued by such a strategy and it will easily justify the "slaughter of sacred cows" by investment in systems rather more than the under-utilisation of machine tools. Let us briefly consider the factors which influence tool management within a company.

2.9.2 The Tool Management Infrastructure

It should be obvious by now that any tooling and workholding methods should be the quick-change type. This means the time to strip and re-build the complete set-up for a batch is a few minutes, at worst. Any quick-change tooling/workholding equipment can be widely purchased in a "systems approach" to their assembly and offers the following key requirements in the case of modular quick-change tools (workholding equipment is considered chapter 4):

Rigidity: in order not to compromise the cutting data, quick-change tooling rigidity should be at least equal to the traditional fixed tools.

Repeatability: any quick-change tooling coupling for a pre-set tool must be dimensionally accurate and relate to the cut-size within the machine tool. In this manner most trial cuts are eliminated, but it requires a coupling repeatability of better than 5 μm.

Speed and simplicity: tools should be of small size and light weight, with simple fixing and fast to change.

Adaptability: any quick-change tooling should be available for use on both automated and manual machine tools, across the whole workshop.

Automatic identification: this tooling can have fitted "tagged/intelligent" chips which may be identified either at the machine tool itself, or in the tool preparation area.

Wherever a system has been developed, an organised and well-planned facility is needed to prepare the tooling requirements (off-line) so that they might be:

built into pre-defined assemblies from a range of standard stocked modules

replacing worn inserts on used assemblies returned for rebuilding/servicing

measuring tools and sending offsets to specific machine tools

inspecting tooling to ensure that they are fit for immediate use

assembling fixtures, gauges, and tooling as a complete kit to be issued to the appropriate machine tool

In order to ensure that a consistent and accurate tool preparation occurs, a documented procedure for inspection, service, and build, is necessary for each tool. These points can be controlled by using a computerised tool management system, as only one data file needs updating with the instructions on assembly; servicing and inspection can be presented in a step-by-step approach if needed. Many of the more sophisticated systems available offer a link to CAD software and allow tools to be shown graphically assembled as tool parts.

As the tools travel around the workshop, through a variety of stages of preparation and measurement, going to the machines and back to the tool preparation area for re-service, each stage of the kit's cycle must be controlled. Information about the tool kit's progress must be available at any instant and a means of exercising control is to link each station to a central computer via direct numerical control (DNC). As the unique data referring to any tool is stored within the central computer, its identity can be accessed and in this way its progress can be precisely tracked within the manufacturing facility. If this elaborate method of tool control is too costly or complicated for the present needs of the company, then a simpler manual system using printed labels – preferably bar-coded – may be used for tool identification when delivered to and from the machine tool. It should be noted that paper labels on tooling can become detached during the machining cycle.

There is no real alternative for a tooling requirement when used in conjunction with an FMS and permanent machine-readable identification is necessary. Such tool identification systems as previously mentioned allow the necessary data to be retrieved from and input to a central computer, or machine tool as well as the preparation area, if required. With these implemented memory circuits within the tagged/intelligent tooling, they can quite readily perform functions automatically, together with extra information for the operation and tool servicing needs which complements the database. In order to maintain complete control over all of the items necessary for a kit, we can extend our stock control over all the tooling requirements out on the shop floor (Fig. 2.32). Such a logistical problem – what is where at any time, and its condition, amongst other necessary details – requires a computerised tool management system to monitor such a complex task. Tool control software allows these physical transactions associated with tooling, servicing, kitting, recalibration, etc., to be achieved without losing track of individual items. Yet another advantage of using such tooling management systems is that all the stock levels are continuously monitored, allowing replenishments to be made once any stock level falls below a preset value.

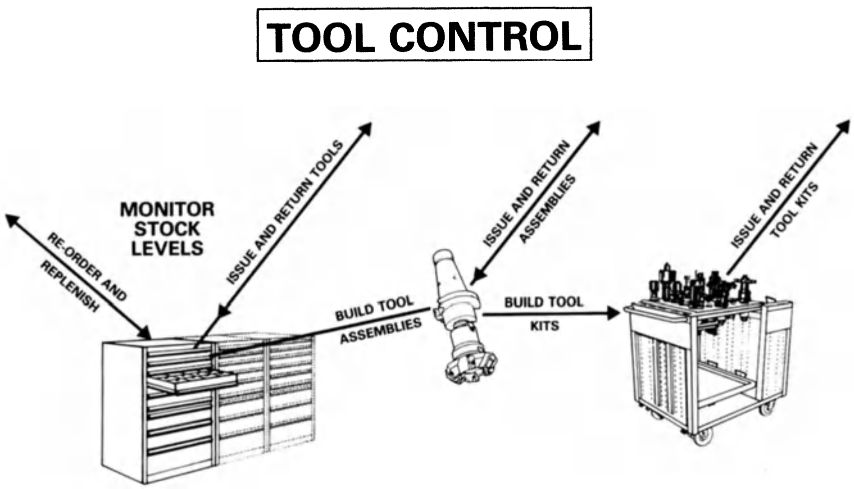


Fig. 2.32. Tools must be precisely controlled at the "focal point" of kit build-up/replenishment, namely in the tool preparation area. [Courtesy of Sandvik (UK) Ltd.]

Whenever there is a requirement planning needed for tools and fixtures, then the logical system is MRP, but a problem exists with most implementations. Usually, these MRP solutions do not have the capacity to handle the necessary volume of detail, particularly when we want to reduce batch sizes whilst increasing the number of batches. A simple remedy to this problem would be to use the FMS tool control software, which is supplied by several machine tool builders, and is, in effect, a mini-MRP system, which covers just a small section of the machines, although at the necessary detailed level, as proposed in Fig. 2.33. Such systems can monitor the tool's remaining life and prioritise tool preparation in such a way that the necessary tools can be delivered to each machine in regular batches. This system also identifies tools and removes exhausted, or redundant tooling from the machines. If using tool control software is not practicable, then another answer can be to use a tool control system to store the tool kit details for each job, whilst provisioning and preparation of the tools are controlled at the kit level by the MRP.

It must be obvious from the foregoing arguments, that it is clear to us that these tools are of little value unless they are properly supported with reliable data and are accessible to each class of user, such that:

classification by application, cutting data and tool life for the process planner or programmer is necessary

inspection and measurement details, their service and build instructions for tool preparation can be achieved

replenishment rules, their sourcing and JIT validation for purchasing is possible

It is a big undertaking to create a tool file with this level of detailed content from a large assortment of tooling requiring support. A good first step in the process of creating an efficient database is to begin a tool rationalisation process. In most

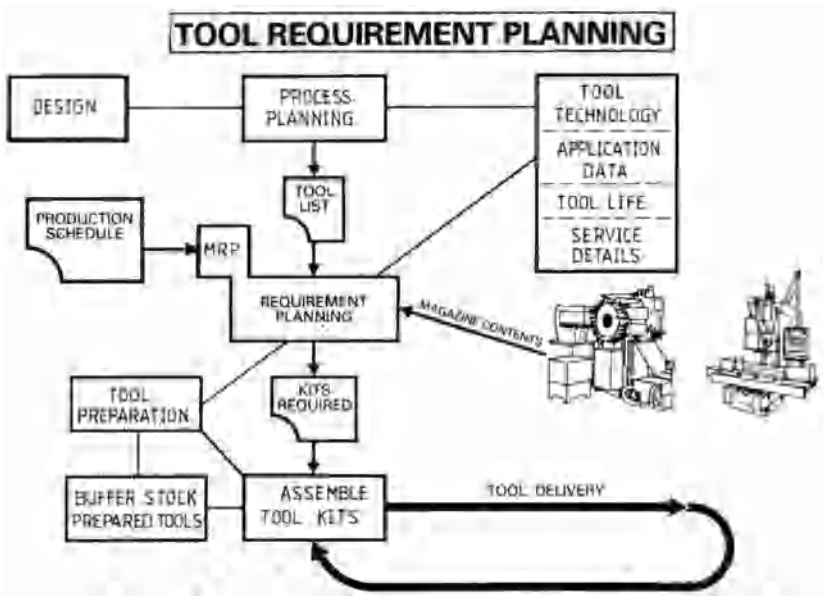


Fig. 2.33. Any tool requirement planning system is based upon extraneous manufacturing factors such as product design and the master schedule. [Courtesy of Sandvik (UK) Ltd.]

workshops where tooling has proceeded without a degree of tool standardisation, even simple rationalisation schemes will result in tooling inventory reductions in the range 60%–90%. This rationalisation exercise is an important production engineering function and the maintenance of the technological data within the tool file and assortments used must be continuous. Any cutting data and tool life related to specific part production should be reviewed in the light of the actual experienced tool life and may form the basis of judgements made on the returned tool condition and re-servicing data. This data should be reviewed and then used to modify the tool life estimates used prior to any actual experience of cutting the part. Therefore, any tool changing at the machines is based on a realistic and predicted tool life, whilst the tooling is protected in-cycle from the vagaries of the cutting process by some form of tool monitoring.

In order to achieve a consistent part quality, it is important to have a secure source of tool supply of reliable quality, with realistic lead times. This minimises unplanned machine stoppages. It is now possible to have a direct computer link to the tooling suppliers in many cases. These links can be interactive – allowing the tool store's computer to be connected directly to the supplier's computer, or alternatively used in the automatic batch mode, giving the ability for the user's tool control system to update itself overnight from the supplier. So that a computer can keep abreast of the latest product developments by tooling manufacturers and so avoid any unnecessary dependence on obsolete cutting tools, an involvement by the suppliers in defining and reviewing a company's tooling range is particularly important.

2.9.3 Tool Presetting Equipment

It must be clear to the reader by now that the tool preparation facility plays a critical role in any part manufacturing exercise. Crucial to any cutter build-up is the tool presetting equipment and it simply will not do just to index inserts around and then use them in this manner without some form of tool presetting. In turning operations this can be completed using the "tool-eye" – a tool presetting probe on the machine, but whenever there is a need to mill (which is a facility increasingly offered on turning centres with driven/live tooling facilities) then because of more than one cutting edge being present, it is imperative that cutting edges are precisely set up in a tool presetting device, prior to loading onto the machine. Axial and radial motion of the milling insert within its pocket can be considerable and in order to obviate the re-cutting effect caused by an insert standing too proud from its pocket, the only method to assess its position is by using a tool presetter.

There are a range of tool-presetting machines available today, ranging from very simple mechanical transducer-based equipment, to the state-of-the-art automatic edge finding sensors with the ability to show the coordinates on a VDU, or send these offsets through a DNC link to the machine tool's CNC tool table. Such systems can retrieve information from CAD/CAM systems and use the tooling data to show not only the tool build-up, but also to indicate their part numbers and where such tooling components might be located in their respective part bins. This and many more features are available on such highly developed tool presetters and in many instances their cost can easily approach that of a small to medium sized machining centre. Typical of the middle-ranged presetting machines is that depicted in Fig. 2.34, where an optical tool presetter is shown, using linear scales for accuracy and positive locking of slideways via electro-magnetic clutches. Adaptors can allow both turning and milling cutters, together with drilling and boring cutters to be readily preset. When-

Fig. 2.34. An optical tool presetting device with the ability to preset cutters to a micrometre and assess whether each insert is seated correctly in its respective pocket. A DNC link can be established to any machine tool. [Courtesy of Devlieg.]

ever there is a call for a full data record of tooling presetting details, then a machine can be specified which can provide not only a DNC link, but also a data-link to other peripheral devices and full integration into the computerised tool management software. The benefits to be gained from such a capital outlay can be measured in terms of accurate and speedy set-up times from part-to-part and the minimised down-time resulting from tool rebuilds. Such indirect costs are often difficult to quantify accurately, still more to present in a feasibility study for future planned investment, but the obvious gains can soon be realised when such machines are fully employed within a company's manufacturing facility.

To complete this chapter on cutting tool technology, which is by no means an exhaustive account of these technologies – with such areas as the tooling costs, machinability of materials and so on not being mentioned – more needs to be stated on the advantages to be gained from employing specific software used for the tool management function and this will be the theme of the final section.

2.9.4 Tool Management Systems

With the development of CNC machine tools, there has been a steady trend towards smaller batches; this fact has made the tool management function an increasingly important issue for machining operations. If we initially consider a traditional manufacturing facility, where any form of tool management is left to the supervision of the machine operator, then a limited number of tools is present at each machine. These cutters were maintained and replenished from spares and consumables via the operator's liaison with the tool storeman. Any techniques and cutting data used with such tooling lay with the accumulated knowledge of the skilled operator. This meant that the part-programmer, or process planner, could ignore the separate functions of the machine tool's operation, the tool kit and the operator, treating them as a self-maintaining system of well-proven performance. Any work destined for these individual machines and operators could be left to a detailed process definition by each operator. However, a problem soon arises in such circumstances when an increase in work diversity occurs, particularly as a result of flexible manufacture which enables the batch sizes to be reduced and is exacerbated if part manufacture is coupled to the versatility offered by the latest CNC machines.

In order to cope with such work diversity, individual machines need to acquire very large complements of tools and this causes a situation to be reached when neither the machine operator, nor the part programmer is sufficiently in control to accept responsibility for the tool range dedicated to a particular machine. Whenever CNC machines are introduced, the organisation usually changes to one in which:

the process is defined in detail in an area remote from the shop floor

a machining program and tool list is presented to the machine, via a tool kitting area, with the process data and tooling fully defined – although some question occurs as to the quality of this definition

the machine operator can now run the program with the minimum of alterations

when batches become smaller, the pressure to run a given program without alteration becomes very great. Optimised metal cutting is sacrificed and conservative cutting data is used, making the success of the whole operation critically dependent on the ability of the tool kitting area to supply and support whatever tooling the part programmer specifies.

Obviously it is desirable to establish some systematic feedback of experience from the shop floor to the programmers. Such information enables decisions to be made on tool choice and realistic cutting data, also relevant data is available to the tool kitting area indicating which tools they should be geared to support. In order to achieve meaningful data feedback, the best technique is to incorporate a tool management system for the whole shop, which may be centred around a tool file controlled by the management through a tool file editor. With large companies this tends to be a computer-based system, but it can also be satisfactorily operated using a manual card system. However, it must be organised in such a way that it is accessible by a range of personnel: process engineer, part programmer, tool storeman, purchasing department, machine operator, file editor, and management. The file should contain all the information these individuals require in respect of every tool:

tool identicode – if necessary cross-referenced to the tool supplier's code

application area – the same tool might be needed to be used for a variety of applications

cutting data – for a range of materials to be encountered

tool geometry and dimensions

expected tool life

usage

spare parts

It must be emphasised that the success of any tool management operation lies in the fact that the quality of tool data is imperative. As the file is built up progressively, it includes only those tools which have proven their worth on the machine and are considered productive in their area of application. The cutting data on tool life expectancy should be that established in practice on the machines. The part programmer would use tools exclusively from the tool file when defining the part programs and new tools would only be added after a proper investigation of their feasibility of performance in a specific cutting application. By accepting this limitation, we can be sure that any tools called for in the process are available and are properly backed-up with spares – since the tool storeman also has access to the file. The data and machining times used for any product price quotation are based on those actually achieved on the machine.

A key function in any tool management system is the tool file editor, as this person must:

scrutinise any reported deviations from the cutting data and tool life

investigate the claims from manufacturers of any new tooling offering higher productivity

weed out any obsolete tools which have been displaced by new additions

find new tooling for new products as they arrive

So, by using the tool management system in such a manner, the tool file will systematically accumulate knowledge of each section of operation and ensure that the cutting performance will continually improve. This continuous improvement in cutting performance and efficiency is analogous with the improving skill of an operator on a conventional single-purpose machine tool, but now we have a system which is more than able to cope with a larger and more complex situation. An effective tool management system can be built up progressively and this prevents "hiccups" occurring even when a new part programmer, tool storeman, or indeed machine operator is started. The sophisticated tool management system can be interfaced to a range of other software packages in use by the company and in so doing help control the complete manufacturing function within the company.

Before we leave this crucial aspect of tool control, it might be worth some further comments on the building up of the tool file. The important point with such a system is to start small and keep the information added to the file sound. A good practical test might be: after a week of putting good data on file for the one hundred most popular tools, the information flows through the system and starts highlighting the tooling requirements and, as such, drives on the further development of the file. Conversely, a heavy desk exercise might be to add two thousand tools onto the file, but utilising provisional data. This intense effort would be rewarded by dud answers and discredit the system from the outset. Any testing and tool prove-outs need not, of necessity, demand extra effort, as simply organising the efforts already being made by your own tooling engineers and those of the tool suppliers decreases your own contribution to obtaining sound cutting data. Often most of the knowledge accumulated by such people when building up their testing and trouble-shooting for a specific product will "evaporate" once the current batch is completed, because there is no framework in which it can be recorded. Thus, when a similar batch occurs in the future the tooling engineers must "re-invent the wheel" – a waste of manpower resources. If for no other reason than to simply record the cutting data – which, by the way, is a complete waste of its potential – then great benefits will accrue to the company which reduces lead times considerably following the purchase of a tool management system.

There are a whole host of methods to reduce tool prove-out to a minimum and certain machining and non-machining test methods have been developed to enable useful data to be attained speedily and efficiently. The methods of machinability assessment at present available are reviewed briefly in the companion volume, and they may well prove to be worth considering in order to further reduce a company's efforts in this area.

As the subject of cutting tool technology is critical to the success of any manufacturer engaged in cutting processes, this chapter has tried to highlight just some of the current developments in this rapidly developing field. Obviously, an in-depth knowledge of such a complex subject cannot be attained easily, but an appreciation of the pertinent points should have been gleaned from reading this review. Yet another area of improvement in cutting performance coupled to better part quality can be gained by the correct use of cutting fluids, and in order to at least appreciate these benefits, the following chapter has been written.

Chapter 3
Cutting Fluids

3.1 Introduction

Cutting fluids, or coolants as they are generally known, play a key role in manufacturing industry. They are essential for taking full advantage of today's high performance machine tools. However, their physical and chemical properties must be carefully chosen to fit the required task and they must be used correctly.

There are two basic metalworking processes used in the manufacturing of parts and they are:

stock removal (cutting processes)
forming

In stock removal processes the geometric shape of the workpiece is altered by mechanically cutting away areas of the stock material – as described in some detail in chapter 2. In forming, by contrast, the material is pressed or squeezed into shape by applying exterior forces, so the composition and the mass of the material remain unaltered. This chapter will be solely concerned with the former process of stock removal processes. Prior to a discussion on cutting fluids, some general comments on the cutting process will be made so that the advantages to be gained from using such fluids may be more fully understood.

3.2 Stock Removal Processes

The various processes and parameters involved in machining by stock removal can be simply explained if we consider single-point cutting operations typified by turning, as depicted in Fig. 3.1.

If we consider a simple "shear plane" model for the formation of the chip, it starts to form at the point where the tool enters a cut in the workpiece. The cutting edge penetrates into the work being driven by the cutting force and separates the chip from the stock. This separation does not occur by a splitting action as expected when

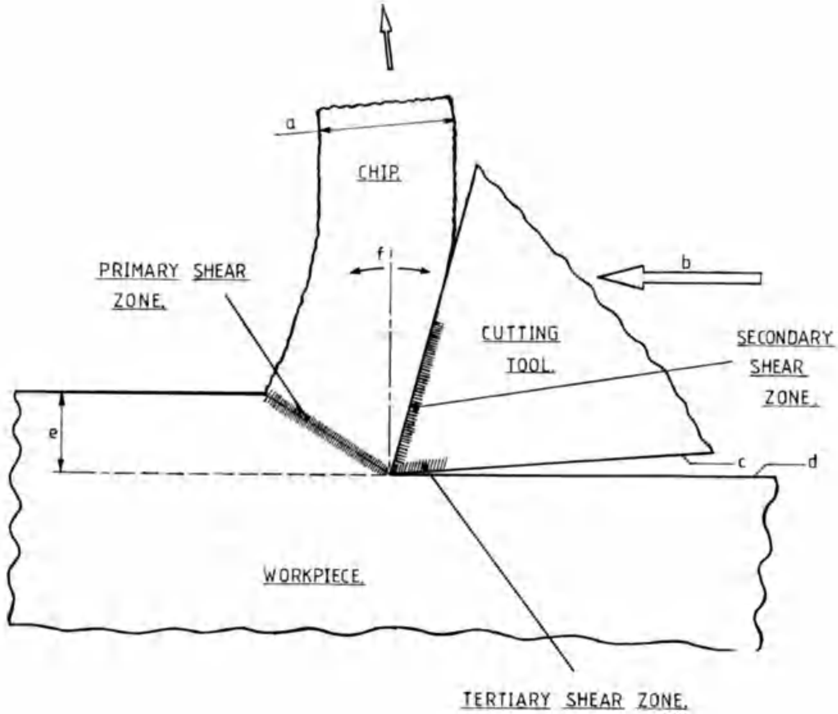


Fig. 3.1. Schematic diagram of stock removal process. a chip thickness; b cutting speed; c tool flank; d machined surface; e depth of cut; f rake angle.

cutting wood, but instead the metal is sheared and lifted away. As the chip is pared away the metal is deformed plastically, with the chip thickness formed always being greater than the depth of cut, or as is more correctly termed, the underformed chip thickness, for turning operations.

As can be seen in Fig. 3.1, as shearing takes place along the primary shear zone, the metal of the chip is deformed and flows along the tool face in a non-uniform manner with some stiction occurring in the secondary shear zone – at a junction of the metal and tool interface. This flow pattern is quite complex and the relative velocity changes across the width of the chip and along its contact region – at the interface with the tool, which is often termed the secondary shear zone. In this region a high resistance to deformation occurs and results in the chip exerting a large pressure application as it contacts the tool face. This fact produces an enormous friction between the chip and the tool face, generating a high temperature where they come into contact. The work done whilst cutting is nearly all converted into heat, as shown in Fig. 3.2a, where most of the heat is carried away by the chips. Although some heat is retained in the tool and workpiece, as depicted in Fig. 3.2b, and the isotherms show the temperature distribution across the workpiece, tool and chip. A typical temperature distribution, as illustrated in Fig. 3.2b, would be generated by the following machining parameters: workpiece steel 850 N/mm^2; cemented carbide insert grade P20; rake angle 10°; depth of cut 0.32 mm; cutting speed 60 m/min. It is usual to show the cutting edge with a sharp point, but in reality this is rarely present, as many inserts have a chamfered edge preparation and even if a sharp edge is ground, it soon becomes progressively

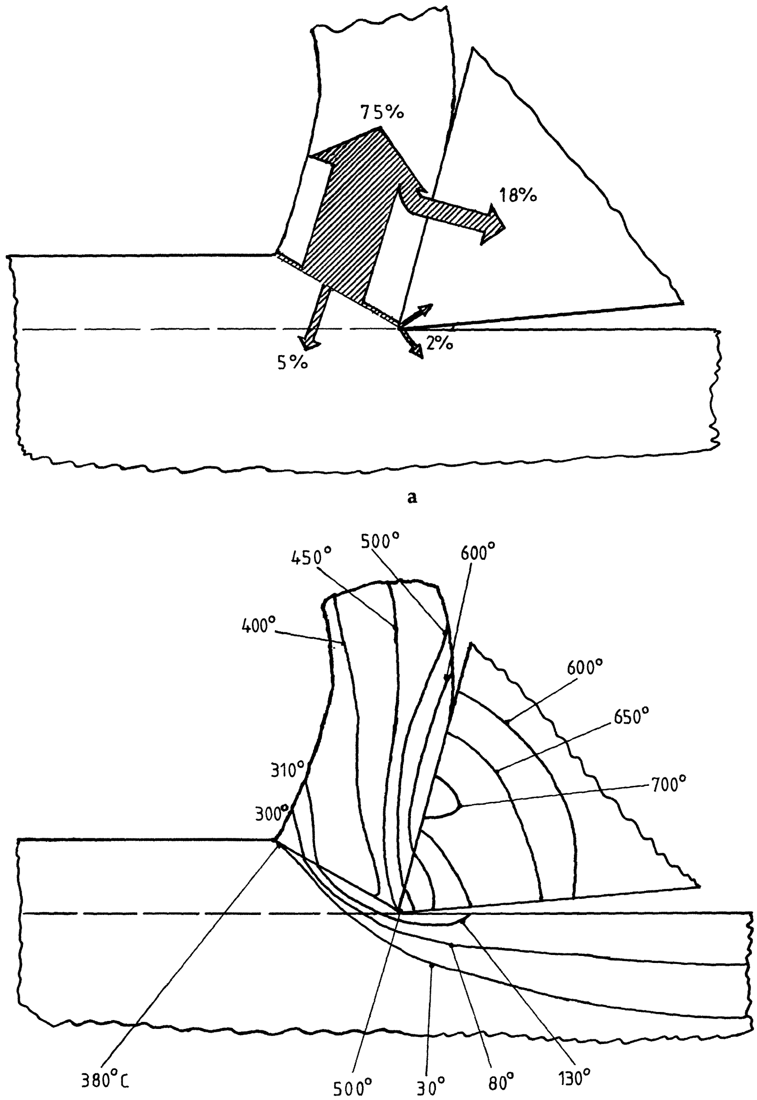


Fig. 3.2. The temperature distribution in the workpiece, tool and chip. **a** The heat dissipation during cutting. **b** Isotherm distribution. [After Kronenberg & Vieregge.]

rounded as cutting is initiated. This has the effect of modifying the shearing action, and below a certain position on this nose-rounded point the tool tends to plough rather than cut, causing some work-hardening and residual stress in the machined surface, promoting partial elastic recovery. This tertiary shear zone – where flank wear occurs – can cause large modifications to the machined surface, but this is beyond the scope of this book and for more information the reader is advised to study the effects of surface integrity written elsewhere.

3.2.1 The Shear Plane, Thickness of Chip and Friction

The shear plane, thickness of chip and friction are all closely related and influence each other. Most of the plastic deformation and separation from the workpiece takes place in the shear plane. The separated chip rubs against the tool's face under high pressure, which prevents it from flowing smoothly. This in turn leads to a build-up in the shear zone, the plastically deformed metal is pushed along it and accumulates so that the cross-sectional area of the chip increases and the chip becomes thicker. The greater the resistance, the greater the friction of the chip, leading to a larger shear area and more energy going into the deformation.

As already stated, the work of cutting is almost entirely converted into heat, with most of it being in the work of plastic deformation, but also a large percentage being involved in overcoming friction. Since most of the work of plastic deformation is expended in the shear zone, nearly all the friction is between the chip and the tool, and it follows that most of the heat is generated in these two regions. This relationship is of crucial importance for machining techniques and in the subsequent use of cutting fluids; although reducing the friction between the chip and the tool when using coolants, the resultant chip is thinner, the shear area is smaller and the amount of heat generated is lessened. As a result of the influence that cutting fluids have during machining, the frequency of tool changes decreases. An illustration of this relationship is shown diagrammatically in Fig. 3.3. The angle between the shear plane and the cutting surface is termed the shear angle. If there is less friction here, this angle is smaller and so the shear area is correspondingly reduced, and as a result less heat is generated.

3.2.2 Wear and its Causes

Whilst machining, the tool will wear and at the tool point this is predominantly promoted by frictional effects in the contact area which is further influenced by the mechanical loads and thermal strain present. Finally, any overall wear is produced by a combination of these individual causes, all of which are interrelated. High temperatures and pressures coupled with chemically sterile surfaces are ideal conditions for particles of workpiece material to become pressure-welded to the tool face. This is the classic built-up edge condition which is usually unstable and due to the velocity of the chip flow, attrition of tool material occurs as it is torn off the tool's face. Other debilitating factors which contribute to tool wear are diffusion processes, mechanical wear – plastic deformation is particularly prevalent at high cutting speeds and feedrates – and tool oxidation. As this is a complex relationship, it is often difficult to determine where one wear factor dominates over another.

As described above, tool wear can manifest itself in a number of ways and typical examples are simply shown in Fig. 3.4, where cratering, flank and oxidation wear are depicted. In the final analysis, however, the source of all the trouble is the effects of heat. Its influence on tool wear is critical and if just a slight decrease in temperature results, the increase of tool life is several fold. The diagram in Fig. 3.5 shows, for example, how a reduction of temperature of, say, 30 °C, from 510° to 480 °C, results in an increase of tool life of up to five times, from 20 to 100 minutes. To summarise, during machining, the heat is, in the main, generated in two ways. These are:

by plastic deformation of the workpiece, accounting for some 66%–75% of the heat generated

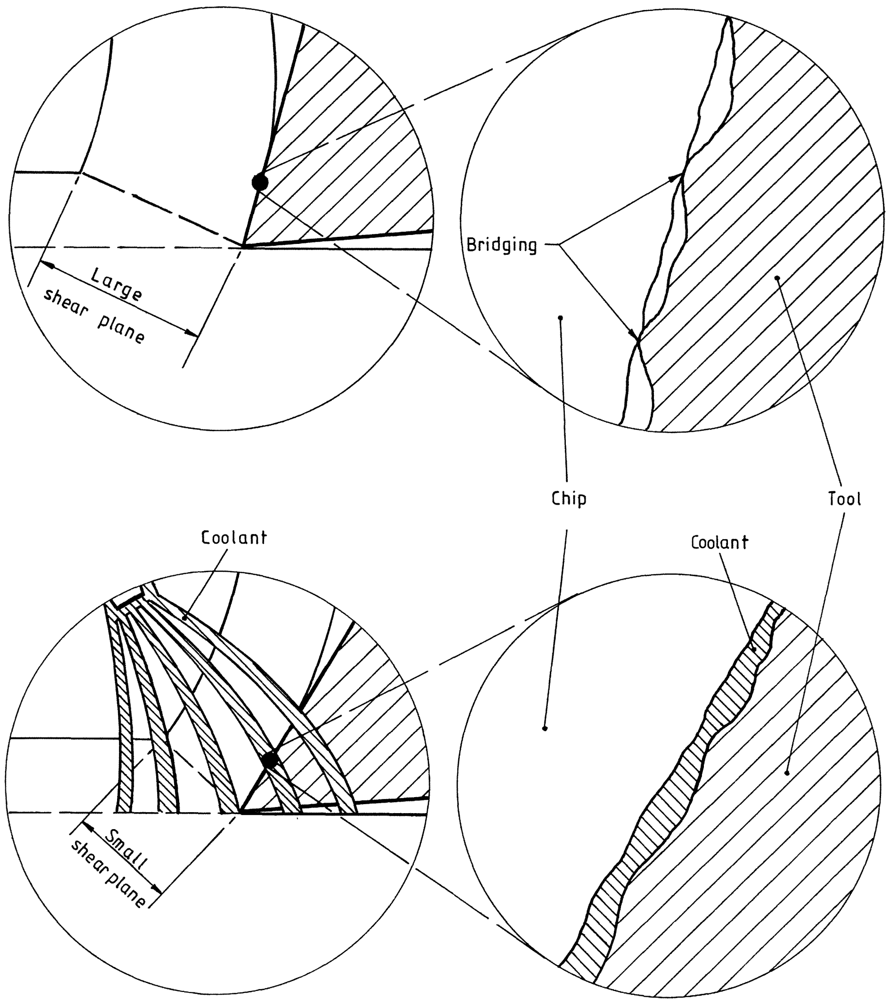


Fig. 3.3. The effect of rake angle on the thickness of the chip. [Courtesy of Cimcool.]

from friction of the workpiece against the tool, which mainly results at the tool/chip interface

Therefore any means of reducing the temperature of the workpiece must initially aim at lowering the energy of deformation and friction. By reducing the friction, this in turn also reduces the energy expended in deforming the material. Friction against the tool is the product of "roughness peaks" on the chip as it rubs against similar peaks on the tool's surface (Fig. 3.6). At the point where two peaks rub together there are enormous temperatures and pressures generated, with typical pressures being $150\,kg/mm^2$ or more, having temperatures in the region of 1000 °C or higher. This condition results in the peaks being literally welded together before being torn apart

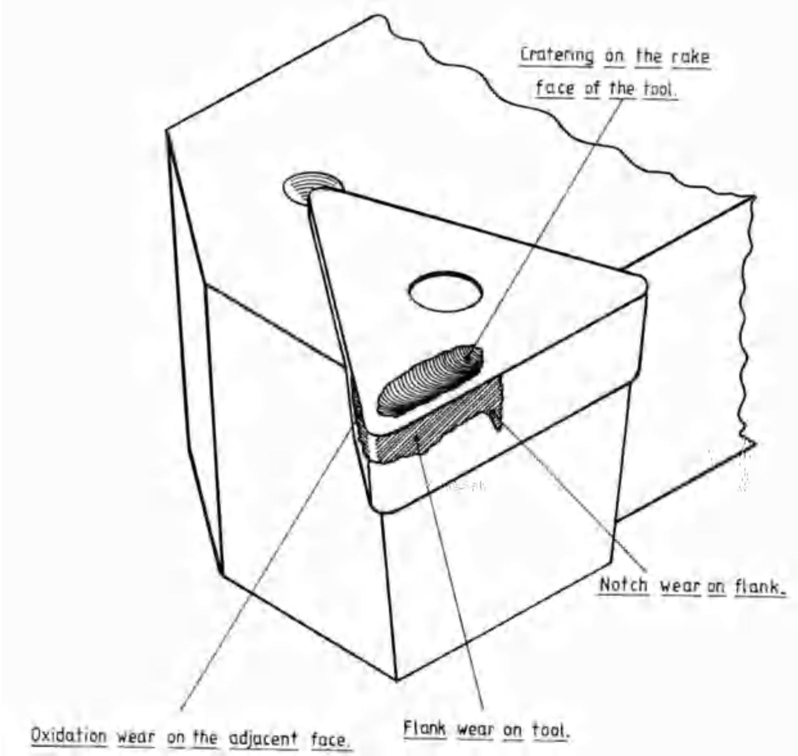


Fig. 3.4. Types of wear at the cutting edge.

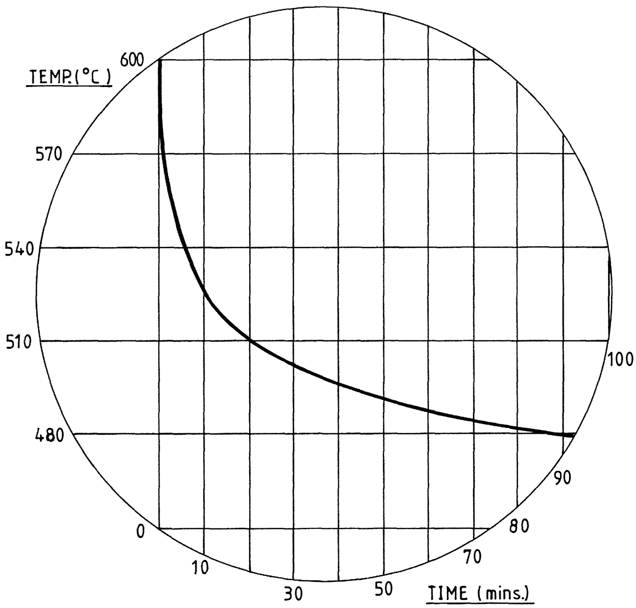


Fig. 3.5. The effect of temperature on the tool life. [Courtesy of Cimcool.]

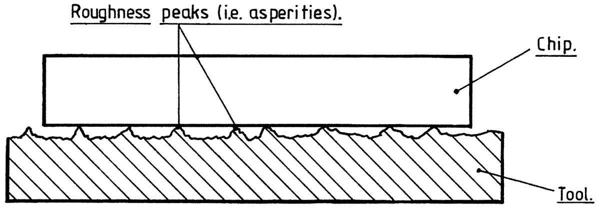


Fig. 3.6. The friction between the chip and the tool. [Courtesy of Cimcool.]

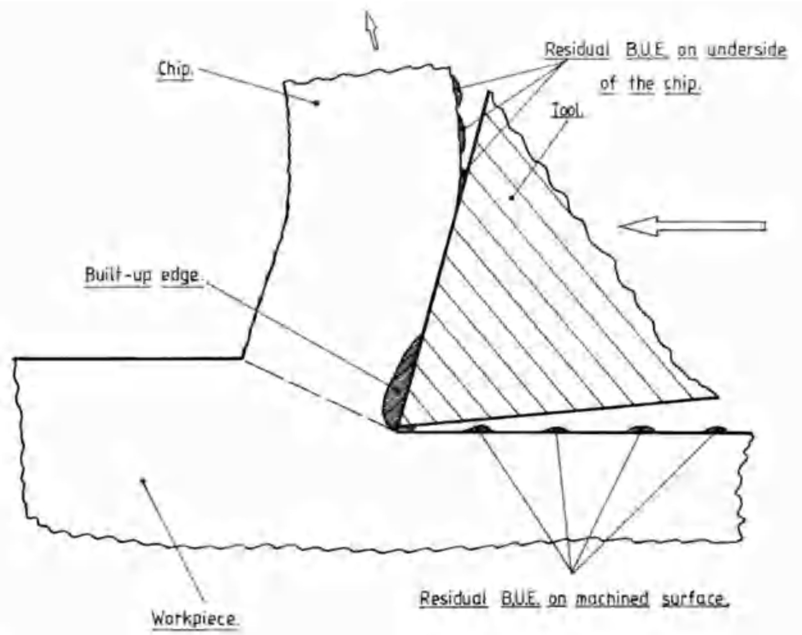


Fig. 3.7. Build-up on the tool and residual effects on the workpiece and chip.

again. The tearing action can consume up to 25% of the machine's power which is a significant loss. As these "microwelds" are pulled apart, small fragments of tool material are forcibly removed and transported away by the chip, which leads to cratering of the tool's surface in the region just behind the cutting edge on the rake face. Such a cratering process leads to a concentration of heat at the cutting edge and as a result it produces cracks and breaks at the edge making the tool's edge blunt.

When enough of these "microwelds" have been formed in the vicinity of the cutting edge, they cannot be completely pulled away by the chip; this leads to a build-up on the tool's face (Fig. 3.7). From time to time this unstable built-up edge is fragmented allowing parts of this extremely work-hardened material to be carried away by the chip. As this built-up edge expands and is forced onto the flank face, parts become detached and adhere to the machined work surface resulting in a degradation of this finish. The whole built-up edge is removed regularly by the chip's velocity and this causes tool material to be torn away in this region – usually termed attrition. Abrasive wear may also occur when high oxide layers or sand particles and other oxides are present. They, in turn, cause high flank wear, gouging of the rake face and notch wear at the depth of cut region on the flank. Flank wear is a greater problem than crater wear, as it has a direct relationship on the degradation of the machined surface and usually terminates the tool's life. Often flank wear in excess of 0.5 mm is sufficient to mean an effective "end point" in the life of the tool, even though it might be possible to continue cutting until 0.7 mm flank wear occurs. The reason for stopping machining at this supposedly lower than optimum value is to predict safely the life of the tool prior to rapid deterioration and a subsequently inferior surface finish on the part. There are many other conditions which can cause wear of the tool, such as diffusion, oxidation and plastic deformation, but these are beyond the scope of this book and have been discussed fully elsewhere (see the Bibliography).

3.2.3 The Task of Cutting Fluids

In view of just some of the problems of tool wear mentioned above, the main tasks of cutting fluids are to lubricate the tool and cool it, whilst enhancing the finish produced on the workpiece. The fluids reduce the friction between the contact surface of the tool and workpiece – at their interface (Fig. 3.8) – whilst carrying away the heat generated in cutting and deformation. A secondary but accepted advantage is that they also help carry away the chips as they are formed.

The combined effect of cooling and lubricating is to reduce tool wear, and as a consequence improve the surface finish coupled with improvements in the dimensional accuracy as its overall criterion for use. The relative amounts of cooling and lubricating necessary vary according to the work undertaken and are dependent – in the main – on the cutting conditions. When cutting is being done at low speeds, for example, the anticipated effect is that temperatures will also be relatively low, so under these conditions the cutting fluid provides lubrication. At high cutting speeds the converse may be true. However, cutting fluids will only improve the life of the tool if the cutting speed does not exceed a certain range, which is dependent on the cutting conditions. Even within this range, above a certain speed the lubricating properties of

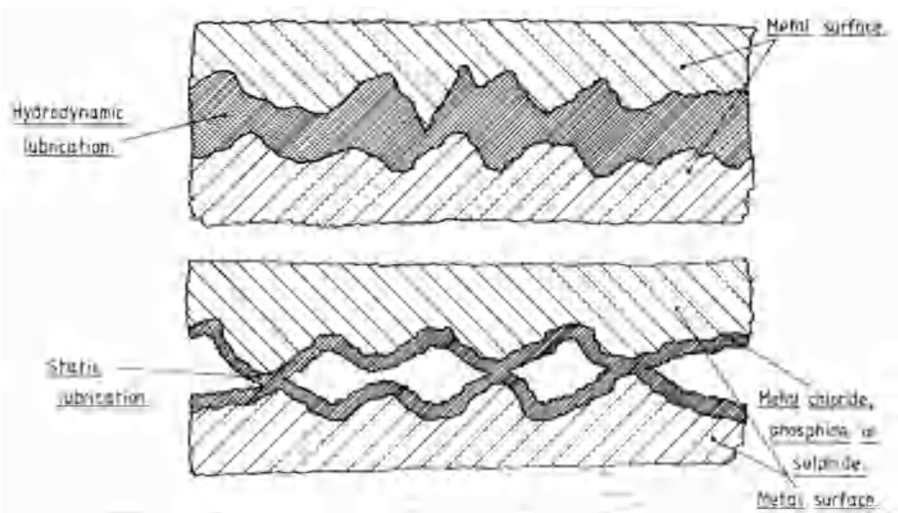


Fig. 3.8. Boundary lubrication. The effectiveness between rotating surfaces.

the cutting fluid start to play a lesser role and any improvement in tool life is dependent mainly on the ability of the fluid to carry away heat.

Effective cooling depends on the cutting fluid's capacity to absorb heat, carry it away, then dissipate it before re-use. Some substances do this better than others, with water being supreme in this regard. So, when a high degree of cooling is necessary, a water-miscible system is preferred. When it comes to lubricating, extremely high demands are placed on the cutting fluid because of the high temperatures and pressures generated at the interface between the tool workpiece and chip. In order to prevent, or at least reduce, this friction it is necessary for a film of lubricant to keep the two surfaces apart (Fig. 3.8). Fluid lubricants – oil, water, or similar – cannot do this since the high pressure between the surfaces prevents the liquid from penetrating between the roughness peaks where they come in contact (Fig. 3.8). The type of friction which arises is known as dry friction, or boundary friction. Away from the points of contact there is only an extremely fine film of lubricant, one or two molecules thick (Fig. 3.8). As a comparison, the illustration also shows hydrodynamic lubrication, where the surfaces are separated by a continuous film of lubricant. In order to be effective as lubricants, cutting fluids must be able to provide boundary lubrication at the high temperatures and pressures generated during machining.

The boundary lubrication properties required will naturally depend on the type of machining:

light cutting operations: the usual cutting fluid components such as fatty acids and emulsifiers provide adequate lubrication

heavy cutting operations: special extreme pressure (EP) additives are necessary

The extreme pressure additives build up intermediate films on the cutter, either by adsorption, or by chemical reactions and in so doing reduce the metal-to-metal contact between the surfaces, although complete separation of the surfaces during machining remains impossible. Such EP additives make use of the high temperature and pressure in the boundary friction area to begin the chemical reactions with the metal surface and as such build up a "reaction film" in the valleys between the peaks. This "reaction film" is much easier to pull apart than the microwelds, so that both friction and wear are reduced. The chemical reaction, however, only starts at a certain temperature which is different for each type of additive.

The extremely high performances of which modern machine tools are capable, can only be achieved if all the factors involved in their operation function perfectly together as a whole. Obviously a key element in this performance is the cutting fluid. The cutting fluid is not only at the point of cutting: small quantities will penetrate the hydraulic and lubricating systems of the machine tool and have an effect there, in fact, it is impossible to prevent cutting fluid splashing onto parts of the machine. Conversely, small amounts of slideway lubricant and hydraulic oil leak out and get into the cutting fluid. This oil leakage is often termed "tramp oil". The cutting fluid must still perform satisfactorily even when it has adsorbed high levels of "tramp oil". As an aside, it is not generally recognised that through "total loss" the amount of "tramp oil" consumed during continuous use of a large machining centre can amount to over £1000 per annum. It is a high, indirect cost which is often not budgeted for in many part costing calculations. Yet another effect of using cutting fluids is that it is impossible to avoid the fluid coming into contact with people. This contact may be either via direct or indirect contact – through the immediate surroundings, or by polluting the wider environment.

The characteristics demanded of cutting fluids go far beyond the main properties of simply cooling and lubricating and may even include some contradictory requirements. The following list highlights some of the commonest requirements of cutting fluids, either individually, or in composition:

cutting fluid
lubricant
able to flush away chips
pressure resistant
chemically stable
biologically stable
a protection against corrosion
able to form emulsions
non-foaming
non-harmful to skin
wetting
easy to wash away
non-flammable
transparent
possible to filter
compatible with other machine tool components
stability of odour
easy to dispose of
not harmful to the environment

3.3 Types of Cutting Fluid

The many different types of cutting fluids available can be classified according to widely varying criteria, although a more or less unified system of terminology is laid down in the industry standards and guidelines. This provides commonality, which reflects both the chemical and technical requirements of the users. Most technological countries have relevant publications and typically the German version includes the following:

DIN 51 385
VDI guideline 3035
VDI guideline 3396
VKIS (Verbraucherkreis Industrieschmierstoffe)

On the basis of these publications, the following classification is perhaps the most useful from the user's point of view and, broadly speaking, groups cutting fluids into two main types:

"oil-based"
"aqueous"

The "aqueous" cutting fluids can be divided into "emulsifiable" and "water-soluble" types. The former "oil-based" cutting fluids are supplied as ready-to-use products, whilst "aqueous" types are normally supplied in the form of a concentrate, which must be mixed with water prior to use. Once mixed with water, the "emulsifiable" types form an emulsion, whereas the "soluble" variety forms a solution. In both cases, the resulting cutting fluid is termed "water mixed".

3.3.1 Mineral Oil, or Synthetic Lubricant?

The raw material used to make cutting fluids can be naturally occurring oils such as mineral oils, animal or vegetable, or fats. Of these the mineral oils are probably the most commonly used industrially. These, like other naturally occurring oils, tend to be complex mixtures of widely varying compounds. Such compounds consist mainly of carbon and hydrogen, and as such are usually referred to as "hydrocarbons". In addition they will contain sulphur, nitrogen and various trace elements.

In order to separate mineral oil into "stock oil", offering natural lubricating properties, thermal processes are used. These partly-refined "stock oils" are still chemically complex mixtures of hydrocarbons with widely varying characteristics. As an example, "crude oil" is a mixture of more than one thousand hydrocarbons with different chemical structures. Such widely varying characteristics make it impossible to supply mineral oil to closely defined specifications, which limits its uses and performance as a cutting fluid. The complex structure of a cutting fluid made up entirely from naturally occurring oils is illustrated in Fig. 3.9.

Synthetic lubricants cannot be compared with lubricants extracted from naturally occurring oils – since the properties of the latter are always an aggregate of the properties of their many different components and so cannot be exactly predicted. The synthetic lubricants are made from two types of raw material:

mineral oil (polyalpha olefin and alkali aromatics)
polybutenes

At present, synthetic hydrocarbons predominate. However, the synthetic lubricants not derived from mineral oils are becoming increasingly important. These, in particular, include derivatives from the fractioning of plant oils. The most important classes of compounds are esters and polyglycols.

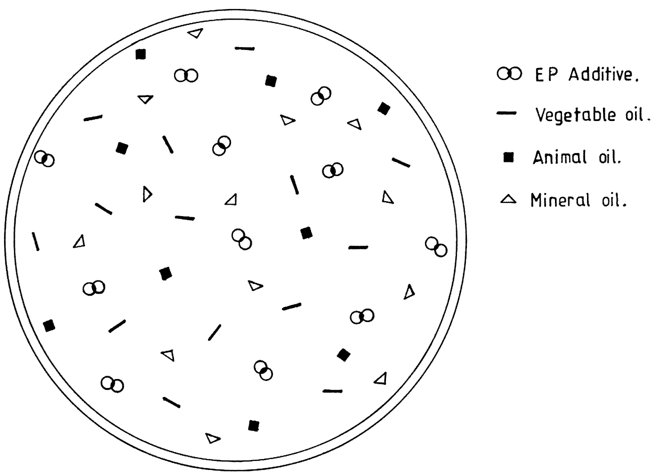


Fig. 3.9. The schematic structure of a oil-based cutting fluid. [Courtesy of Cimcool.]

All cutting fluids, whether aqueous or oil-based, may contain mineral oils, synthetic products, or a combination of both. The choice of raw material and composition depends on many factors and is one of the best-kept secrets of the lubricant manufacturer.

3.3.2 Oil-based Cutting Fluids

Cutting oils, as the oil-based cutting fluids are often known, are usually mineral oils with or without additives. The additives may be either natural or synthetic. As well as mineral oils, other naturally occurring oils – animal, vegetable, or synthetic lubricants – can provide the raw materials for making oil-based cutting fluids.

Compared with aqueous solutions, the main advantages of oil-based cutting fluids are better lubrication and resistance to pressure. Any additives are used to improve:

lubrication
protection against wear
protection against corrosion
stability
foaming control

3.3.3 Aqueous Cutting Fluids

A large proportion of the cutting fluids used in machining are aqueous and these combine the excellent heat absorbing capacity of water with the lubricating power of chemical substances. Such cutting fluids offer excellent cooling, lubricating and wetting properties. They can be used in all types of stock removal processes, with the proviso that the machine tool has a suitable lubrication system and the spindle and slideways are sufficiently well sealed to prevent the ingress of water from the cutting fluid. Protection against lubricant ingress is most often the case with modern-day machine tools. When adequate protection and compatibility of lubricants and hydraulic fluids on the machine tools are chosen, this makes it possible to use water-mixed cutting fluids. Furthermore, the use of such types of cutting fluid is not solely limited to machining steels, and providing the characteristics of the cutting fluids are chosen to match the material, they may also be used on non-ferrous metals.

Aqueous cutting fluids can consist of naturally occurring oils such as mineral oil, synthetic material, or a combination of both, but in the main are present in the form of an emulsion, or solution. Other forms of cutting fluids such as suspensions, gels, or pastes are rarely used in the manufacturing process.

The commonest form in which aqueous cutting fluids are used is an emulsion. An emulsion is a disperse system formed by the mixing of two fluids which are not soluble in each other. In the emulsion, one of the fluids forms the internal phase, which is dispersed in the form of droplets suspended in the external phase, or "medium" as it is often known. Such corresponding cutting fluids are of two types – "emulsive", or "emulsifiable" – of which the former type is the more commonly used. The "emulsive" cutting fluid consists of an oil in water emulsion in which oil forms the internal phase. The counterpart to the "emulsive" type is the "emulsifiable" solution, which consists of a water in oil emulsion, but in this case the water is the internal phase – lately this cutting fluid is becoming less important.

An aqueous "emulsive" cutting fluid always contains a stock oil, usually mineral oil, synthetic hydrocarbon, synthetic ester, or fatty oil and so on, together with certain additives. The most important additives tend to be:

"emulsifiers"
corrosion inhibitors
stabilisers and solubilisers
anti-foam agents
microbiocides
complex formers

Considering these in turn, the "emulsifiers" are necessary to help form a stable emulsion and as such are very important for the technical characteristics of the cutting fluid. "Emulsifiers" make it possible for the oil droplets to form and remain suspended in water, preventing them from merging and floating upwards to form a layer on the surface. "Emulsifiers" reduce the surface tension and form a film at the boundary surface. These "emulsifier" molecules are bipolar in characteristic and as a result line up like the bristles on a brush, with one end towards the oil and the other end towards the water, as shown in Fig. 3.10. In this way, the "emulsifier" forms a film which is one molecule thick at the boundary surface.

The main task of corrosion inhibitors in any aqueous cutting fluid is to prevent the water in the fluid corroding the parts of the machine tool. The mechanisms by which different corrosion inhibitors work vary widely and one commonly used version of inhibitor consists of an additive which forms a protective film on the metal's surface. These corrosion inhibitors consist of long, narrow molecules which are negatively charged and as such are attracted to the metal in contact (Fig. 3.11). The polarised film subsequently formed is no thicker than the molecules themselves and so is invisible.

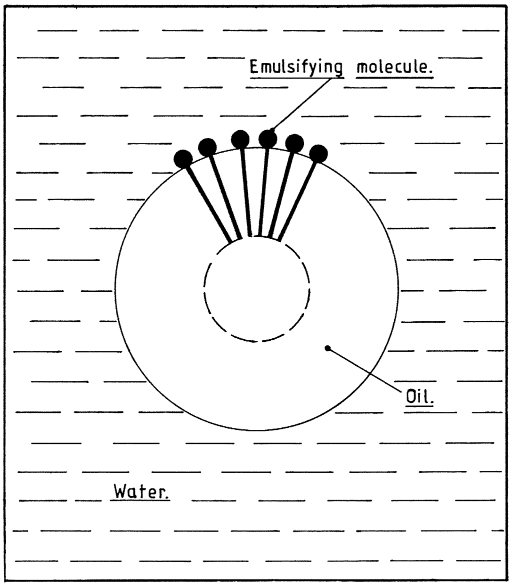


Fig. 3.10. An emulsifying molecule at the boundary surface in an oil-in-water emulsion. [Courtesy of Cimcool.]

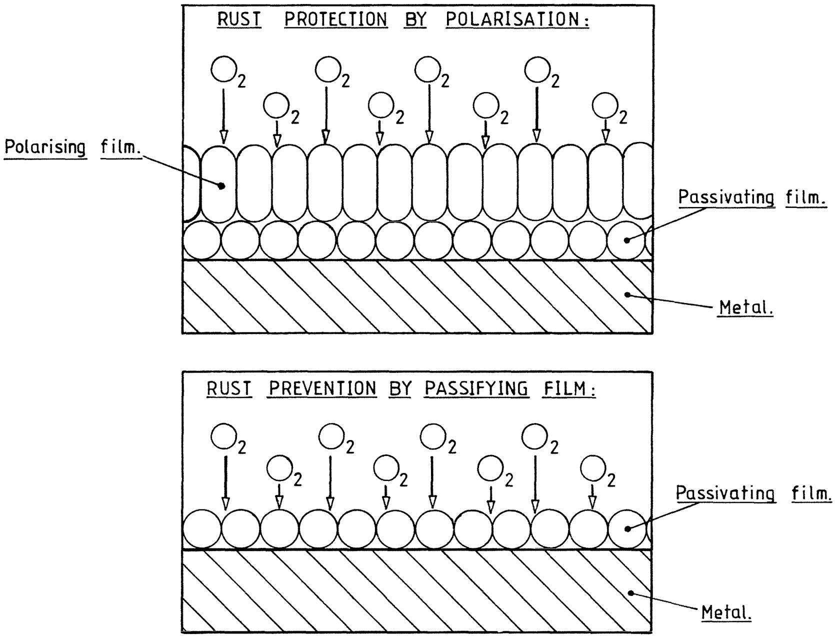


Fig. 3.11. The principle of polar and passivating corrosion protection. [Courtesy of Cimcool.]

Nevertheless, it effectively prevents the electrochemical process of corrosion, such as passivation by means of nitride, but they are now being phased out.

Stabilisers extend the life of the concentrate considerably, whilst solubilisers increase the oil's solubility. Various alcohols and glycols can be used as stabilisers, or solubilisers. Anti-foaming agents – often termed "antifroth" or "defrothing" agents – prevent the formation of foam. Silicones, whilst subject to certain restrictions in their usage, are very popular anti-foaming agents. A typical restriction might be that after machining with such silicones, it may be impossible to either paint or coat them at a later date.

Microbiocides are sometimes added and the purpose of these additives is to prevent the growth of microbes in water-mixed cutting fluids. Their use, however, is usually limited owing to skin care considerations, but more will be said on this aspect later in the chapter.

The main constituent of any aqueous-based cutting fluid is obviously water and, by nature, is impure. This impurity depends on the source – rain water, river water, spring water, ground water, and so on. It may contain dust particles, oxygen, nitrogen, calcium and magnesium salts, often with smaller quantities of ammonia, boron, fluorine, iron, nitrate, calcium, strontium, aluminium, arsenic, barium, phosphate, copper and zinc. Additionally there are micro-organisms present – typically algae, bacteria, fungi and viruses, although in different orders of magnitude. So, depending on its composition, water can affect the cutting fluid in many ways and since the composition varies throughout the year, these seasonal variations will have an effect on its use. By far the greatest effect on the properties of the cutting fluid is caused by the hardness of the water. Its hardness depends on the concentration of calcium, magnesium, and other heavy metals like iron and manganese. Hard water may cause a soapy deposit,

Table 3.1. The minimum requirements for water quality [Courtesy of Cimcool.]

Condition	Unit	Allowed maximum
Hardness	mmol/l	1.8–10.8
	(°d*	5–30)
pH level	–	6–7
Chloride in water	mg/l	<100
Sulphur in water	mg/l	<100
Condensed particles	mg/l	<500
Number of parts	l/cm^3	<10

* °d was the former unit.

which will eventually block the filters or destabilise the emulsion and may have a detrimental effect on the fluid's corrosion protection. Soft water can be a problem, but for another reason, it may promote foaming under strenuous cutting operations.

The degree of alkalinity of the water can be expressed as a pH value and this is an important measurement. Alkalinity, in the main, affects the growth of microbes and the degree of corrosion protection afforded by the emulsion. If alkaline levels increase this gives better corrosion protection, in particular when machining ferrous workpieces. Therefore, in view of the importance of the water composition for the effectiveness of a water-mixed cutting fluid, it is essential to know the quality of the water available and to take account of this factor when choosing a concentrate. Cutting fluid manufacturers carry out water analysis, as do the local water authorities. The minimum requirements for water quality for cutting fluids are shown in Table 3.1.

3.3.4 Classification According to Composition

Normally cutting fluids are sold under the following classifications, according to composition:

synthetic
semi-synthetic
emulsion

Synthetic cutting fluids are those which contain very little or no natural oil. The various components such as cutting fluid are finely distributed in water, so forming a watery transparent solution (Fig. 3.12). The applications of synthetic cutting fluids range from light to heavy cutting and grinding operations.

In order to ensure the necessary lubricating power desirable for heavy cutting operations, some products contain synthetic lubricants (Fig. 3.13). The properties of synthetic cutting fluids can be summarised as follows:

very clean
excellent corrosion protection
long life of cutting fluid
excellent cooling
transparent
easy to mix

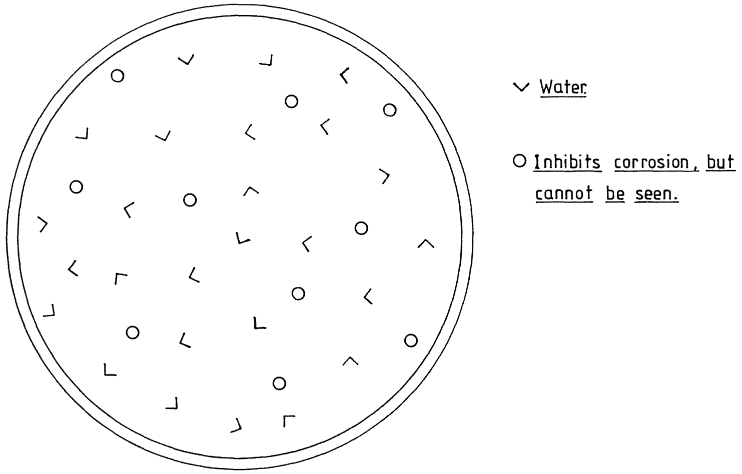


Fig. 3.12. The schematic composition of a synthetic cutting fluid. [Courtesy of Cimcool.]

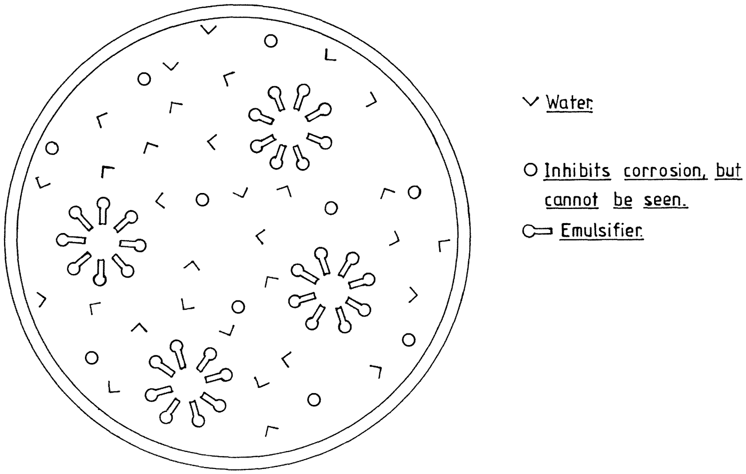


Fig. 3.13. The schematic composition of a synthetic cutting fluid for heavy cutting. [Courtesy of Cimcool.]

do not burn or produce smoke
very good for grinding operations
prevent glazing of grinding wheels

Semi-synthetic cutting fluids contain up to 41% oil and when mixed with water they have a translucent property (Fig. 3.14). EP additives and synthetic lubricants can be added in order to widen the range of possible applications. The properties of semi-synthetic cutting fluids can be summarised as follows:

clean
excellent corrosion protection

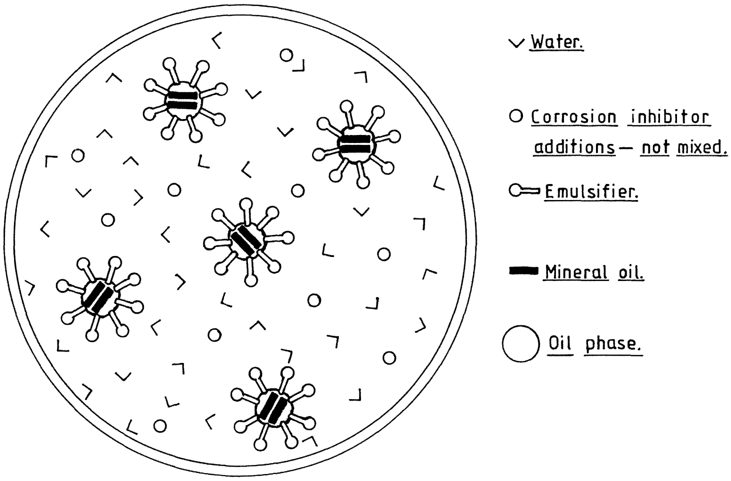


Fig. 3.14. The schematic composition of a semi-synthetic cutting fluid. [Courtesy of Cimcool.]

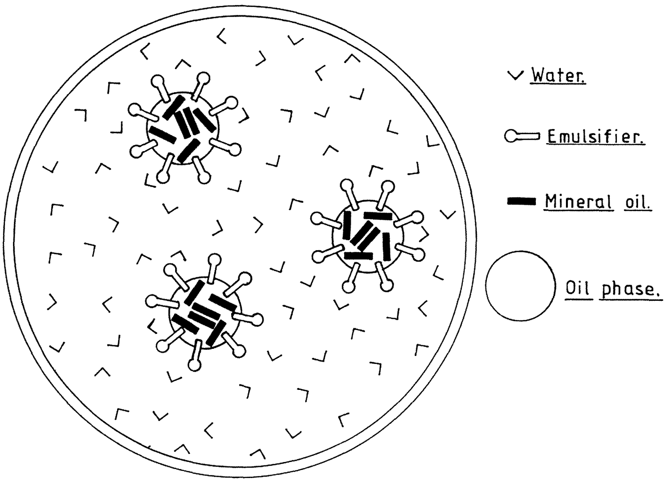


Fig. 3.15. The schematic composition of an emulsion cutting fluid. [Courtesy of Cimcool.]

long life of emulsion
excellent cooling
good wetting properties
easy to mix
do not burn or produce smoke
prevent glazing of grinding wheels

Emulsion cutting fluids contain a high proportion of oil and when the concentrate is mixed with water it has a milky appearance (Fig. 3.15). Products intended for very heavy cutting operations also contain EP additives (Fig. 3.16). The properties of an emulsion cutting fluid are as follows:

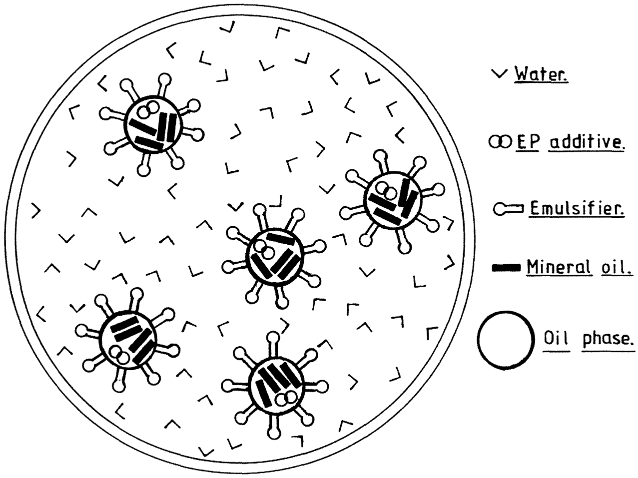


Fig. 3.16. The schematic composition of an emulsion cutting fluid for heavy cutting. [Courtesy of Cimcool.]

clean
good corrosion resistance
long life of emulsion
easy to mix
do not burn or produce smoke

The differences in the range of application of synthetic, semi-synthetic and emulsion cutting depend on the cutting requirements. The heavier the cutting, the higher the cutting force required and the greater the oil content. This means that synthetics are used on light cuts, whereas emulsions are necessary for heavy cuts, whilst semi-synthetics can be used as a general purpose alternative.

3.3.5 Computer-aided Product Development

Cutting fluids are very complex products and a large amount of research development is needed to perfect them. The number of raw materials which have different characteristics and the number of interreactions between them means that the possible combinations are enormous. Even when most of the possible combinations are obviously unnecessary and as such can be disregarded, there are still thousands which can be used and it is desirable to choose the best. This situation is analogous to "looking for a needle in a haystack", where the conventional empirical methods become no better than searching at random. Evaluation using computer technology provides the solution to the problem and using statistical techniques coupled with specially developed programs, it is possible to screen the many thousands of combinations reducing them to just one or two. In this way it is possible to obtain the optimum solution rapidly and with accuracy, as shown by Fig. 3.17, where computer-aided design (CAD) is used to select a corrosion inhibitor. Such techniques have brought about a new era in cutting fluid product development and CAD is not only used to screen out formulae which do not fit the required characteristics, but can uncover previously unsuspected properties resulting from synergies. The term "synergies" refers to the outcome when substances are combined and produce "side effects" which add to, or even amplify, each other giving a much stronger resultant effect. As an example of this phenomenon, anionic emulsifiers normally have corrosion inhibiting properties, but these are so slight that such "side effects" are usually disregarded. By using CAD, it is possible to find emulsifiers – usually several are necessary – whose side effects add up synergetically.

When the correct emulsifiers are chosen and in the right proportions, not only is the desired emulsifying action obtained, but at least some of the required corrosion protection also occurs. In Fig. 3.17 an example of the "construction" of a corrosion inhibitor system using a variety of inhibitors, either singly or in combination, can be appreciated. The zero line on the vertical axis of the graph represents no effect whilst numbers greater or less than zero represent a positive or negative effect, respectively.

Such computer-aided designing of chemical compounds makes it possible to develop "atomised" cutting fluids far faster than previous techniques and "paves the way" for the prospect of discovering entirely new combinations. The use of computers in developing, analysing and testing of cutting fluids, enables very rapid modifications to be incorporated in order to meet new technical or commercial requirements. Not only will CAD methods guarantee a chemically stable product with just the right properties, they also reduce the risk of choosing the wrong type of cutting fluid, both for the manufacturer and the user. In order to maximise the benefit from CAD product development, it is still necessary to undertake practical tests during the development stage. For this purpose, a technique referred to as "calibration of laboratory test methods" is used, in which any tests are modelled as closely as possible on the actual operating conditions used by a leading machine tool manufacturer. Such a technique existed before CAD was introduced for cutting fluid development, but now forms a useful adjunct to this method.

3.3.6 Quality Control

For practical reasons industrial producers of cutting fluids have to use mass produced raw materials and chemicals which may be less pure than the raw materials used in the laboratory. Not only are there variations in quality owing to production processes, but differences can also occur depending on the source and the season of the year. In order to ensure constant quality of the finished product despite these variations, the factors which determine the quality of the raw materials have to be checked before they enter the production process. The technique of "preventative" quality control is computer-aided statistical process control, which enables the researcher to set the upper and lower quality levels for a particular raw material. On the basis of statistical analysis of the frequency of occurrence of a component's maximum and minimum acceptable levels, the correlation between the analysis and results is determined. Raw materials analysis using advanced equipment therefore plays a very important part in the manufacturing process.

Computer-aided statistical process control is also used to determine the most suitable manufacturing method and to monitor the production process. Regular tests are carried out in the laboratory and under practical conditions (Fig. 3.18), with the results analysed by computer. This enables the cutting fluid manufacturer to control the quality of the finished product whilst maintaining it at a constant level.

An important criterion for the quality of the final product is its stability. Synthetic cutting fluids give fewer problems in this respect than semi-synthetic and emulsion

Fig. 3.17. Computer-aided design (CAD) used to select a corrosion inhibitor. [Courtesy of Cimcool.]

cutting fluids. In the case of the latter two, not only must cooling water and lubricating oil be brought together – two naturally incompatible substances – they must also be persuaded to remain mixed together under widely varying and extreme conditions. When different degrees of water hardness, varying mix ratios and a diverse range of impurities occur, they will strongly threaten the stability of the water–oil system. The conventional way of stabilising such a system is to add plenty of emulsifiers. This can lead to excessive foaming, especially if the water is soft, which in turn makes it necessary to add anti-foam agents. These anti-foam agents are expensive and only work for a limited period, so the stability they give only lasts a short time.

More important for stability is the size and distribution of the oil droplets in the water phase. It is the even distribution of the many oil droplets which makes the oil–water system stable. The growth of micro-organisms affects the droplet size – these droplets become larger and the number of droplets decreases. Oil–water systems with many small, evenly distributed oil droplets are therefore more stable than systems with bigger and fewer oil droplets. The size and distribution of the oil droplets also have an important effect on the foaming behaviour of the emulsion, which in turn is strongly affected by the hardness of the water and the turbulence produced in the machine, or the centralised coolant supply system – in the case of some flexible manufacturing systems.

There are a large number of possible tests for checking the quality of a cutting fluid and those most commonly used are "stability tests". Such tests measure not only the physical stability, but also the bacteriological stability – sometimes termed: biostability, biostatic properties, or resistance to bacteria growth. In Germany, test methods of this type are denoted by the DIN51367 and 51368 standards, but similar tests are listed in the standards of most technological countries.

Foaming behaviour: a slight tendency to foam is important for some types of machining, particularly in grinding machines, or when deep-hole drilling. There are certain cleaning systems available such as full jacket cyclones and hydrocyclones, which promote foam formation. There are no standard methods for the measurement of foam formation and collapse, but the laboratory circulating pump method is a good approximation of practical conditions. In this method the cutting fluid is forced through a spray head so that the spray falls onto the surface of the liquid and the time taken for foam to form and then collapse is measured.

Tests for adhesion are often carried out and low adhesion means there will be little tendency for the product to build up layers of deposit. This type of test is mainly used for synthetic products and again there is no standard test method; although one method used is to soak a pile of washers in the cutting fluid for a certain time, then dry them and test for adhesion.

The compatibility of the cutting fluid with paints and elastomers is tested by visual inspection of painted sheet metal after it has been immersed in the cutting fluid for a certain time, according to the DIN53521 standard.

The acid/alkaline level in the cutting fluid is important and is usually measured in the laboratory using an electrochemical pH meter, in accordance with the DIN51369 standard.

3.4 Choosing the Right Cutting Fluid

Many factors have to be taken into consideration when choosing a cutting fluid and the relative importance of these different factors will vary in each individual case. For

Fig. 3.18. Apparatus for testing cutting fluids to obtain quantitative data. [Courtesy of Cimcool.]

that reason, it is not possible to offer general rules for the selection of a cutting fluid. Inevitably a compromise is necessary, although an understanding of the factors involved makes it possible to achieve the best choice under given circumstances. When choosing a cutting fluid it should always be borne in mind that the machining process plays an important part in productivity, operator health, efficiency, safety and the quality of the work.

3.4.1 Factors Affecting Choice

The main factors which must be considered when choosing a cutting fluid are:

business philosophy – what are the relative weights given to goals such as efficiency, quality-consciousness, market position and economic position of the company?

production program – what is the scale of production: single item, batch, or mass production? Which machining processes are used?

hardware – what production equipment is available? Are the machine tools supplied with cutting fluid individually or from a central system? Are particular cutting fluids recommended by the manufacturer of the machines?

protection of people and the environment – to what extent are personnel exposed to cutting fluids before, during and after use? Are there local constraints on disposal? These criteria can be divided into two groups – commercial and production criteria.

The commercial criteria determine the weight to be given to various production criteria. For instance, if the time factor is more important than the cost factor, then higher cutting speeds will be used and so the demand placed on the cutting fluid will be greater.

If different materials and types of machining processes are involved in the production process, then a universal cutting fluid might be a better choice than a number of different products, even if they would individually give better performance.

In one-off and batch production, individual machines are more likely to have their own separate cutting fluid supply than in mass production where centralised systems are the norm. The production criteria for the choice of cutting fluid includes the type of machining process, the machining conditions – material, cutting speeds, tool material, and so on – together with the machine tool. On the basis of these decision criteria, an initial choice will usually be made regarding the type of cutting fluid to be used – whether an aqueous or oil-based type is required.

When selecting a cutting fluid it is important to take the manufacturer's instructions into consideration. If they are ignored it may render guarantees invalid. Many manufacturers specify that certain products must be used – this usually applies to special, difficult machining operations – whilst many others only specify the general type, e.g. aqueous or not, to be used, whilst some may not specify anything. Usually it is possible to rely on a manufacturer's tables which indicate their most suitable product for particular machining operations. However, before consulting a manufacturer's table, the following factors must be known:

type of machining operation

water characteristics – hard/soft, chloride, sulphate, bicarbonate content

type of material to be machined – beware of aluminium and copper

type of filtration on the machine tool, or in the centrifage – no filtration, sump only, paper filter, centrifuge and so on. Semi-synthetic products are not recommended for centrifuges, whilst washable filters should only be used with synthetic, or semi-synthetic products.

As a general rule of thumb, emulsions with EP additives should be used for heavy cutting work, whilst synthetic products are normally best when cutting at high speeds. By way of an illustration, if we consider multiple machining operations undertaken on machining centres, the cutting fluid should be chosen for the range between the highest and lowest cutting speeds. Once a particular product has been chosen it is still necessary to carry out a practical test as only such a test will confirm if the right choice has been made. At this stage, and perhaps later, support from the cutting tool manufacturer in the form of systematic sampling, laboratory tests and advice are very important.

3.5 Handling and Use of Cutting Fluids

In order to maintain the properties of the cutting fluid and give it a long service life, correct handling, use and care are necessary. An essential part of this care is the constant monitoring of the parameters and general condition of the cutting fluid during use.

3.5.1 Instructions for Use

When the product is supplied to the user, it is usually accompanied by a health and safety sheet. This lists the main constituents: the physical characteristics, information of hazard class, protection and first aid measures, together with all the information necessary for correct handling and use. The purpose of this sheet is to indicate the dangers of incorrect use and to check whether the product meets certain specifications. The health and safety data sheet provides a very useful basis of comparison for results later obtained during use. It is always advisable to make sure you obtain this document and follow carefully the recommended instructions.

3.5.2 Product Mixing

Aqueous cutting fluids are usually supplied in the form of concentrates and the ease with which they can be mixed together varies, depending on the amount of oil they contain. Concentrates with high oil concentration may require vigorous stirring in order to form the actual emulsion. Other products contain little oil and in fact are preformed emulsions in which the concentrate has already been mixed with water to form a stable emulsion. In order to prepare them for use, such concentrates only have to be stirred into water at the correct ratio.

Instead of mixing manually, it is much simpler and more economic to use a proprietary mixing device as shown in Fig. 3.19. Such a device can be mounted on the wall, or directly onto the cutting fluid container, and it is connected to the water supply. If this is the case it is necessary to ensure that the water is of suitable quality.

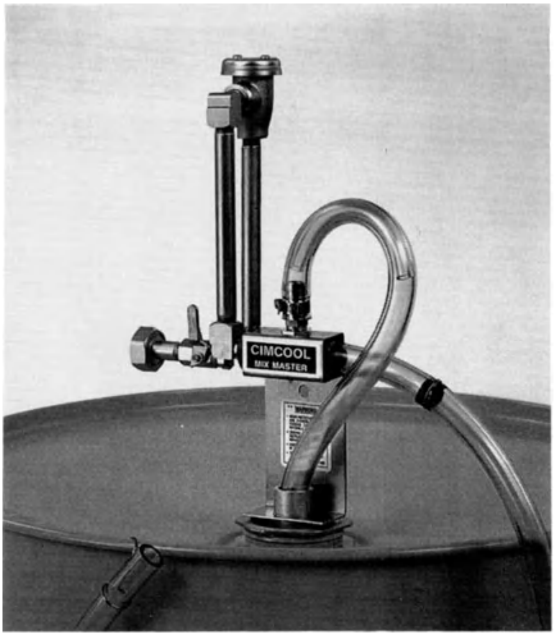


Fig. 3.19. A "Mix Master" automatic mixing unit for making up aqueous cutting fluid. [Courtesy of Cimcool.]

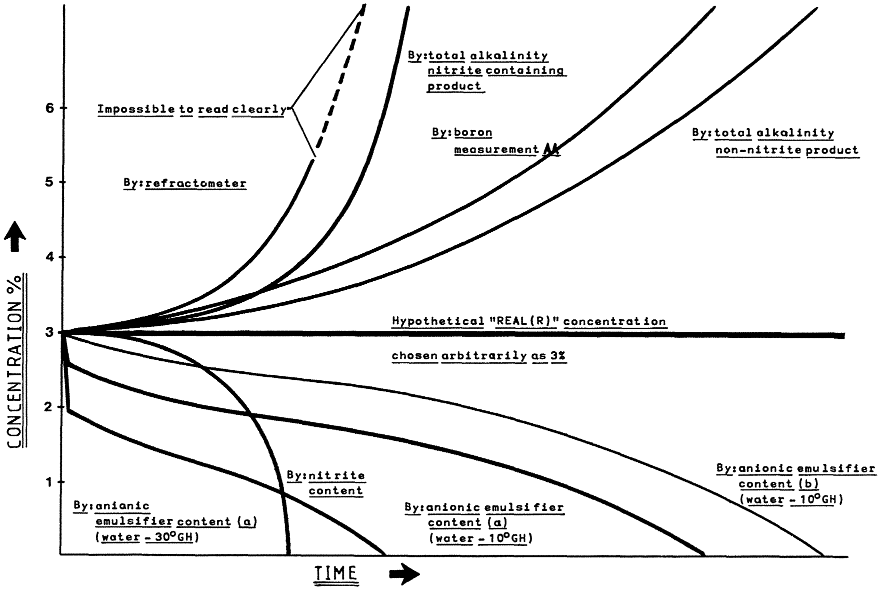


Fig. 3.20. Illustrates the results of the concentration measurements using different methods. [Courtesy of Cimcool.]

If mains water is used the local water authority will provide the necessary information, but if water from another source is used it will have to be analysed by the user.

Figure 3.20 shows the results of the concentration measurements obtained using different methods, such as:

refractometer assessment
measurement of total alkalinity of a product containing nitrate
boron determination by the Atomic Absorption (AA) method
measurement of the total alkalinity of a product not containing nitrate
hypothetical "real" concentration R, set arbitrarily at 3%
determination of anionic emulsifier content (b) at water hardness of 10° GH
determination of anionic emulsifier content (a) at water hardness of 10° GH
determination of nitride content
determination of anionic emulsifier content (a) at water hardness of 30° GH

The hardness of water can easily be determined with sufficient accuracy using indicators in the tablet form, whilst the pH value and bacteria count can be estimated using the tests described in section 3.5.4. There are more detailed tests that can be made, but they require the facilities of a laboratory; however, in such cases the cutting fluid manufacturer's laboratory service can offer assistance.

3.5.3 Monitoring the Cutting Fluid in Use

Whilst in use the cutting fluid is subject to various influences which may affect its properties. Such factors include leakages from the manufacturer's lubrication and hydraulic systems (often termed "tramp oil"), contamination introduced on the workpiece or by people – spilled drinks, or particles of food do not belong in the cutting fluid! – as well as other environmental influences. It is paramount that the health monitoring of the cutting fluid is continuous and at periodic intervals, whilst spot checks may also be necessary in order to detect undesirable changes in the properties and allow the corrective actions to be taken. Hence monitoring and care of the cutting fluids are crucial to their life, but which characteristics have to be monitored? The most common tests include the measurement of:

concentration
pH (alkalinity)
corrosion protection
stability
bacteria count

Now we will consider such tests in more detail.

3.5.4 Cutting Fluid Testing

Testing Concentration Levels

This is an important preventative measurement for water-mixed cutting fluids. There are a variety of methods available, but in all cases the results should be treated with a certain amount of caution. As previously mentioned, Fig. 3.20 depicts how a range of methods of assessment can give different results.

For semi-synthetic products, the concentration measurement by means of a refractometer is very popular, although the results tend to be accurate only when fresh mixtures are assessed. The more contamination there is from lubricating systems, the less accurate the results.

A refractometer is a portable hand-held instrument. A few drops of cutting fluid are placed on the prism. A lid is closed over these droplets and the instrument is held up to the light and viewed through the eyepiece. A light and dark interface is apparent within the eyepiece and a measurement is obtained against the engraved optical graticule – which has its readings calibrated in %. The % reading is compared against a calibration chart to obtain the cutting fluid dilution level. Such instruments can be used to obtain dilutions for a range of cutting fluids.

NB: Only adjustable refractometers should be used, as prior to taking the reading they must be set to zero.

Testing for pH Level

A simple yet important test which should be carried out on water mixed with cutting fluids is the measure of the pH value. The pH value, or hydrogen ion concentration, is a measurement of the acidity or alkalinity of a solution. Water-mixed cutting fluids are alkaline with a pH of 8–9.5. A change in the pH value indicates a disturbance of the hydrogen ion equilibrium. This in turn points to a deterioration in the properties due to biological or chemical action – in other words to heavy external contamination.

The simplest way of measuring pH is using indicator strips which are dipped in the cutting fluid. More exact measurements can be obtained by means of electronic pH measurement according to DIN51369. Yet another method is by titration – a quantitative analysis method to determine alkalinity. In contrast to the pH value, which only gives a degree of alkalinity, titration also determines the rate of change of alkalinity which helps to estimate the cause of the alteration. So, when a rapid rise in alkalinity is detected, this points towards a contaminant, whereas a fall in the level of alkalinity indicates bacteria growth and a decrease in effectiveness of the additive. Too high a degree of alkalinity (which can be caused by adding excessive amounts of highly alkaline bactericides, for example) is one of the main causes of skin irritation; therefore regular checking of alkalinity of cutting fluids in use is very important.

Corrosion Protection

Measurement of corrosion protection is an important preventative measure for water-mixed cutting fluids, in order to avoid unexpected corrosion of the workpiece owing to insufficient corrosion protection. With some products even small variations in concentration can adversely affect corrosion protection. The degree of corrosion protection can be measured simply, according to DIN51360 and DIN51759 – the steel chip method. These tests are most reliable if local water and actual chips taken from the machine tool are used.

Stability

Deviation in the stability of the emulsion in use can be determined quickly using the centrifuge method. In this method the centrifuged sample of emulsion is compared, under specified conditions, with the standard – giving an indication of the cutting fluid's stability.

Bacteria Count

The most accurate but expensive method of determining the bacteria levels present in the cutting fluid is by actual counting – according to the German unit for example. A simpler method of achieving good estimates is using dip slides. The slides are dipped in the cutting fluid then incubated and compared with sample pictures – offering a good attribute quality control test.

3.5.5 Cutting Fluid Maintenance and Health and Safety

Corrective measures may have to be taken as a result of test findings and a variety of products are available on the market for this purpose. These include:

topping up – to correct the concentration
foam agents – to prevent foaming
system cleaner – for initial disinfection before filling up with new cutting fluid
bactericide – to improve biological stability

If the cutting fluid is used properly, it should not be necessary to add bactericide as a corrective measure. However, in the majority of cases some bactericide will have to be used. Nevertheless, bactericide should be used sparingly since, as already mentioned, excessive amounts can lead to a sudden rise in alkalinity and may cause skin irritation.

Health Hazards

Measures to protect the health of operators are also an important part of cutting fluid maintenance. Cutting fluid manufacturers normally offer proof that their product has no harmful dermatological, or physiological effects – usually in the form of a skin health certificate, which is separate from the safety sheet. Long-term exposure under certain climatic conditions will inevitably lead to undesired changes in skin condition – irritation for instance – and even water causes changes in the skin condition after prolonged contact.

The main health protection measures to be observed are as follows:

as far as possible avoid direct contact with cutting fluids in any form whatsoever

use cosmetic skincare products – skin creams, barrier creams, mild soaps, etc., to minimise the danger of skin damage

monitor cutting fluids continuously during use, in order to prevent possible causes of skin irritation arising in the first place

see that personnel are repeatedly informed about the correct use and handling of cutting fluids

Information about possible dangers to health and the appropriate counter measures are freely available from a variety of sources, from trades unions, industry associations, and the coolant manufacturers themselves. In specific cases, a doctor – such as the work's doctor, when appropriate – can ask the manufacturer for information about the composition of a product.

3.5.6 Self-contained System, Central Supply System, or Individual Supply Unit?

A machine tool may either have its own self-contained system for cutting fluid or it may be supplied from a central system, or individual supply unit. In a central supply system, the individual machine tools are connected to a common circuit with a centralised supply unit.

In a central supply system, the cutting fluid is kept clean by having to pass through high performance filters. Such systems also make possible intensive monitoring and maintenance of cutting fluid. They offer the advantages of cleanliness and longer life of the cutting fluid and more economical operation.

A separate cleaning unit, instead of being connected to the central supply system as described above, is a self-contained cleaning fluid circuit purchased with the machine tool, which is filled up individually. This makes monitoring, cleaning and maintenance of the cutting fluid more difficult, although in certain cases this type of supply has to be used. One method of reducing the disadvantages of this type of supply is to use separate accessories of cleaning units, such as an oil separator.

An oil separator, which can be built onto an individual machine, separates out oil which has leaked from the lubricating system (tramp oil) and which floats on the surface of the fluid. The recovery unit depicted in Fig. 3.21 is used for periodic cleaning of the cutting fluids used in machines with their own self-contained circuit.

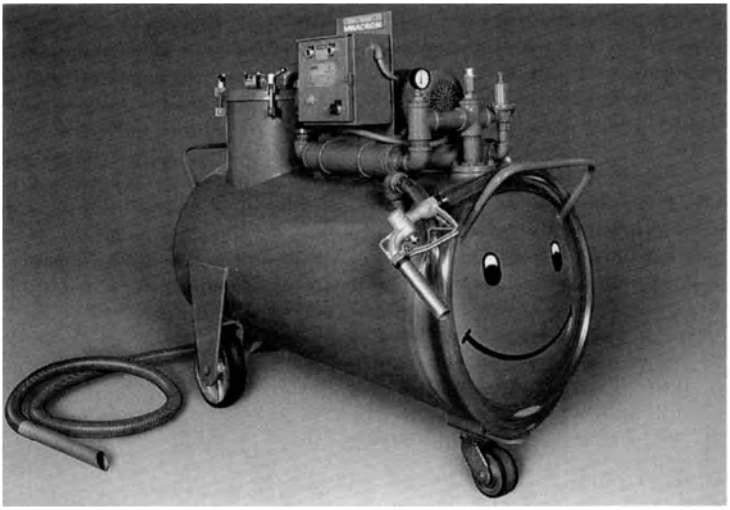


Fig. 3.21. A cutting fluid recovery unit. [Courtesy of Cimcool.]

Using such a portable unit, the cutting fluid can be quickly removed from the machine and filtered, reducing machine downtime and prolonging the life of the cutting fluid.

An individual supply unit can be used to offset the disadvantages of a central supply system. These systems are in fact a central system in miniature which mix the concentrate with water, remove lubricating (tramp) oil which has leaked out, whilst regenerating the used cutting fluid and returning it to the machine tool's circuit.

3.5.7 Disposal of Used Cutting Fluid

Any coolant which has reached the end of its useful life, whether soluble oil, preformed emulsion, solution, or pure oil, cannot simply be indiscriminately poured away or disposed of at will. Waste cutting fluid normally contains toxic substances which were either present when it was new, or are due to contamination during use. Possible contaminants include leakage from the lubrication and hydraulic systems of the machine tool and sometimes also nitrite adhering to the hardened workpieces. This means that used cutting fluids are quite a different matter from the original product – even pure water, if it was used as a cutting fluid, would absorb so much contaminant that it could not simply be poured away.

Used cutting fluids should be considered as toxic waste and must be disposed of accordingly. The disposal of waste water is governed and controlled by the local water authority: their advice should be sought before action is taken. The disposal method used for cutting fluids – reprocessing, incineration, or other, will depend on the cost and the amount of toxic materials. Toxic substances which should not be present in cutting fluids and therefore require disposal are nitrate, chlorine compounds and polychlorinated biphenol (PCB); reputable manufacturers try to avoid them, although this may not be possible in certain formulations. Nitrate, however, which was once popular as a corrosion inhibitor, is used much less frequently of late. PCB should not occur at all in cutting fluids – in the past it used to occur as a result of illegally adding re-refined used oil. Chlorine compounds, used as EP additives, are no longer included in most cutting fluids on the market at present. In order to keep disposal costs as low as possible it is advisable to collect and store separately the different types of cutting fluid.

There are various processes for reprocessing or disposal of used cutting fluids, such as chemical and thermal processes, and one promising process for the future is ultrafiltration. Which individual processes are possible and economical will depend on local regulations.

3.5.8 Economic Aspects

The cutting fluid forms part of the production process and so its economic performance can only be judged in relation to its overall effect on the process as a whole. When seen in this light, the purchase price plays only a minor role. Of much more importance are the costs which occur if the cutting fluid does not do its intended job correctly and in every aspect. The purchase price is therefore not the only economic criterion.

A product which is initially more expensive but offers better performance and a longer life can turn out to be less expensive in the long run than a cheaper variety. Furthermore, the cutting fluid also has an effect on tool wear and surface finish, which have to be taken into consideration as cost factors. In addition to the directly measurable costs, the constant product quality and the service provided by the cutting fluid manufacturer also play a significant role in its economic performance.

In summary, it can be said that cutting fluids play a vital role in the metal cutting operation and as much care over their selection is required as would be made when purchasing a machine tool. After all, this is a resource which will, at best, improve productivity and quality greatly and, at worst, cause poor cutting tool performance, part rejection and real damage to the machine tool and any workholding equipment in situ.

In chapter 4 we will consider the effects of utilising work-holding devices and review just some of the methods of workpiece constraint.

Chapter 4
Workholding Technology

4.1 Introduction

In the past, when machining operations were allocated minutes rather than timed in split seconds, and accuracy was limited by machine deflection under load, the time spent and precision obtained in clamping the workpiece to the machine tool were of little consequence. The manually operated chucks and mandrels were used for rotating components, whereas vices and a variety of table clamps – based upon the ubiquitous T-slot – catered for stationary, or prismatic parts.

With the advent of CNC technology, machining cycle times were drastically reduced and the desire to combine greater accuracy with higher productivity has led to a reappraisal of workholding technology. For one thing, there is little point in slicing "expensive" seconds from the time spent in cutting parts or changing tools when it takes maybe a minute or more to remove the machined workpiece and then reclamp a new component. Power operation has added another variable in workholding technology and has been around for a long time, with clamping systems based on hydraulic, pneumatic, or electrical inputs. Power alone is no longer sufficient for modern workholding systems which must now have three main attributes to be considered successful:

faster operating speed so that their use causes the minimum delay in productive machining time

improved accuracy, meaning little or no workpiece adjustment is necessary after fixing

versatility, allowing a number of operations to be undertaken at a single clamping – either on the same machine or on a series of machine tools as is the case in a flexible manufacturing cell

Many machine tools are designed for the rapid changeover of large and complex components and are often designed from conception to accept pre-clamped workpieces on transfer pallets or similar. New techniques of computerised workholding, frequently aided by robotic operation, are now becoming commonplace in modern manufacturing shops.

Workholding technology by its very nature is a vast subject which encompasses an extremely diverse range of part complexities. On the one hand it may be that a simple chuck will suffice, or clamping of the part in the traditional T-slots, whereas at the other extreme, a specially engineered chuck or automatic clamping cycle is needed for either complex part locations and restraint, or for workholding when untended machining is taking place. Generally the workholding requirements for a turning centre are significantly different from those of a machining centre. The part is rotated on a turning centre, whereas on the machining centre it is in a fixed relationship with the table, assuming for the moment that we ignore the fact that a fourth axis – usually a rotational one – may be present. Although even these clear-cut divisions are not strictly true, as we have seen earlier in the book, it is possible to either lock the chuck on a turning centre, or indeed index it through specific angular divisions, or continuously on turning centres with "C-axis" control, whilst milling and other operations occur. Similarly, by fitting either a 4th/5th axis to a machining centre, the workholding arrangements may be similar, if not identical, to those used on turning centres. As one would expect, there is simply not enough space for an in-depth review of all the methods for workholding, indeed, it would be almost impossible to cover the subject adequately in a book let alone a chapter. With this in mind, it is the intention to discuss some of the popular methods of workholding and associated technologies and offer perhaps an insight into some more unusual clamping and location techniques available today, although the almost infinite methods of restraining workpieces depend upon a range of variables such as:

the budget allocated for workholding equipment
the accuracy of part location required
size of batch: whether one-off, small, medium, or large
part complexity
dedicated or flexible workholding requirements
part rigidity: delicate or robust parts to be machined
number of features to be machined: whether all, or just some as is often the case with castings/forgings
multiple or single workpieces setup
unique workholding methods, and so on

As is often the case with cutting technology, the workholding requirements are only considered after the purchase of a new machine tool and can restrict the true production potential of this equipment if insufficient budget is allocated. Budget restrictions will compromise our ability to effectively "tool-up" the machine in the most efficient manner and can be quite a significant financial commitment. It is simply not good enough to use the old workholding equipment from its predecessor and expect the new machine tool to perform at its fullest potential, unless such tooling was of the necessary sophistication, or that simple part holding demands were all that were necessary. Tooling engineers must be familiar with the latest techniques in workholding technology available and their benefits – as already discussed – in terms of improved part location, adaptability of workholding, speed of tool changing and expected pay-back period, if their implementation is going to be of real financial benefit to the company.

Prior to a discussion of the myriad range of workholding techniques alluded to above, it is worth spending a few moments describing the basic principles of part location and its effective restraint, as they are major considerations which cannot be overlooked for any successful machining operation. A rigid body – the workpiece – has six degrees of freedom (Fig. 4.1) and if, after clamping, it has freedom to move in

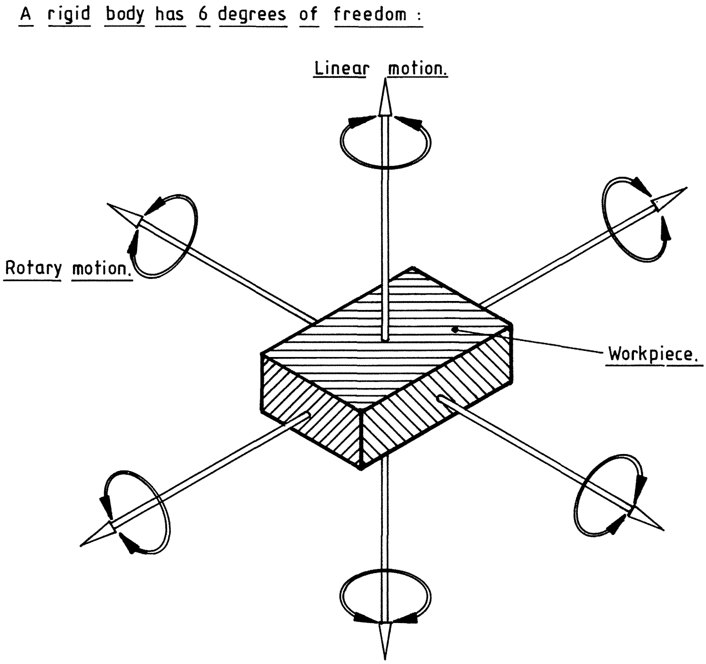


Fig. 4.1. The restraint and location of the workpiece during machining operations. Restraint: a workpiece requires an applied force to overcome the cutting forces exerted during machining. Location: the workpiece must be positively located in a known relationship to the machine tool axes.

any plane or rotation about that plane, then the workholding device is a failure with part scrappage being inevitable. Even when it seems that the part is restrained sufficiently, if the dynamic loads imposed by the cutting forces are sufficient to either move, or deflect the part through, say, a poor clamping pressure, or less-than-robust workholding, then this will also lead to part scrappage and often premature cutting tool failure. Flexure of the workholding equipment cannot be tolerated, as these unstable conditions would obviously be a source of vibrations to the cutting tool which would have a disastrous effect not only on tool life, but on the surface finish of the part.

Just as important as part restraint is location. If the part is not located in the correct relationship to the axes of the machine tool and in a known position, this would be another source of machined-part error. It is one thing to clamp a component with sufficient force, but still another to locate the part correctly. If both of these objectives are achieved then there is every expectation that a satisfactorily machined part will be produced. In addition to determining the position of the workpiece, the workholding device must absorb the tool forces and transmit the necessary torque – in the case of turning operations. This workholding setup must not cause damage, or deformation of the workpiece beyond permitted limits. Just how one achieves these criteria will be discussed in relation to several of the techniques used for many years and some rather novel methods now coming into prominence.

4.2 Turning Centre Workholding Techniques

Machining operations on turning centres, or CNC lathes are carried out predominantly on rotational parts which are symmetrical to the machine's centreline, in that cylindrical, tapered, contoured and screwout surfaces are generated by the simultaneous motions of X and Z axes. This is not strictly correct, as previously discussed, as on many turning centres a full "C-axis" control allows features such as cam profiles to be machined, and the prismatic milling of flats, splines and keyways, together with the drilling of pitch circle diameters, or cross-hole drilling and tapping operations to be undertaken. Machine tools can be provided with a wide range of machining capabilities, allowing the technique termed "one-hit machining" to be undertaken. With this method, complete part features can be machined at one setting of the workpiece, giving a range of production benefits in terms of both machining time reductions and improved part accuracy. If all these operations are machined whilst in situ, on either the turning or machining centre, then the part accuracy in terms of dimensions and features is assured.

For any workholding device used on a turning centre there is a direct "trade-off" between part accuracy and the flexibility of workholding. Fig. 4.2 shows some of the major techniques of workholding on turning centres, with their respective advantages and disadvantages to the tooling engineer. It is clear that when there is a need for an almost universal workholding system such as the "automatic jaw" and "chuck changing", then these are associated with some loss in accuracy when compared to, say, the custom built "dedicated" chucks. Conversely, these "dedicated" chucks although highly accurate can only hold discrete parts and do not have the flexibility of workholding associated with those shown on the left of Fig. 4.2. Often some compromise has to be made between accuracy and flexibility (although at the expense of the two extremes – "dedicated" and "chuck-changing") which may play a significant role in our decision to purchase one type or the other. Normally, "dedicated" chucks are less expensive to purchase and may often be used on turning centres and CNC lathes with the same location mounting, whereas the "chuck changing" devices require specialised hard- and software to facilitate their use and to gain the advantages of their full potential in untended machining environments. The indirect cost of obtaining such part workholding flexibility is not cheap, but where there is a need for fully automatic techniques, it has been shown that significant pay-backs can result when such methods are correctly implemented.

4.2.1 Collets and Collet Chucks

The simple construction of collets means that they are trouble-free in operation and maintenance, with Fig. 4.3 showing just a small selection of the diversity of sizes and designs available. Such collets are most frequently used for clamping bar-shaped components of a variety of cross-sections and are designed to match a definite workpiece diameter. Only parts having the same accurate stock, or preturned diameter can be faultlessly clamped, whereas those with varying diameters cannot. For this reason, it is necessary to store a range of closely-stepped collets. Another attribute of collets is the favourable clamping of thin-walled workpieces. When workpiece diameters do not correspond to the collet diameter there is a danger of straining the collet and it subsequently distorting.

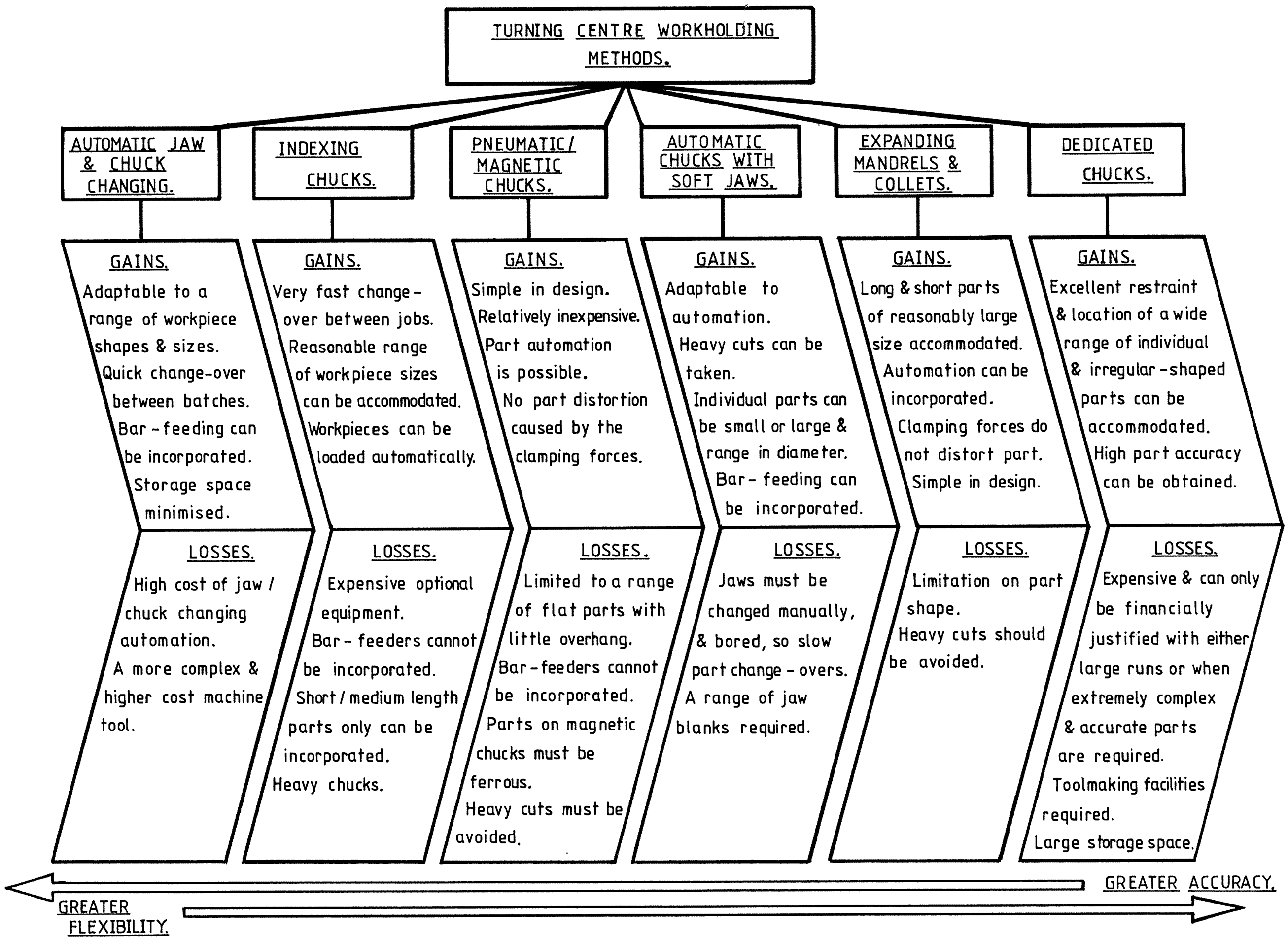


Fig. 4.2. Workholding methods for turning centres and their advantages and limitations.

Fig. 4.3. A typical range of turning centre collets. They can also be used on workholding fixtures, or auxiliary 4- and 5-axis devices fitted to machining centres. [Courtesy of Crawford Collets.]

Probably the major advantage of such collets is the absence of clamping marks on the workpiece after turning which is the result of a uniform distribution of clamping force around the bar stock. An added bonus is that roundness error is significantly improved on the machined bar and this can be attributed to such uniform pressure application. The clamping force is much less than for conventional power chucks and this may cause the component to rotate within the collet, if subjected to heavy roughing cuts. If high stock removal is required then using a hybrid power-operated collet chuck – which is a combination of the conventional collet and power chuck – will suffice. Collets are ideal for use when bar stock is loaded into bar feeding mechanisms. They provide high precision as the clamping mechanism is directly within the spindle nose of the headstock, and as a result no overhang occurs. Yet another benefit accrues because if long bars must be machined between centres then such "chucking" methods increase the potential working volume of the turning centre. Let us now consider the hybrid collet chucks which are playing an increasing role in workholding applications.

With pressure collet chucks, a larger circular form error through slipping of varying clamping device parts must be taken into consideration. Through the uniform arrangement of the clamping jaws coupled to their minimum weight, there are no perceptable losses through centrifugal forces. Such chucks with power clamping require an exact regulation and reproduction of clamping pressure whenever possible. With these newer jaw clamping techniques there is a plurability of individual clamping jaws, which are mechanically drawn-back through pressure springs and allow a much larger clamping range to be encompassed, offering much greater adaptability over their conventional collet chuck cousins. These collet chucks can cope with up to 10 mm diametrical change and as a result, fewer chucks are needed when compared with conventional collets, but this must be offset against a much higher overall cost. Most collet chucks are insensitive to contamination and as a result of the centrifugal force, the dirt is flung out of the chuck. Hydraulic or electrical energy can be used for clamping. The workpiece size range of such devices can be 1.5–200 mm diameter, with considerable torques being transmitted. The principle of operation of such power-operated collet chucks is quite simple: the collet is drawn to the rear of the headstock via a power transmitter over a draw-tube. An obstruction occurs by means of a taper in the housing and this limits its rearward motion, resulting in the jaws being forced radially inwards until they locate on the bar stock's periphery. The clamping pressure is then uniformly distributed over the entire length of the clamping jaws. NB: Such clamping force constitutes approximately twice the tensile force on the draw-tube. Releasing is effected in the reverse order.

4.2.2 Face Drivers and Live Centres

It is usual to use both the face driver and live centre in conjuction with each other when turning a range of components. The face driver (Fig. 4.4) provides the means by which rotation is transmitted, whereas the live centre (Fig. 4.5) offers support. It is the normal practice to place the face driver in the headstock spindle nose, which may require sleeving. Usually the live centre resides in the tailstock, although when one is not available and a twin-turret turning centre is used, it is possible to position it in a turret pocket and this supports the workpiece, whilst turning is carried out by the other turret. Dead centres are not commonplace for supporting workpieces on turning centres as higher speeds are employed, even though they are more robust and offer a higher precision location than the "live" varieties. The reason for this is quite obvious, owing to higher speeds, more heat is generated leading to greater wear, considerably reducing the dead centre's life. Another obvious point when using this technique for workpiece support is that a "pre-op" is necessary whereby, at the very least, the centres will have already been machined. It is normal practice to face-off the stock prior to centre-drilling as this is a source of error in centre misalignment. Although some error can be accommodated with "floating" driving pins, as opposed to fixed pins on face drivers, see Fig. 4.4c, Fig. 4.4b will also achieve the same objective.

The operating principle is best discussed in conjunction with the general arrangement of the setup given in Fig. 4.4. Clamping between centres is obtained by centring the workpiece between the centre point of the face driver and the rotor tip of the live centre, by means of centre-drilled centring holes. When an axial force is applied – usually by motion of the tailstock's barrel – the face driver's driving edges grip the front face of the workpiece. Simultaneously the face driver's axially moveable centre point will be pushed inward. The result is the workpiece held between centres whilst the rotational drive is transmitted via the driving pins and this ensures a high degree of workpiece concentricity. Such systems are often employed on conventional lathes and may be just as easily utilised on turning centres, offering rapid workpiece changes and as such minimising down-time.

Probably the major disadvantage of such an arrangement is the indentations in the workpiece face resulting from the driving pins gripping it and the effect this might have on any surface finish requirement. Often though, some degree of uniform indentation can be tolerated and under these conditions, such a set-up becomes feasible. With such techniques, light-to-medium depths of cut can be sustained with ease, but roughing cuts may cause slippage owing to the high torque values present. Not a problem as such, but one which needs mentioning is that the level of axial force obtained may require monitoring, as too low a force means that the workpiece is not held tightly enough; conversely too high a force promotes excessive driving pin wear, which in turn causes wear of the live centre and spindle bearings. There are a number

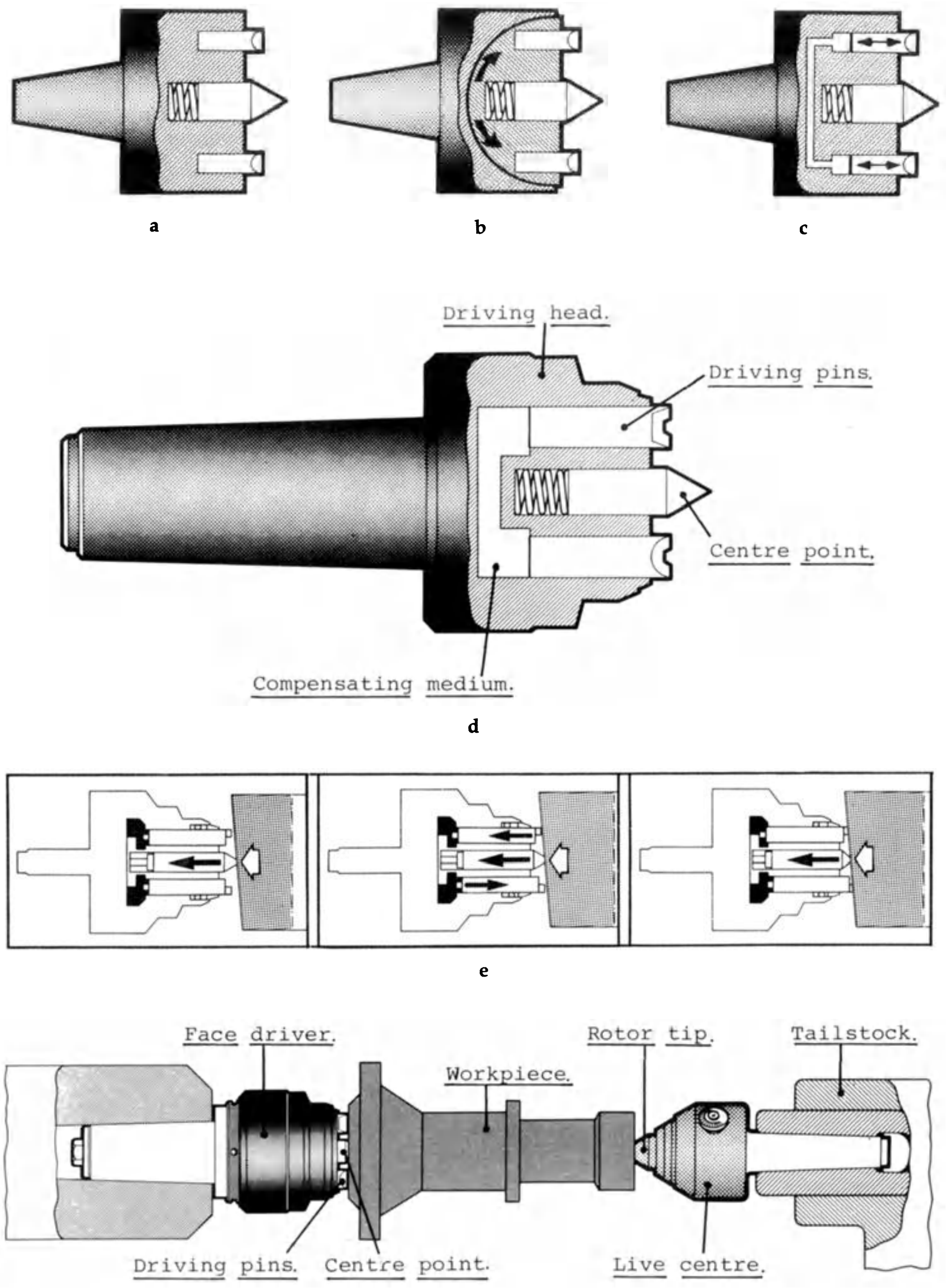


Fig. 4.4. Typical face drivers in turning operations. **a** Face driver with fixed driving pins. **b** Face driver with fixed driving pins on a floating cup-shaped plate. **c** Face driver with axially (i.e. "floating") moveable driving pins. **d** Detail of type **c**. **e** Typical applications. **f** General arrangement of setup. [Courtesy of Sandvik (UK) Ltd.]

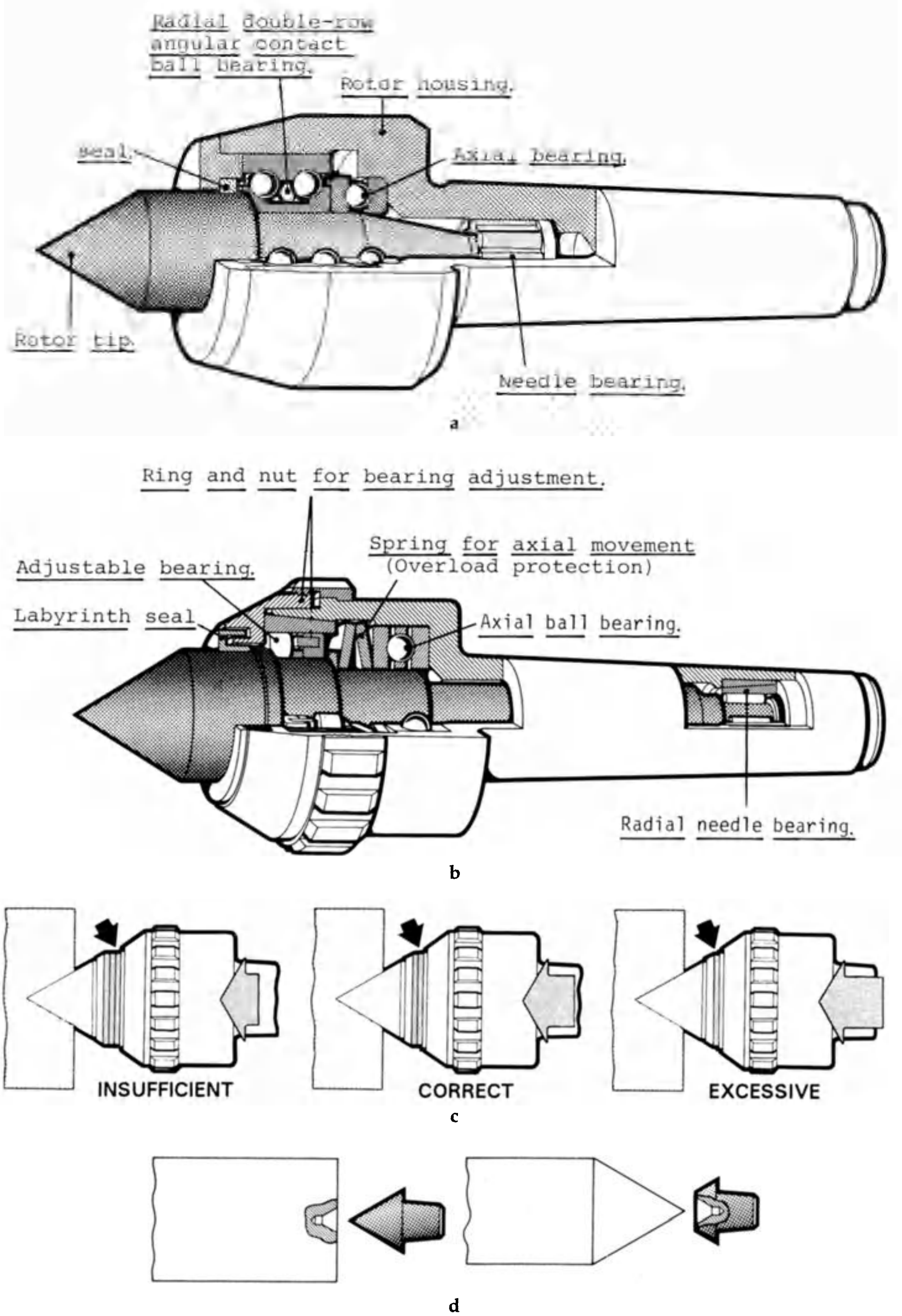


Fig. 4.5. Typical "live" centres used for support in turning operations. **a** Designed for normal operation. **b** Designed for high-precision operation. **c** Axial force indicators. **d** Interchangeable centre tips (centring plugs). [Courtesy of Sandvik (UK) Ltd.]

of methods of determining axial force levels, such as a meter which measures the hydraulic pressure exerted by the tailstock, or an axial force indicator built onto the driving centre.

The penetration depth of the driving pins into the workpiece's face should be at least 0.2 mm before turning commences. The force per mm of the driving pins' edge length is of great importance, as already mentioned, and the optimum effect is obtained when the force per mm edge length is 25–35 daN. This can be obtained by choosing the correct driving pins, as the following example attempts to show.

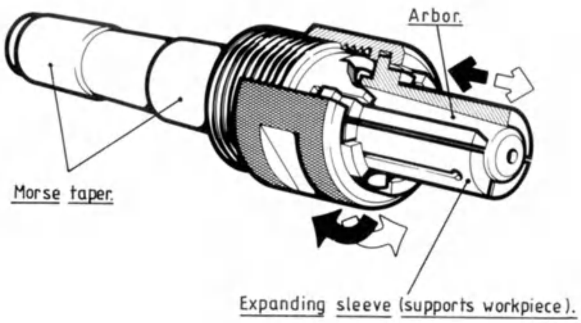
In a machining operation on a turning centre, the total force from the tailstock is 1650 daN. The face driver has five driving pins, each of which has an edge length of 11 mm. The total edge length is 5×11 mm = 55 mm and the force per edge is then $\frac{1650}{55}$ = 30 daN/mm, which means that the force per mm is 25–35 daN.

Driving pins are designed for either right- or left-hand rotation, although symmetric pins may be used when the direction of rotation changes during the machining program. Pin design, pitch circle diameter, as well as the number of pins available can be varied to suit most applications, from the ranges stocked by suppliers. An important point worth commenting on is the direction in which cutting takes place, as this has a significant effect on the tailstock force necessary. In the calculation above it was assumed that turning was toward the headstock, if, however, it is toward the tailstock then the pressure requirement must be at least twice as high; although when undercuts are being machined a value 1.5 that of the original level should be adequate. The force exerted by the tailstock is a function of the chip cross-section and the ratio between the workpiece diameter and the gripping diameter of the pins. This force can be found from manufacturers' charts, but yet another factor needs to be considered. The tailstock force is also dependent on the workpiece material, since hard materials require greater specific cutting force than soft materials. This means that a larger driving force is also necessary. Having determined the tailstock force we must multiply it by the material factor for the workpiece material to be cut in order to get a realistic value of the actual operating pressure.

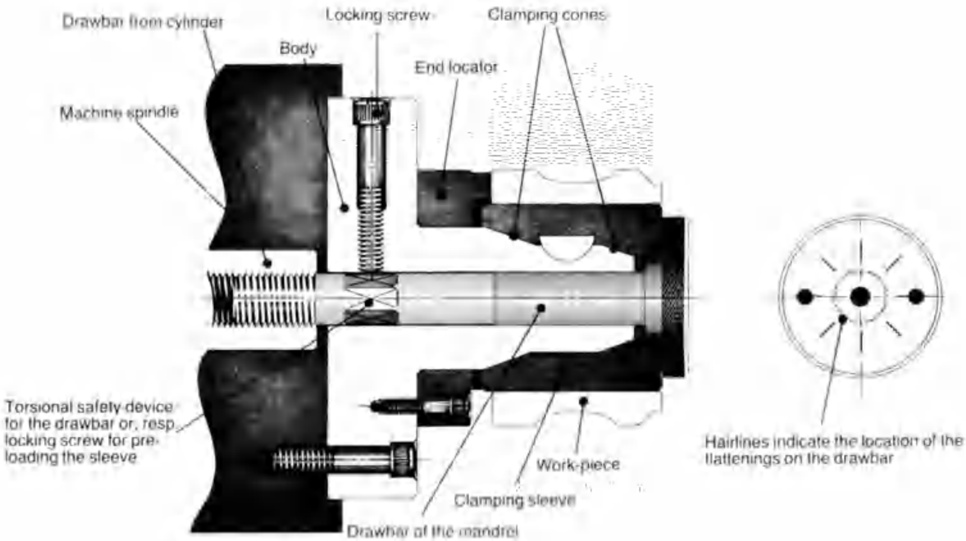
Live centres can be purchased in a range of configurations and bearing designs, dependent upon the level of precision necessary (Fig. 4.5). Most companies offer a choice of rotor tips and some come with force indicators to obtain the optimum pressure needed for workpiece support. If one assumes that one end of the part is held in a chuck or similar, the other end needs the support of a live centre. It would be easy to overload the centre and decrease its life, or distort the component, as the sensitivity of pressure application of the tailstock is rather crude. A force indicator – either a dial or markings on the live centre – allows one to obtain the correct level of force for a given workpiece/workholding combination. Such loads can be obtained from monograms produced by suppliers and are related to the axial force applied and the axial travel of the rotor within its housing in mm, for specific designs of live centres, offering speedy methods of obtaining the necessary force requirements.

4.2.3 Expanding Mandrel Applications

The operation of an expanding mandrel is very simple and usually consists of a double-slit sleeve with an internal diameter (see Fig. 4.6a). Sleeves of varying outside diameters can be employed on the same arbor, allowing a large range of internal diameters and a variety of workpieces to be held using one arbor with different sleeves. High concentricity of the external diameters of the parts is obtained by such setups in one operation, furthermore, better machining economy is obtained if,



a



b

Fig. 4.6. Two examples of expanding mandrels used on turning centres. **a** Conventional expanding mandrel with manual adjustment. **b** Power operated expanding mandrel. [**a** Courtesy of Sandvik (UK) Ltd. **b** Courtesy of Forkardt GmbH & Co.]

under other circumstances, more than one setup was necessary. Concentricity of commercially purchased mandrels is of the order of less than 0.01 mm concentricity, with an expansibility of 0.5–5 mm, depending on the sleeve's diameter and type used.

Mandrel mounting is usually achieved in one of three ways:

1. between centres: such mandrels are clamped between centres and have provided the precision centre holes and a flat surface for driving dog attachment, this is usually the arrangement on conventional centre lathes.
2. morse taper: such mandrels can be mounted directly into the machine spindle with a matching internal taper, or they may require sleeving.
3. flange mounting: this method (Fig. 4.6b) provides a mounting against the spindle nose and so offers good stability, since the large axial contact surface is obtained

between the machine spindle and the mandrel, an appropriate adaptor is required for the mechanical interface between spindle and the mandrel.

Generally there are four techniques for clamping the workpiece onto the mandrel:

manually
with a ring
using a screw/nut
by drawbar

The manual "knock-on" principle is the simplest, whereby the workpiece is placed on the middle of the sleeve which is allowed to slide down the arbor. Once the sleeve, together with the workpiece, is lightly clamped, the larger end of the arbor is struck against, say, a piece of wood, to intensify the clamping pressure. Furthermore, when machining has been completed, the part is released by a similar technique, but in this case it is the smaller end of the mandrel which is struck against the wood.

The ring method (Fig. 4.6a) of mandrel clamping is obtained by the ring, which is mounted on a threaded portion of the arbor behind the sleeve. When rotated and tightened in this manner, the sleeve is drawn up the taper until the part is firmly clamped. Two parallel flats are normally provided for tightening using an open-ended spanner, or perhaps a hole for tightening with a hook spanner. Normally manual tightening of the ring is sufficient for light-duty machining operations.

The screw/nut design achieves part clamping by placing the workpiece onto the sleeve which has a threaded nut on the smaller end. The sleeve is expanded by effectively being pushed up the taper of the arbor by the rotation of the nut on a threaded portion of the arbor, using a spanner.

Lastly, probably the most popular expanding mandrel technique on turning centres is the use of a drawbar (Fig. 4.6b). Clamping is affected by the drawbar which passes through the headstock to the smaller end of the expanding sleeve and as it is drawn backwards by an automatic cylinder of either hydraulic/pneumatic power, the sleeve expands up the arbor and locates and restrains the workpiece. This technique lends itself nicely to automatic loading of parts, although a manual operation is also possible with the less sophisticated designs.

Before we complete our discussion about the expanding mandrel, it is worth describing the influence of torque – from the cutting action – and its effect on the successful turning of workpieces. Archimedes' principle of the lever is well known and this same principle applies to rotating bodies acted upon by tangential forces. When a part is clamped onto the expanding mandrel, an axial force is necessary for the sleeve to radially expand and this is achieved by either the drawbar, or the tightening torque of a wrench. This axial force produces a radial clamping force on the workpiece owing to the sleeve's expansion. During the machining operation the part is acted upon by the tangential cutting force "Fs". This applied force promotes a torque "Ms", which attempts to rotate the workpiece whilst it is held on the expanding mandrel. Frictional force present between the workpiece and the sleeve is directly proportional to the radial clamping force and as a result causes a holding torque "Mh". This holding torque is equal to the force of friction multiplied by half of the clamping diameter; furthermore, it is easy to see what influence the part diameter has together with the tangential cutting force, which is the result of the cutting data utilised. In the following example we can gain an appreciation of how the cutting torque proportionally increases with the diameter of the workpiece:

Cutting data: Finishing turning insert
Material: SIS 2541
Cutting speed v = 100 m/min
Feed s = 0.4 mm/rev
Depth of cut a = 2.5 mm
Tangential force Fs = 2200 N

Results:

Test	*Tangential force*	*Workpiece radius*	*Torque*
1	2200 N	50 mm	110 Nm
2	2200 N	75 mm	165 Nm

In conclusion we can appreciate that a larger workpiece diameter coupled with the high cutting data, result in a greater torque "Ms". This means that a greater force of friction is necessary between the sleeve and workpiece, in order for the mandrel to be able to turn the workpiece successfully. Every size of mandrel is designed for a maximum force on the drawbar together with an associated maximum tightening torque. The moral therefore is to choose a mandrel size that provides an adequate torque when machining either large workpieces, or using high cutting data, or both.

4.2.4 Specially Engineered Chucks

Often there is a need to either manufacture or purchase specially engineered workholding equipment (Fig. 4.7) if the proprietary items are not available ex-stock from the suppliers. Although many of the specialist workholding companies offer such a service, this customisation is not cheap and the purchase should be gauged against:

expected batch size, or frequency of occurrence of such batches

cycle time/setup benefits accruing from its purchase, against more conventional workholding practices

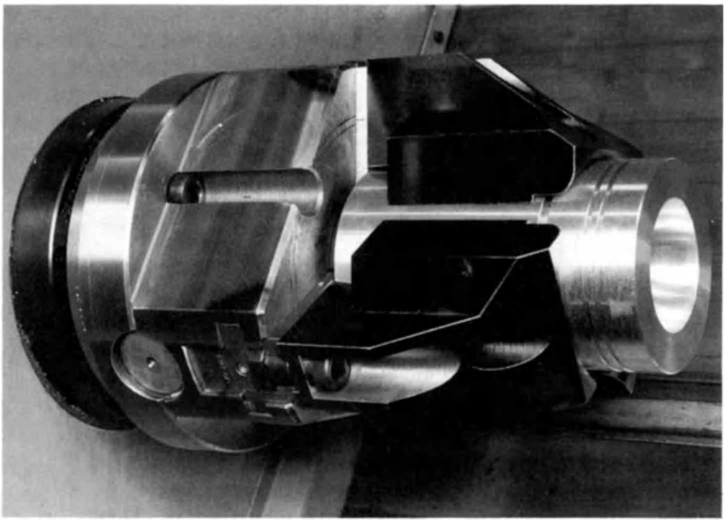


Fig. 4.7. A specially engineered chuck for the machining of piston crowns. [Courtesy of Gildemeister (UK) Ltd.]

improvement in part quality resulting from specially engineered chucking techniques
cost of the specially engineered chuck in comparison with conventional methods and the anticipated pay-back resulting from such implementation

If all or some of these considerations gives positive benefits then the purchase of such specially engineered chucking will be worth while. Occasionally though, it may even be deemed a profitable exercise when only one of the listed criteria is realised, such as perhaps the improvement in part quality of critical high-cost value-added items, requiring long lead times for their renewal, or if there is simply no other means of successfully manufacturing the part and still retaining some profit margin.

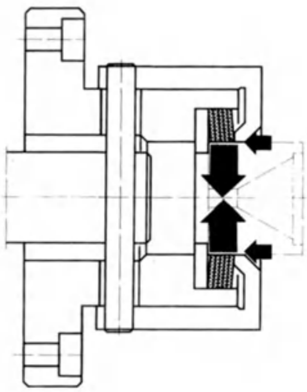
Finally, as a word of caution, whenever it is necessary to manufacture such specially-engineered chucks, unless the company has a highly developed toolroom with good design skills, it is best left to the workholding suppliers who can provide their expertise in its design and build. If a company manufactures "in-house" equipment for workholding it is at best often a compromise, and better solutions and of course profitability would have accrued from the purchase of specialised suppliers' products. Good workholding practices are not cheap and a realistic budget for such equipment will more than pay back the company in terms of better profitability, improved quality, cycle time reductions and confidence of staff in the equipment, and so on. Failure to consider some of these factors could prove very costly, and loss-of-face resulting from third rate solutions to workholding can be felt across a range of activities within a company.

4.2.5 Conical Clamping Rings for Workholding Applications

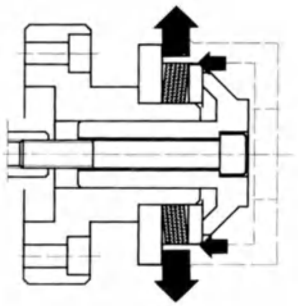
The principle of operation of the conical clamping ring for workholding can be gauged by Fig. 4.8 and the following description. The axially exerted operating force exerts an elastic change in the taper angle and subsequently the diameter of the clamping disc. If the inner diameter is supported by a mandrel, the outer diameter increases; conversely, if the outer diameter of the clamping disc is supported, the inner diameter decreases. Therefore the initial operating force is transformed into a radial force five to ten times greater, which is used to clamp the workpiece. At the same time the operating force causes a tilting movement of the clamping disc. This movement is utilised to force the workpiece against a longitudinal face register during clamping. The clamping disc is manufactured in the form of a conical ring made of hardened and special spring steel, with slots to give it particularly high flexibility.

In a similar manner to the collets mentioned in section 4.2.1, the clamping ring grips the entire outer or inner circumference, as shown in Figs. 4.8a and 4.8b, respectively, and as such, clamping marks are minimised on the part's surface. This radial clamping force produces friction between the clamping disc and the workpiece and as the force applied is of uniform intensity around the whole circumference of the workpiece, it guarantees maximum clamping accuracy and permits the transmission of high torques, even on parts prone to distortion.

In order to overcome the machining forces that are present on CNC machine tools, several clamping discs are placed side-by-side and are held together by a rubber compound forming a bonded disc pack. The workpiece is automatically centred and clamped through the change in diameter of the clamping disc and its tilting motion forces the workpiece against the location face. The combined effect of the diametrical expansion and pull-back action guarantees the exact centring and aligning of the workpiece without any additional adjustment.



a



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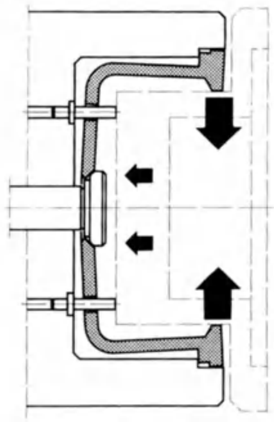


c

Fig. 4.8. Utilising the principle of a hardened spring steel conical clamping ring for workholding applications. **a** Disc pack chuck for outer clamping. **b** Disc pack mandrel for inner clamping. **c** Basket chuck for outer clamping. [Courtesy of Ringspann (UK) Ltd.]

With such a system it is possible to clamp a range of component shapes and sizes, depending upon the clamping ring configuration; for example, using the disc pack (Figs. 4.8a,b), diameters up to 200 mm can be clamped, whereas clamping using elements for very short locations allows diameters up to 600 mm to be successfully held. Other arrangements with modified disc clamps allowing longer workpieces to be clamped are possible, as shown in Fig. 4.8c.

4.2.6 Pneumatic and Magnetic Workholding Equipment

Although, strictly speaking, both of these techniques should be discussed under separate headings, the general configuration of the workholding equipment is remarkably similar, in that a function of the success of both systems is the requirement for a medium-to-large surface area for either the vacuum or magnetism to act. In the first instance we will consider the basic requirements of pneumatic devices for workholding and then go on to describe the operating principle of magnetic equipment together with some applications.

Pneumatic Workholding Devices

The word pneumatic is derived from the Greek "pneumos" meaning breath, and as such obtains its component clamping force by the evacuation of air from under the constrained surface to form a vacuum. This implies that the surface to be constrained in such a manner needs to be flat to within tolerable levels and it is more often the case that flat stock is the basic material from which the workpiece is machined. There is a wide range of chucks, fixture plates and self-contained vacuum units which have found increasing favour in the aerospace industry, and are now proving to be popular in general precision engineering companies. Referring back to aerospace applications for the moment, it has generally been considered good working practice to machine a range of parts from flat stock. This fulfils several functions: it allows many parts to be cut at one setup, improves the soundness or integrity over other techniques (as the part is machined from solid) and decreases part cycle time (as many parts are machined successively). Therefore a plate from which the parts are to be manufactured – often an aluminium alloy – is positioned on the pneumatic workholding fixture. The CNC part program cuts out the parts successively to depth, but leaves them attached together by about $\frac{1}{2}$–1 mm of stock. This is necessary for two reasons: first, to ensure the vacuum is maintained and, secondly, to provide rigidity between each part as it is successively cut out of the wrought stock. Once all of the parts have been machined the vacuum seal is broken and the parts can be simply broken out and deburred.

One of the vacuum chucks shown in Fig. 4.9 has self-centring jaws/stops which are adjusted to suit the component stock to be machined and allows setup time for further parts to be minimised. It is essential to obtain a good sealing face for the constrained surface, yet at the same time allow for the evacuation of air to obtain suction on this face. The chuck, or fixture plate, usually has grooves on its working surface, although sintered faces can be used and suction is achieved through the porosity of interconnected pore channels enabling the air to be evacuated. Obviously, simply applying a vacuum to the chuck will not produce suction as the air will be freely drawn between other grooves not covered by the constrained surface. This problem is easily remedied by applying self-adhesive aluminised foil over the surface and slitting the

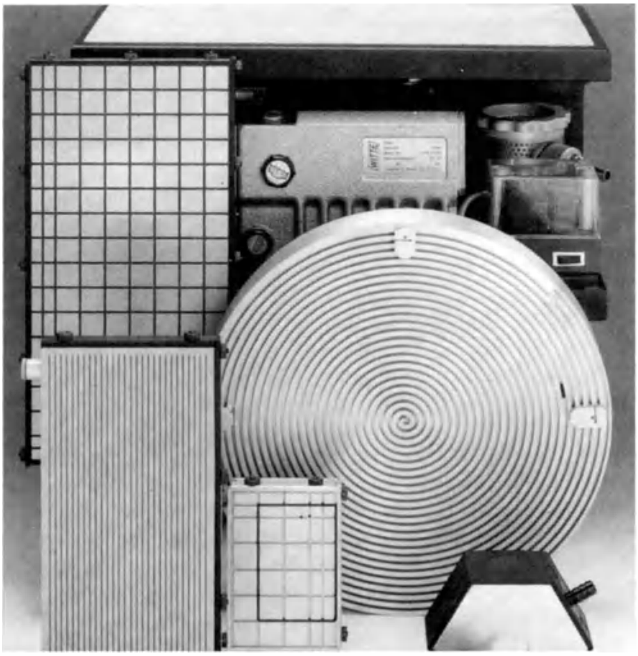


Fig. 4.9. A range of vacuum chucks, fixtures and clamps for turning and machining centres. [Courtesy of Thame Engineering.]

foil within the vacuum area. If the whole area is not to be used then O-shaped neoprene seals can be positioned at the periphery of the constrained part profile. As the vacuum is applied, the elasticated seal is compressed until there is metal-to-metal contact between the vacuum equipment's working face and the constrained surface; this sealing improves suction considerably. If for some reason the vacuum chuck, or fixture plate, has been roughened or scored, then vacuum grease applied to this surface will improve suction.

Vacuum workholding techniques can be utilised whenever there is a large surface area to be constrained and may be successfully utilised for both ferrous and non-ferrous materials. As there are few, or no moving parts to such equipment, they are considered to be very reliable and relatively inexpensive to purchase, requiring little in the way of maintenance. Probably the major limitations to vacuum equipment are that when a large overhang occurs, or the part has a small surface area to be evacuated, this can pose restraint problems. Such techniques can readily accept medium-to-heavy cuts and as such may be used for both roughing and finishing operations on non-ferrous and lower tensile steels. Manual and automatic operation are possible with this workholding technique and its use should be encouraged.

Magnetic Workholding Devices

This equipment utilises the well-known magnetic principle that "unlike" poles attract, whilst "like" poles repel. Such chucks are usually self-contained items with permanent magnets in situ within the device and are often referred to as "cold chucks". The critical factors in magnetic workholding include the material involved and the area to be held – the larger it is, the greater the magnetic flux or clamping force; this is also dependent upon any air gaps present, with the magnetic pull being in inverse proportion, together obviously with the power of the magnet. In order to minimise the effect of component distortion due to the magnetic clamping of the part, self-adjusting bi-pole extensions may be used. Under such conditions when the part has perhaps a non-uniform surface, the component can be positioned on the chuck at the three desired points and the power is switched on allowing the system to adjust itself to the workpiece, which is an important feature. To understand this self-adjustment principle more easily, the following analogy may help: if we imagine that our body is lying on a bed then the springs within the sprung mattress automatically adjust to our body contours. Not only can an irregular contoured shape be accommodated, but "surface poles" can be fitted to the chuck to secure the part even more firmly as these additional security aids can also be magnetised.

Some of the advantages to be gained from using such chucks are:

no moving parts occur and the structure is both solid and robust and unlikely to distort under heavy loads

being termed a "cold chuck", there is no power to the chuck coils during machining, hence no build-up of extraneous heat on the workpiece, owing to conduction from these coils

once the chuck is demagnetised, the workpiece also is automatically demagnetised and for difficult materials an additional demagnetising cycle can be offered

moving poles can take up to 5 mm of plate/part distortion, or steps when clamping – with large stepped faces being accommodated with different pole heights

the magnetising/demagnetising cycle takes approximately 6 s to complete

We can appreciate that the potential usage of magnetic chucks relies upon the fact that the component can be magnetised, but what principle controls its operation? This will now be considered in conjunction with Fig. 4.10, which is true for chucks, tables, cubes and tombstones. Fig. 4.10a schematically represents the magnetic circuit of a commercially available chuck. The magnetic field of the two permanent magnets (1) is paralleled with that of the reversible permanent magnet (2). Thus, a magnetic flux is produced which extends beyond the ferrous yoke (4 and 5) and reaches the workpiece (6) to be gripped. When reversing the polarity of the magnet (2), the magnetic field is short-circuited within a ferrous yoke (4 and 5) and the holding surface is demagnetised (Fig. 4.10b). The polarity of the magnet (2) is reversed by an electromagnetic field generated for a very short time (less than 0.01 s) by the coil (3), which encloses the magnet (2). This is the only moment when the electrical power source is applied to the chuck, so heat is minimised.

Not only is the system extremely reliable, it also has the benefit of damping down resonance in box-like parts, or hollow castings when machined, which aids the cutting operation considerably. Although magnetic chucks, tables and so on perhaps involve a higher capital outlay than some alternative workholding methods, they offer many advantages, from quick setup times, virtually no maintenance – except perhaps to the top workholding surface – and can be utilised across a range of machine tools, which further extends their versatility. When turning with magnetic chucks, a rotational speed limit is imposed and is usually at 1000 r.p.m. maximum – which is not too much of a problem with large diameter workpieces. In section 4.7.6 a more in-depth discussion concerning magnetic principles and the problems of milling will be encountered, together with some details on magnetic milling workholding methods.

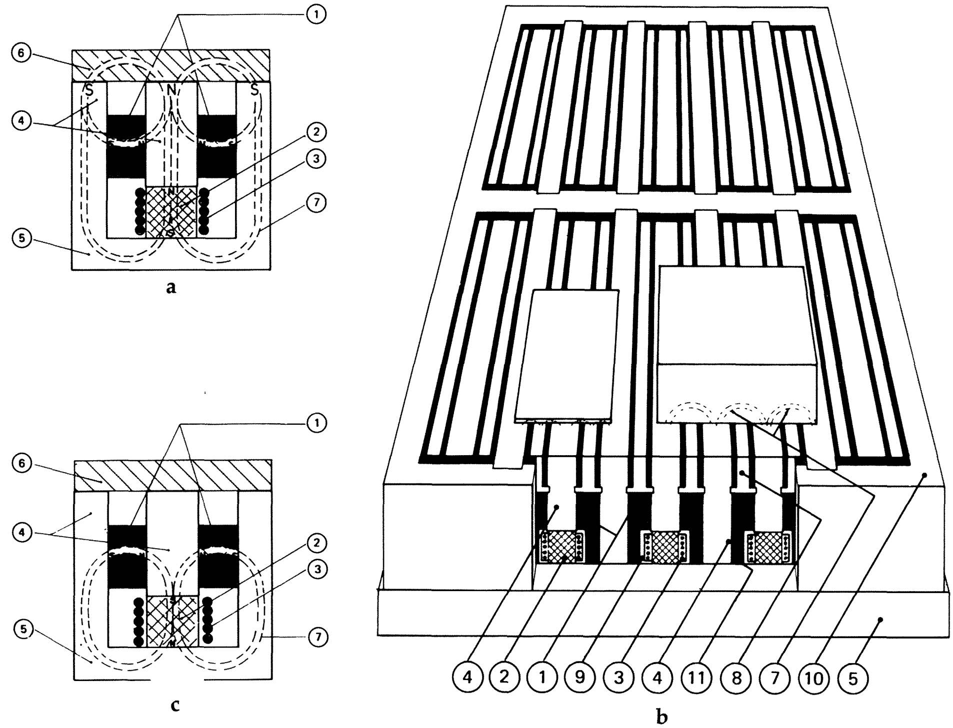


Fig. 4.10. The workholding principle for ferrous materials using magnetic chucks, tables, cubes, etc. 1, static permanent magnet; 2, reversible permanent magnet; 3, coil; 4, direct polepieces; 5, armature; 6, workpiece; 7, magnetic flux; 8, induced polepieces; 9, dielectric; 10, ferro-magnetic frame; 11, thermosetting epoxy resin. [Courtesy of Technomagnetica (UK).]

The "magnetic option" is both practical and very commercially attractive for ferrous part workholding applications, but when non-metallic, or indeed metallic materials need to be machined, the adhesive clamping technique might be the answer, when lighter cutting loads are expected. The next section discusses this unconventional technique, which has been successfully utilised for some years by many companies.

4.2.7 Adhesive Workholding Applications

The technique of effectively sticking a component to a surface at first seems rather absurd, but upon reflection it has some positive merits if used for the correct applications. For many years the method of using double-sided adhesive tape has proved its worth for restraining acrylic sheets and other non-metallic materials in both turning and milling operations under light-to-medium cutting forces. The major advantages of utilising adhesive bonding are that the part can be machined all over, with the exception of the constrained surface, but more importantly, there is no distortion of the component as a result of clamping forces.

Components can be adhered to face plates on turning centres, or placed directly onto machining centre tables, or pallets, and assuming that the surface area of the part is large enough, it can prove an effective way of workholding. If the part profile needs to be machined using this technique, a sacrificial surface between the underside of the part and the workholding surface proper is advisable. This additional safety feature will protect the workholding equipment from the undesirable machining marks that would otherwise occur. If it is necessary to machine more than a one-off, then the use of such a sub-plate might be deemed prudent because dowel pins can be positioned with respect to the part, for either centralisation on turning operations, or axes alignment and datuming for milling operations. This system of workholding under the correct conditions is both very cheap and reliable, as well as quick to set up, but should only be used on components with general tolerances, as there is some elasticity in the adhesive causing part inaccuracy for high precision.

4.3 Advanced Workholding Methods on Turning Centres

As has been the practice in the past, many components are machined from wrought stock and this can pose a problem for workholding on turning centres when all-over or "one-hit machining" is the requirement. Usually it is relatively simple to "front-turn" all the part features and dimensions at one setup, but problems regularly occur when we try to machine features on the rear of the part. Such "back-turning" operations are frequently necessary and under most conditions a part clamping requirement must be broken-down to facilitate the component being repositioned to allow such otherwise inaccessible features to be machined. This loss of part restraint and location can result in quite significant tolerance and form errors when wall-thicknesses are thin, or if key features are of high dimensional and geometrical tolerances. Readers who have taken a part out of a workholding device will be familiar with the problem of repositioning the component back into the chuck, or fixture. It is the unwritten rule, "never move the part once it has been clamped": if it is necessary, then keep setups to the minimum. Not only is repositioning and clamping of the part highly undesirable, it is costly both in terms of efficient utilisation of the machine tool and significant additions to the part cycle time, particularly as today many machine tools can perform complete machining operations in seconds.

Turning centres which offer "back-turning" or "second operations" are not cheap to purchase and in order to amortise the cost on such high technology equipment, it is more than likely that "first operations" on the front face of the part can be machined simultaneously. Just such a machine tool is shown in both Figs. 4.11 and 4.12. If we consider the general arrangement, as depicted in Fig. 4.11, we can see that there are two turrets (bottom and top), with two chucks present in this case (front and rear). Parts might be loaded by a gantry robot, but more often than not, such machine tools are fed using the bar-feeding method, which is both fast and efficient whilst ideal when wrought bar stock is to be used. If we assume that a bar-feeding operation is expedient, then the part passes through the front chuck to a pre-stop and the front face features are machined according to the part program requirements. Whilst the front chuck is rotating, the rear chuck is rotated and its speed of rotation is synchronised to that of the part held by the front chuck. The rear chuck is advanced rapidly to grip the part and several options can occur at this stage: the component may be parted-off to length, or it can be released by the front chuck, pulled back to a predetermined length by the rear chuck and regripped, then parted-off. During the rapid reverse motion to its home position with the component, the rear chuck's speed can be changed. Simultaneously the front chuck will have been replenished with the

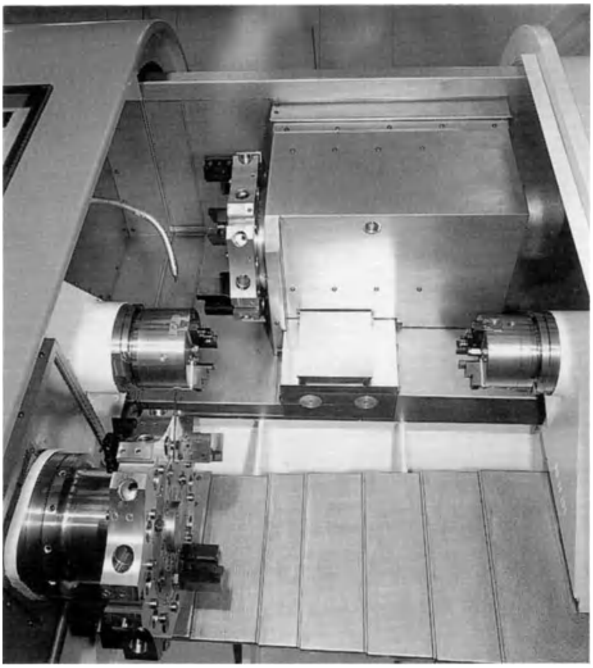


Fig. 4.11. A twin-turret 2-spindled turning centre having the ability to synchronise rotations of chucks. This allows the rear spindle to advance and grip the part and retreat, allowing "backturning" to commence. [Courtesy of Gildemeister (UK) Ltd.]

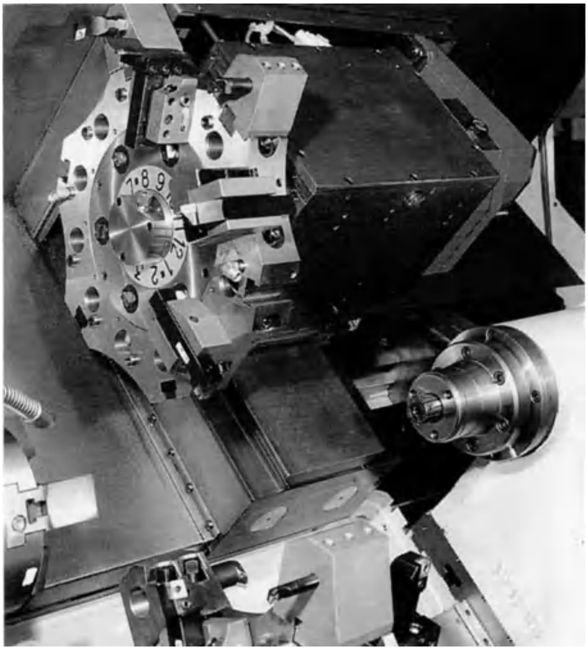


Fig. 4.12. An expanding mandrel in the rear spindle allowing "backturning" by the lower turret. [Courtesy of Gildemeister (UK) Ltd.]

wrought stock from the bar feed and the top turret begins front turning operations as before, whilst the lower turret machines the part's back features in the rear chuck as necessary. This means that two independent first and second operations may be performed in synchronisation, which often negates the use of a further setup at best, or reloading and machining on another turning centre. Such machine utilisation is highly productive and can be improved still further when prismatic features – flats, splines, keyways, etc. – are also cut in situ using "live/driven tooling". Such turning centres can have upwards of seven axes control, but are not as difficult to program as one might otherwise imagine. Obviously, workholding equipment can be changed to suit the part geometry and in Fig. 4.12 we can see that the rear chuck has been removed and an expanding mandrel is present, whilst the front chuck jaws have been changed for bored-out soft-jaws.

In recent years, such turning centre configurations have become a popular concept with many machine tool companies and most offer twin-turret and spindle machines. Customers are demanding highly productive machines with such levels of complexity to keep ahead of the competition, offering a vast range in potential part setups and machining facilities as highlighted here, which may be considered as the state-of-the-art equipment at present, particularly when programmable steadies and other accessories are added to the machine specification.

4.4 Programmable Steadies – their Role in Workholding

Traditionally, the size of a lathe and turning centre has been measured by its "swing" over the cross-slide and the distance between centres of the largest component which can be held successfully. Usually large diameter components do not present a problem unless their overhang is significant and under such conditions a steady may be used to support the part whilst turning or boring operations are undertaken. Machining of long, slender workpieces can present almost insurmountable problems, owing to part restraint and its subsequent deflection caused by the tool forces. Under such conditions it is desirable to utilise a programmable steady, usually in conjunction with a chuck, or face driver (see section 4.2.2), with a rotating centre in the tailstock. If one tries to machine the whole length of the slender bar at one set-up, without the aid of a programmable steady, several anticipated problems will arise. In the first instance the supporting contribution made by the tailstock as the cutting tool is fed along the bar toward the headstock is steadily diminished. This means that the bar would deflect with greater intensity as the tool approaches the bar's central region and once past this point, the support of the contribution made by the headstock's end support is progressively felt. Such deflection, resulting from the radial force component from the tool, causes a "barrelling effect" to the workpiece – meaning the central region of the part is larger than the two ends. Even when "orthogonal cutting" is attempted or "balanced turning" tried (this latter technique is when both top and bottom turrets turn the diameter, with one cutting edge slightly ahead of the other and sharing an equal depth of cut) there is still a tendency to "barrelling", but it is less pronounced. The simple remedy is to use a programmable steady, but with such auxiliary equipment it must be used in the correct operating sequence; this means that "bearing bands" are turned at a variety of positions to support the long, slender part in a specific manner. It will simply not be sufficient to use the programmable steady in a position behind the tool's cutting point and progress in tandem with the tool along the bar's length. The correct method to achieve a constant diameter, is to machine the "bands" along the bar at a specific linear distance apart, which is dependent upon the bar's diameter and its length. For example, if the bar is, say, 25 mm diameter with a length of 800 mm, then probably three "support bands" for the steady are sufficient when the diameter needs to be reduced by 2 mm along its entire length. First, a band is machined 200 mm away from the tailstock and the steady is positioned on this band, then the second "band" is cut 200 mm from this position – with the supporting contribution of the steady at "band" position one providing the support. Finally, the programmable steady is moved to the second band position, at the bar's central region, and a third band is cut 200 mm linearly from this one, where the support from the headstock and the central band's contribution to the bar's support are felt. The bar is now ready to be turned along its entire length, by repositioning the steady in the initial sequence of cutting the three "bands". With the programmable steady at band position one the required diameter is turned up to it and the tool retracted. The "steady" is now moved to the "central band" (the second one cut), the tool is repositioned just behind the place where the tool had previously been retracted and the bar is turned up to the second "band". Lastly, the same sequence occurs, namely the tool is once again retracted and this time the programmable steady is repositioned on the third "band" and the tool is re-engaged to machine up to this third band and the steady is retracted, allowing the tool to cut up to the headstock end.

Such a complex sequence of "support band" machining and tool motions is necessary if one is to guarantee that the correct diameter is produced with no form errors present (barrelling) resulting from the influence of tool forces on the workpiece. The correct use of fully-programmable steadies, with their independent control of position along the bedway and the opening/closing of the roller fingers, allows workpiece support to be consistently and efficiently achieved. Although programmable steadies can be supplied fully programmable, as we have discussed above, it is possible to obtain a similar effect, but at reduced cost, by simply using a steady with adjustable support fingers held in the second turret at one of the tooling stations (Fig. 4.13). Therefore, the cutting tool to be used is held in one turret with its motion under the primary motion axis control, whilst the steady is in position in the second turret. The steady's motion along the bed is under the independent control, both linearly and radially, of the secondary motion axis control and in this manner achieves a pseudo "fully" programmable motion. Specialised equipment such as programmable steadies are useful when one expects to be machining long, slender bars, or those requiring additional support.

4.5 Workpiece Delivery to "Stand-alone" Turning Centres

The supply of parts to any productive CNC turning centre must be continuous and as such reduces the work-in-progress (WIP) to a minimum with any delays in work progression being assigned to essential tool and machine maintenance rather than intermittent workpiece supply. If bar stock is the means by which workpieces are manufactured, then so long as a steady supply is provided by an efficient bar-feeding system, little interruption in production will result. The problem is that inevitably many parts are not manufactured from wrought bar stock and this requires some other means of effecting part delivery, if workpieces are either presented for second machining operations or if they are castings/forgings. Whenever the part needs to be

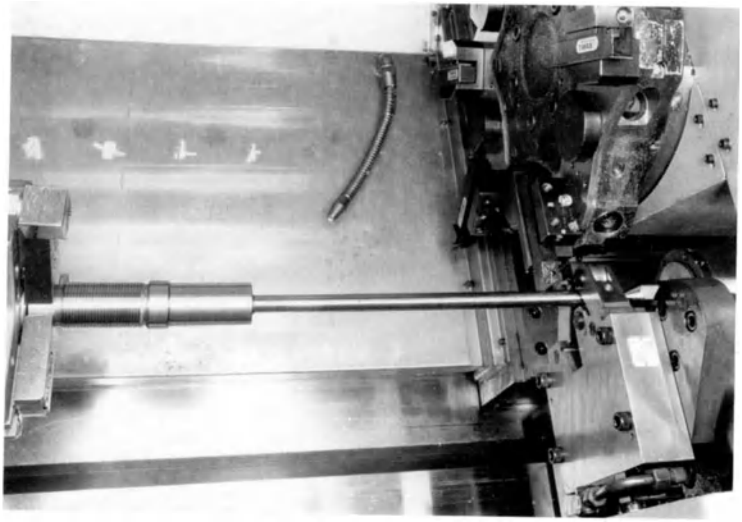


Fig. 4.13. Supporting a long slender workpiece using a programmanle steady whilst the top turret turns the diameter. [Courtesy of Gildemeister (UK) Ltd.]

manipulated into the workholding device, some transfer system for loading/unloading is desirable. Simply achieving part transfer manually on a highly productive machine leads to irregular delivery over a series of shifts, and operator fatigue. The simple fact that a turning centre is going to be worked hard over its working week makes some form of automatic part delivery system necessary. It always amazes the author when visiting factories that many companies use operators to load/unload components with short cycle times but have either rejected out-of-hand, or only superficially considered, automatic part delivery systems as expensive but unnecessary extra capital costs. The fact that operators are being paid – sometimes over three shifts – is an uneconomic strategy. The extra cost of an automatic workpiece delivery system would have meant that its cost would have amortised quickly and part quality would be consistently maintained; denial of these facts is indicative of poor perception by the management; such auxiliary equipment offers considerable manufacturing improvements within a company. Any company operating large stocks tied-up in WIP is missing an economic opportunity to improve its competitiveness and together with an improvement in the manufacture of part quality goes a reduction in WIP. Such reductions can fund expansion, or improvements in the capital plant within the factory to compare with the highly competitive manufacturing countries in the world which spend a significant amount of time, effort and cost in obtaining such reductions – which is a point not to be overlooked.

Typical of such automatic workpiece transfer systems is that illustrated in Fig. 4.14, where a gantry robot is used to load and unload parts from a turning centre in an efficient manner. By using gantry-type robots, considerable part delivery benefits are offered over the stand-alone machine tool:

floor space is minimised

machine tool modifications are kept to a minimum – as loading/unloading is through the top of the machine

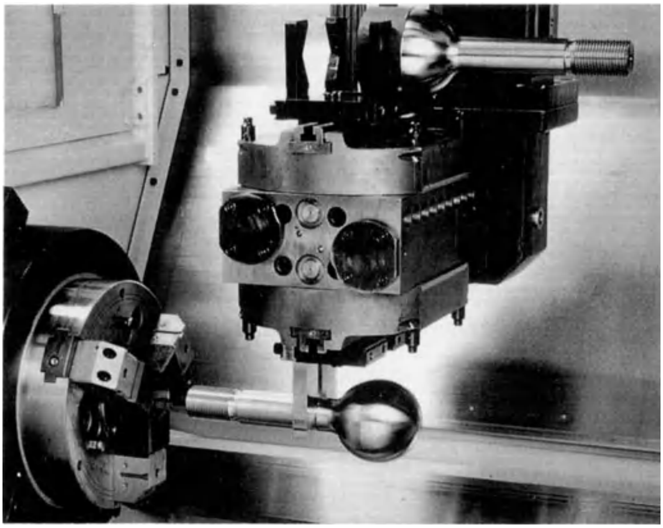


Fig. 4.14. Using a gantry robot to simultaneously load and unload workpieces to a turning centre. [Courtesy of Gildemeister (UK) Ltd.]

palletised work can be presented at a delivery station for easy loading/unloading to the machine and as such can keep WIP within acceptable levels

cycle times are optimised as consistent part delivery is assured

parts can be automatically removed and placed into receiver gauge stations for 100% inspection or at statistically acceptable intervals, if required

If the batch changes to a different geometry then as often as not the gripper needs to be replaced to pick up the part on the registered feature; this implies gripper jaw-changing. Yet another feature often available with such gantry robots is the ability to change jaws automatically and this further increases the part changing versatility, allowing mixed batches to be successfully accommodated.

All these advanced features with sophisticated collision protection and proximity sensors in situ are purchased with one thought: to increase productive potential, and if utilised under the correct conditions, considerable advantages – as suggested above – will result.

4.6 Part-catchers

Once the part has been manufactured by the turning centre, this suggests that considerable time, effort and value – added cost – have occurred, and the efforts directed at improving tooling, workholding and modifying part-programs aim to ensure that part quality is consistent. The last thing a company needs after the part has been manufactured, with all these cost factors built into the workpiece, is for it to be either unacceptable through blemishes to the surface finish, or damaged in some other way as it is either handled or parted-off. Often a critical time in the life of a manufactured part occurs as it has its final cut taken – particularly bar stock; the parted-off workpiece falls to the bottom of the swarf tray, but may strike the side of the casting of the slant bed on the way. Some damage will inevitably occur to the part and depending on the likely service application, this may be significant or not. To avoid such problems, yet offer some slight support to the part – particularly if it is a long, slender component which might "whip" at the final moments of its attachment to the bar stock – a part-catcher should be used. Part-catchers are often thought of as options of equipment which are rather unnecessary, but when used in the correct circumstances they can be of positive benefit in ensuring consistent component quality.

A typical part-catcher in the act of gathering a component is shown in Fig. 4.15, where the turned part is gently removed and lowered into a parts bin automatically. The one shown is quite sophisticated, as it has a linear motion after the part is captured, removing it from the working envelope of the turning centre, allowing further machining to commence. In their most simple form, they literally do just as their name implies – catch the part, as it is parted-off and as such avoid further damage as it descends! Part-catchers which simply catch the part present themselves to the working position automatically upon receipt of the desired command from the CNC and can accept a range of components into the tray without modification. The type shown in Fig. 4.15, however, needs to be modified to accommodate the specific part features and although they offer much greater workpiece protection, they tend to be less flexible as a result. Furthermore they offer real benefits when either the

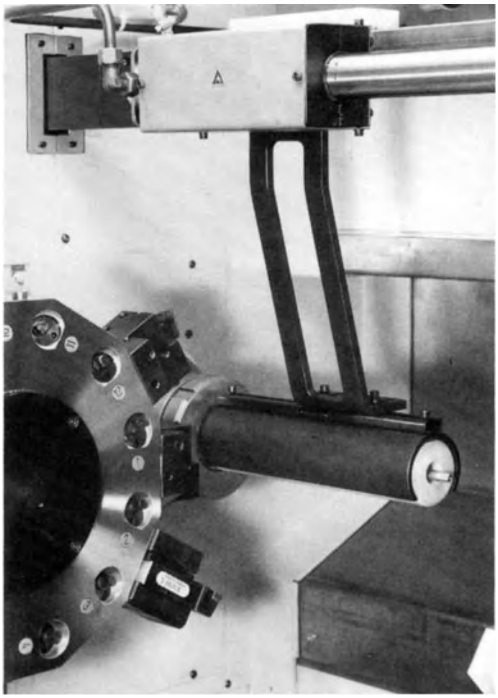


Fig. 4.15. A part-catcher partially supporting the workpiece and minimising damage whilst the parting-off operation is undertaken. [Courtesy of Gildemeister (UK) Ltd.]

component production runs are long or if the part geometries are similar – in terms of their dimensions – for a group technology (GT) approach.

This completes the review of turning centre workholding technology and we will now go on to consider similar techniques and methods used on machining centres.

4.7 Machining Centre Workholding Techniques

The general comments made about workholding techniques for turning centres (section 4.2) are equally relevant for machining centres, where the choice of equipment used is dependent upon the anticipated batch sizes, their physical dimensions, adaptability, but strangely, rarely upon accuracy. It is often the case that part inconsistencies are caused by inadequate clamping and workholding methods, rather than the actual machining problems or material variations. If a company demands highly accurate parts – regardless of the batch size – then the only way to ensure that the tolerances are maintained is by using "dedicated fixturing" techniques. Fig. 4.16 gives a range of workholding methods for prismatic part manufacture and so on, and whenever we require greater accuracy – such as with "dedicated fixturing" – then it follows almost exclusively that the flexibility of the parts to be accommodated is somewhat lessened, whereas the reverse is true for "modular fixturing" where greater flexibility in workpiece accommodation is obtainable, but at the expense of accuracy. "Modular fixturing" will always suffer in terms of the problems of part restraint and location in comparison with the more permanent workholding methods, but they are popular whenever the part variations cannot be exactly predicted, or if their range is large – but more will be said on the various merits of each technique in their specific sections to follow.

The ubiquitous T-slot in the machining centre table has remained unchanged for many years and is the main means of fixturing grid or sub-plates used on vertical machine tools in particular. The development of the T-slot table was refined at the turn of the century and on most conventional machine tools has proved its worth. However, with the assistance of computer techniques, workholding methods have been developed recently which drastically reduce set up times and bring into question the whole philosophy of utilising T-slots for part restraint with their inevitable location problems – but this will be the subject of a more detailed discussion later in the chapter. The role of the T-slotted table is not completely redundant and when clamping diverse part geometries in one-off, or small batches, then it offers some benefits which will be the subject of the next section.

4.7.1 Workpiece Restraint Using Conventional and Machinable Clamps

Probably the most diverse and popular clamping medium for workpieces is that of individual clamps which are strategically positioned around the part to ensure its correct restraint. Normally these are durable steel items made either "in-house" for special applications, or purchased as sets from proprietary manufacturers either individually or more specifically in sets with clamps, studding, T-slot nuts, washers and nuts, together with adjustable packing in a range of sizes. Such clamping techniques require some skill in their distribution and positioning around the part in order that the part is perfectly restrained and positioned in the correct attitude to the axes

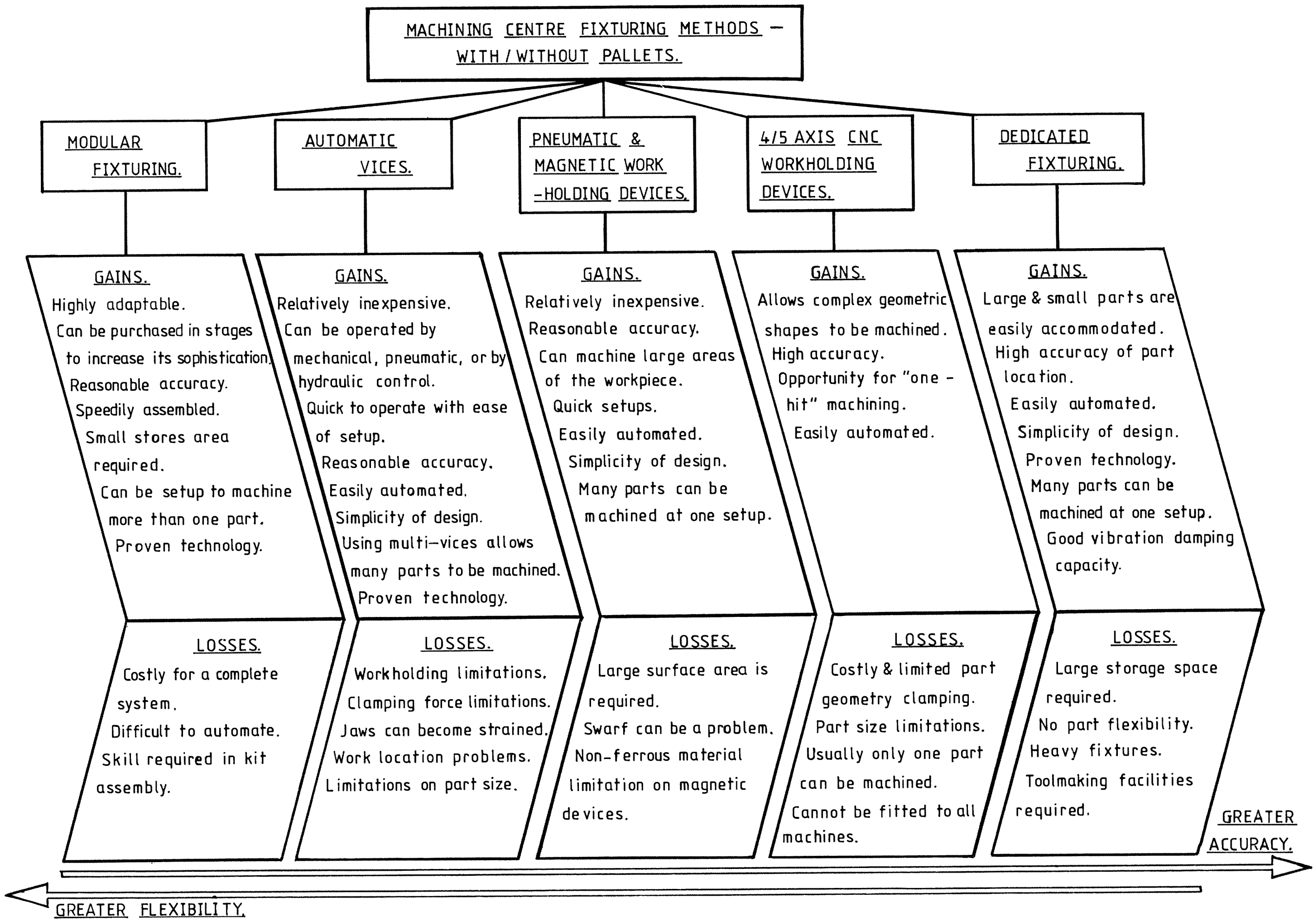


Fig. 4.16. Workpiece fixturing for machining centres and their advantages and limitations.

travel to minimise setup time. Utilising tenons which slide into the T-slots and then "stand proud" of the table surface allow the part to register against it – under many circumstances this will align the part in the desired orientation to the machine axis, but it may still require the part to be "interrogated" by the touch-trigger probe to finalise its actual position with respect to the machine's and program's datums (see Fig. 2.30). Such clamping methods will restrain the workpiece when it is subjected to the forces produced whilst machining, but when restraining parts liable to distortion then the clamping force should be sufficient to hold the part, but not to distort it or mark it, i.e. "pressure marks", in any way. This form of workpiece restraint often means that the clamping positions must be catered for in the CNC program in order to avoid tool crashes. Often when moving in rapid or feed modes within the working envelope it is possible to program "safe zones" which prohibit the cutter path within such forbidden areas (see Fig. 4.17) and are user definable. Not only can the position of clamps be excluded from entry by the cutter during the program's execution, but if irregular heights are present on the part with bosses or protrusions, then these may also be designated "safe zones". If by chance the cutter is accidentally programmed to go within a "safe zone" then the following action can be expected, with many controllers having this facility:

as the "safe zone" is reached by the cutter its forward motion is immediately stopped

a rapid motion in the positive Z-axis direction occurs to the pre-defined "R plane" ⟨NB: the "R plane" is a pre-set height which does not interfere with the protrusions, or clamps on the part and where it is safe to allow the rapid moves to take place over the part⟩

motion continues until the "safe zone" has been straddled – in the desired direction – and the cutter descends to its previous height in the Z-axis and motion to the predetermined target position is continued.

This means that when the "safe zones" are allocated to areas within the working envelope, the cutter can be programmed to ignore, with impunity, the clamps or other features so designated and freely move as dictated by the part program.

Returning to our previous theme in this section, namely the use of clamps in workholding, but more specifically machinable clamps, they find tremendous potential usage when the machining forces are low, which does not prohibit the use of lower clamping force. Under such circumstances it is possible to machine a small portion of the clamp as it restrains the part. This does not mean that such a clamp can be considered as a consumable item – far from it. When the part is initially set up, it is normal for only the first cutter pass to actually machine a portion of the clamp, when applicable, with further parts restrained in such a manner not having their clamps machined. This is an advantage when designing or considering part fixturing problems – knowing that when potential clamping areas are restricted, owing to part geometry – such machinable clamps can, at worst, be partially machined. Not only do these clamps offer benefits over conventional clamps when the occasion demands, but owing to the softer materials from which they are made, they minimise "pressure marks" normally caused by excessive clamping pressure which aids surface finish and reduces distortion.

As we have seen with this application, when low cutting forces are present this is one method in our clamping repertoire which can be used. There are often circumstances when a greater clamping force is needed and this prohibits the use of ordinary clamping techniques. Sometimes loading, clamping and unloading parts conventionally is too time consuming. Utilising hydraulic clamping might be the solution under such circumstances and this theme will now be reviewed.

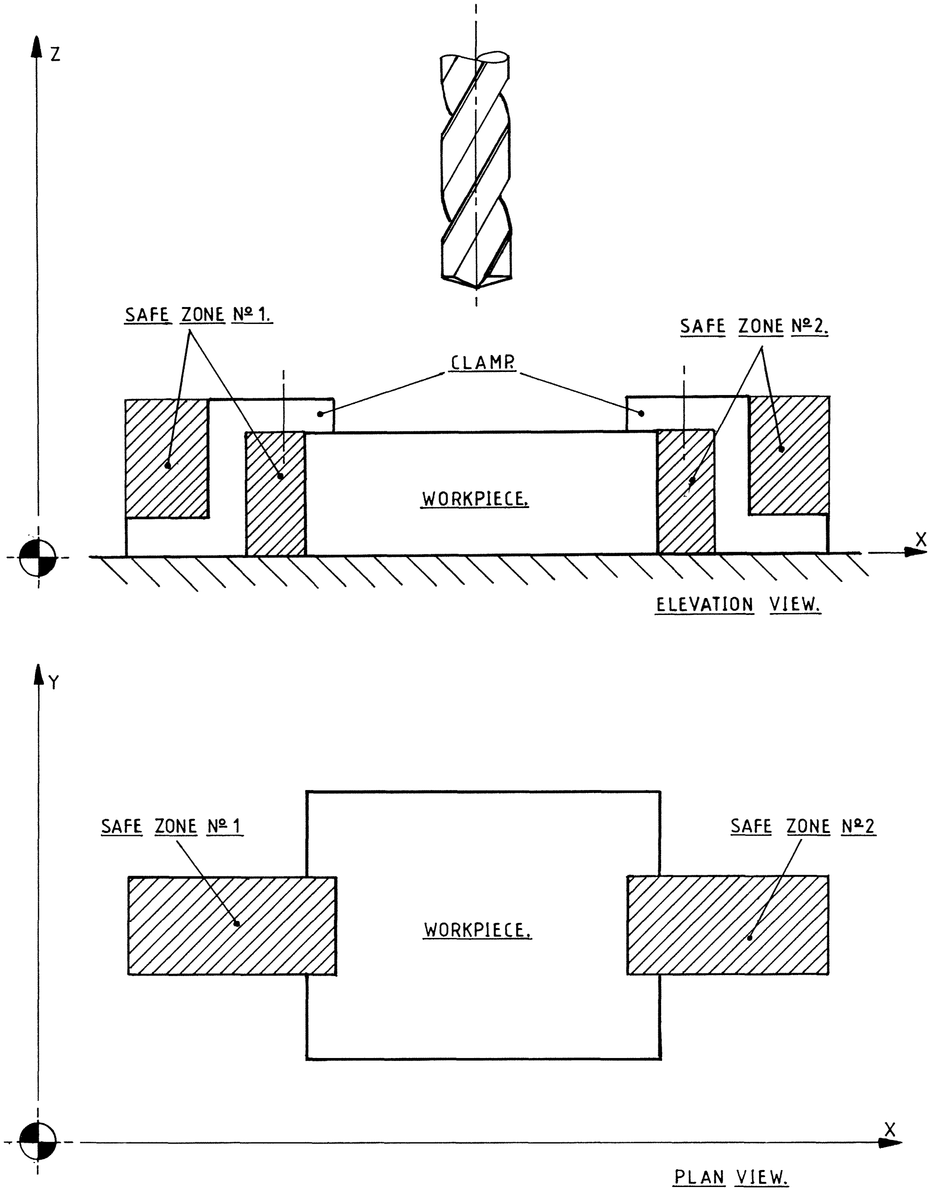


Fig. 4.17. The programmed safe zones for the clamping positions which are related to the machine zero and avoid crashes.

4.7.2 Hydraulic Clamping Applications

The hydraulic clamping principle used for restraining workpieces is quite simple and is generally based on the conversion of pneumatic pressure to hydraulic pressure. Such systems (as depicted in Fig. 4.18) are easy to handle with the operator needing

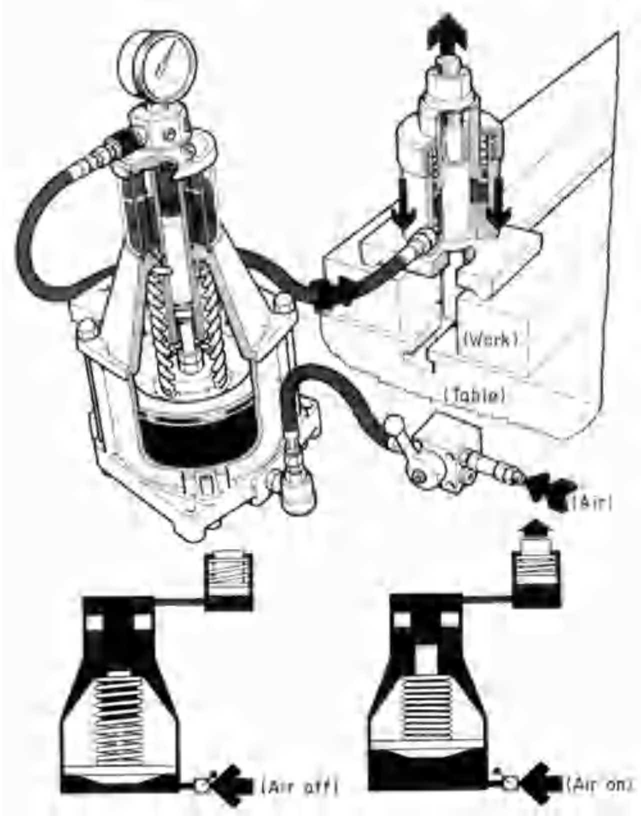


Fig. 4.18. The clamping of workpieces using pneumatic input to intensify the hydraulic pressure on the part. Principle of operation: compressed air is fed via a pneumatic connection into the pressure converter. The raised pressure in the hydraulic oil in the pressure converter is transmitted via the hydraulic connection to the clamping cylinders, which clamp the workpiece. [Courtesy of Sandvik (UK) Ltd.]

no special knowledge of hydraulics or pneumatics. When the control valve is opened or closed, full locking or release is obtained within a second. Such rapid mode of operation leads to short changing times for workpieces and thereby lower down-time costs. Such methods are particularly applicable where mass production is demanded and the part requires many clamping points. When several clamping cylinders are used simultaneously, a uniformly large and simultaneous clamping force is produced at each clamping cylinder. Furthermore, the variations normally expected in clamping force between different clamping occasions are eliminated. Such systems are very robust and, under normal working conditions, the system – excluding rubber seals – lasts through at least 500 000 load changes.

With many applications it is important to know the pressure to which a given area is subjected, namely the force per unit area. By way of illustration, if two containers, both weighing 5000 N (F1), are to be placed on a concrete floor that can withstand a certain maximum pressure, then their load per unit area is affected by the cross-sectional area in contact with the floor. In the first instance the container with a 1 m^2 cross-section (A1) exerts a pressure on the floor (P1) of:

$$P1 = F1/A1 = 5000/1 = 5000\,N/m^2$$

In the second case, the container's cross-section in contact with the floor is $10\,m^2$ (A2); it follows that the pressure P2 will be:

$$P2 = F2/A2 = 5000/10 = 500\,N/m^2$$

Conversely, the force is dependent upon the magnitude of the pressure and on the size of the area on which the pressure acts. For example, if we assume that a piston has a force of 1000 N which acts on an area of $0.2\,m^2$ and is connected by piping to another piston which has an area of $0.05\,m^2$; in order for a smaller piston to maintain an equalising pressure its force must be considerably greater, as follows:

$$\text{Large piston's force and pressure} = P1 \times A1 = 1000\,N \times 0.2\,m^2$$
$$\text{Small piston's force and pressure} = P2 \times A2 = P2 \times 0.05\,m^2$$

Using this data to find the equilibrium pressure required by P2, this may be found using the following equation:

$$P1 \times A1 = P2 \times A2$$

and by substituting the known values for force and area we obtain:

$$1000\,N \times 0.2\,m^2 = P2 \times 0.05\,m^2$$

therefore

$$\frac{1000\,N \times 0.2\,m^2}{0.05\,m^2} = P2$$

thus P2 must produce a pressure of 4000 N for hydraulic equalisation.

Most hydraulic clamps work on this pressure conversion principle, being based on the fact that the same total force is distributed over a smaller area which gives a higher pressure. The hydraulic clamping system shown in Fig. 4.18 is typical of this principle and consists of four main components: pneumatic connection, pressure converter, hydraulic connection and the clamping cylinder. The compressed air, which is the system's power-supplying medium, can be taken directly from the existing compressed air system in the workshop. A non-return valve in the pneumatic connection ensures that the clamping force at the clamping cylinders does not fail owing to a failure in the compressed air supply. The system is adjustable for both air and hydraulic pressure – meaning that clamping force is variable to meet the needs of a particular workpiece clamping application.

The pressure converter can achieve a hydraulic pressure of up to thirty-six times the original input pressure, allowing secure clamping to any workpiece being machined. The quick-action couplings cannot be released once the system is operational, eliminating the possibility of accidental disconnection. The high pressure piston in the pressure converter presses out oil, causing expansion of the clamping cylinders. The clamping cylinder's annular pistons move instantaneously, owing to the fact that the entire hydraulic section of the system is filled with oil. This means that an immediate reading is obtained on the pressure gauge confirming the applied pressure for clamping. The only limitations of such clamping techniques are that the number of clamping cylinders which can be connected to a pressure is limited by the oil volume discharged from the pressure converter. The size of the clamping cylinder needs some thought on how it might achieve effective clamping in the restricted areas – although by utilising indirect clamping techniques this problem will cause us less concern.

Such hydraulic clamping applications can be utilised across a range of accessory equipment for machining centres – typified by vices and so on, as we shall see later.

For now it is sufficient to say that yet another popular application, such as using sequenced hydraulic control, can be achieved for larger components needing profiling work. With this system technique, as the cutter progresses around the profile each hydraulic clamp will unclamp and move to allow access to the part by the cutter, with the restraint being maintained by the rest of the clamps. Sequenced clamping is a means of overcoming partial "breakdowns" of clamping and improves non-productive cycle time considerably. In fact, the whole field of hydraulic clamping techniques could be significantly expanded and applications can be found for its use in many companies as yet not using the method.

We have mentioned that vices are one area of hydraulic application for workpiece restraint, let us now consider how such equipment can be satisfactorily utilised in a production environment.

4.7.3 Vice and Multi-vice Applications

The traditional machine vice for part gripping has been around since the inception of milling operations and until recently had seen only modest development. With the advent of CNC machining techniques where more and more emphasis was placed on part throughput, this has meant that radical redesign of this equipment was essential. So popular are machine vices of one sort or another that it would be highly unusual to find a company involved in the machining of prismatic parts without such workholding equipment. Their popularity stems from the fact that they are able to accommodate a range of parts, from small intricate prismatic shapes to long, slender workpieces – if used in conjunction with an identical vice. If compound angled setups are necessary, then vices can be readily purchased with sine bars incorporated or swivelling motions in two planes. Even these swivel vices are not exorbitantly expensive and have the benefit of lasting for many years of continuous usage, and with the additional benefit of being usable on other CNC machining centres as well as conventional milling machines, drills and so on.

Vices for CNC machines often require multi-part setups and to cater for such occasions, manufacturers often design them around a "modular" principle. Such design techniques enable one to specify either singular workholding or multiplepart clamping with the vices arranged adjacent to one another (often preferred on vertical machining centres), or at right angles (the orientation favoured on horizontal machining centres). These vice arrangements are shown in Fig. 4.19 and are of the manual clamping type. It is important, when using a new vice, to remember never to overstrain the equipment by applying shock-loading to the vice handle as this can increase the torque on its screw and nut beyond the design limits and strain the vice's thread. Not only will there be potential damage to the thread, but the movable jaw can also tilt somewhat, causing the gripping faces to be "out-of-square" with one another – this will adversely affect part gripping pressure and its subsequent location. Once a vice has been strained through misuse, it is useless for precision applications.

With many of the more sophisticated vice designs there is a range of aids enabling the part to be speedily set up with respect to the requirements in the part program. Two such aids are "location holes" for positioning on the sub/grid plate – this aligns and positions the vice in the correct coordinates in two axes – and workpiece stops which are used for positioning the part in the vice at the required attitude and place with respect to its datum. Not only can the vice be located on its traditional surface ground base, but the end face can be ground allowing the vice to be positioned back-to-back, in tandem, or four may be positioned in a square formation for use on a

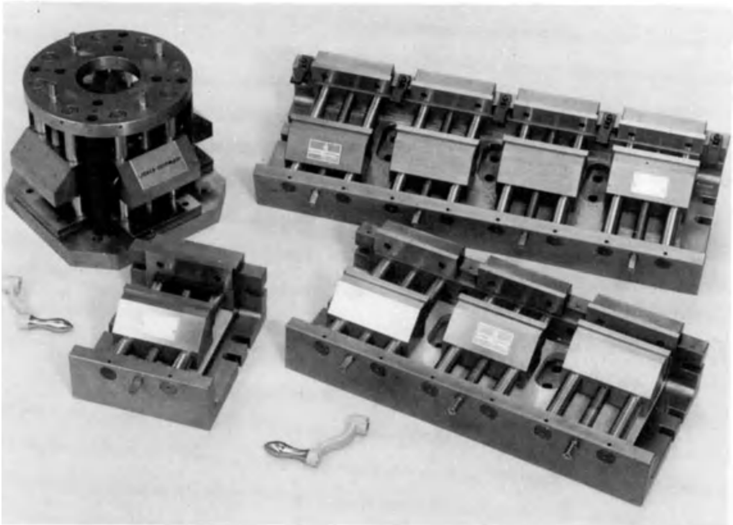


Fig. 4.19. A range of multi-vices offering many configurations for multi-part setups on vertical or horizontal machining centres. [Courtesy of Jones & Shipman.]

horizontal machining centre. The vices may have hydraulic power intensification: as the vice handle is tightened it operates as follows:

the initial mechanical clamping operation is performed by turning the handle. The course lead screw spindle brings the movable jaw into contact with the workpiece – at this point, resistance is felt on the handle

on turning this further in the clockwise direction, it disengages automatically and the system switches over to hydraulic clamping

when rotated still further, a thrust pin is moved axially and this results in a high clamping force – by the displacement of the oil in the hydraulic unit

NB: Cup springs ensure automatic retightening and prohibit part loosening during machining.

Such vices can have a preset limit established for the clamping force – this is an important design feature when delicate components might otherwise be inadvertently damaged. Such vices can also be mechanically clamped without hydraulic power intensification. This can be useful when several parts, whose contact faces are not flat, are to be clamped one after another. Not only can a range of location and positioning orientations be effected, but the jaws are interchangeable, allowing stepped jaws, V-jaws (for round components), together with special purpose soft-jaws to be accommodated.

Often vices need to be palletised for future use in a range of automated machining centre environments, ranging from delivery from pre-set stores to an FMS/C, or onto multiple pallets situated on "stand-alone" machines. This requires part fixturing to maintain its clamping pressure until needed, which might be minutes, hours or occasionally, days. As these systems are utilised in an unmanned condition, the part must be held in situ and to achieve this an automatic coupling device for the hydraulic clamping system is necessary. Such equipment permits the hydraulically operated machine vice to be used in an automatic work cycle. To connect the coupling system requires pallet positioning to an accuracy of ±0.7 mm. The coupling system consists of the coupling unit and its corresponding nipple holder, with each coupling unit being able to combine with several different nipple holders. To connect, or disconnect the coupling system, a coupling piston moves against the coupling nipple holder, simultaneously opening the shut-off valves on both sides. In this position the workpiece can be clamped/unclamped. After the part has been clamped, the coupling piston retracts and the shut-off valves close automatically. A proximity switch monitors the extended coupling piston. The workpiece remains clamped with the applied pressure and any axial forces occurring whilst the coupling system is being connected are positively absorbed by the system and do not affect the pallet. Experience has shown that even with well-sealed clamping elements the pressure drops 1.2 – 2 bar per hour; although this pressure drop should be put into context, as the maximum working pressure of 400 bar means that the "drop" is not too great a problem in the short-to-medium term.

To complete this review of vice configurations used on machining centres, it is worth mentioning the CNC self-centring machine vices which are becoming increasingly popular. Such vices have two movable jaws which can centralise the component with high clamping accuracy and allow a great versatility in component clamping arrangements. The vice can be used to clamp either one part with a self-centring action, or two parts separated by a central stop; with the latter, the axial guide of the screw spindle is released so that both jaws can move without restraint and adapt themselves to the part geometry to be clamped (either externally or internally). Typical clamping repeatability is of the order 0.01 mm, with the option of automatic drive being force multiplier, worm drive with force multiplication, hydraulic motor, or pneumatic motor.

4.7.4 Four- and Five-axis Rotary Tables

One of the major problems for any machining operation, whether it is on a turning or machining centre, is the ability of the cutter to avoid fouling the part whilst it is in the process of being machined. Normally, this is not too much of a problem on a turning centre, where the main problems tend to be fouling of tooling on the machine tool's elements rather than the workpiece – particularly when 2-axis turning. The problem is compounded, however, when we have to machine components of free-form shapes such as impeller blades, aerofoil sections, re-entrant angles, compound-angled holes, etc. Even machining centres equipped with a fourth axis – such as "horizontals" – will often have tool fouling/interference problems when machining such features. Under these conditions it is usual to specify an auxiliary axis such as a fourth/fifth axis on a vertical machine tool, or up to a sixth axis on a horizontal machining centre. Such equipment allows the extra axes to move relative to the cutter and thus avoids interference with the workpiece. The more axes available, the greater the freedom to cut re-entrant angles on parts, up to a limit, of course.

A typical "full" fourth axis rotary table is depicted in Fig. 4.20, where holes and slots are being machined on a vertical machining centre. Whenever a fifth axis is incorporated onto the rotary table it allows simultaneous and complete control of both axes of rotation, around the three linear motions on, say, a vertical machining centre. This level of rotational controlled motion can be quite expensive and needs either high value-added parts to be made in smaller batches, or frequent usage, to ensure costs are amortised. Often the requirement is only for limited angular indexing and this

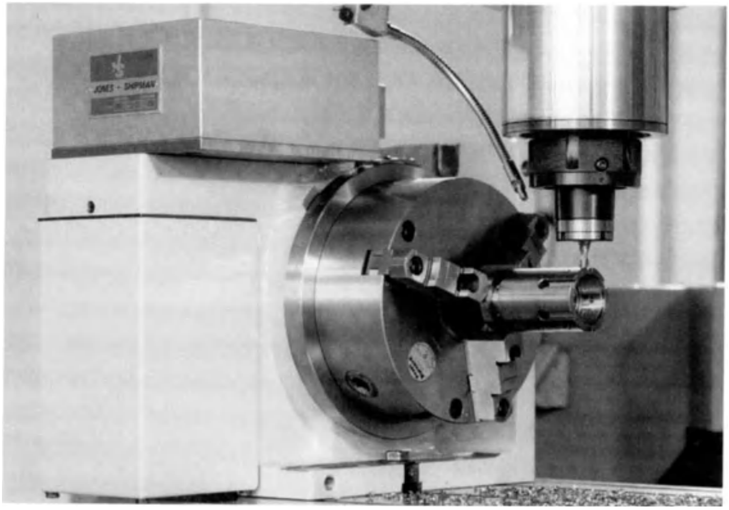


Fig. 4.20. A "full" 4-axis rotary table on a vertical machining centre. This extra CNC axis offers greater machining versatility. [Courtesy of Jones & Shipman.]

simply needs a more elementary angular control which reduces the cost considerably. These "indexing tables" can once again be in two axes, but do not need the greater complexity of rotational positional control of "full" rotary tables. They find applications when splines, angular hole pitches, keyways, slots and so on need to be machined in the workpiece.

These "indexers" and "full" rotary tables can accept a range of parts, with tailstocks, steadies, automatic chucks, etc., which can be provided, further increasing their versatility. More will be said on the topic of multi-axis machining in the following chapter, but for now it is sufficient to simply review the equipment. Such proprietary equipment – rotary tables – offer, as we have seen, the solution to the problem of cutter entry to the part geometry. Yet another problem exists when we try to support and locate with some precision parts of unpredictable and diverse nature. Under such conditions the "modular fixturing system" is of positive benefit in the tool kitting area and this will be the subject of the next section.

4.7.5 "Modular" Fixturing Systems and their Economics

The popularity of modular fixtures has increased considerably since the Second World War and they are now available from a range of companies offering variations on the original design, depicted in Fig. 4.21. Substantial savings can be made from their purchase, which quickly justifies the initial cost of the system. It has been found that savings of over 80% can be attained when compared with traditional fixturing, in the following areas:

jig and fixture design time
fixture material costs
fixture manufacturing lead times

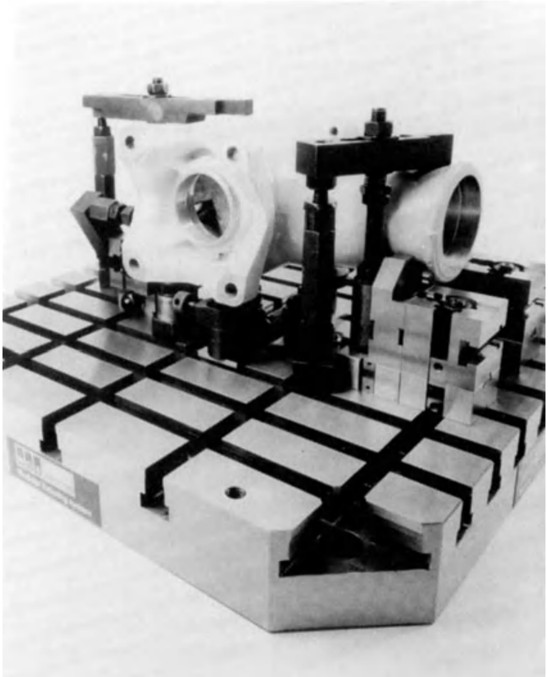


Fig. 4.21. A pallet featuring the "modular fixturing system" which offers the benefits of reusable elements, flexibility of setup, speed in assembly and, as a result, an overall reduction in fixture costs. [Courtesy of WDS Wharton.]

fixture manufacturing costs
tool storage space requirements

Yet further benefits can be gained in the reduction of manufacturing lead times, together with improvements in reducing down-time on the machining centres.

Some engineers are always sceptical about claimed benefits from the purchase of such equipment and in most cases a "detached viewpoint" may be a good thing, although in this case it is not justified. There is clear evidence from the many respectable companies utilising this modular tooling philosophy that cannot be repudiated. An example of a typical situation can be taken from a case study in a large manufacturing company in Illinois, USA, which builds special purpose machine tools and systems. This company instigated the purchase of modular tooling in 1984 and found immediately that their fixture assembly time reduced by 25%, meaning an annual saving of $100 000. The company had a diverse range of parts requiring machining, amounting to some 25 000 components, with up to 70% of them being one-offs – the average "batch" being 1.7, with half made only once. In order to meet the need for extreme flexibility the company installed an FMS and two years later purchased modular tooling. Prior to this time the workpiece fixturing had not kept pace with developments in machines and systems. Around 70% of fixtures were originally assembled from conventional angle plates, blocks, clamps and other components, with the remaining 30% being special purpose fixtures. These assembly methods usually meant an average lead-time of two to three days for their design and two to four weeks for construction. Such traditional workholding procedures have many shortcomings, including:

too many dedicated fixtures being necessary, with limited flexibility and standard setup procedures

some built-up fixtures had accessories which did not have the necessary rigidity or accuracy and took too long to assemble

Such problems led to a trial of the modular fixturing two years after an FMS incorporating twelve machining centres was installed. The company purchased about \$70 000 of fixturing technology with a setup area at one end of the line, where the modular fixturing elements were stored in cabinet drawers. Ultimately a centralised parts-staging and setup area for serving a system of modular workhandling fixtures drawn from a computerised high-rise storage system was envisaged.

The company has benefited from modular fixturing with around 150 different setups per week being possible using two people/shifts, from graphic displays or CAD/CAM drawings. By way of comparison, the old setup procedures utilising traditional workholding have been improved considerably and now assembly takes about 25% less time. Furthermore, the use of dedicated fixtures has been reduced from 30% to a total of only 10%, giving projected savings of \$100 000/annum. Such savings do not take account of the gains in cost resulting from rejects in positional inaccuracies with the older workholding techniques, nor does it consider the benefits of cost resulting from storing and controlling the large range of dedicated fixtures originally utilised. This would make the overall savings considerably greater/annum, which more than covers the implementation cost of such modular fixturing technology. If these are the advantages in terms of cost, space, setup time, storage and by no means least, reductions in part scrappage, how does the modular fixturing system operate? This will be the theme of the remainder of this section.

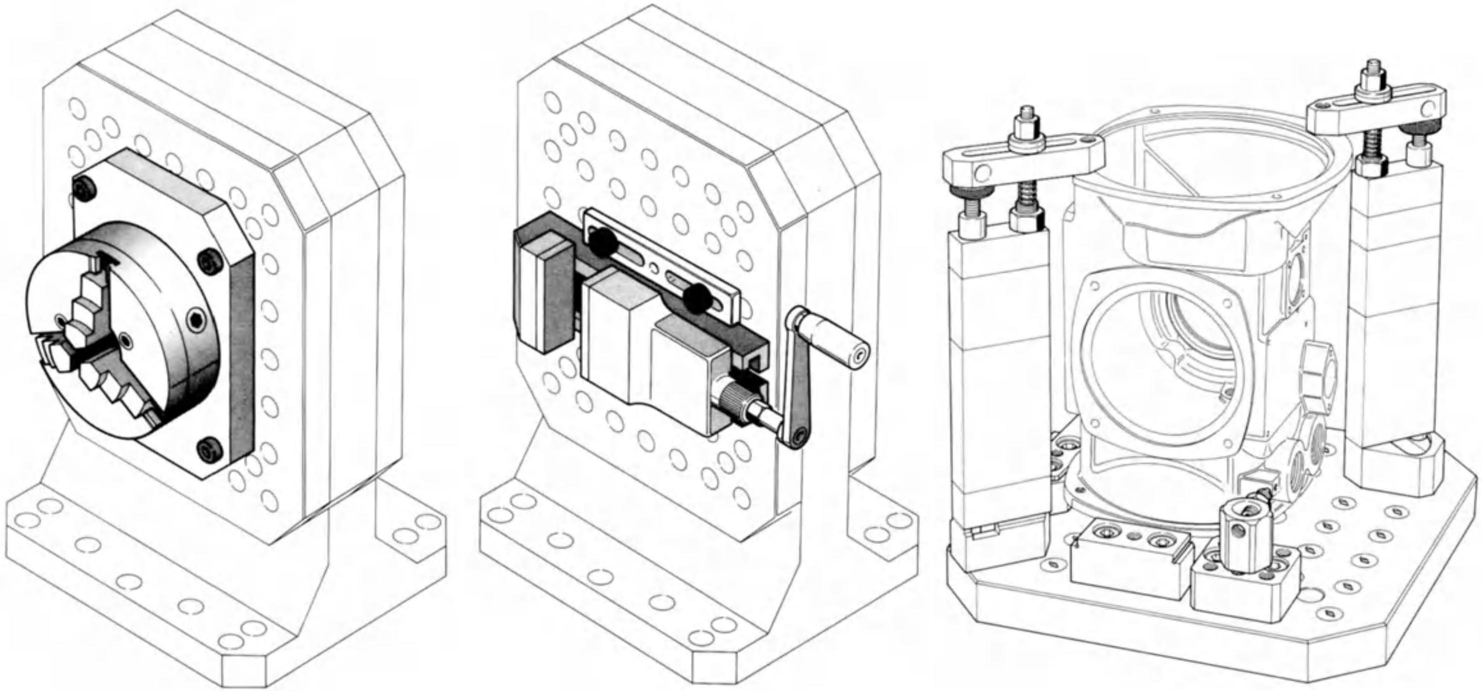
Modular fixturing can be likened to a three-dimensional "chessboard", which is composed of a base and construction elements offering the advantages of rapid and precise location and attachment of elements to support and restrain the part in the correct attitude for machining. Such elements used to build-up the fixture (typified in Fig. 4.21) are normally displayed on a "shadow board", or are securely "nested" in cabinet drawers. This allows one to quickly assess if the required element is available and its precise location for rapid fixture build-up. Not only can the individual elements be used to set up fixtures which would otherwise require "dedicated" fixturing – such as cast and forged components requiring machining – but vices, chucks, etc., can be incorporated onto pallets, or "tombstones" as necessary (see Fig. 4.22).

The basic design of modular fixturing systems differs in their design philosophy and the attachment of elements to build-up each fixture. Such systems have been available for a number of years with two different connecting principles being established:

slot-based systems

hole-based systems

The former slot-based systems (Fig. 4.21) appear to be the most widely spread in manufacturing and the basic assumption follows the example of the slotted table on machine tools. The slot system, when combined with support and clamping elements, becomes a workholding system. Its main connection principle is by way of assembling



a b c

Fig. 4.22. The adaptability of "modular fixturing" for machining centres. **a** A chuck fitted to a grid plate on a "tombstone". **b** A vice positioned on a grid plate on a "tombstone". **c** Workpiece setup using elements from the "modular fixing kit" for a machining centre. [Courtesy of Wix & Royd Ltd.]

individual modules – or elements – with matching T-units, or tenons. For example, with the T-unit connection system, assembly is instigated at the hardened T-slot base plate – being wear resistant – with the force transmission between slot and T-unit taking place in different ways for each coordinate axis:

X-axis – frictional and form locking
Y-axis – form locking
Z-axis – frictional locking

These basic considerations are of prime importance to the fixture designer, who would previously, using conventional methods, transmit the clamping forces by form locking the component to the fixture. The major advantage of the modular fixturing approach is the option to position modules freely in one direction, permitting a favourable adaption to the component's geometry.

The latter system of modular fixturing – hole-based system (Fig. 4.22) – relies on bolts and dowel pins, or just bolts in the case of lower accuracy requirements, as the connecting and positioning elements. The initial purpose of the hole-based system was to avoid the costly manufacture of the slotted elements by using circular matching surfaces. Such a system requires the matching holes to be absolutely parallel and their pitch dimensions to have close tolerances. There are several methods of achieving the desired matrix of holes, but the better systems incorporate a tapped and bored hole which may be used for either positioning or fixing the modular elements.

In most companies, the initial stimulus to consider the cost of modular fixturing systems appears to be that:

production costs are too high
flow of production is too rigid – possibly due to long lead times using conventional production equipment

However, in the tooling/fixturing department the objectives might be:

a significant reduction of fixture costs
more flexible fixture back-up

In order to successfully introduce modular fixturing into the company, several interrelated questions must be raised:

is the purchase of a fixturing system economically justified?
when, or after how many fixturing systems does the pay-back start?
are the components in question a long-running series, or are modifications to be expected?
is multi-sided machining required in one setup?
will the base plates together with the fixturing set be able to accommodate the component's size and shape?
how complicated are the parts?
will the fixtures be used once only, or repeatedly and if so, how often?
how do the costs of alternative dedicated fixtures compare?
what are the costs for assembling and dismantling such fixturing systems?
how much are maintenance costs?
what is the relationship between the positioning and clamping time of fixturing and special-purpose fixtures?

are the required elements available during the application term of the fixturing system?
will the demands on the system be satisfied with existing modules, or would additional elements be necessary?
which fixturing system suits the requirments of the component in question?
how many fixtures are expected to be assembled from the fixturing system per year?
what is the expected amortisation period for the system?
can qualified personnel be recruited for the assembly of such systems?

To answer these questions and in order to justify a modular fixturing system, or indeed a special-purpose fixture, the assembly/dismantling costs, compatible special fixture costs and the application time must be evaluated.

When numerous plants – companies with various subsidiaries – are considered, the economical advantages of fixturing systems are particularly obvious as a centrally located system can be used. Normally, under these conditions the workholding system is located where the most frequent usage occurs. The plant located at various sites could rent assembled fixtures for a fee – usually 12%–15% of the cost for a special-purpose fixture. This rental period normally averages ten days and has a beneficial influence on efficiency and feasibility.

In order to establish a feasibility study, the total costs of a fixturing system need clarification and it is essential with such a study, to compare it against special-purpose fixtures. The cost of a modular fixture can be identified according to the formula established by Dr Brueninghaus, as follows:

$$MF_{tot} = N(1 + Y)\left[C_{ass} + C_{MF_c} \cdot T_u\left(\frac{1}{T_w} + \frac{IR}{2} + 0.05\right)\right] + C_{MF_s} \times T_N + \Delta C_{c_{man}} \quad (£)$$

Nomenclature:

MF_{tot} = total cost of modular fixture (£)
N = number of different fixtures necessary (number)
Y = relative number of repetitive assemblies (number)
C_{ass} = assembly costs for one modular fixture (£)
C_{MF_c} = cost contribution of modules (£)
T_u = average utilisation of fixture (days)
T_w = write-off period (10 years)
C_{MF_s} = storage cost for modular system (£)
T_N = period for cost consideration (years)
$\Delta C_{c_{man}}$ = production costs of components (£)
IR = calculated interest rate (£)

NB: Probably the most meaningful way of establishing some form of cost comparison, is to compare the cost of a modular fixture with that of a dedicated fixture – given that the modular fixture is applicable, of course.

There is no point in undertaking an extensive and time-consuming feasibility study on modular fixturing if there is not an organisation within the company to back up such a purchase of tooling, as the production planning, assembly, together with other associated sections within the company need to be considered if it is to be successfully implemented.

To complete this appraisal of modular tooling it is worth mentioning the fact that such systems can be partially automated, in that a hydraulic clamping of parts can be

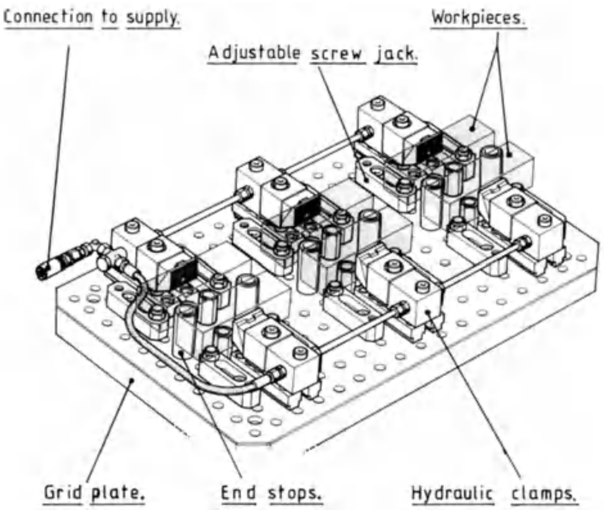


Fig. 4.23. Hydraulic clamping of multiple parts based upon the "modular fixturing concept" on a hole pattern in a grid plate. [Courtesy of Wix & Royd Ltd.]

effected as shown in Fig. 4.23. This allows the fixture to restrain several parts at once and they may be loaded/unloaded speedily by switching the hydraulic supply on or off. Finally, such systems can be incorporated for ease of design and element construction into a computer-aided fixture design package. This level of operational activity brings fixturing right up to date, as the interaction between all the associated departments needing information on fixturing techniques, costs, availability and their logistical position within the company at any instant is assured. In the following section we return to the theme of magnetic workholding practice previously discussed in section 4.2.6, but we will now consider the applications and indeed some of the problems associated with milling components by such methods.

4.7.6 Magnetic Workholding for Milling Operations

Magnetic workholding devices for milling have not been as popular as for surface grinding operations of ferrous parts, where they are almost universally accepted. Yet in many cases magnetic techniques can have the positive advantages of ease and speed of setup, positive location, uniform clamping pressure and resulting minimal workpiece distortion and so on. If permanent magnetic tables are required, they are usually obtainable in three configurations:

Permanent magnetic tables, which are switched on and off mechanically.

Fine pole permanent magnetic tables, which are also switched on and off mechanically – they use neodymium iron boron (NdFeB) "Rare Earth" permanent magnets.

NB: In both cases the movable grid, which comprises the magnetic and non-magnetic alternating assembly, is mechanically moved to magnetise the steel inserts in the top plate which are separated by non-magnetic spacers and it is demagnetised by the grid's magnetic reversal.

"All-purpose" magnetic tables; these may be switched on and off by a micro-chip controller which also interlocks the chuck into the machine controls for total switching safety – a single pulse of current through the table's coils remagnetises the Alcomax magnets in opposite directions for switching on or off. In the on position the pair of magnets, ferrite and Alcomax, have both magnets magnetised in the same direction, with the easiest path for the magnetic flux being through the workpiece, holding it in position. To switch off, a pulse of current through the coils remagnetises the Alcomax and ferrite magnets in the opposite direction and allows an easier path for the magnetic flux within the body of the table, releasing the workpiece.

As described earlier, it is the amount of magnetic flux induced in the workpiece which determines how well it can be held magnetically. For maximum clamping force, as much magnetic flux as possible must be induced in the workpiece and on a simple part this means positioning evenly over the North and South poles of the table. It is known that the pull is proportional to the square of the magnetic flux density in the contact face of the workpiece with the table – up to the point of saturation of the workpiece. Therefore, if we double the contact area this doubles the magnetic pull. When we reduce the flux density by 10%, this reduces the pull by 19%. If the flux density is halved, the magnetic attraction (pull) is reduced by 75%. Any reductions in flux density can occur when the flux encounters a magnetic resistance – usually termed "reluctance". Simple examples are air gaps – which are non-magnetic and offer high reluctance, as well as factors in the workpiece material. There are five main factors which affect the flux density and the pull on any given size of workpiece:

contact area
surface finish
workpiece material
material condition
workpiece thickness

We will now consider each in turn and in more detail.

Contact area. The ideal condition offering the highest resistance to machining forces is where the air gaps are kept to a minimum and there is a large continuous contact area. The poorest results are obtained where air gaps are large and a very limited (line) contact occurs.

Surface finish. The smoother the surface the greater the contact area and the higher the magnetic pull. It follows that a lapped finish has insignificant air gaps present offering best magnetic workholding, whereas a coarse surface – such as a cast component, will provide many air gaps and the grip is poor.

Workpiece material. It is possible to induce high values of magnetic flux and subsequently produce greater attraction pulls in some materials compared with others. Steel typically offers a high flux. Brass and aluminium, where no flux at all is induced, are termed non-magnetic materials. In between these two extremes, a whole range of materials exists with varying magnetic properties.

Material condition. If a material is heat treated, this affects its physical structure and its ability to absorb flux. Annealed materials are the best, whereas hardened materials do not absorb flux as easily and tend to retain a degree of magnetism when the table has been switched off – this can make it difficult to remove the workpiece from the table. Residual, or retained, magnetism can be removed from a workpiece by using a demagnetising cycle.

Workpiece thickness. The flux path within the workpiece is a semi-circle from the centre of one table pole to the centre of the next. If the workpiece is thinner than the optimum – this value being the flux radius – it cannot absorb all the flux and some passes through it, termed "unabsorbed flux". The resultant magnetic pull will be lower than when the flux is absorbed by a thicker workpiece. This problem of unabsorbed flux can be minimised if a table with a fine pole pitch is purchased, although it would be compromised if such a table were to be used for thick parts with heavy cuts. When a workpiece has a profile and it is anticipated that repetitive machining is required, then an additional top plate to the table can be manufactured to suit this profile. This modification can increase the surface area considerably and the pull may be improved by up to 150%. If thick workpieces need to be machined, then a simple jig is made from mild steel in a non-magnetic material which simplifies work holding and positioning, giving accurate and repetitive location to the part.

As we are able to appreciate from Fig. 4.24, where a magnetic cube is retained on a horizontal machining centre, with the parts simply located in the required attitude for milling operations, the use of magnetised workholding techniques offers considerable productive savings:

jig and fixture costs are lowered
part changeover times are improved
low maintenance costs and reliability improve

It is recommended that the machining rates for each job are assessed and gradually built up to the optimum until sufficient data is gathered about the materials, contact areas, workpiece thicknesses, etc. To ensure maximum rigidity of the part, it is suggested that extra packing/location pieces are used, when the full chuck area is not being utilised.

Fig. 4.24. A magnetic cube on a horizontal machining centre, with typical cutting data being: cutter diameter 160 mm (face mill); 268 r.p.m. (speed); 300 mm/min (feed); 4 mm (depth of cut); 125 mm (width of cut); 150 cm^3/min (stock removal rate). [Courtesy of Eclipse Magnetics Ltd.]

The mechanical forces to be resisted in milling operations are generally much greater than for grinding, and the cutting action may be of an intermittent nature as each cutting edge strikes the workpiece. Furthermore, the direction of the forces will vary from any instant during the machining operation. The table's purpose is to hold the work down. Any resistance to sideways movement of the part is approximately five times less than the downward pull and it is obviously important to have side and end stops present. Suitable blocks positioned between the side and end stops and the workpiece should be used to ensure the work is over the North and South poles. It is advisable to use the climb milling technique in preference to conventional milling. During vertical milling operations, the position of the table should be adjusted to control the directions of the mechanical forces so that the workpiece is pressed against the stops and not driven away from them. The centre of the milling cutter should move along the centre line of the workpiece whenever possible. These are the main criteria for good magnetic workholding practice, but let us look a little more closely at the specific problems encountered by three milling techniques:

up-cut milling
down-cut milling
face milling

In up-cut milling (Fig. 4.25a), the cutter attempts to pull the work up whilst pushing it along the table. The machining force is "F", which is tangential to the cutter. Its horizontal component "F_h" is resisted by the end stop to the left and the friction between the workpiece and the table's face. The vertical component "F_v" is resisted by the magnetised pull of the table. Fig. 4.25a demonstrates two very important points: first that the table's purpose is to hold down the work, and secondly that the end stop is there to resist sliding motion and should always be used.

Down-cut milling (Fig. 4.25b) promotes a machining force "F" downwards towards the table and to the bottom right-hand corner of the workpiece, so the end-stop is placed at the end where the cut starts. As the cut proceeds, the machining force helps to hold the workpiece down onto the table's face and this means that heavier cuts can be taken than in up-cut milling operations. Down-cut milling is always recommended as a result and therefore this presents no problems of overcoming backlash on machining centres, as the ballscrews are pre-loaded (see further details in chapter 1, section 1.3.2).

Face milling operations (Fig. 4.25c,d) offer more variable machining conditions than those for both up- and down-cut milling operations. For example, in Fig. 4.25c, the action of the cutter tends to push the work towards the left-hand end and to the side of the table, because the centre of the cutter is over the centreline of the workpiece – this is termed "on-centre" face milling. This condition cannot always be attained and sometimes it is necessary to position the workpiece off-centre, in relation to the cutter's centreline. For "off-centre" milling (Fig. 4.25d), the workpiece is still pushed to the same side as that of "on-centre", but in this case, towards the end-stop on the right. It is always advisable prior to beginning a cut to make a quick check before the feed is engaged to ensure that the correct positioning of the workpiece, end-stop, side-stop, packing and thrust blocks suit the particular cutting conditions.

NB: Preventative maintenance can always be carried out on magnetic tables whenever they exhibit slight wear, or some surface damage. This usually takes the form of regrinding to rectify any wear/distortion – with the magnetism off, of course.

This completes the review of milling workholding techniques and we will now turn our attention to some of the delivery systems used which may, or may not, incorporate the part with the fixture to the machine tool.

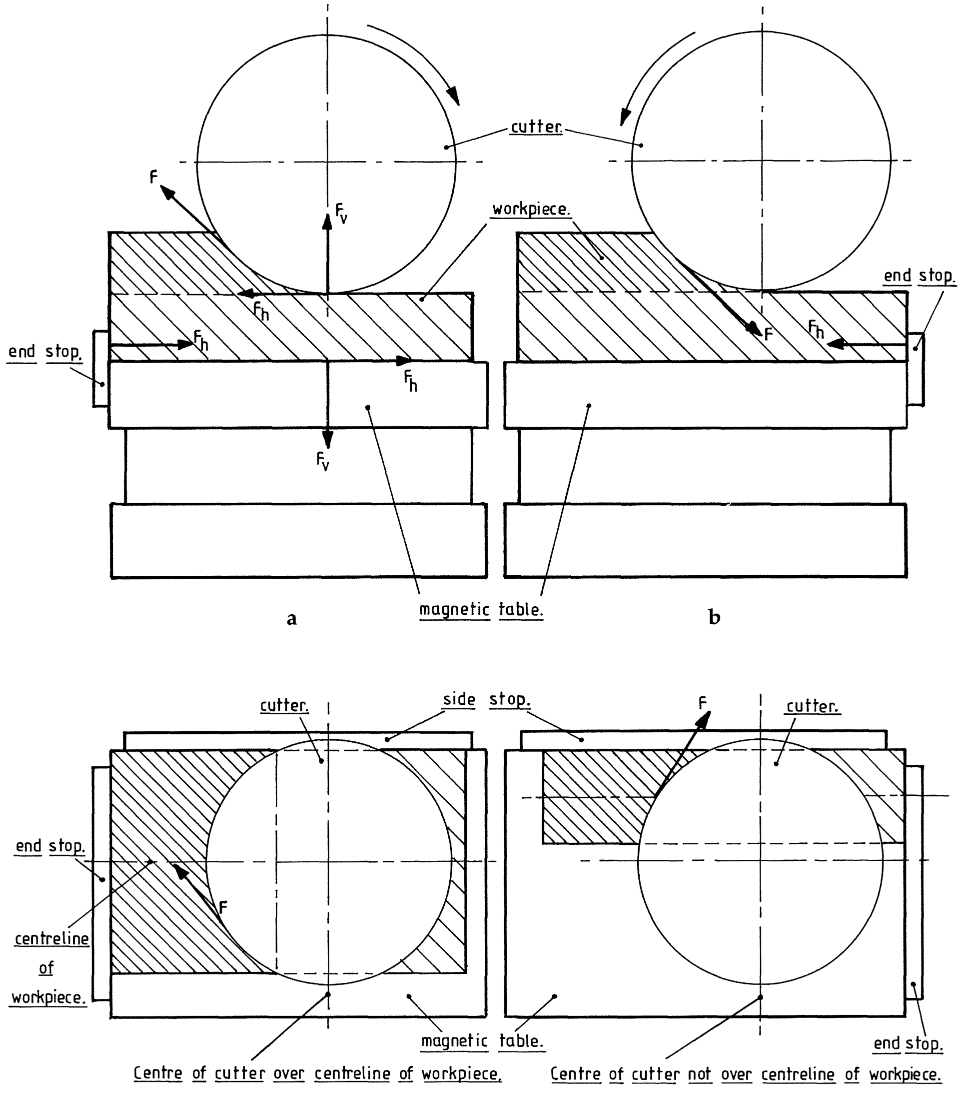


Fig. 4.25. The force vectors with different milling techniques on magnetic tables. **a** Up-cut milling. **b** Down-cut milling. **c** On-centre milling. **d** Off-centre milling. [Courtesy of Eclipse Magnetics Ltd.]

4.8 Workpiece Delivery Systems to Turning and Machining Centres

In order to considerably increase the flexibility of "stand-alone" turning and machining centres, some degree of automated part delivery is essential if a diversity of parts is the requirement. Not only is it important to ensure that a degree of workpiece flexibility occurs, but that work is continuously available to feed the machine tool – minimising down-time. A whole host of equipment to achieve consistent and rapid part deliveries has been developed and we will consider some of the more popular techniques for both turning and machining centres. It should be said that the success or failure of automated equipment falls heavily on the ability to feed parts regularly to the machine tools and this does not mean large buffer stores where parts pile up awaiting machining. Let us now begin this review by looking at a totally automated production environment and then go on to consider a degree of automation on "stand-alone" machine tools.

4.8.1 Complete Automation of an FMS using Automated-Guided Vehicles (AGVs) and its Control Principle

Whenever a company has a production commitment needing twenty-four hour machining capabilities, it is important to minimise intervention by operators whenever possible. Having operators under such circumstances is a high cost resource which can be significantly reduced, allowing the automation costs to overcome this loss of manual flexibility, but obviously not encompassing the whole of man's abilities. Any such automated system must offer a pay-back which is on a time-scale that is short and offers a competitive advantage to the company. Running a system in unmanned, or minimally manned circumstances needs many solutions to day-to-day involvement which would otherwise occur if operatives were present. These include ensuring that tooling is monitored and always available, parts are delivered to the machine tools at the correct time, placed and fixtured in such a manner that production can begin immediately. Not only must these factors be considered, but a well-proven scheduling and monitoring system is necessary. If we assume that features such as planned maintenance and all other production details are assured, we may consider the problem of ensuring that part delivery is attained under the best possible circumstances to enhance our productive capabilities.

Whenever a range of machine tools, such as machining centres, requires parts to be scheduled to them at pre-determined intervals, whilst at the same time allowing other parts to be either held in small buffers, or loaded onto coordinate measuring machines (CMMs) and so on, this can be efficiently achieved using automated-guided vehicles (AGVs), as shown in Fig. 4.26.

Most AGVs use wire-guided controls to ensure that a predicted path is assured. The "loop control principle" of an embedded wire in the floor and the alternating current is employed and controls the vehicle in the following manner. Loop control is based on the fact that an electric conductor through which an alternating current is flowing builds up around itself a pulsating magnetic field, which is strongest in the immediate vicinity of the conductor. A pulsating magnetic field passing through a coil creates an electric current between the coil terminals. This current is proportional to the strength of the magnetic field. A loop control antenna of standard type has two coils, one on each side of the loop. The difference in voltage between coils provides, after amplification, the control signal for the steering motor. If the antenna is correctly positioned, directly above the loop, the two coils provide equal voltage and the steering signal is therefore zero. If the antenna moves to one side or the other of the loop, the signal from one of the coils will increase whilst the other will drop, causing a steering signal to be generated. The steering signal will be positive when the antenna moves in one direction and negative when it moves in the other, and as such, it determines the direction of rotation of the steering motor.

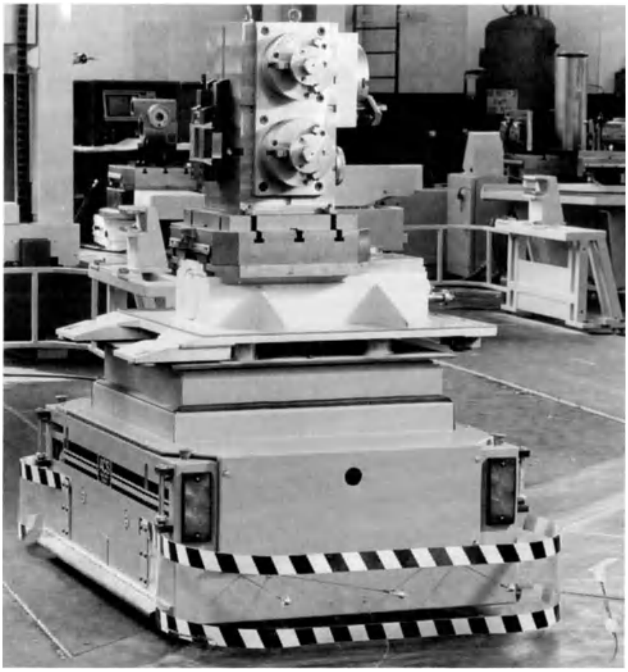


Fig. 4.26. An automated guided vehicle in the process of delivering a range of palletised workpieces held on a "cube" to a horizontal machining centre. [Courtesy of Cincinnati Milacron.]

In most cases the loop consists of a 1.5 mm PVC insulated electric cable which is grouted into a narrow groove, 15–20 mm deep, in the floor. The groove width is determined by the number of loops to be run in the same groove, and is usually 5–15 mm. Any loop should not be installed too close to solid iron constructions, as this will greatly affect the magnetic field of the loop. The loops are powered by AC at various frequencies, generated by a loop power unit-frequency generator. The frequencies are in the range 1000–2000 Hz in the loop control systems, with a loop current rating generally about 0.5 A. To provide this current, the frequency generator would normally require a voltage of less than 10 V. Thus, the power fed into the loop by the generator can be compared with that of a torch battery.

The loop power unit is a frequency generator which feeds current into the loop and thereby the magnetic field of the loop pulsates at a specific frequency. This means that as the carrier (AGV) follows the control loop, it listens only to the pulsating magnetic field which has a specific frequency. This is an important characteristic of the carrier which enables it to differentiate between, for example, two loops when they are fed with currents of different frequencies. The length of the control loop can vary from just a few metres up to several hundred metres. The longer the loop, the higher the current frequency and the greater the capacity needed for the frequency generator to activate the loop – this forms a limiting factor for maximum loop length, with certain other factors also being important when determining loop length.

A variety of loops can be installed in an FMS, each of which has its special steering frequency which the carrier is capable of recognising. By providing the carrier with orders to follow one of these frequencies (loops), to a certain position and then switching to another control or steering frequency, the carrier is given a route selection mode. To make the carrier travel slowly at, for example, bends, and subsequently pick up speed on straight stretches, the carrier must know exactly where it is along a given route. This necessitates an extra loop with a different frequency at the corners. As the carrier is also able to recognise this extra frequency, it knows when it is approaching a corner and can therefore change from high to low speed.

We have now seen that an AGV can be made to follow a control loop and select a given route, therefore in order to provide a usable transport function for pallets to machining centres, it is also necessary that we:

provide the carrier with some form of handling equipment, such as a load platform with either a powered roller top, or some other form of load carrier for the pallets

inform the carrier what it is required to do and where it is to be carried out

Below are listed some of the examples of what a carrier can achieve and where it can be achieved.

What can be done:

stop/start

travel at high/medium/low speeds

travel forward/reverse

report on its position

carry out prescribed manoeuvres with its handling equipment

keep a check on its battery charge condition

Where function includes how the carrier:

can be guided to the correct area of the shop floor, by means of route selection

can be stopped in the correct position

The wireless broadcasting of information telegram transmission takes place:

from the carrier to stationary equipment, for example, a presence signal

from stationary equipment to the carrier, for example, stop orders, loading/unloading orders for pallets, frequency selection for route following to machine tools or pallet buffers and so on

A "telegram" consists of a number of information bytes, which are sent one after the other and each bit can, in principle, represent a function. This means that a "telegram" can be equivalent to many functions. The carriers and the stationary equipment both have communication units which can transmit and/or receive "telegrams". These communication units each have an antenna for wireless transmissions, which are made inductively between the antenna – not to be confused with the loop control antennas – of the carriers.

This is how an AGV operates and it is almost exclusively used in large FMS installations for either of two aspects:

loading/unloading of palletised workpieces (Fig. 4.26) to machine tools, inspection machines, etc.

delivery of tooling in complete magazines, or individually to machine tools

A feature of such AGVs is their ability to palletise multiple part setups on each pallet (Fig. 4.26) in an almost infinite part orientation. Each pallet is unique and is coded by a variety of means, such as:

binary coded pins
programmable microchips
bar-coding
radio transponders, and so on

Thus, when a part is scheduled onto a coded pallet, the AGV knows:

where it is
where it must go to
the part program to be loaded once on the machine tool
its destination once machined

It achieves these tasks by a two-way dialogue interrogating the host computer, or cell controller, which sequences and schedules moves and software transactions accordingly.

NB: This is obviously an over-simplified account of the complex task of running an FMS.

4.8.2 Gantry Robot-loading Turning Centres

The utilisation of manual machine tools is often extremely low, with the total number of hours in a year being 8760. For a typical one-shift production department the total number of working hours is approximately 1650 and in mixed manufacturing runs only about one third of this time is used for actual machining operations. The remaining time is spent setting up, changing parts, inspection check-ups and so on, together with a certain amount of idle time. In order to improve this situation, the "limited manpower production" techniques enable productive increases outside normal working hours, offering greater flexibility in meeting variations in demand.

Incorporating a gantry robot onto a stand-alone turning centre (Fig. 4.27) in conjunction with a conveyor for small part buffering, allows components to be loaded/unloaded at any predetermined time and this reduces idle time considerably. It is very important in any robotic application to be able to load and unload workpieces simultaneously and gripper design must take account of this important feature. The production functions of a typical gantry robot are to:

have freely programmable movements

utilise the same control system as the machine tool, if possible, and enable parts to be rapidly set up

be able to handle all types of components – within the constraints of the machine, allowing the collection/replacement of parts in various positions

be able to handle heavy workpieces

enable components to be changed over rapidly

enable complete machining and transferring of parts to auxiliary operations

enable manual operation

Fig. 4.27 shows a typical portal construction, consisting of a horizontal beam which is parallel to the machine's spindle centreline and supported by vertical pillars. The shuttle carriage runs along guides in the portal beam and is driven by a DC motor, with an encoder, enabling the carriage to be numerically controlled. The vertical slide on the carriage unit can be positioned along its guideways by means of a feed system, also using numerical control. The gripper unit is held on the vertical slide and

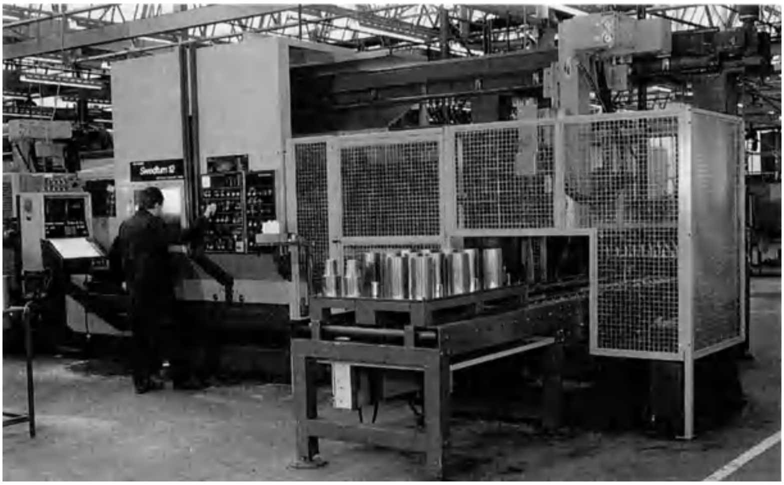


Fig. 4.27. Handling raw material billets by means of a computerised part changer (CPC) for automatic loading into a 4-axis turning centre. [Courtesy of SMG (UK) Ltd.]

normally features a double-sided gripping unit which rotates around a horizontal axis. This unit consists of two pairs of grip jaws which can be set and replaced on "master" jaws. These grip jaws can clamp both external or internal diameters, with each pair of grip jaws being held on either side of the indexable axis. This axis can be positioned in four different angular positions: 0°; 90°; 180°; 270°. Both the rotary motion and the movement of the grip jaws are hydraulically operated, with various operations being programmed by M-codes.

A typical gantry (Fig. 4.27) has five degrees of freedom:

the horizontal movement of the shuttle carriage in the longitudinal direction of the machine
the vertical movement of the gripping unit
indexing of the gripping unit, 4 × 90°
the independent movements of the gripping jaws – two motions

The shuttle carriage's horizontal and vertical motions are numerically controlled and freely programmable, for both speed (0–20 m/min horizontally and 0–60 m/min vertically) and indexing of the gripping unit simultaneously.

This gantry can also have an automatic gripping jaw change incorporated into the system, to further increase its versatility, and it may be used in other modes: to either change modular quick-change cutting heads, or even complete chucks and so on. Yet another feature which may be added is an electronic measurement control unit, for quality assessment of dimensional features on the finished part, using: callipers, receiver gauge fixtures, touch-trigger probes. The measured values are transmitted to the control equipment and the computer will continuously correct the tool setting so that specified tolerances are held. If a measured value falls outside this specified tolerance limit, or indeed if the pre-set value for maximum tool compensation is exceeded, then the machine will immediately stop.

Such sophisticated gantry systems offer a wide degree of part control, flexibility, and quality assessment, whilst considerably improving productivity and are easy to incorporate into an FMC. Not only are gantries becoming increasingly popular for these reasons, but they also use only a small amount of floor space – an expensive premium in most manufacturing departments – and have the moving parts well above the machine, allowing them to be safely guarded. Lastly, gantry robots can be added to most machine tools relatively easily, without major modifications to the machine tool, which might otherwise be costly and still give access for operator intervention, or manual setup and running.

4.8.3 Rail-Guided Vehicles (RGVs) for Prismatic Manufacture on Machining Centres

The statements made about AGVs in section 4.8.1 are equally valid for rail-guided vehicles (RGVs), but a fundamental difference exists in the method of operation of each system. The ability of an AGV to move around and about the manufacturing department is the result of following "loop control" wire/s grouted into the floor. There is basically no limit to its freedom of movement, providing of course that the cableloop has been established. Conversely, the RGV is much less adaptable and is confined to moving on rails, as its name indicates, but it has significant advantages over the AGV in certain applications.

The RGV, because of the rail-guidance, is much more positive in its progression from one pallet station to the next and it can move at higher speed with greater precision. This greater precision of placement at each pallet station enables the designer to have an easier pallet loading arrangement and this reduces the cost of the RGV. Often AGVs require a scissor-lift mechanism to ensure that pallets are loaded onto the machine correctly, as they often have different loading heights. Yet another function of RGV delivery alluded to above, namely speed of operation, means that only one RGV might be necessary to service a range of pallets to the machining centres in the cell (Fig. 4.28), which is yet another cost saving.

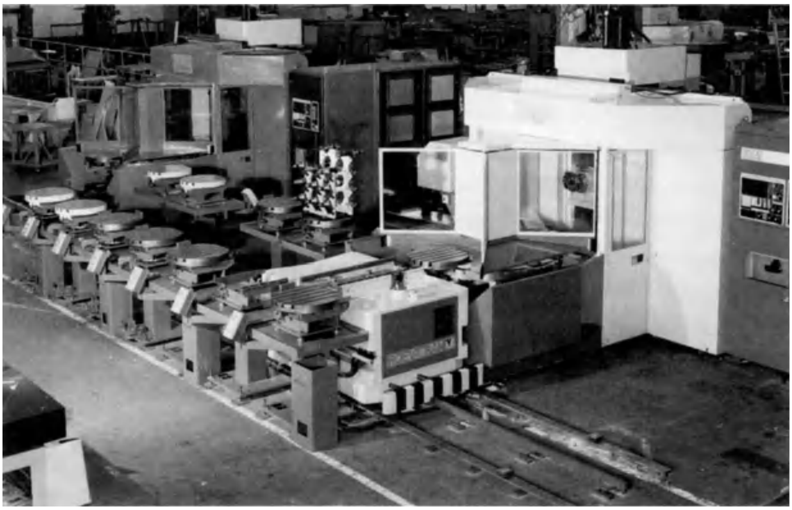


Fig. 4.28. A rail-guided vehicle (RGV) automatically delivering palletised workpieces and cutting tools to two horizontal machining centres in an FMC under test. [Courtesy of FMT.]

An RGV can quite easily be incorporated into a cell configuration and may be retrofitted with only minor disturbance to an already existing line of stand-alone machining centres. The RGV concept has become extremely popular as a result, not only for part scheduling duties to each machine tool, but also to supply tooling carousels/magazines automatically (see Fig. 4.28). This flexibility of tool and part supply means that unmanned machining is possible over twenty-four hour periods. Many companies now using RGVs in flexible manufacturing cells are obtaining production efficiencies greater than 90% during the lifetime of this cell, offering a pay-back in about two to two and a half years. Such amortised costs allow capital equipment expenditure to be confidently predicted and, coupled with the twin benefits of increased profits and greater flexibility, give a company a "competitive edge" in the market place.

This completes the review of the chapter on workholding technology, with one notable exception: a discussion about computerised workholding techniques and the advantages to be gained from embracing such a philosophy. In this final section of the chapter we will see that such workholding arguments are not fanciful; they offer major advantages to both small and large companies which have the foresight to capitalise on the advances in the software developments, coupled with its mutually advanced workholding techniques.

4.9 Computerised Workholding Techniques – the Philosophy behind the Applications

More and more industrial developments move towards increased competition, which forces the need for greater efficiency in both human and technical production resources. One factor resulting from such increased competition is the number of products and their variants offered to customers by manufacturers. This highly competitive situation leads towards completely different manufacturing philosophies, like small batch production, and furthermore, to a direct demand to reduce intermediate stock levels and approach "just-in-time" (JIT) production.

An efficient small-batch, or indeed, one-off production capability demands quick setup times. Such setups require repeatability without renouncing the requirements of both time and precision. If long and unsure setup times are the norm, this will obliterate any possibility of economical small batch production. In today's competitive world, where highly productive machining centres and efficient workholding methods are employed, it is quite possible to reach a one minute setup time. Even though it is expected that many companies have such potential, few reach these short setup times. The main reason for this shortfall in workpiece setup is that invariably the organisational and technical system solutions are not adapted to the latest computer-aided techniques of production.

The computer-aided production technique demands an industrial environment which differs markedly from that of a conventional manual arrangement. There are two production areas which must be addressed:

"indirect production", comprised of all the activities to prepare for "direct production"

"direct production", which creates an income, but only when the machine tool is manufacturing parts

It follows that the set-up time is the borderline between "indirect" and "direct" production. Any production resources can be divided up into three specific areas: hardware, software and a new term, "know-ware", this being the relationship between the machine tool, computer and knowledge. All areas must fulfil the demands of system solutions of fixed references and knowledge, in order that they may be linked together efficiently. Such systems allow "closed circuits" which are a prerequisite for a one minute setup.

Common for all production machines are the three basic components:

work spindle
machine table
control system

Most machining centres offer linear control in three axes: X, Y and Z, with the machine control system's purpose being the predictable patterns of movement controlling the relative state between the cutting tool, machine tool's spindle and the fixturing/workpiece. In order to enable a one minute setup to function, fixed references are necessary in the spindle and on the machine table. These hardware references, as well as the software, must be defined, thus unambiguously closing the circuit between the linear movements of the machine, the spindle and the machine table. To achieve the goal of a one minute setup, requires complete configuration – setup of the holding and fixing of tools on the machine table, the correct choice of cutting tools and setup data which appears on the CAD/CAM screen within a minute, to predetermined positions relative to the machine's datum in the X, Y and Z axes.

Usually there is a range of different machine tools of various types and sizes within the manufacturing facility and all of them should be integrated within the total closed-loop technology environment, allowing uniform solutions for the hardware, software and know-ware. As a cautionary note, the objective of a one minute setup will not be achieved by simply purchasing costly machine tools, accessories, computers and CAD/CAM programs, if at the same time we do not ensure that knowledge is available on the spot where the technique is to be used.

It is current practice to have machining centres automatically changing pallets and cutting tools within 15–20 s; this means potentially that we are ready to proceed with the next product after this time – often on multi-palleted machines, or by delivery to an FMC. Such pallets are expensive and in order to optimise the number of pallets required, it is common practice to change the fixtures. Usually there is no special technique developed to change fixtures on the pallets and this results in excessive change-over times, whilst often lacking precision. Even when machine tools are fitted with the ubiquitous T-slot tables, they lack the three references of cutting tool, machine tool's spindle and fixturing/workpiece to the known datum, which leads often to setup times of hours and days, at worst, instead of 5–10 min.

This lack of development in machine tool T-slotted tables over the last hundred years poses the real problem in that only one reliable reference is known – the Z-axis setting plane. Thus the demand for fixed reference positions necessary for one minute setup is not met. As the closed loop is not achieved, then the table must be adapted to preset the X and Y axes positions in the desired relationship to the datum for confirmation of the workpiece's position. Often the T-slotted table is either replaced by thread holes and dowelling positions, or a grid/sub-plate is added to the table with holes and threaded grids. This latter modification forms the basis for a different approach to the problem. A pre-drilled/tapped precision fixture uses expanding mandrel dowels to locate ancillary location aids and allow parts to be confirmed in known relationships to the machine tool's datum. Expansion-shell mandrels eliminate both play between the hole and the mandrel and also any deviations within the precisely drilled pattern on the fixture.

The precision fixturing system depicted in Fig. 4.29 offers repetitive assembly to within 0.005 mm using the expansion-shell mandrels, with holes of 20 mm diameter and an H7 tolerance being at hole distances 100 ± 0.01 mm, having a tightening moment of 10 Nm for the mandrels. Each dowel hole for the expansion-shell mandrels is precisely known in relation to an alpha-numeric coding and these reference holes possess unmistakable positions relative to the built-in electronic machine datum for the machine tool on all coordinate axes. This means that the reference holes close the loop as described above, fulfilling the requirements between the spindle and machine table zero points/datum and as such are the prerequisite condition for setting up according to our one minute setup production strategy.

Finally, using this precision fixture and its ancillary equipment for part setup in conjunction with computer-aided manufacturing (CAM), the table can be called up from the software in the computer library and will quickly be brought up for setting up the simulation directly on the display, as illustrated in Fig. 4.30. This provides the basic data for the operator's setup and becomes a communication link between "man" – machine – computer.

To summarise the advantages of computerised workholding techniques:

reduction in the cost of holding and locating devices
CAD/CAM integration
has the ability to be combined with modular-based fixturing systems
fulfils the requirements of closed-loop technology offering one minute setups
minimises operator setup times and improves the degree of machine tool utilisation
suits any machine tool with a T-slot table

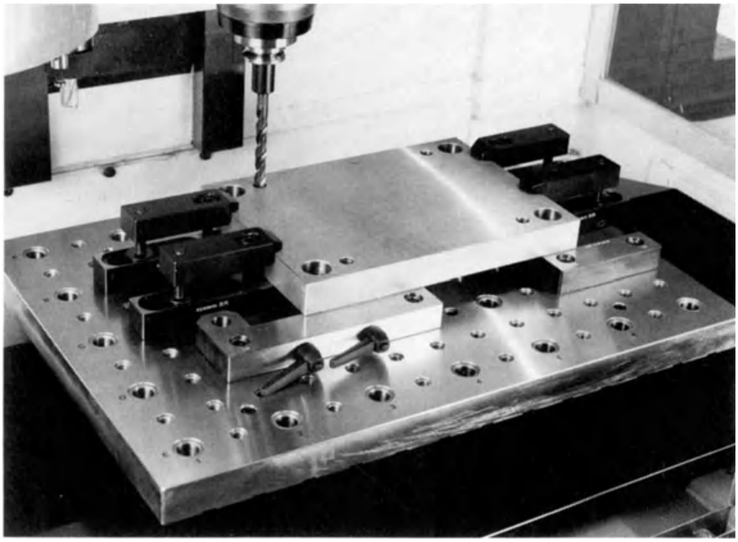


Fig. 4.29. A part setup on the precision fixture which is left permanently in situ on the table and accessories are quickly added when the workpiece geometry changes. [Courtesy of System 3R International.]

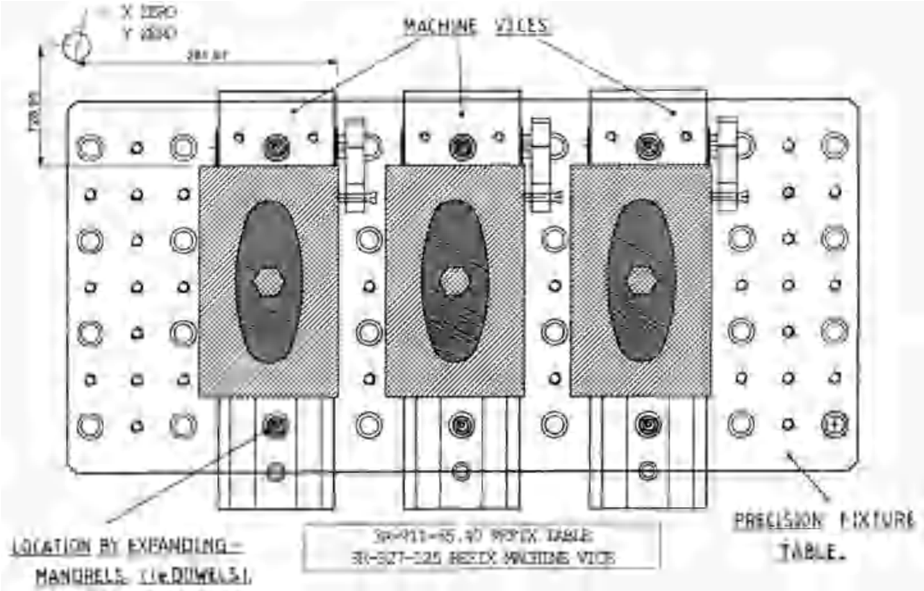


Fig. 4.30. A computer "hardcopy" off the CADCAM system showing the multi-vice setup where the precise location of each part is known. [Courtesy of System 3R International.]

simple, reliable fixture changes, due to unmistakable positions and reference holes utilising distinct alpha-numeric modular spacing

existing special and standard devices can be integrated to the same high degree of rigidity and accuracy, at very low cost

under appropriate conditions of usage, the pay-off period will be less than twelve months

links together the various makes and types of metal-working machines in a horizontal closed-loop technology concept

provides links between "man" – machine – computer power, obtaining a solution to long operator setting times by one minute setups which simplifies both the resetting of fixtures and their degree of utilisation

This completes our review of some aspects of workholding technology, but it is by no means an exhaustive account of the myriad methods available for part setups for manufacturing engineers. In chapter 5 we will go on to consider some of the methods by which part programs are written and review some typical CNCs as well as discuss other inter-related methods and equipment presently in service.

Chapter 5
CNC Controllers and Programming Techniques

5.1 Introduction

The development of machine tool hardware since the introduction of numerical control in the late 1940s and early 1950s, has been progressively evolving and continues to do so, as we saw in chapter 1. Even more dramatic than this development are the rapid advances in software engineering and electronic integration during this time and the speed of change has not abated. In fact with the advent of CNC in the 1970s, controller sophistication has considerably increased. The advantages gained from utilising CNC technology over conventional manual skills were argued in chapter 1. The maturity of the latest controllers, in terms of their programming ability and reliability, makes them even more necessary for fast "turn-around" of parts coupled with improved productivity and flexibility in accommodating design modifications on components with the minimum of disruption to production.

The research and development departments where such systems are designed are continually looking for ways of simplifying controls and machine interfaces. System specialists are attempting to widen the scope of CNC and move into areas where its application would have previously been impracticable. The current machine controllers offer greater ease in their use – often termed "user-friendliness", a much abused term – with some versions allowing "conversational language program" (CAP) input in plain English, as an alternative to the conventional "word address format", yet to be discussed. As we shall see, with the more sophisticated and expensive CNCs, fully integral programmable logic controllers (PLCs) having a 32-bit data processing capability are increasingly being offered. The advent of Manufacturing Automation Protocol (MAP) and other Local/Wide Area Networks (LAN/WAN) has allowed previous stand-alone machine tools – often termed "islands of automation" – to be successfully interfaced to other machines, or peripheral devices typically associated with Flexible Manufacturing Cells or Systems. Such communication ability allows the successful data transfer of information from one controller to another, without corruption – often euphemistically termed "hand-shaking" – but more will be said about data transfer and communication techniques in the final chapter. Most systems are designed for "modularity" and "compatibility" – this latter term we have briefly touched on above. "Modularity" of the hard/software, means that the system/

machine tool designers have greater design flexibility, whilst an expansion in size and power of the integral PLC can accommodate both soft/hardware additions within the confines of the controller.

Most of the current controllers allow the programmer a variety of means of programming parts, such as:

"word address programming" – where a series of alpha-numeric characters, "G" and "M" codes associated with numbers, are used to control and manage the numerical distances between one feature and another

"parametric programming" – uses "free-variable" values which can be assigned to linear distances for either motions or calculations of slideway moves to obtain a component feature within the program. Such "parametric" techniques allow skeletal programs to be developed for a range of parts and by changing assigned numerical values, a feature can be changed at will, it can be used for a "Group Technology" (GT) approach for families of parts. "Parametric programs" can be condensed into fewer "blocks" of information for a desired part, when compared with "word address" formats and as such require less memory space (see section 5.4.10)

"conversational programming" – or as it is sometimes termed "blueprint"/"shop floor" programming – is achieved by answering a series of questions related to the desired part feature, e.g. pitch circle of holes, which is then compiled into a format acceptable to the CNC for tool motions. NB: A "graphics capability" is required to build up the desired features of the part and for "tape prove-out" (see section 5.4.11)

"background"/"parallel programming" – allows an operator to program a different part from one that is at present being machined – using a different area of the memory of the CNC for its compilation. This considerably speeds up the lead-time necessary for the production of a successive part

"off-line programming" – is usually undertaken on either a CAD/CAM workstation, or using "computer-assisted part programming" (CAPP) equipment normally with a "direct numerical control" (DNC) link to the controller through the RS232 interface, or via punched paper tape and tape reader into the controller – rather an old-fashioned method nowadays. NB: "Off-line programming" can be achieved away from the machine tool. This overcomes the distractions associated with programming in a production environment and as such, allows the programmer to develop programs under ideal conditions whilst not affecting the demands of production

"digitising" – often termed "reverse engineering", whereby a model or component's dimensional features are "captured" and used as a basis for the generation of a part program. NB See Figs. 5.32 and 5.33, together with a description of the process, in section 5.7.

In the following sections we will see how the use of programming aids can minimise the length of programs. This may be an important criterion when one is faced with either a small memory capacity in the CNC, or many parts already stored in the memory, or a complex part geometry, which might otherwise take up considerable space in this memory. These programming aids are usually available for most CNC controllers, or may be offered as "options" from many universal/proprietary builders. Such options are: "mirror-imaging", "scaling", "angular rotation", "datum shifting", "canned-cycles", "subroutines" and "nested subroutines", which all reduce the length of the part program considerably, with the secondary benefit of minimising the expertise necessary in writing such programs. The structure of "word address programs" will be enlarged upon later – arguably the most common technique used in developing CNC part programs for both turning and machining centres. For the sake of clarity this topic will be based, in the main, upon one controller made by a popular universal CNC builder. It should be said that there is not enough space within the text to devote to an exhaustive account of how such part programs are developed, but an appreciation of the main aspects of the logical structure and compilation of a program is all that is anticipated from the reader. To gain more insight into and appreciation of the unique problems associated with programming/operating machine tools, specific courses and their respective manuals are available when either CNC machines are purchased, or new personnel require retraining. Such courses give the would-be programmer a measure of expertise in part program development/manipulation and its subsequent operation for given part geometries. Any specific CNC machine tool offers a unique intellectual challenge to the programmer which must be overcome in order that satisfactory part programs are developed.

Prior to a discussion on the part programming philosophy and strategy needed to produce successful programs, there will be a brief review of just some of the typical controllers currently available from both universal and proprietary builders. It is hoped that this will give the reader a greater insight into the subject of CNC controllers and aid in the understanding of later sections in the chapter.

5.2 CNC Controllers – a Review

In order to discuss the diverse range of controllers available for CNC machine tools, it is necessary to try and highlight the differences with just a few of those currently available. One of the most popular controllers is made by GE Fanuc. It offers a highly sophisticated design and programming ability. This high-speed controller was first shown at the "7 EMO" exhibition in Milan in October 1987. It became available to customers during 1988 and by the 1990s has seen universal acceptance across a large range of machine tool builders. Its principal features are that owing to its high processing speed, it can be used for complex die sinking, or high-speed machining operations. It also offers a number of artificial intelligence (AI) features, allowing it to make logical decisions in concert with changing process needs, including: simple "conversational programming" and guidance in intelligent failure diagnostics.

By using multiple 32-bit high-speed Motorola 68020 microprocessors, together with the original 32-bit multi-master bus, it can achieve machine command processing rates up to ten times faster than most currently available CNCs. Furthermore, an ultra high-speed programmable machine controller allows interface commands to be executed up to eight times faster than previous systems. With such advanced microelectronics comes a controller which has been significantly reduced in size, principally because of using surface mount and customised large scale integration (LSI) electronic component technology. Reliability is another bonus of such technology integration, whilst a high-speed backplane bus architecture allows its boards to be utilised in virtually any number and combination. Such a system has a fully digital interface to high performance AC servo-control technologies, giving a quick-response servo-system that is unaffected by mechanical load variances – this means that with fully electronic absolute position detection, machine referencing is made a thing of the past.

For high-speed machining capability, this controller can command multiple axes in both rapid traverse and cutting speed up to 100 m/min with a resolution of 1 μm, or alternatively, traverses at 24 m/min with 100 nm resolution. Speed of machining can be increased still further if the optional 32-bit subprocessor is used, permitting super high-speed machining of continuous short blocks. For example, if the requirement is for 3-axis simultaneous DNC operation in 1 mm continuous blocks, machining speeds of 15 m/min in EIA format, or 30 m/min in binary format input can be achieved. This requires the RS 422 interface to process data up to a maximum speed of 86.4 kbps – reading the high-speed information from the host computer. Such simultaneous control necessitates processing capabilities of the highest order, in order to minimise "shocks" to the machine as it: starts, stops, accelerates, and decelerates. Therefore a "look ahead" capability of up to 15 blocks of command information is necessary and a smoothing of acceleration/deceleration occurs.

Much more could be said about such a controller, mentioning such features as its ability to make automatic decisions of tools and cutting conditions, the arbitrary tool path editing function, tool interface checks with on-screen animation, automatic process determination – creating machining processes to cut parts if the blank and part figure have been defined, together with a variety of interpolation modes: linear, circular, cylindrical, involute, spline, polar coordinate, exponential, spiral, circular thread, and finally hypothetical axis interpolation. However, this would entail a chapter alone, although several such advanced features will be discussed later in this chapter.

The Siemens Sinumerik controller offers a competitive alternative to the one described above and both are available, when suitably configured, for either turning or machining centres with multiple axis capability. The Sinumerik universal controller utilises a range of "soft keys" situated below the screen, enabling the operator to choose which menu to monitor. In the previous controller more "soft keys" allow considerably more functions to be chosen as the operator desires. Any of the currently available sophisticated controllers have the capability of compensating for minute variations that occur in the manufacture of the leadscrew. Such leadscrew error compensation must be achieved in all axes simultaneously and in the Sinumerik up to 1024 compensated positions in all axes are possible. The distance between all compensation positions is selectable in the range 0.01–320 mm on any axis, whereas the resolution can vary 1–64 μm. Such errors are determined by laser interferometry for each linear axis as explained in chapter 1, but may be modified at periodic intervals when the machine tool is recalibrated.

Both of the previous controllers can be termed "universal" and as such may be purchased for a variety of machine tools and configured accordingly. However, some controllers are manufactured by "proprietary" machine tool builders and are generally not sold for incorporation onto other company's machines. The Electropilot (Gildemeister (UK) Ltd) controller has been built with a totally different philosophy. What is particularly noticeable about this controller is the absence of many of the "keys" associated with the other controllers, making it popular and very easy to operate on the shop floor, but still having a high level of computing sophistication. This modular multi-processor system utilises 16-bit microprocessors, supplemented as necessary with 32-bit units, coupled to specific processors for axis control. This allows the controller to be expanded from 2- to 4-axis machines catering for: rotary axes, interfaces to DNC, linking into larger manufacturing systems, or with the host computer.

The Acramatic controller (Cincinnati Milacron) is a "dedicated" universal controller which can be fitted to either machining or turning centres. Yet again it has many of the features described on the more sophisticated "universal" controllers mentioned above, but it has been "customised" for a specific application. A novel feature of its 4-axis cousin, is that when programming part features, one need only worry about the relative motions in two axes, namely "X" and "Z". Once the program has been compiled and proven, it automatically selects operations using the second turret for either simultaneous machining such as: "balanced" turning, drilling and turning, boring and screwcutting, and so on, simplifying multi-axis turning operations still further.

A major problem either overlooked or rarely addressed by companies looking for a machine tool, is the time and number of "key strokes" necessary to input a program successfully into the controller's memory. This is particularly relevant when a company must write and "prove-out" the programs at the machine tool. If many "key strokes" are necessary to write a program, each one is an opportunity to produce an error, requiring further editing under the distractions of a shop floor environment. Comparison between the amount of "key stroke" processing and the time it takes to input the same program is a good "bench mark" of its "user-friendliness" and programming logic. Any company considering the purchase of a CNC machine tool, will not find this a wasted effort during any feasibility study undertaken on their "short-list" of machines.

To complete this review of CNC controllers, the latest top-of-the-range Acramatic controller (Cincinnati Milacron) is worthy of mention. It has an almost word processor-like capability allowing "cut and paste" editing of part programs, so that single characters, blocks, or strings of characters can be defined, erased, copied, or inserted quickly and easily. Probably its most unique feature is the touch screen with pop-up windows and a calculator which provide easy function selection with less risk of error. The controller offers a real-time multi-tasking operating system in which nine microprocessors share in performing a range of tasks, optimising machine productivity and part quality, whilst the operator is involved on background tasks – such as downloading a program, or tool data revision. Whenever demanding applications are the requirement, such as running at maximum processing speed and accuracy, this necessitates the controller having optional 32-bit Intel 80386 processors.

A multiple set-up support package makes this controller ideal for any untended operations, providing scheduling, sequencing and status definition capabilities usually available only in workstation managers and similar off-line systems. As well as pallet and part scheduling together with sequence definition, users can define the pallet, fixture, and part offsets up to a maximum of 16 pallets of parts, but with sufficient offsets available to accommodate up to 64 parts for these pallets. With such a comprehensive "pallet pool", the tooling database, of necessity, must be large and the tool tables have a separate program memory, allowing users to manage up to 500 tools, with the expanded optional memory. Additional features include over 20 000 metres of part storage on a 20 megabyte hard disk, with 32-character alphanumeric program identifiers, coupled to RS 491 level II data line and terminal emulation capabilities. Such controllers are becoming "industry standards" for machine tools, offering greater flexibility, sophistication and adaptability to both operator and programmer alike.

5.3 The Sequence Used to Generate Part Programs

Prior to writing a part program for a machine tool there are many important considerations which must be addressed, if the part is to be manufactured successfully. It is simply not just a matter of stating the component geometry, or even considering the motions of the tool's path, without taking into account such crucial factors as how the part is to be held and on what machine, which tools should be selected and cutting data utilised. Considerable skill is necessary if these inter-related decisions are going to produce a component that is "right first time".

If we consider the sequence necessary in the generation of a CNC program, it can be thought of as four fundamental stages:

problem description
processing
control
adaptation

From Fig. 5.1 one can gain an appreciation of the many inter-related activities which go towards the successful completion of a part program. In this example, the part is either defined by a CAD/CAM system, or developed using a programming language such as "word address" at the formative "problem description" stage. The geometric data for the blank and finished part may include sub-programs together with the cutting sequence within its main program, giving the programmer a process description that can now be "processed". At this stage, assuming that the initial part program is acceptable, the details such as specific tooling requirements, workholding and materials can be defined. It is also assumed that a machine tool has already been chosen which will be compatible with the expected production demands for the part, in terms of both quantity and quality required. Knowing the machine tool specification can allow a degree of flexibility in our calculation of the cutting sequence and the distribution of cuts, cycles and axes chosen. For example, during this "processing" stage and assuming that a 4-axis turning centre is specified to manufacture the parts, we might want to "balance turn" the part, or machine features using the C-axis – perhaps with "driven" tooling. Decisions are made to produce the part in the most efficient manner and at this stage "collision monitoring" problems can be explored through the use of a graphical display of the cutting sequence. This will ensure that collision of both tools and workholding equipment is avoided in the dynamic display on the screen; furthermore this output can be plotted for a "hard copy" file, for later use/verification.

Finally, once the programmer is happy that all these conditions have been met and any anticipated problems resolved, the final CNC program is produced together with the necessary time calculations and a copy is stored in either the program library, perhaps using a DNC link, or for permanent hard copy storage on an NC punched paper tape, together with the complementary setting sheets, times, etc. It is important to ensure always that a "back-up" copy of any part programs is safely stored away from the machine tool in some secure and fire-proof environment. This is because it is quite easy to over-write and erase a program left in the machine tool memory inadvertently, or lose the programming sheets kept within a planning office, with no particular tape library facilities. It should be remembered that a company's time, cost and expertise are tied up in such programs and they should be treated as a valuable resource, worthy of protection.

In the following sections we will explore how the structure of a CNC program is produced and go on to consider how this relates not only to the machining and turning centre's datums, but mention the methods of choosing coordinates relating to the workpiece and some of the special features allowing the programmer greater ease in defining the part, whilst minimising its length. Later on, other sections will look at specific cases of interpolation methods and actual part programming problems, as well as the effects of cutter compensation and the use of "canned cycles". Finally, applications such as high-speed machining methods and digitising techniques will be referred to, followed by CAD/CAM solutions, in producing complex profiles on components.

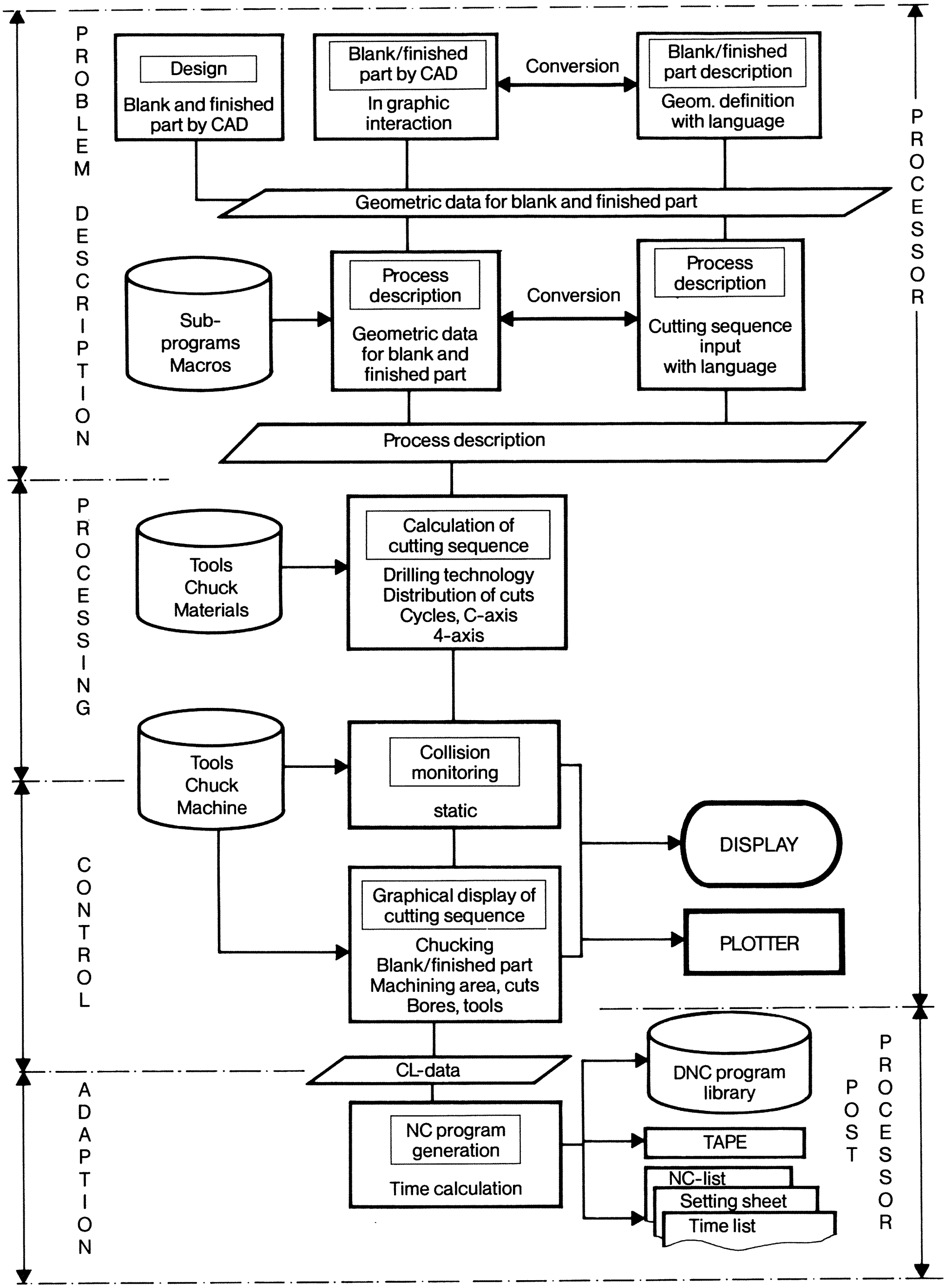


Fig. 5.1. Generating a sequence for a CNC program. [Courtesy of Gildemeister (UK) Ltd.]

5.4 The Fundamentals of CNC Programming

By now the reader should appreciate that any CNC machine tool is guided by its part program through the controller. In order to perfrom the necessary machining operations, the controller needs specific information such as:

workpiece dimensions
tool travel and the axis of the slideways
machining sequence
tool selection
speeds and feedrates

The program will sort this information into the necessary sequence and then translate it into a language which can be understood by the controller. In the following programming examples they have been written in an accepted ISO code, with all geometric/linear values in metric units. The programming instructions describe just the standard range of functions of the system, with the maximum values specified being limit values and during operation they may be restricted by machine data, interface unit and input/output devices.

Program Structure

The programming examples throughout this chapter are based on the DIN 66025 structure.

Any part program is comprised of a complete string of blocks which define the sequence of operations for a machining process on a CNC machine tool. The part program (Fig. 5.2a) comprises:

the character for the program start
a number of blocks
the character for the program end

The character for the program start always precedes the first block in the part program, whereas the program end character is obviously contained in the last block.

If we consider the part program structure in terms of its input/output format, one may use a mixture of "subroutines" and "canned cycles" as being components of the program. As was mentioned earlier, more will be said on these topics later in the chapter, but for now it is worth mentioning that such "canned cycles" and "subroutines" are normally generated either by the machine tool builder, or the controller manufacturer – assuming it is made for universal use. Most standard program memories can store about 200 part programs and "subroutines" simultaneously, with their input sequence being purely arbitrary. Usually, whenever the programmer enters a part program manually, termed "manual data input" (MDI), with the "block number soft key" activated, any future "block numbers" are generated automatically with either steps of 5 or 10 between them, or as on some controllers, step numerical values can be varied, from the first block. The "cancel" key can be used to delete any entered block number, or the "edit" key could be used to overwrite this block's information.

Block Format

A block contains all the data necessary to implement an operating procedure, which can contain several words and the "block end" character (see Fig. 5.2b). There is

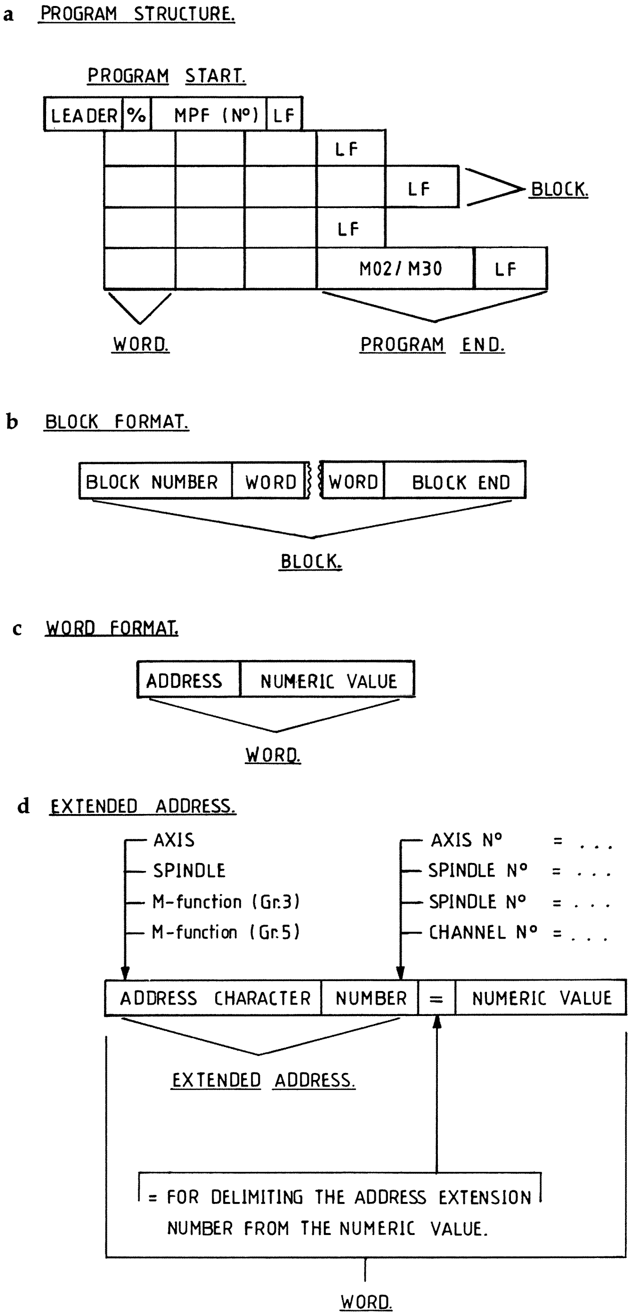


Fig. 5.2. The fundamentals of programming, based on DIN 66025. [Courtesy of Siemens.]

usually a finite limit to the length of block and this might typically be around 120 characters; furthermore, the block is displayed in its entirety over several lines, when approaching the maximum value. Any block is entered under an address "N" with block numbers being freely selectable. Defined "block search" and "jump" functions can only be guaranteed if a block number is used no more than once in any program. It is also permissible to program a block without a block number and in this case it is not possible to either "block search" or use the "jump" functions. Obviously any block format should be made as simple as possible, by arranging the words of the block in the sequence of the program key, as shown in the block example below. NB The controller has a "default condition" where "G" and "M" codes are automatically preset upon controller at start-up and must be over-written when changes are required, such functions are "modal".

N6832 G..X..Y..Z..F..S..T..M..LF
where
N = address of block number
6832 = block number
X..Y..Z.. = position data
F = feedrate
S = spindle speed
T = tool number
M = miscellaneous function (see section 5.4.8)
LF = block end

Each block must be terminated by an end-of-block character "LF". Such a character may/may not appear on the screen, or its equivalent, depending upon the controller, although when a program is printed out it is usually omitted.

Block Elements

There are two types of blocks designated in most controllers:

main blocks
sub-blocks

With the "main block", it must contain all the words that are necessary to initiate the machining cycle in this section of the program. A main block is normally identified by means of a ":" (colon) character, instead of the address character "N", as depicted below.

:20 G01 X 15 Y − 20 F 250 S1100 M03 LF

Conversely, a "sub-block" contains only the functions which are different from those in the previous block:

N12 Y40 LF

A main block and several sub-blocks can constitute a section of a part program:

$$\begin{array}{l} : \\ \left.\begin{array}{l} \text{N210} \\ \text{N220} \\ \text{N230} \end{array}\right\} \text{Section} \end{array}$$

At this stage is our discussion of the various block formats, it is important to realise that the "preparatory" and "miscellaneous" functions, together with other "words", may be designated as either

modal
non-modal

A "modal" function remains active until it is either cancelled, or superseded by another complementary "word", e.g. G-code for a G01, whereas a "non-modal" word is only active in its particular block. Such a program structure reduces the repetitiveness in programming whilst simultaneously simplifying and reducing program lengths.

Deletable Blocks

Whenever program blocks must not be executed during every program run, they can be "skipped" by entering some character such as a "/" in front of the block number with the word. Such deletion of blocks is activated via either the machine control panel, or the interface controller. Any deleted block/s must form a loop, with the start and end at the same point, or the program may be executed incorrectly, although a section can be "skipped" by deleting several consecutive blocks.

Word Format

A "word" is an element of a block, comprising an "address character" and a string of digits (see Fig. 5.2c). The address character is usually a letter, with the string of digits being specified with a sign and decimal points. Such a sign "+/−" value is written between the address letter and the string of digits, although the positive sign can be omitted.

Extended Address

The structure of an "extended address" is depicted in Fig. 5.2d, simply as an example of the sophisticated designations and subtle distinctions that can be made within a block. However, owing to the complex nature and variations of such an address, it is not possible to describe, in the space available, its use in the detail necessary, so further discussion will not be given and the reader should refer to specific programming manuals for an actual CNC controller, if more information is required.

5.4.1 Machine Tool Reference Points

Any CNC machine tool has a means by which each axis can be referenced with respect to a known datum. Normally several axis delimiters exist (i.e. datums):

software stops
hardware stops
  (a) micro-switches, or similar
  (b) mechanical buffers – preventing axis over-travel

When a machine does not have a "fully digital interface" with advanced software control, it will need to reference the axes prior to use, then a "home" position-datum must be known to ensure that any motional travel under CNC control is related to such a reference. Confirmation that "home" has been established for each axis is necessary and usually either lights or LEDs for each controller axis will confirm that the software stop position has been reached, after a short "hunting" motion.

Of course, the arrangement of such origin positions, datum points, will differ for different machine tool configurations, which is related to the machine's coordinate system. Two such systems are illustrated in Fig. 5.3, for turning and machining centres, and it is apparent that in both cases several datums are present. Obviously, a machine zero reference position, or "home" occurs, for the establishment by the machine tool manufacturer of the origin for all axes, which synchronises the system. Other datums which must be established are for the workpiece reference point and zero offset, together with the tool reference point. The workpiece zero is defined for programming the workpiece dimensions and it may be freely selected by the programmer. The relationship of this datum to the machine zero is defined as its zero offset in one or more planes. The datum point for the tool setting positions cannot be varied in one aspect, namely the gauge line for a tool on a machining centre, or the turret's centreline for a turning centre, but their reference point coordinates can, of course, be modified.

Many CNC controller builders offer a range of other offsets, selected by suitable G-functions, such as settable zero offsets, or programmable zero offsets for the workpiece.

5.4.2 Types of Coordinates – Dimensioning Systems

The traversing movement to a particular point in the coordinate system can be described by means of three types of coordinates:

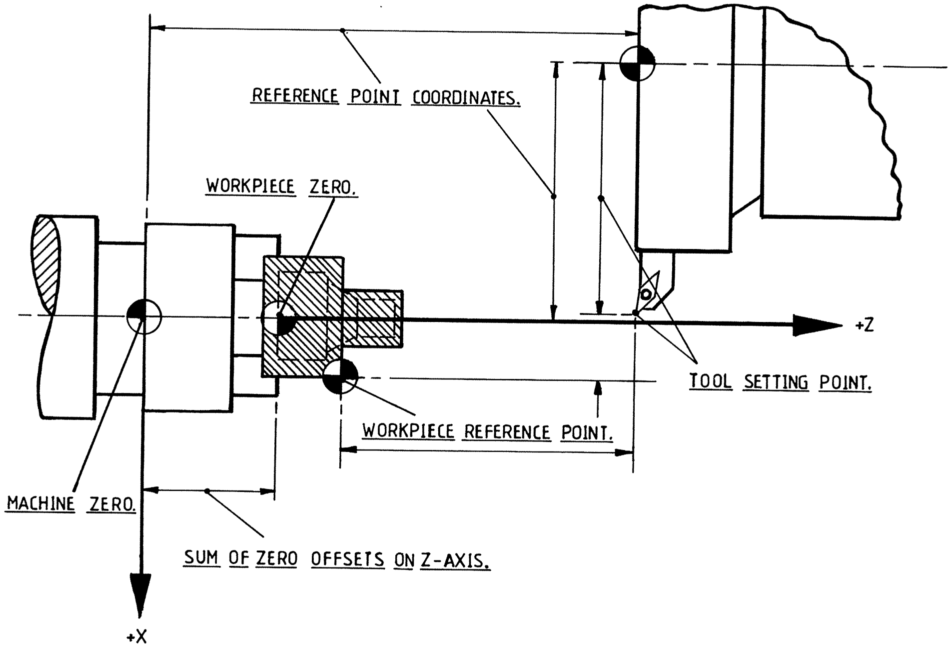
absolute dimensional positions – data input "G90"
incremental dimensional positions – data input "G91"
polar dimensional positions – data inputs either G00, G01, G02, G03

If "absolute" position data input is selected (Fig. 5.4a), all the dimensional inputs refer to a fixed zero, which is usually the workpiece zero. The value given to associated position data specifies the target position in the coordinate system.

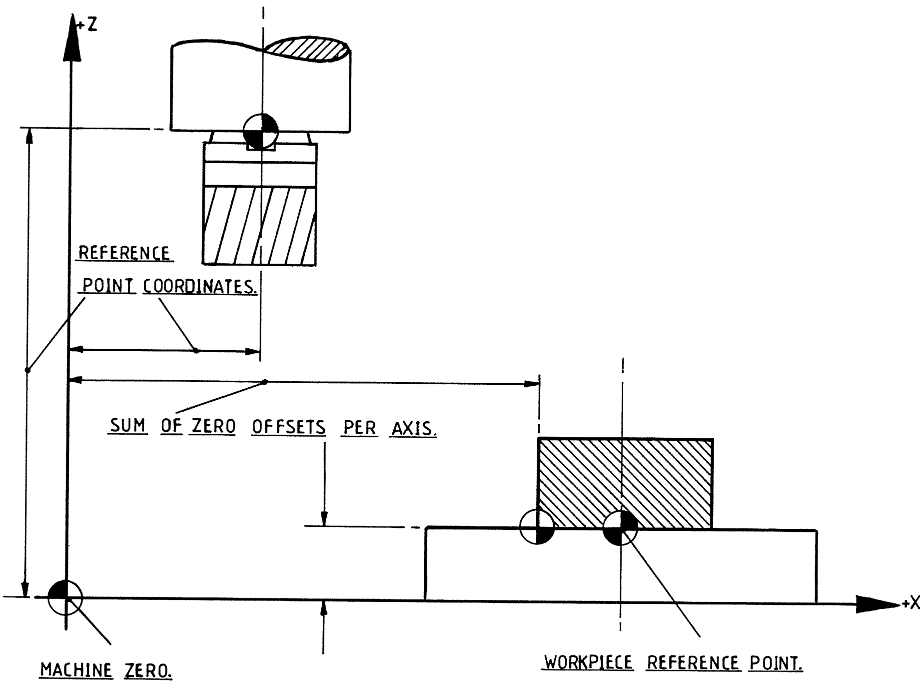
When "incremental" position data input is selected (Fig. 5.4b), the value of the position data corresponds with the path to be traversed. The direction of axis movement is specified by the positive/negative sign.

NB: It is possible to switch between absolute and incremental position data input, from one block to the next as desired, since the controller's actual value is always referred to the zero. Furthermore, a zero offset is calculated for both the absolute and incremental programming of part features.

With many control systems, it is possible to program part features using "polar" position data input (Fig. 5.4c); however, there is a variety of methods of machining polar features. Using point-to-point, linear, or circular interpolation motions, polar features can be developed, but to differentiate polar from rectangular coordinates, particular word address commands are used. If, for example, a series of holes on a pitch circle diameter is to be drilled, the centre of these holes (known as the "pole") must be established in the plane to be machined. If we assume that the X and Y plane



a



b

Fig. 5.3. **a** The reference points for turning centres (basic configuration). **b** The reference points for machining centres (basic configuration).

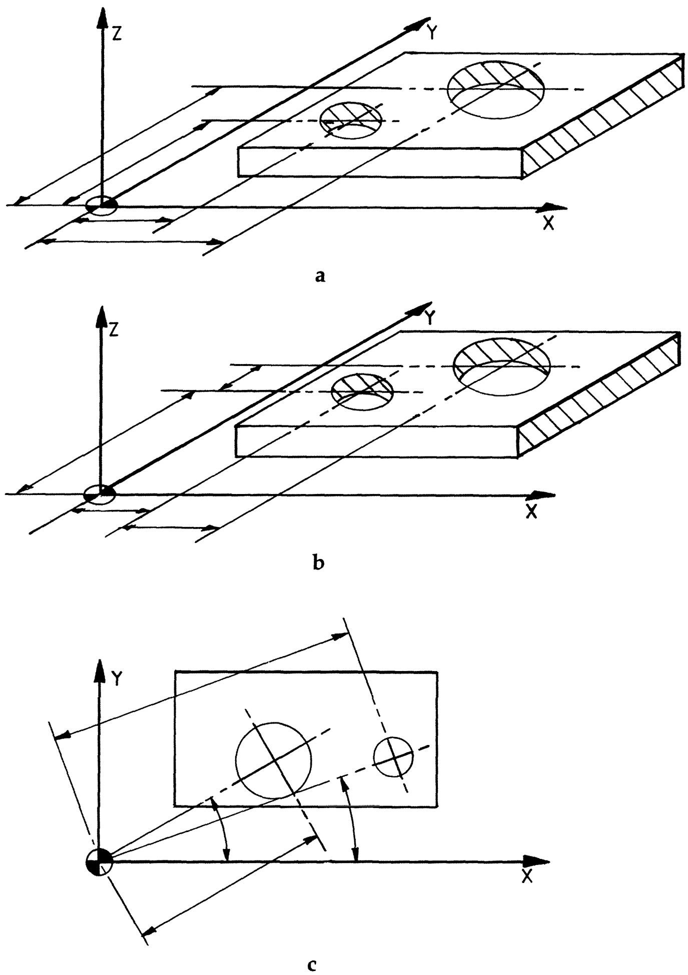


Fig. 5.4. **a** Absolute coordinates. **b** Incremental coordinates. **c** Polar coordinates.

is utilised with positive signs, then the linear distance from our workpiece zero in the "X-axis" is denoted by an "I" character and in the "Y-axis" by a "J" character. Two more word address characters must be designated to confirm the first hole position to be drilled, the radius of the hole given the character "R", which is always a positive sign, and the angular position of this hole, denoted by the character "A". Further holes to be drilled – possibly using "canned cycles", of which more will be said later in the chapter – simply require their angular positions to be confirmed in the relative blocks; although if the holes around the pole differ in radial values, then both the angular and radial characteristics, "A" and "R", must be stated for subsequent holes to be drilled. The characteristics of "I", "J", "R", and "A" will differ only marginally if, for example, the "X" and "Z" planes were chosen and a "K" character substituted for the "J", with the others being the same designations. Later on, a more detailed description, together with programming examples of a linear, circular, helical, and cylindrical interpolation is explained in section 5.4.4.

5.4.3 The Cutter Transformations of Angular Rotation, Mirror-imaging, Datum Shifting and Scaling

Such programming aids, when available in the controller's logic, offer several benefits to a programmer in the work required to execute a feature, whilst compressing the program into fewer blocks of information and as such, minimising memory space. These programming aids, termed "cutter transformations" are used because they have the ability to transform a cutter path from the current programmed position to another.

Let us begin by examining the "angular rotation" cutter transformation and then go on to consider the benefits to be gained from the others in turn, namely "mirror imaging", "datum shifting", and "scaling".

Angular Rotation

Whenever a geometric feature such as a milled contour, or drilling pattern needs to be rotated around a fixed position, then the "angular rotation" cutter transformation can be used as illustrated in Fig. 5.5. When such features as impeller blades need to be machined in a fixed angular relationship to each other then we only need to be concerned with cutting one blade entirely when programming the cutter motions and relying on the angular rotation function to execute the remainder. Polar translation is closely allied to rotation and permits a programmer to reposition a feature with respect to a centre/pole, allowing the feature to be rotated about this predetermined centre. An added bonus of such translation is that complex-shaped features requiring angular positional location may be programmed as if they were orientated to the true "X-Y" axes – which simplifies calculations.

Mirror-imaging

The "mirror-imaging" cutter transformation (Fig. 5.6) permits the machining of a contour, or hole pattern, by the inversion of one or more axes, enabling the feature to be machined in another plane. Such "mirroring" of a coordinate axis permits contour machining/drilling in the following relationships:

with the same dimensions

at the same distance from the other axes

on the other side of the "mirror axis", but as a "mirror-image"

During the "mirroring" sequence the controller inverts:

the sign of the coordinates of the mirrored axis

the direction of rotation, in the case of circular interpolation, i.e. G03 to G02, or vice versa

a machining direction, i.e. G41 to G42, or vice versa

Whilst "mirroring" is active in the part program, there is no "mirroring effect" on either the tool length offsets, or the zero offsets on a machining centre. Conversely, in the case of a turning centre, the following condition will be "mirrored" on the "X-axis" – the position of the tool cutting point – although when "mirroring" on the "Z-axis" this does not apply. A "mirroring" operation is always in relation to the

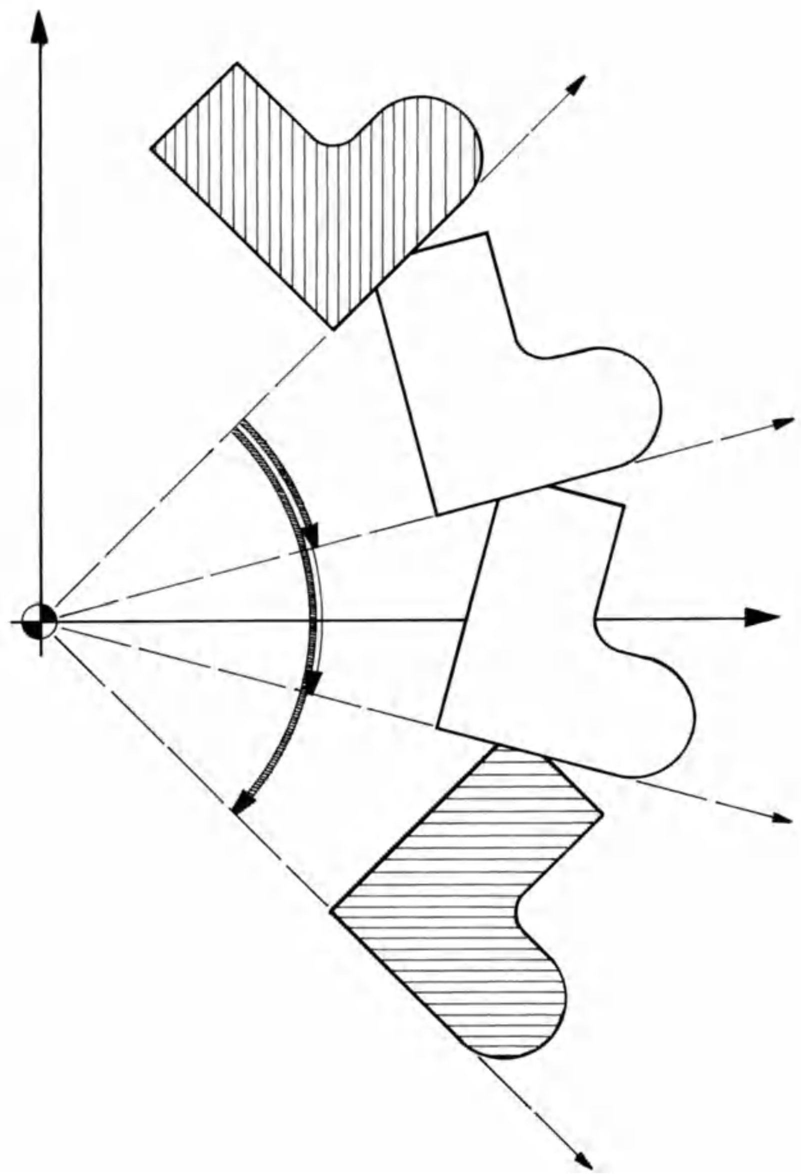


Fig. 5.5. Angular rotation of the coordinate system around the actual datum, i.e. either "absolute" or "incremental".

coordinate axis so that contours, etc., may be "mirrored" in the exact position where they are required to be machined. The position of the program start necessitates the "mirror-call" such that the axes of the coordinate system are located exactly between the programmed contour and the "mirrored" contour. In order to achieve this axis symmetry, the zero of the coordinate system can be offset to the correct

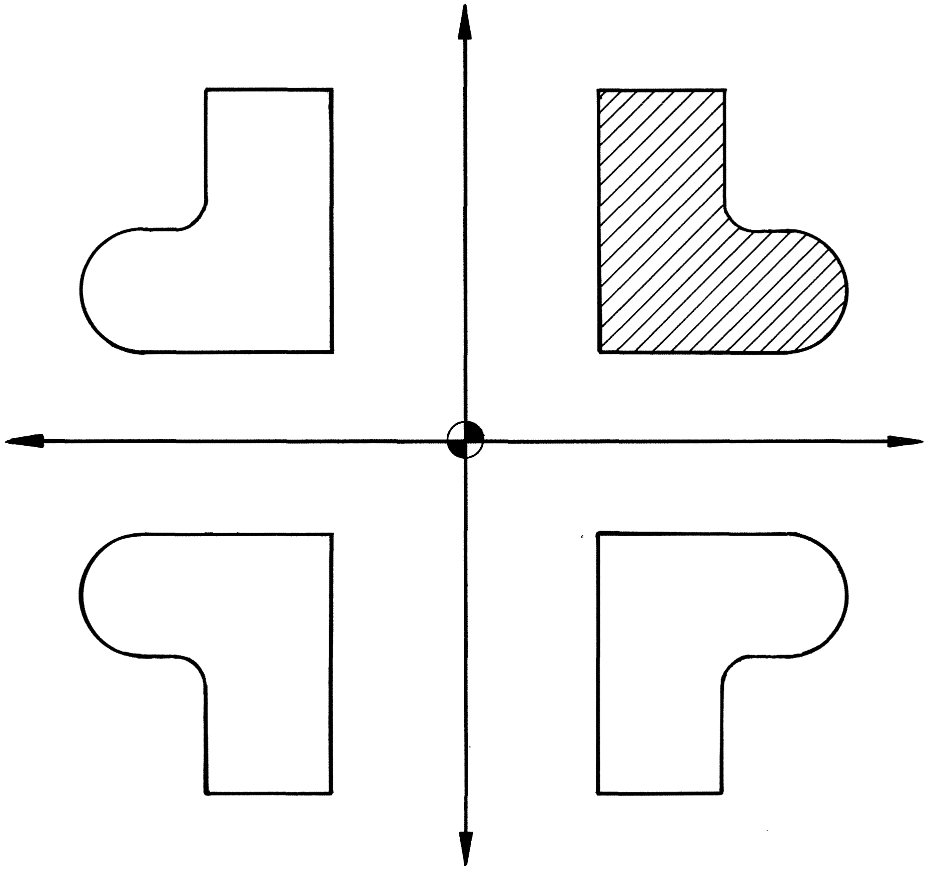


Fig. 5.6. Mirror-imaging of milling/drilling/boring patterns in one or both axes of the maching plane.

position, before any "mirroring" call in the program is activated – normally using "M-functions".

NB: A controller manufacturer has set distinct rules for the engagement of such cutter transformations and readers need to familiarise themselves with the specific programming manual to gain a greater insight into their execution.

Datum Shifting

The cutter transformation known as "datum shifting" or "preset absolute registers" is, in the main, used in milling operations, but it can also have applications for turning. However, in this case, we will only consider its use for milling/drilling applications. Probably the most often used preparatory function for "datum shifting" is "G92" – shown schematically in Fig. 5.7. It enables the programmer to "shift" the zero datum to any position within the main machine tool's envelope in the X, Y and Z planes. These "shifts" are of a temporary nature, lasting only whilst the part is

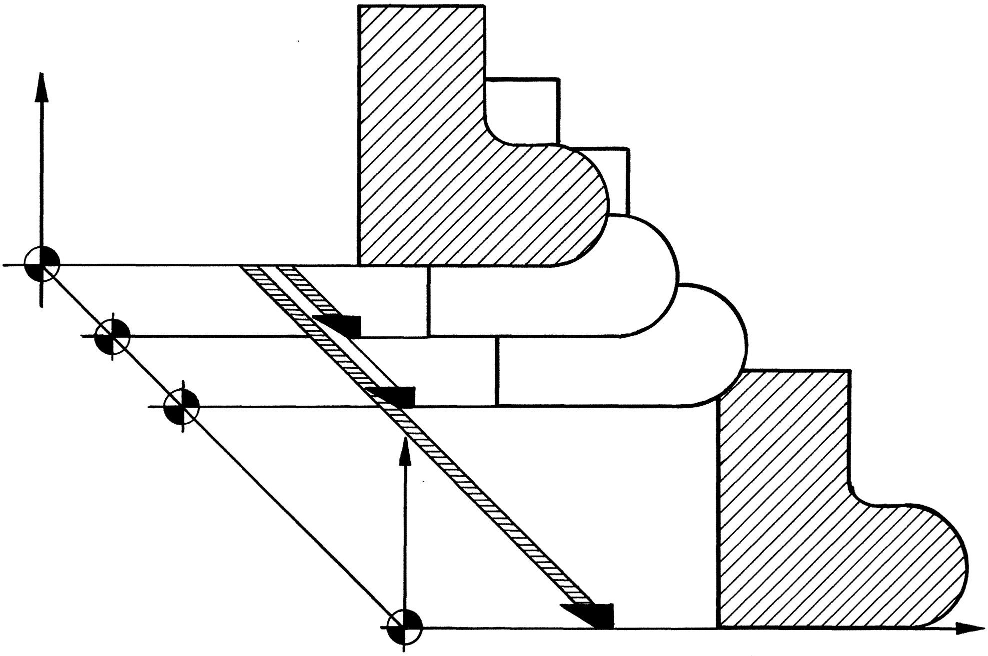


Fig. 5.7. Datum shifting of the coordinate system. i.e. either "absolute" or "incremental".

being machined and either are reset to the original datum, or "shifted" to a new one. The purpose of such "shifts" of datum positions can be threefold:

to cut a range of identical parts out of wrought stock – a technique favoured by the aerospace industry for aluminium and its alloys, and described in chapter 4

for machining identical parts held on a multiple fixture and, in this case, the "datum shifts" allow the same part to be machined with little additional increase in block lengths – usually as a "sub-routine", but more about this technique later in the chapter

machining different parts held on multiple fixtures – but differing from the example given above after the "shifts" have been "called": "sub-routines" for each individual part to be machined are "called" until all the parts have been cut and the datum is reset to the initial position

Scaling

"Scaling" is a very helpful cutter transformation when used, in particular, for milling contours and to a lesser extent for drilling operations. A typical schematic of the "scaling" of a contour is given in Fig. 5.8, illustrating the range and size variation that can be achieved by using "scaling factors". Scaling allows not only internal and external features that are identical to be machined – "capturing", for example, the outside profile and using it as a "sub-routine" which has been appropriately "scaled" to give an identical but reduced internal profile – but it can also be used to change,

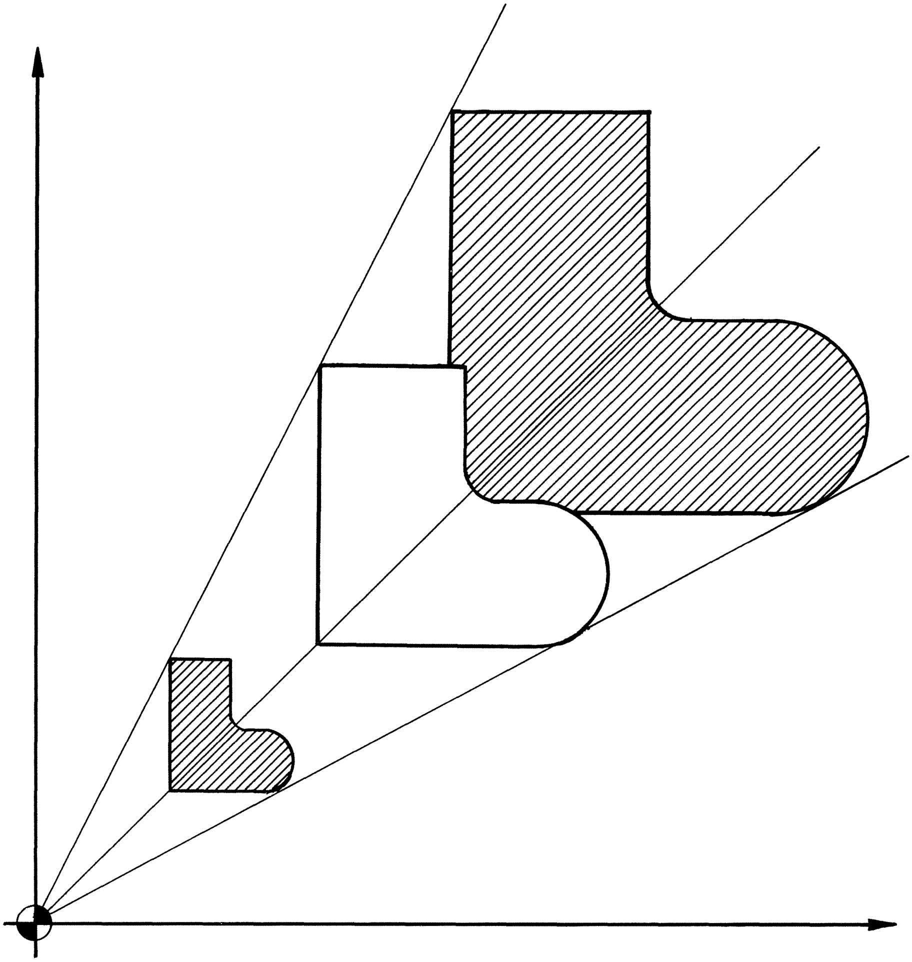


Fig. 5.8. Scaling factor: the enlargement or reduction of contours, automatic calculation of shrinkage and growth allowances, etc.

say, a circular interpolated shape, or spiral into an elliptical profile by "scaling" one axis. Such "axis compressions" of circular interpolated features give a considerable scope – outside the expected specification of the controller – and may be used to simulate parabolic interpolation. This means that once the tool path of a symmetrical profile has been generated, it may, at will, be compressed to achieve an almost free-form shape, which would otherwise only be expected from "captured geometry" sent to the controller via DNC or equivalent, through a CAD/CAM workstation. It is very easy to "compress" one axis using the correct preparatory "G-code" at one instant, then cancel the "scaling" and compress another axis either within a "skeletal" part program, or in future blocks as necessary.

Not only is it possible to use this technique for producing a range of products in a "group technology" approach, similar to "parametric programming" – yet to be described – but if a contour is large or the program is complex, by reducing its size and using a high "feedrate-override", tape prove-out times can be considerably reduced. The "G-codes" used for "scaling" and their cancellation are at the discretion of the controller manufacturer and the rules for their implementation/engagement are stated in the relevant programming manuals.

NB: When an axis is "scaled" – or indeed both axes for part symmetry – this also means that the component's relative position "drifts" (see Fig. 5.8). This requires the use of a "datum shift" in combination and proportion to the scaled axis, or axes, in order that it is machined in the correct position/orientation to the detailed drawing requirement.

5.4.4 The Programming of Motion Blocks

In chapter 1 we saw that each axis – whether primary, secondary or tertiary control – is designated as either a linear or rotary motion. Each axis motion can be controlled and programmed at will as a "rapid" or a "feed" motion and in this section we will discuss such motion control in more detail along with interpolation techniques, together with the preparatory functions needed to successfully engage them.

Axis Motion without Machining – Using Preparatory Function G00

If rapid motions are required then they are programmed by means of the position data G00 – with some controllers one or both of the zeros can be omitted – together with a target position specification. The target position is reached using either an absolute position data input (G90), or an incremental position data input (G91). Any path programmed using the G00 function is traversed at the maximum possible speed (rapid traverse) along a straight line by linear interpolation, without machining the workpiece. The maximum permissible speed of an axis is monitored by the controller and is defined as machine data for the axis. If simultaneous rapid traverse is required in several axes, the traversing speed is determined by the lowest axis speed specified in the machine data.

When the G00 preparatory function is programmed, the feedrate previously "active" under an "F-word" will be stored but can be called again by initiating a G01 function.

Axis Motions with Machining

A controller will implement either linear or circular interpolation depending on the type of axis motion required, as shown below:

linear interpolation – produces linear motion by paraxial moves in either two or three axes

circular interpolation – produces a circular motion in a plane by the synchronised movements of two axes

Linear Interpolation

This preparatory function (G01) allows the tool to travel at a set feedrate along a straight line to the target position, whilst simultaneously machining the workpiece.

The controller will calculate the tool path by means of linear interpolation. Linear interpolation effects a motion:

in one axis direction, either a linear or rotary axis

from the starting position to the target position which can be programmed using either absolute or incremental position data

at the programmed feedrate

at the programmed spindle speed

An example of 3-axes linear interpolation can be seen in Fig. 5.9a, with word address program:

```
%10LF
N1 G00 G90 X40 Y60 Z2 S500 M3 LF
N2 G01 Z-12 F100 LF
N3 X20 Y10 Z-10 LF
N4 G00 Z100 LF
N5 X-20 Y-10 LF (or: X0, Y0)
N6 M30 LF
     N1 = tool rapid traverse to P01
     N2 = infeed to Z-12, feedrate 100
     N3 = tool traverse along a straight line in space to P02
     N4/N5 = rapid traverse clear
     N6 = end of program
```

Circular Interpolation

The tool traverses between two points on a contour in a circular arc, whilst simultaneously machining the workpiece. To achieve such cutter motion the controller must calculate the tool path using circular interpolation, based upon the following rules when machining along a circular arc:

in a clockwise direction with G02

in an anti-clockwise direction with G03

in the desired plane in the case of milling by a freely selectable plane with G16, or,

$$\left.\begin{array}{l}\text{in the X–Y plane with G17}\\ \text{in the Z–X plane with G18}\\ \text{in the Y–Z plane with G19}\end{array}\right\}\text{ see Fig. 5.9b(ii)}$$

around the programmed centre point of the circle

from the starting position on a circular path to the programmed end position

The preparatory functions of G02 and G03 are "modal" in action, with the circular motion being executed in any selected plane – XY, XZ and YZ. The rotation direction of the cutter in various planes is defined in the following manner – standing facing the axis which is perpendicular to the plane. The tool will move in a clockwise direction with G02, or in an anti-clockwise direction with G03. The interpolation parameters determine the circle or circular arc in conjunction with the axis commands, with the starting point at "KA" (see Fig. 5.9bi) being defined by the preceding block. The end position of the arc "KE" is defined in this case by the chosen axis values of "X and Z". The centre point of this arc is "KM" and may be defined in one of two ways:

by the interpolation parameters

directly using the radius

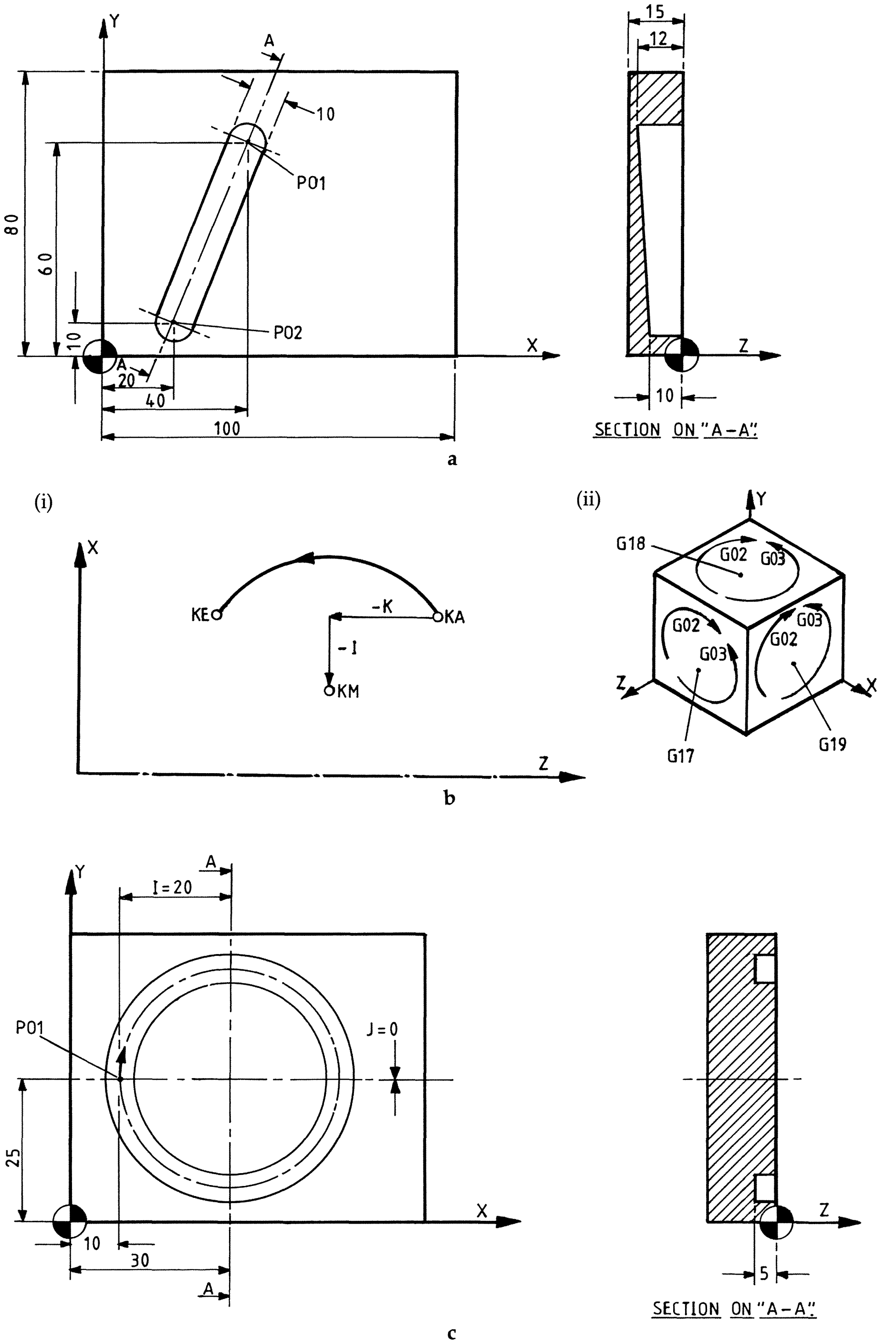


Fig. 5.9. Linear and circular interpolation applications, according to DIN 66025. **a** Linear interpolation in 3 axes. **b** (i) Circular interpolation with interpolation parameters. (ii) Circular interpolation. **c** Interpolating a full circle in the X–Y plane. [Courtesy of Siemens.]

Interpolation Parameters (I, J and K)

The interpolation parameters "I, J and K" are the paraxial coordinates of the distance vector from the starting position to the circle's centrepoint. In accordance with the DIN66025 standard for word address programming, the interpolation parameters "I, J and K" are allocated to the respective axes "X, Y and Z". Such interpolation parameters must always be entered as incremental position data, irrespective of whether the axes "X, Y and Z" are programmed using absolute, or incremental position data (see Fig. 5.9bi).

The sign chosen is based upon the direction of the coordinates from the starting point of the circle, or arc (Fig. 5.9bi). If a value of zero for the interpolation parameter is assigned, its sign is not programmed. Similarly, any end position coordinates which are the same as at the start point for the circular path need not be programmed – typically when generating a full circle – but at least one axis must be programmed, i.e. "X0, Y0 or Z0".

In the example shown in Fig. 5.9c, we can see that a full circle has been programmed into our rectangular block, with a typical execution of the part program shown below, but noting that according to the rules above, the start and end positions are the same.

```
%20 LF
N1 G00 X10 Y25 Z1 S1250 M3 LF
N2 G01 Z-5 F100 LF
N3 G02 X10 Y25 I20 J0 F125 LF
N4 G00 Z100 M5 LF
N5 X-20 LF
N6 M30 LF
```

N1 = tool rapid traverse to point P01
N2 = infeed to Z-5
N3 = X–Y plane automatically selected – i.e. a "default condition". Tool traverses clockwise around the full circle (G02)
N4/N5 = rapid traverse clear
N6 = end of program

If one incorrectly inputs the values for the interpolation parameters "I, J and K", the circle end position check will detect such programming errors – this is providing that they are not within the tolerance range. Under such conditions no circular interpolation results, furthermore, it is usual for some form of alarm to be displayed. Problems can arise, however, when the programming error is within the tolerance range and the end position of the circular arc will be approached exactly – by offsetting the centrepoint of the circle, but the tool path between the start and end positions will be as follows:

when the interpolation parameter is too high, undercutting of the circle occurs and the circle end position check may be suppressed

if the interpolation parameter is too low, extra stock is left on after the circle has been machined

NB: The setting range of a typical system for the tolerance and the circle end position is $\pm 1\,\mu m$ to $\pm 32\,000\,\mu m$ and this tolerance range can be compensated for by entering it as a value without a sign.

Radius Programming

For many applications, dimensioning drawings, using the radius, is a better method of specifying the feature rather than the diameter. By using such characters as "U" or "B" when programming it simplifies the task, as illustrated in Fig. 5.10a,b, for defining the circular path the tool must take when generating a contour. The programming logic dictates that since the radius to be machined is used in conjunction with either a G02 or G03 preparatory function, it can only specify a definite circular path within a semi-circle. Therefore it is necessary to specify additionally whether the traversing angle is to be greater or smaller than 180°. In order for the controller to discriminate between the various magnitudes of angle required, it is allocated one of the following signs:

+U/+B, for angles less than or equal to 180°
−U/−B, for angles greater than 180°

It is not permissible to program the radius by such methods if it has a traversing angle of either 0° or 360°. When full circular paths are demanded they must be

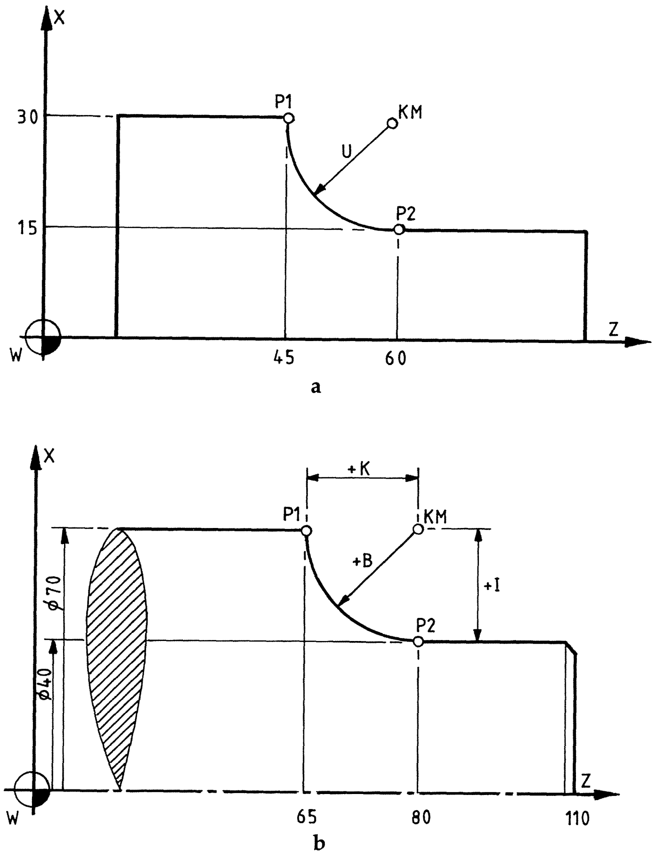


Fig. 5.10. Programming radius bends in turning operations. **a** Radius programming. **b** Circular interpolation. [Courtesy of Siemens.]

programmed utilising the standard interpolation parameters described earlier in this section. We have seen how G02 or G03 determines the direction of movement around the circle, which is defined by means of the circle end position and the interpolation parameters. In the examples below we can gain an appreciation of the same circular path generation, but in either case the radius may be defined using either a "U" or "B".

Example 1. Relating to Fig. 5.10a, for milling using radius programming:
N5 G03 G90 X60 Y15 U15 LF . . . i.e. tool traverses from point 1 to point 2, or conversely –
N10 G02 X45 Y30 U15 LF . . . i.e. tool traverses from point 2 to point 1.

Example 2. Relating to Fig. 5.10b, for turning using either interpolation parameters or radius programming:

interpolation parameters:

```
N5 G03 G90 X40 Z80 K15 I0 LF
N10 G02 X70 Z65 K0 I15 LF
    N5 = tool traverse from P1 to P2
    N10 = tool traverse from P2 to P1
```

radius programming:

```
N5 G03 G90 X40 Z80 B+15 LF
N10 G02 X70 Z65 B+15 LF
    N5 = tool traverse from P1 to P2
    N10 = tool traverse from P2 to P1
```

Helical Interpolation

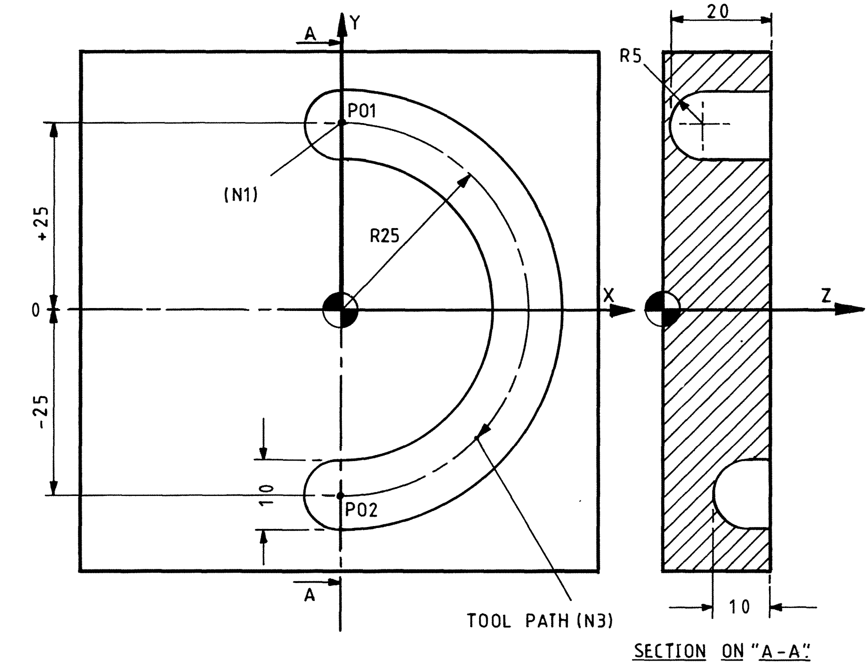
Helical interpolation can be achieved by the simultaneous motions of three linear axes which are perpendicular to each other. Such interpolation necessitates programming a circular arc and a straight line, which is perpendicular to the end point of such an arc in a single block. When the program is processed, the individual motions of the axis slides are combined in such a manner that the tool describes a helix with a constant lead. By choosing either G16, G17, G18, or G19 the circle plane is selected. It is always necessary to program the axis coordinates X, Y and Z. The axis for the linear interpolation motion can be programmed either before or after the circular arc/circle has been defined. Whenever a fourth axis is incorporated onto the machine tool and used for the circular interpolation mode, the linear interpolation requirement is selected using a corresponding parallel axis. The programmed feedrate is adhered to on the circular path: however this is not the case for the actual tool path.

In Fig. 5. 11a, a helical cutter path is required to generate this component feature, as shown in a typical program:

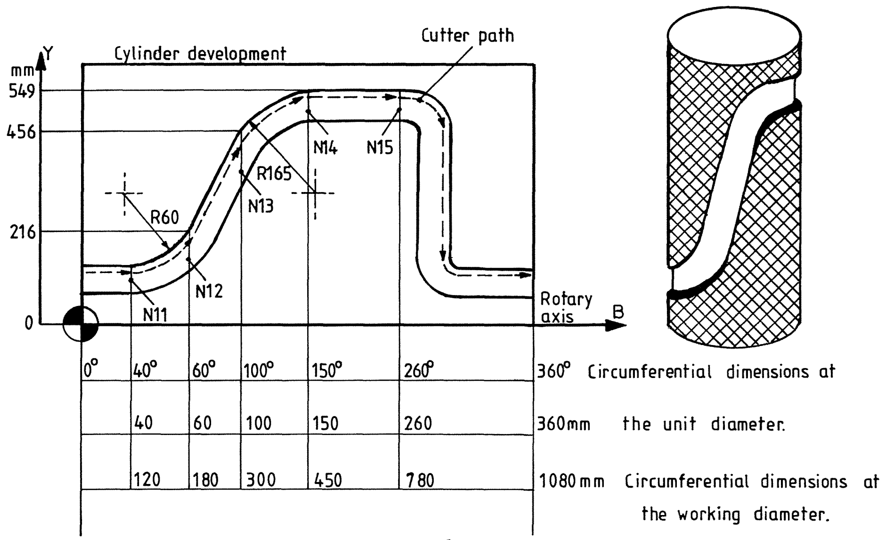
Helical interpolation:

```
30% LF
N1 G00 X0 Y25 Z1 S800 M3 LF
N2 G01 Z-20 F150 LF
N3 G02 X0 Y-25 Z-10 I J-25 LF
*
N5 M30 LF
```

N1 = XY plane automatically selected (default condition) with tool traversing to P01



a



b

Fig. 5.11. **a** Helical interpolation. **b** Cylindrical interpolation. [Courtesy of Siemens.]

N2 = linear interpolation with infeed to Z-20 depth
N3 = tool clockwise traverse on a helix (G02) to P02
* N4 = rapid traverse clear – not shown
N5 = end of program

Cylindrical Interpolation

Using cylindrical interpolation allows the machining of cylindrical paths with one rotary and one linear axis, together with a constant rotary table diameter. It is also possible to program both linear and circular contours using an "intersection cutter radius compensation". In this case the position of the rotary axis is entered in degrees and then it can be converted to circumferential dimensions of the working diameter internally by the controller.

Typical details which must be considered for a specific controller are as follows:

$$\text{the ratio "P"} = \frac{\text{machining diameter}}{\text{unit diameter}}$$

and is programmed via a "G92 P" for this purpose. Input system "unit diameter" in metric units is 114.592 mm. This "unit diameter" (d) is derived from the relationship;

$$\pi \times d = 360$$

therefore the "unit diameter" (d) $= \dfrac{360}{\pi}$ (mm)

No characters other than the axis name can be written in a block containing G92 P..

Example. N..G92 P.. C LF
Where, P.. = the factor for the unit circle, working diameter/unit diameter
C = the rotary axis

Typical input resolution for "P" is 10^{-5} and the action for the factor for the unit circle is modal, until it is reset or reprogrammed using either an M02 or M30. The programmed feedrate is maintained on the contour and if the factor is not 1, this axis – the "C" – can only be interpolated with one further axis. This factor 1 must be set for any interpolation with more than two axes.

The following programmed example relates to the illustration of cylindrical interpolation given in Fig. 5.11b:

```
N10 G92 P3 B LF
N11 G01 G42 B40 Y200 LF
N12 G03 B60 Y216 P+60 LF
N13 G01 B100 Y456 LF
N14 G02 B150 Y549 P+165 LF
N15 G01 B260 LF
.
.
N26 G92 P1 B LF
```

N10 = selection of cylindrical interpolation
N26 = cancellation of cylindrical interpolation

Polar Coordinates

Polar coordinate programming is invariably used when holes on pitch circle diameters (PCD) are required – angular faces, or similar manufacturing activities. Normally drawings are dimensioned with an angle and a radius (see Fig. 5.4c) which can be entered directly in the program with the aid of polar coordinates. Polar coordinates can be programmed in a variety of ways using the following preparatory functions:

G10 – linear interpolation, rapid traverse
G11 – linear interpolation, feedrate (F)
G12 – circular interpolation, clockwise
G13 – circular interpolation, anti-clockwise

So that the controller can determine the cutter's traverse path, it requires the centre point, radius and angle to be known. The centre point is entered in the usual manner using the perpendicular coordinates (X, Y and Z), together with absolute position data at the initial stage of programming. A subsequent incremental position data input using G91 may be used, although this method always refers back to the last centre point programmed. The action of employing a centre point entry is modal and can be reset by means of either M02 or M30. The radius can be programmed via a "B" or "U" address, without a sign, and the angle is entered under an "A" address, also without a sign, with an input resolution of 10^{-5}. Such programming always refers to the first positive axis of the centre point coordinates – the reference axis and this positive direction corresponds to an angle of 0°.

In the following examples of programming polar features on components (Fig. 5.12) we can gain an insight into its flexibility and simplicity in producing part programs. In the first instance we will consider programming polar coordinates for holes dimensioned with respect to a common centre point (Fig. 5.12a):

N10 G10 G90 G81 X.. Y.. A.. U(r1) R1 = ..Ra = .. R11.. LF
N15 G10 A.. U(r2) LF
N20 G10 A.. U(r3) LF
N25 G10 A.. U(r4) LF
N30 G80 LF
X.. Y.. = centre point of the polar coordinate system
A.. U(r) = hole positions in polar coordinates

NB: G10 must be programmed in each block, since G81 is terminated with a rapid traverse.

In Fig. 5.12b, polar coordinates are used to mill a hexagon using the following word address program format:

N12 G11 G90 X50 Y35 U20 A0 L5 (POINT; P1)
N13 A60 LF (P2)
N14 A120 LF (P3)
N15 A180 LF (P4)
N16 A240 LF (P5)
N17 A300 LF (P6)
N18 A0 LF (P1)

NB: The angles are referred to the X-axis since the centre point coordinate in the X-plane is programmed first.

In the next two programmed examples using the preparatory functions G12 and G13, they affect a traversing motion along a circular arc between two points. In these

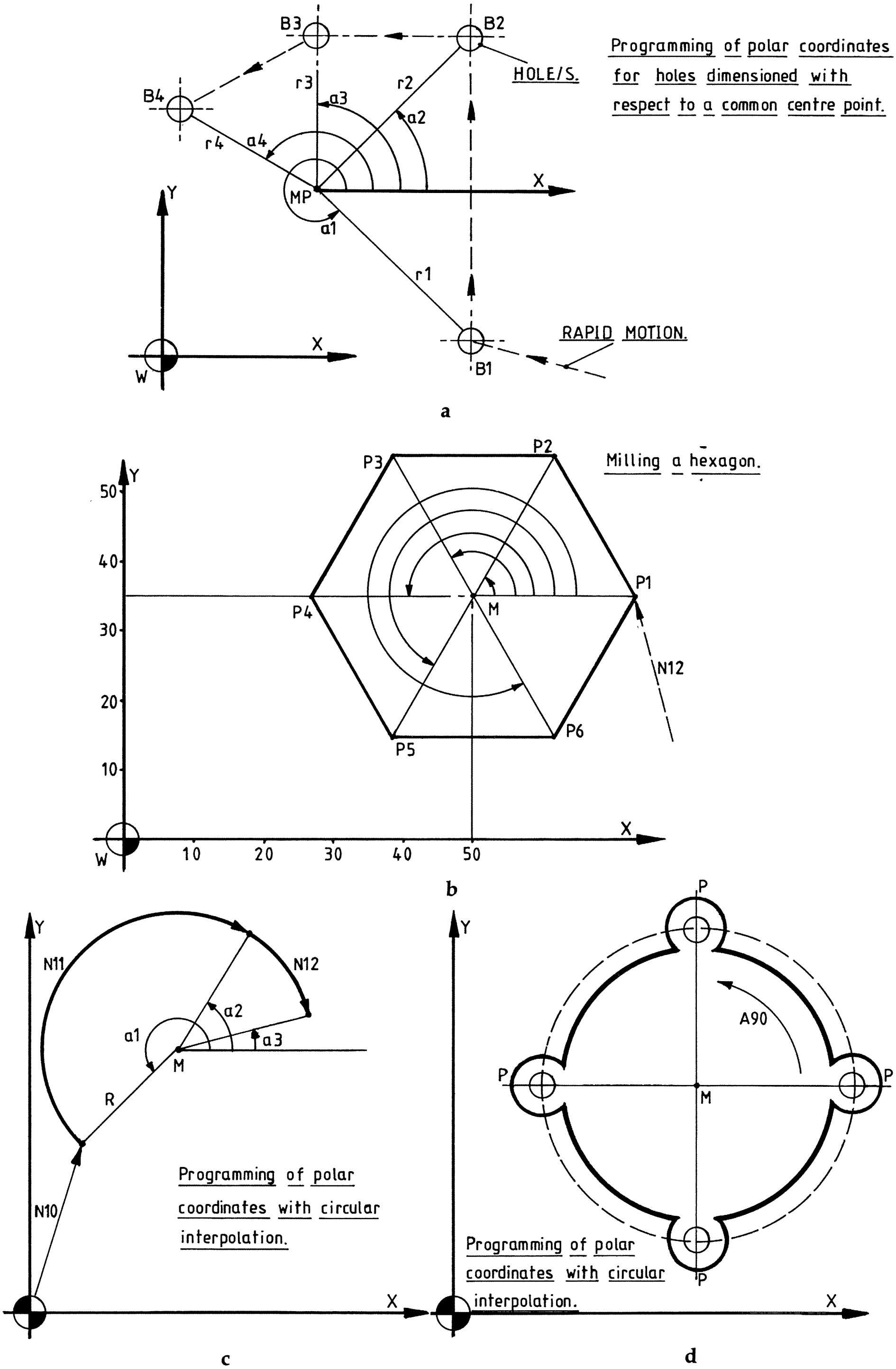


Fig. 5.12. Polar coordinate programming using **a** G10, **b** G11, **c** G12 and **d** G13. [Courtesy of Siemens.]

examples the programming of polar coordinates with circular interpolation will be considered.
Example of the preparatory function G12 (see Fig. 5.12c):

```
.
.
N10 G11 X50 Y30 A120 U25 LF
N11 G12 A75 LF
N12 G12 A15 LF
.
.
```

Example of the preparatory function G13 (see Fig. 5.12d):

```
%40 LF
N5 G00 G90 X120 Y100 LF
N10 G13 X100 U20 Y20 A0 F100 LF
N12 G81 R2=...R3=...R11=...LF
N15 A90 LF
N20 G81 R2=...R3=...R11=...LF
.
.
.
N35 G00 Z100 M30 LF
    N5 = hole position P1 approached
    N10 = polar coordinate selection and position
    N12 = call of bore cycle
    N15 = approach of P2
    N20 = call of bore cycle, etc.
    N35 = traverse clear
```

5.4.5 Feed Motions

The characteristic of the feedrate is that it determines the machining speed and is adhered to with every kind of interpolation, even when tool offsets are required to machine a contour. The value programmed under an "F" address remains in the program (i.e. a modal function) until it is superseded by a new "F-value". Any "F-value" is deleted either at the end of the program or upon reset and obviously it is a requirement to program the feed function prior to use. When a specific feedrate has been programmed it can be modified at the operator's panel – normally in the range from 1% to 120% – by means of the "feedrate override" switch. The programmed value corresponds to the 100% setting on the "feedrate override" switch.

Feedrates are programmed in either mm/min, or mm/rev, by a selection of the following "F-functions":

G94 F.. = feedrate in mm/min
G95 F.. = feedrate in mm/rev
G96 F.. = feedrate in mm/rev
G96 S.. = constant cutting speed – "S" denotes the feedrate is in m/min (see below)

Constant Cutting Speed

"Constant cutting speed" is a very useful function on a turning machine, whereby the controller determines the spindle speed for the current diameter with reference to the programmed cutting speed. The relationship between the turned diameter, its spindle speed and feed motion, permits optimum matching of the part program to the turning centre, the material being machined, and the cutting tool. The zero point of the "X-axis" must be at the centre of the turning centre and this is ensured by the reference point. When we calculate the spindle speed using the "constant cutting speed" technique, the following conditions must be considered:

actual spindle speed value
zero offset in the X-direction, using, for example, one of the following functions:
 the settable zero offset (G54, G55, G56, G57)
 programmable zero offset (G58, G59)
 external offset

The "constant cutting speed" can be cancelled using a G97 preparatory function, with the final speed – relating to the previous G96 – being retained as the constant speed. If the X-axis is moved without further machining, an undesirable speed change can be avoided which is an aid to further programming. It is also possible to considerably reduce a set feedrate on many controllers using an M-function. The programmed feedrate can be reduced by 1:100 with an M37 and may be reset with M36, if either a superfine finish is required, or slow feeding is necessary – rather than a "dwell" – to minimise cutter vibration and its subsequent affect on the workpiece.

5.4.6 Thread Cutting – an Introduction

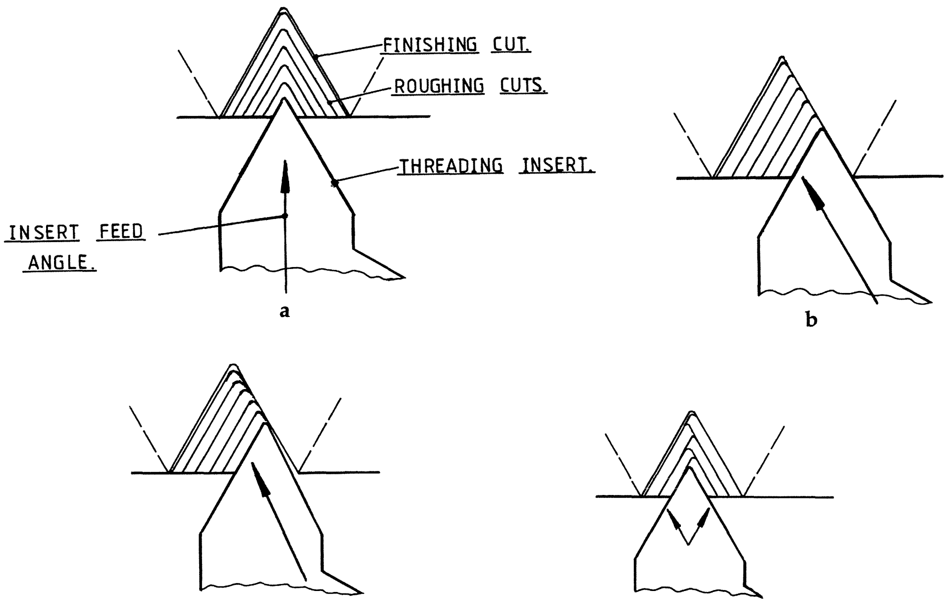
The machining of threads can be undertaken on both turning and machining centres and in the latter case the machine must be equipped with a helical interpolation capability – if thread milling is necessary. A large range of threads for specific applications can be cut, such as:

constant lead threads
variable lead threads
single or multiple-start threads
tapered threads
external or internal threads
transversal threads

Before we consider some examples of the part programming such threads as described above, it is worth discussing the variety of techniques that is available for producing infeeds when cutting V-form threads on turning centres.

Thread Infeed Techniques

There are a range of forming and partial forming/generating methods for producing V-form threads; some of the more popular methods are illustrated in Fig. 5.13.



a b c d

Fig. 5.13. Various methods of producing thread infeeds. **a** Radial infeed (plunge). Metal is removed on both sides of the insert simultaneously. **b** Flank infeed (half-angle). This gives a more easily formed chip and better heat dissipation. **c** Modified flank infeed. There is less wear of the trailing edge and a better surface finish on the corresponding flank. **d** Alternating flank infeed. Both edges are fully utilised, which means a longer insert life.

Radial Infeed

The first example we will consider is that shown in Fig. 5.13a which is termed the radial, or plunge infeed technique. This is the method which is usually adopted when cutting square threads, but can be used to machine V-form threads. It is purely a forming method, which means that the profile produced on the threading insert is replicated on the workpiece – hence the term "forming". However, it suffers from a serious disadvantage when used to form threads – as this method is not normally associated with "canned cycles" – which means that as the full depth of cut is approached (after successive passes) cutting occurs along the whole insert profile making a torn, or poorly finished thread very likely. Such a thread condition is a function of a range of tool, work and cutting data factors:

tool geometry – promoting a poor chip-breaking tendency, together with long cutting edges

workpiece ductility/affinity to the tool, causing a likelihood of torn threads at full depth

feeds/speeds/infeeds progression being inappropriate to good chip-breaking ability

angular relationship of the tool to the workpiece – whether the form is "square" and "true" to the part

The usual method of entering thread data is in terms of thread length and lead, as the following examples will show. Thread length is entered under the corresponding path address, with the start–stop and overrun zones at which the feedrate is increased or decreased being taken into consideration. The numerical values can be entered using either absolute, or incremental position data. Thread lead is entered via such addresses as "I, J and K". For longitudinal turned threads the lead is entered under a "K", with transversal threads it is entered using "I", whereas tapered threads are entered using a "K" address. These addresses must always be entered using incremental position data, but without a sign. Most controllers have a standard input resolution for the thread lead of 0.001 mm revolution, with the programming of the lead of 0.001 mm–2000 mm. Typically, if a thread lead of 1 mm is programmed as the input resolution, it is possible to obtain a resolution of 0.01 mm/revolution with the M37 function. Right- and left-hand threads are programmed using the spindle direction of rotation functions M03 and M04 and these, together with the speed, must be programmed in the block prior to an actual thread cutting operation. This presetting of such functions is necessary in order to permit the spindle to run-up to its nominal programmed speed, as the following example shows:

```
N10 S500 M03 LF
N15 G33 Z... K... LF
```

This programming logic means that the feed does not begin until the zero mark is reached on the pulse encoder, in order to permit threads to be cut in several passes, thus ensuring that the threading insert will always enter the workpiece at the same point on the circumference, with the cuts being implemented at the same cutting speed and, as such, preventing discrepancies in "following errors".

The "feedrate override switch", "feed-off key", "spindle speed override switch" and the "single block mode" have no effect when cutting the thread. Furthermore, the feedrate programmed using the "F-word" will remain stored and only becomes effective again when the next G01 function is programmed.

In this section, mention was made of "canned cycles". The following section explains, using practical programming examples, how such "cycles" can reduce the part program's length and minimise the effort required by the programmer. We will also gain an appreciation of how such "canned cycles" are engaged for specific cutting operations for particular types of threads and the relationship of the threading insert to the workpiece during consecutive threading passes.

5.4.7 Programming Threads on Turning Centres

The following part programming examples illustrate solutions for a variety of thread forms.

Thread with Constant Lead (Fig. 5.14a)

NB: The feedrate preparatory function "F" is not programmed here, since the feedrate is linked directly to the spindle speed via a pulse encoder.

Example 1. Absolute position data input :

```
N20 G90 S... LF
N21 G00 X46 Z78 LF   (P1)
```

Flank Infeed

The flank or alternatively, as it is often known, the half-angle infeed technique is depicted in Fig. 5.13b, which is the popular method used for screwcutting operations on conventional lathes. It is a combination of generating and forming, with the generated flank being the product of successive infeeding passes down this flank, whereas the adjacent flank is formed at full thread depth by the threading insert's profile. Chip forming is more efficient in this case than for the previously mentioned radial infeed technique, but flank wear is associated with the forming insert's clearance flank in particular. This will limit the number of threading passes and hence the screwthreads produced, as this greater flank wearing tendency on the generating edge affects the finish on this flank of the thread. "Canned cycles" sometimes use this infeed technique for screwthread production.

Modified Flank Infeed

The modified flank infeed technique (Fig. 5.13c) answers most of the criticisms levelled at flank infeeding operations. It is a curious mixture of partial generation and forming in the main, and the final pass is at full forming to depth along the thread. As its name implies, the half angle is modified to a more acute angle – usually between 27° and 29° – which can be adjusted accordingly. This means that as the so-called generating infeed is 1°–3° less than the desired angle there is less wear on the tool's trailing flank as a result. When full depth is reached, the complete profile of the thread is reproduced by the threading insert at this last pass. "Canned cycles" often use this infeed technique as it reduces tool wear and improves thread quality over the previous techniques mentioned.

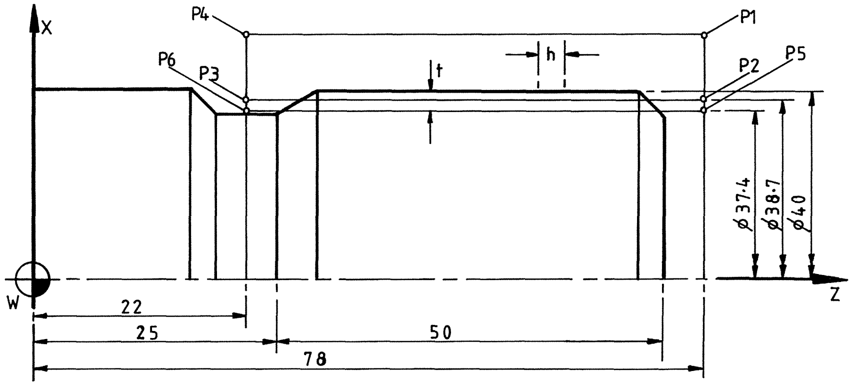
Alternating Flank Infeed

Probably the most satisfactory thread production method is that of the alternating flank infeed technique (Fig. 5.13d), from the point of "balanced" wear on the threading insert. As its name implies, with consecutive threading passes the bias of the insert's cutting flank changes, so that on one pass the left-hand flank cuts and on the next pass the right-hand flank cuts. This technique, when incorporated into a "canned cycle" for threading, fully utilises each cutting edge, which minimises flank wear whilst increasing tool life, and part quality is enhanced further as a result; particularly when cutting with "full depth" threading inserts which allows a limited amount of stock diameter to be removed on the final threading pass, thereby ensuring a true thread profile.

Not all of these infeed techniques are available on every CNC controller and, in fact, other techniques not discussed here may be available, but they will all – to a greater or lesser extent – cut a thread satisfactorily. In the remaining comments in this section we will consider some of the preparatory functions used in part programming threads and go on to mention certain programming considerations required, if a satisfactory threading operation is to be undertaken.

The following preparatory functions are available for machining threads:

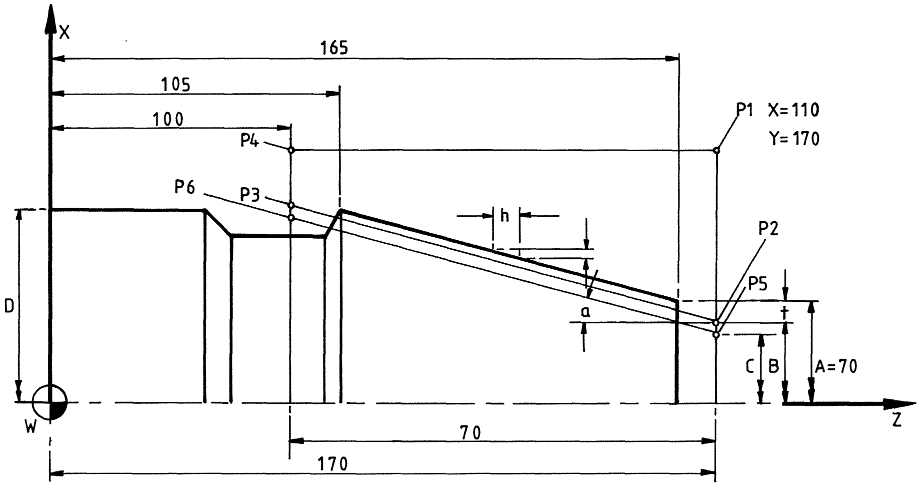
G33 – thread cutting with a constant lead
G34 – thread cutting with a linear lead increase
G35 – thread cutting with a linear lead decrease



THREAD DATA FOR A CYLINDRICAL BAR;

Lead h = 2 mm, Thread depth t = 1·3 mm, Radial infeed direction.

a



THREAD DATA; Lead h=5mm, Thread depth t= 1·73, a=15°, Radial infeed direction. Both end position coordinates must be written. The lead "h" is entered under "K".

CALCULATION OF THE THREAD START & END POSITION COORDINATES;

(A,B,C & D are diameters). 1st cut P2...P3, t = 1 mm.

2nd cut P5...P6, t = 1·73 mm.

A = 70,

B = A - 2t = 66·54,

C = B - 2 (5 * tan a) = 63·86,

D = C + 2 (70 * tan a) = 101·366,

K2 = h = 5,

I = h * tan a = 1·34 mm.

NB * = Multiplication character.

b

Fig. 5.14. **a** Thread with a constant lead. **b** Thread on a tapered bar. [Courtesy of Siemens.]

```
N22 X38.7 LF            (P2)
N23 G33 Z22 K2 LF       (P3)
N24 G00 X46 LF          (P4)
N25 Z78 LF              (P1)
N26 X37.4 LF            (P5)
N27 G33 Z22 K2 LF       (P6)
N28 G00 X46 LF          (P4)
```

Example 2. Incremental position data input:

```
N20 G91 S.. LF
N21 G00 X-... Z-... LF  (P1)
N22 X-3.65 LF           (P2)
N23 G33 Z-56 K2 LF      (P3)
N24 G00 X3.65 LF        (P4)
N25 Z56 LF              (P1)
N26 X-4.3 LF            (P5)
N27 G33 Z-56 K2 LF      (P6)
N28 G00 X4.3 LF         (P4)
```

Thread on a Tapered Bar (Fig. 5.14b)

Absolute position data input:

```
N31 G90 S... LF
N32 G00 X110 Z170 LF             (P1)
N33 X65.86 LF                    (P2)
N34 G33 X103.366 Z100 K5 LF      (P3)
N35 G00 X110 LF                  (P5)
N36 Z150 LF                      (P1)
N37 X63.86 LF                    (P5)
N38 G33 X101.366 Z100 K5 LF      (P6)
N39 G00 X110 LF                  (P4)
```

Calculation of points "P2" & "P3":

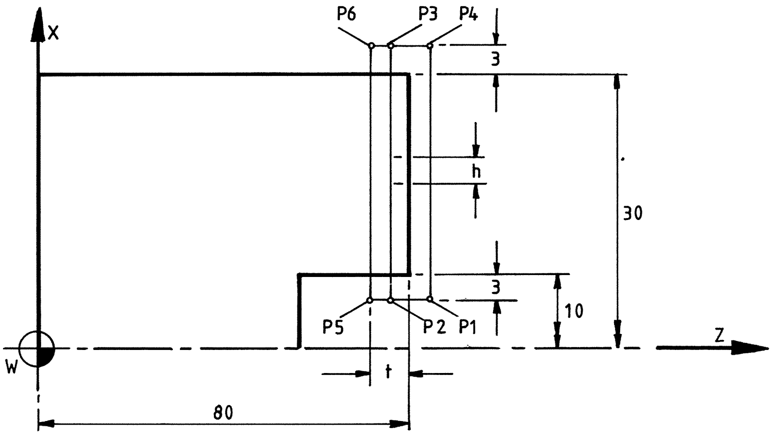
X(P2) = C + 2 mm = 65.86 mm

X(P3) = D + 2 mm = 103.366 mm

Transversal Thread (Fig. 5.15a)

Thread details: Lead h = 2 mm
Thread depth t = 1.3 mm
Infeed direction: perpendicular to the cutting direction
Absolute position data input:

```
N41 G90 S... LF
N42 G00 X4 Z82 LF   (P1)
N43 Z79.35 LF       (P2)
N44 G33 X36 I2 LF   (P3)
N45 G00 Z82 LF      (P4)
N46 X4 LF           (P1)
N47 Z78.7 LF        (P5)
```



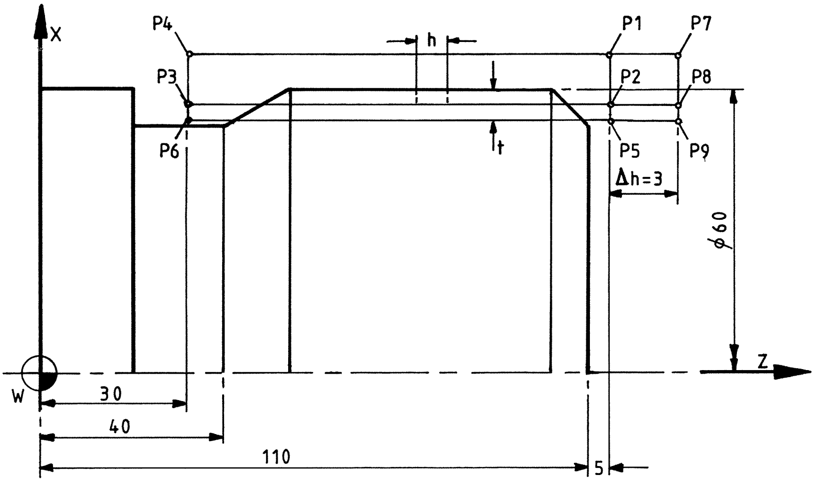


Fig. 5.15. **a** Cutting a transversal thread. **b** Cutting a multiple thread. [Courtesy of Siemens.]

N48 G33 X36 I2 LF (P6)
N49 G00 Z86 LF (P4)
N50
.
.
.

Multiple Threads (Fig. 5.15b)

Any thread cutting operation always begins at the synchronisation point of the zero mark of the pulse encoder. The feed will not be enabled unless a signal is received from the digital rotary transducer. The starting point for thread cutting can be offset in the program, making it possible to cut multiple threads. A "start" of a multiple thread is programmed in the same way as a "single-start" thread. When the first "start" has been completely machined, the start position in this case is offset using an (h) character, allowing the next "start" to be machined and is calculated in the following manner:

$$h = \frac{\text{thread lead}}{\text{number of starts}}$$

The various "starts" must be executed at the same spindle speed, in order to avoid discrepancies in the following error.

Thread details: Lead h = 6 mm
Thread depth t = 3.9 mm
Number of starts = 2

In this example (Fig. 5.15b), each "start" is machined in two steps. When the first "start" has been fully machined, the second "start" is machined by offsetting the start position by:

$$h' = \frac{\text{thread lead}}{\text{number of starts}} = \frac{6}{2} = 3\,\text{mm}$$

Absolute position data input:

```
N35 G90 S... LF
N36 G00 X66 Z115 LF   (P1)
N37 X56 LF            (P2)
N38 G33 Z30 K6 LF     (P3)
N39 G00 X66 LF        (P4)
N40 Z115 LF           (P1)
N41 X52.2 LF          (P5)
N42 G33 Z30 K5 LF     (P6)
N43 G00 X66 LF        (P4)
N44 Z118 LF           (P7)
N45 X56 LF            (P8)
N46 G33 Z30 K6 LF     (P3)
N47 G00 X66 LF        (P4)
N48 Z118 LF           (P7)
N49 X52.2 LF          (P9)
N50 G33 Z30 K6 LF     (P6)
N51 G00 X66 LF        (P4)
```

This completes the review of thread cutting applications although it is by no means an exhaustive account of the thread programming solutions. Notable omissions include: variable lead threads and worms, with thread forms such as acme, buttress and so on, not being described. However, the reader should by now have gleaned a reasonable understanding of thread production techniques on turning centres.

5.4.8 Miscellaneous Functions

The miscellaneous functions contain the primary technical specifications which are not programmed in the words provided with the address letters "F, S and T", where such functions are:

miscellaneous functions "M"
spindle speed "S"
tool number "T"
auxiliary function "H"

Up to three "M-functions" can typically be contained in any block, together with an "S-, T- and H-function". Such functions are output to the interface controller, usually in a specific sequence as follows: "M, S, T, and H". Whether these functions are output before or during the axis movement is specified by the machine data. When functions are output during the axis movement, the following details apply: if a new value must be active before an axis is traversed, the new function must be written in the preceding block.

Several miscellaneous functions are defined in the standard (DIN 66025 part 2), whilst others are defined by the machine tool manufacturer. The following "M-functions" are in general use on the majority of controllers:

M00 programmed stop (unconditional)
This function permits interruption to the program – perhaps to perform a measurement. On completion of the measurement the machine tool can be restarted, with the information entered being retained. This M00 function is active during all automatic operating modes – whether or not the spindle drive is also stopped must be determined from the specific programming instructions for each machine. Furthermore, an M00 function is also active in a block without position data.

M01 programmed stop (conditional)
The M01 function is similar to an M00, but it differs in that it is only active when the "conditional stop active" function has been activated, usually using a "soft key".

M02 programmed
This function signals the end of the program and resets the program to the beginning of the first block. It is always written in the last block of the program and the controller is reset. M02 can be written in a separate block, or alternatively, in a block containing other functions.

M17 subroutine end
Such a function is always written in the last block of a subroutine and can be incorporated with other functions, but cannot be present in the same block as a "nested subroutine".

M30 program end
This function fulfils the same as an M02.

M03, M04, M05 and M19 main spindle control
NB: M19 is only used with a pulse encoder in the main spindle. When an analog spindle speed version is present, the output uses the following M-words for spindle control:

M03, clockwise spindle direction of rotation
M04, anti-clockwise spindle direction of rotation
M05, non-orientated spindle
M19, orientated spindle

Often, an extended address notation with an output of the spindle number – dependent upon the controller type – may be used for miscellaneous functions in this group as the following example shows:

M2 = 19 S..
where: 2 = spindle number
19 = M-function 19
S.. = angle under S

"M19S.." can be used to perform an orientation and main spindle stop, with the relevant angle being programmed via an "S" in degrees. This angle is measured from the zero mark in a clockwise rotation and is a modal address. This modal function value is stored under the "S", it being valid for any angle, which may be used as a repeated stop using simply M19. It should be said that the M19 function does not cancel either M03 or M04.

Freely assignable miscellaneous functions
All miscellaneous functions – the exceptions being M00, M01, M02, M03, M04, M19, M30, M36, M37 – are freely assignable. An extended notation must always be used and the channel number specified for all freely assignable miscellaneous functions, typically as shown below:

M3 = 124
where: 3 = CNC channel number
124 = M-function 124

NB: Further details on the use of these and other functions can be obtained in the specific program key. The meaning of such functions is defined in DIN 66025.

Spindle Function "S"

The data listed below can be entered as an option via the address "S":

spindle speed in rev/min, or 0.1/min *
cutting speed in m/min, or 0.1/min *
spindle speed limitation in m/min, or 0.1/min *
spindle dwell in revolutions **
*: the speed and cutting speed must be programmed in the same input format.
**: dependent on the type of controller.

Further, an extended address notation must always be used and the spindle number specified for an "S-word" as the following example shows:

S2 = 1000
where: 2 = spindle number,
1000 = spindle speed.

Auxiliary Function "H"

Normally, only one auxiliary function per block can be entered under the "H" address for machine switching functions, or movements not covered by numerical control. Depending on the control system used, "H" can be programmed with up to 4–8 decades and such function meanings are described in programming instructions of the machine tool manufacturer.

The extended address notation must be used and the channel number specified for the "H-word" as described below:

H.. = ...

Tool Number "T"

The tool number determines the specific tool required for a given machining operation, as the following example shows:

T1234...
where: 1234... = tool number, the maximum is 4 or 8 decades depending on the system.

The extended address notation must be used and the channel number specified for the "T-word", such as:

T.. = ...

This completes the description of the relative merits of miscellaneous functions and in the next section we will consider the structure of sub-routines and "nesting" together with how they are used in CNC applications. Later, subroutines will be used in conjunction with parametric programming techniques.

5.4.9 Subroutines

Whenever the same machining operation must be performed repeatedly on a workpiece, it can be entered as a subroutine and "called" as often as desired within the part program, or activated using "manual data input" (MDI). A typical standard memory in a controller will be able to store up to 200 average length part programs and subroutines jointly, which can be extended still further if program memory is expanded.

Normally, it is preferable to write subroutines using incremental position data, with the tool being set to the position in the part program just prior to the start of a subroutine call. The workpiece machining sequence, with the tool positioned correctly, can be used to repeat the operation at various points on the workpiece without the need to modify the dimensions in the subroutine.

The subroutine structure (Fig. 5.16a) comprises the:

subroutine start (header)
subroutine blocks
end of subroutine

The subroutine start is typically comprised of the address "L" and the 3 or 4 digit subroutine number.

NB: The subroutine start is not in tape format. When the subroutine end is called, this is used to return to the part program and is defined by the M17 end character. An M17 function is written in the last block of the subroutine and it is permissible to write other functions (except the address "L") in this block.

The subroutine can be called in a part program via the address "L" with the subroutine number and the execution of the repetitions with the "P" address, as the following example illustrates:

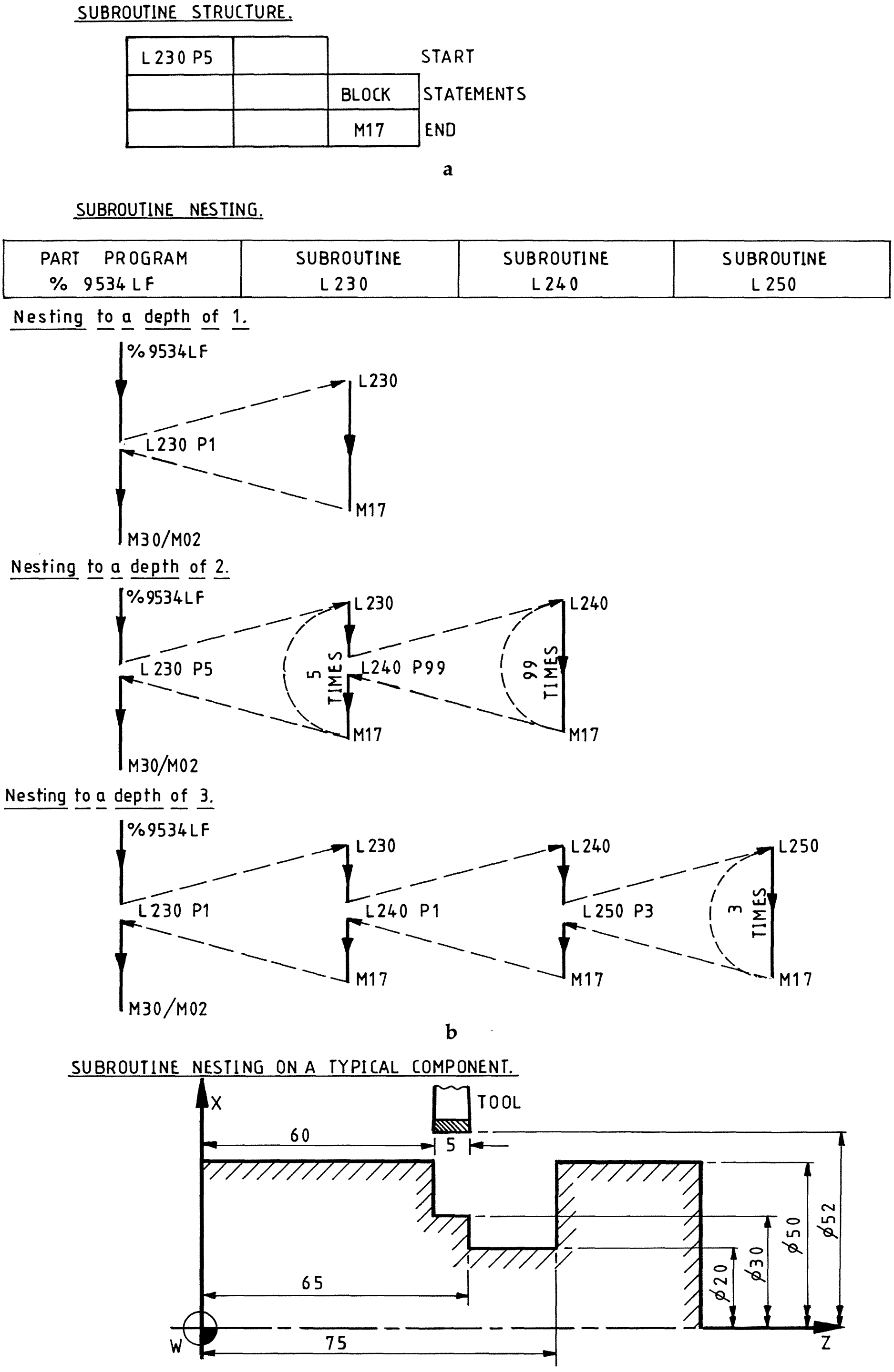


Fig. 5.16. Substructure of program nested subroutines. [Courtesy of Siemens.]

L123 P1
where: L123 = subroutine (1 . . . 999)
P1 = number of repetitions

The following logic should be noted during programming using subroutines:

the subroutine call must not be written in a block together with M02, M30 or M17

if the subroutine is called whilst the cutter radius compensation (CRC) function is active, this can create some problems, therefore see the section on p. 284 on special cases for CRC – blocks without path addresses should be referred to for an understanding of tool path motions

when a subroutine call is written in a block that contains other functions, the subroutine is called at the end of the block

Subroutine Nesting

It is possible not only to call subroutines from the part program, but also from other subroutines and this process is called "subroutine nesting" (Fig. 5.16b). Normally it is only possible to "nest" a series of subroutines to a finite depth, which typically might be three or four – depending upon the controller, with one particular controller having the ability to nest to a depth of 28 subroutines. In Fig. 5.16b, a typical programming application for the nested subroutines to a depth of three, might be:

first nested subroutine – to drill a hole pattern using "canned cycles", such as those shown in Fig. 5.30a,b for either a linear drilling pattern (G26), or a circular drilling pattern (G28) respectively

second nested subroutine – within the first nested subroutine another "canned cycle" can be called to drill the hole pattern chosen, such as the standard drilling cycle (G81) shown in Fig. 5.28a

third nested subroutine – finally, all, or some of these drilled holes might require tapping and this allows us to call up the final canned cycle for tapped holes (G84) shown in Fig. 5.29a, before returning to the main program

The use of such nesting and canned cycle programming activities has the benefit of considerably reducing the number of blocks of information necessary to complete the part program. This not only simplifies such programming activities, but utilises less memory capacity, giving the additional benefit of enabling one to store many more programs in the controller's memory.

As a practical example of the ability of nested subroutines to shorten programs and at the same time give the reader an understanding of the programming logic, the following turning example based upon Fig. 5.16c has been produced:

```
%9534 LF
N1 G90 G94 F.. S.. D.. T.. M.. LF
N2 G00 X52 Z60 LF
N3 L230 P1 LF          (subroutine call)
.
.
N90 M30                (end of part program)
      (subroutine structure)
L230 LF                  (start of subroutine)
NG G91 G01 X-11 LF
```

```
N2 G09 X11 LF
N3 L240 P2 LF          (nested subroutine call)
N4 M17 LF              (end of subroutine – back to part program)
        (nested subroutine structure)
L240 LF                (start of nested subroutine)
N1 G91 G00 Z5 LF
N2 G01 G09 X-16 LF
N3 G00 X16 LF
N4 M17 LF              (end of nested subroutine – back to subroutine)
```

5.4.10 Parametric Programming

Parametric programs offer the programmer a flexible, concise and powerful programming aid and they are used in a program to represent a numerical value of an address. Parameters are assigned values within the program and as such can be used to adapt programs to several similar applications; for example:

different feedrates *

different spindle speeds *

differing operating cycles

components with varying aspect ratios – such as those used in a "Group Technology" (GT) approach to component manufacture (see Fig. 5.17a)

calculating mathematical expressions for – trigonometric functions, addition, subtraction, multiplication and division of numerical values in specific blocks

* useful when modifying different materials to be machined, without changing the main cutting data factors in the part program which might otherwise be necessary when programming using the "traditional" approach.

Often such parametric programming adaptability is termed "free-variable parameters" and a typical assignable parameter might comprise the address "R" and a number with up to three digits. Typically up to three hundred parameters are selectable in the basic configuration within many controllers. Such parameters can be sub-divided into:

transfer parameters

computing parameters

channel-dependent/independent parameters **

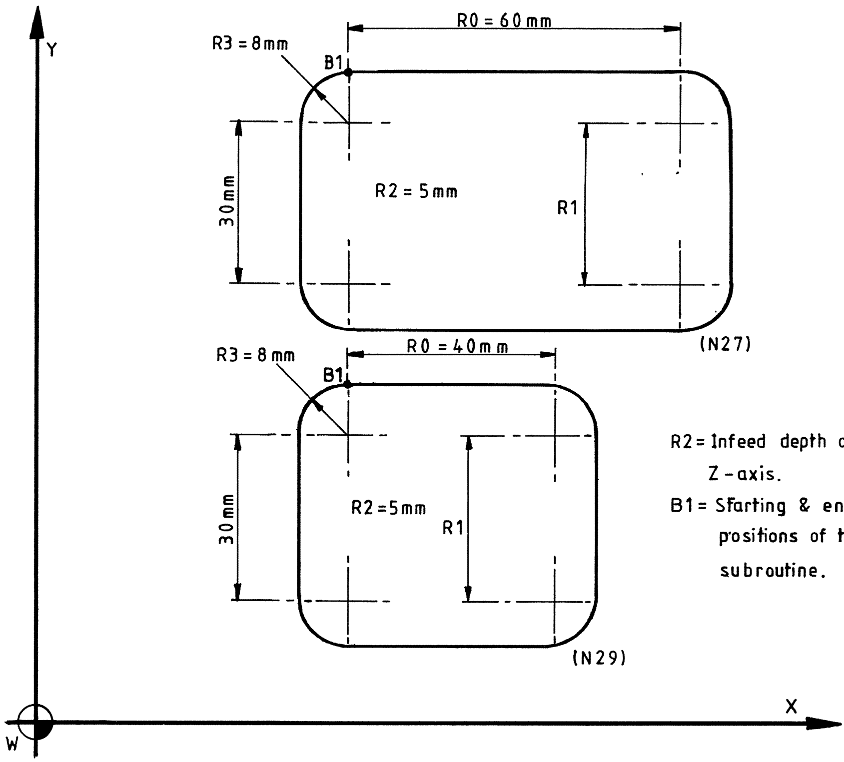
central parameters **

** these parameters are explained in manufacturers' manuals and are outside the scope of this section on parameter programming.

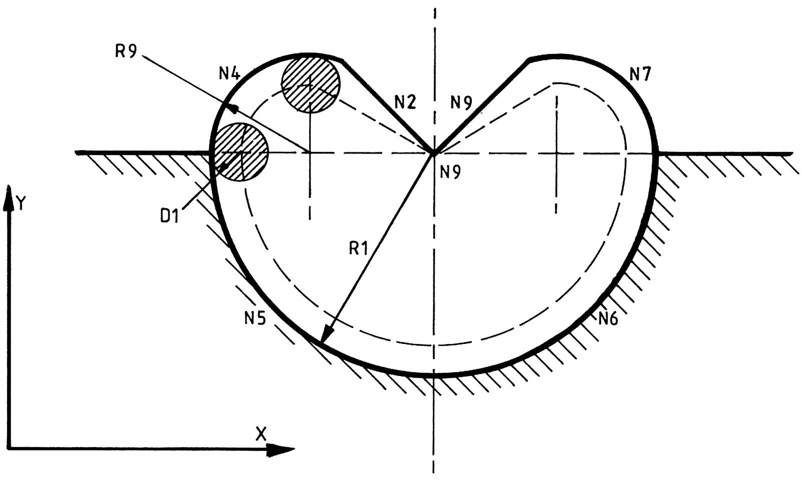
Parameter Definition

Quite simply, a parameter definition may be used to assign certain numerical values together with signs to the various parameters. Such parameters can be defined either in part programs, or in subroutines. A typical parameter definition might be:

R1 = 10 LF



a



b

Fig. 5.17. Parameter programming for similar workpiece geometries and complex shapes. **a** Milling rectangles with variable aspect ratios in the X–Y plane. **b** Using "parametrics" to machine an internal semicircle. [Courtesy of Siemens.]

In a single block, it is acceptable to have the parameter definition, a subroutine call, together with the switching functions present. The value defined for a parameter is assigned directly to the address, as the following example illustrates:

```
%5772
N1...
.
.
N37 R1=10 R29=20.05 R5=50 LF
N38 L51 P2 LF   (subroutine call)
M39 M02 LF      (end of program)
L51
N1 Z=−R5 B=−R1 LF
N2 X=−R29 LF
.
.
N50 M17 LF      (end of subroutine, back to part program)
```

where N37 = parameter definitions
N38 = subroutine call "51", with 2 repetitions

Parameter Calculations

The linking of parameters. As we have already mentioned, all four basic arithmetic operations may be used when parametric programming. It is important to the result of any calculation to link the parameters in a specific sequence as the following tabulation shows:

a6.5

Arithmetic operation	Programmed execution/ Arithmetic operation
Definition	R1 = 100
Assignment	R1 = R2
Negation	R1 = −R2
Addition	R1 = R2 + R3
Subtraction	R1 = R2 − R3
Multiplication	R1 = R2 * R3
Division	R1 = R2/R3

When the result of an arithmetic operation is written in the first parameter of a link, its initial value will be overwritten and as such is lost upon linking. However, the values of any second and/or third parameters are retained. If the value of one parameter is to be assigned to another, the following logic is valid:

R1 = R3 LF, as we can see in the tabulation above.

Calculations Using Numbers and Parameters

(i) *The addition and subtraction of numbers and parameters*

With any parameter it is possible to add to the value of an address, or to subtract from it accordingly. The sequence which follows must be used in such cases: address, numerical value, parameter. When no sign is specified, it is assumed that a positive sign (+) will be the default. In the example below we can see how the parametric logic is used to determine specific numerical values:

N38 R1=9.7 R2=−2.1 LF
N40 X=20.3+R1
N41 Y=32.9−R2
N42 Z=19.7−R1

The numerical result of these calculations:

(Line 40) X = 30
(Line 41) Y = 35
(Line 42) Z = 10

(ii) *Calculations using numbers and parameters*

Unfortunately it is not possible to multiply, divide, add, or indeed subtract absolute numbers and "R-parameters". Therefore under these circumstances we must use "auxiliary parameters", as described below:

Not permissible would be: R10=15+R11
permissible calculations are: X=10+R11

Let us now look at a practical example of such a technique. Assume that the parameter R2 must be divided by 2:

R3=2 Definition of an auxiliary parameter, hence:
R1=R2/R3.

The result of the calculation is contained in R1, with the values of R2 and R3, the auxiliary parameters, being retained.

Parameter String

The following example illustrates a typical parameter string:

R1=R2+R3−R4*R5/R6 . . . . R10

As we can appreciate from this expression, all the four basic arithmetic operations are permissible in any sequence. It is acceptable to link up to ten parameters together in a parameter string and such calculations are performed as follows (based upon the example shown above):

Step 1: R1=R2+R3
Step 2: R1=R1−R4
Step 3: R1=R1*R5
Step 4: R1=R1/R6
.
.
.

i.e. Step 1 R1 = $\underline{R2 + R3}$
↓
Step 2 $\underline{R1 - R4}$
↓
Step 3 $\underline{R1 * R5}$
↓
Step 4 $\underline{R1 / R6}$
↓
R1

NB: It is acceptable to perform any number of arithmetic operations in a block, typically multiplication, parameter strings, addition, and so on, with the limitation being the maximum permissible block length of 120 characters in most controllers. The individual links are calculated by the controller in the programmed sequence.

Such calculations are all very well, so let us look at how parametric programming can be put into practice and the examples chosen for the reader to gain a more complete appreciation are typical milling operations.

Milling Rectangles Using Parametric Programming

The example chosen (Fig. 5.17a) illustrates the variable aspect ratios of rectangles which require milling. The subroutine written below permits a rectangle whose sides are parallel to the machine axis to be machined in the "X–Y" plane:

Example 1 (Fig. 5.17a)

```
L46
N5 G01 G64 G91 Z=−R2 LF
N10 X=R0 LF
N15 G02 X=R3 Y=−R3 I0 J=−R3 LF
N20 G01 Y=−R1 LF
N25 G02 X=−R3 Z=−R3 I=−R3 J0 LF
N30 G01 X=−R0 LF
N35 G02 X=−R3 Y=−R3 I0 J=R3 LF
N40 G01 Y=R1 LF
N45 G02 X=R3 Y=R3 I=R3 J0 LF
N50 G01 Z=R2 LF
N55 M17 LF

    Subroutine call:
N26 G90 X... Y... LF
N27 L46 P1 R0=60 R1=30 R2=5 R3=8 LF
N28 G90 X... Y... LF
N29 L46 P1 R0=40 LF
    where: N26 = first starting position of the current program
           N28 = second starting position.
```

Summarising: by changing the "free-variable" parameters in lines and using subroutines, the variable aspect ratios of the two (i.e. large and small) rectangles can be milled respectively.

Milling an Internal Semi-Circle

In the second example (Fig. 5.17b), the subroutine shown below can be used to rough and finish mill a semi-circular profile. The contour radius and the approach and retract radii (i.e. "scroll-in and-out"), can be varied by using parametric programming. The difference between the workpiece's actual size and its design size can be checked after each cutter pass. This difference may then be entered into the program as the "additive" tool wear.

Example 2 (Fig. 5.17b)

```
Subroutine.
L11
N1 R1=R1−R9 LF
N2 G00 G64 G91 G17 G41 D01 LF
N3 R1=R1+R9
N4 G03 X=−R9 Y=−R9 I0 J=−R9 LF
N5 X=R1 Y=−R1 I=R1 J0 LF
N6 X=R1 Y=R1 I0 J=R1 LF
N7 X=−R9 Y=R9 I=−R9 J0 LF
N8 R1=R1−R9 LF
N9 G00 G40 X=−R1 Y=−R9 LF
N10 R1=R1+R9 M01
N11 M17 LF
```

where: N1 = Calculation of approach circle
N2 = Approach circle positioning
N3 = Working back "R1" to the original value
N4 = Contour approach (i.e. "scroll-in")
N5 = Machining
N6 = Machining
N7 = Retract from contour (i.e. "scroll-out")
N8 = Calculation of workpiece centre point
N9 = Positioning
N10 = Working back "R1" to the original value
N11 = Subroutine end.

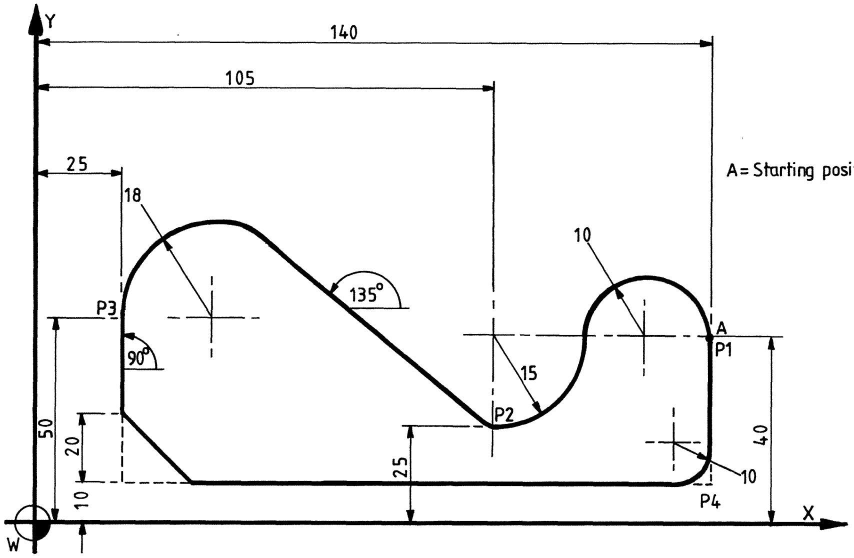
```
Subroutine call.
    %5873 LF
    N1.......
    N2 L11 P1 R1=50 R9=10 LF
    N3....... LF
```

5.4.11 Conversational/Blueprint/Shop-floor Programming

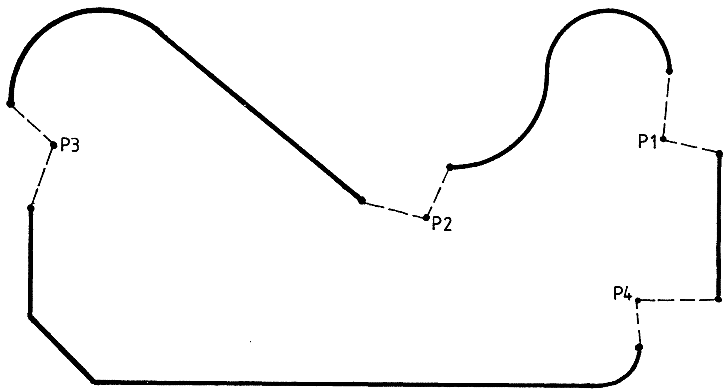
In order to build up a contoured profile to be either turned or milled, multi-point cycles for direct programming in accordance with the workpiece drawing ("blueprints") are provided for conversational programs. The points of intersection of the straight lines of the contour are entered as coordinate values, or alternatively, via angles. These straight lines can be joined together either directly, in the form of a corner, or rounded via radii, but chamfers also can be accommodated. Chamfer and transition radii are specified only by means of their size, with the geometric calculation being performed by the controller. The end position coordinates may be programmed using either absolute or incremental position data.

Contouring Cycle

As we can see from Fig. 5.18a,b, a contoured profile consists of the systematic build-up and assembly of discrete contoured elements (Fig. 5.18b). Later in this section the programming logic for the milled contour will be considered together with some turned examples of "blueprint" programming. Prior to that, it is important to under-



a



b

Fig. 5.18. "Blueprint programming" for 2-dimensional contours. **a** Contouring cycle programming for a machining centre. **b** The elements in the construction of a contouring cycle program. [Courtesy of Siemens.]

stand the use of the preparatory function G09 and its operation. Also discussed will be "F, S, T, H, and M" in the contouring cycle.

If the G09 function is programmed in the contouring cycle block, it will not be active until the end of the block – in other words, until the end position is reached. The G09 preparatory function is automatically generated by the controller when irregular points occur, typically corners, edges, etc., within the contouring cycle.

Linking of Blocks

The linking of blocks is possible with/without either angle inputs, inserted radii, or chamfers, in any sequence. In the following example of a profile milling operation (Fig. 5.18a), the following contouring cycles are used – circular arc – circular arc – straight line – circular arc, 3-point cycle + chamfer + radius, as shown below:

```
L168
N1 G90 G03 I-10 J0 I0 J15 X105 Y25 LF (P2)
N2 G03 A135 U18 X25 Y50 LF (P3)
N3 G01 A90 A0 X140 Y10 U-20 U10 LF (P4)
N4 Y40 LF (P1)
N5 M17 LF
```

The following programmed examples for turned parts illustrate a range of contours for either external or internal features (Fig. 5.19). In the first example (Fig. 5.19a) of external machining, the angle "a" refers to the starting position, whilst angle "b" is associated with the missing vertex. The end position can be programmed using either absolute position data G90, or incremental position data G91. Both end position coordinates must be specified. The controller determines the vertex from the known starting position, together with the two angles and the end position:

```
N10 G00 G90 X30 Z105 LF
N11 G01 A170 A135 X100 Z20 F.. LF
```

The internal machining example (Figs. 5.19b,c) can be determined from the drawing dimensions (Fig. 5.19c), with the starting position being defined anywhere outside the inner cone. The perpendiculars through the starting position and the extension of the internal cone will yield the point of the intersection "A" with the part program continuing, as follows:

```
N13 G00 Xstart Zstart LF
N14 G01 A90 A184 X...Z...LF
```

Finally the last contouring cycle program on a turning centre using blueprint programming, is illustrated below and is based upon the dimensional features shown in Fig. 5.19d:

```
L105
N5 G00 G90 X0 Z332 LF
N10 G01 G09 A90 X66 B-8 F0.2 LF **
N15 A180 A90 X116 Z246 B8 LF
N20 G03 A90 X116 Z246 B8 LF
N20 G03 B40 A175 X140 Z130 LF
N25 G01 A135 A180 X220 Z0 LF
N30 M17 LF
    where ** = linking with B
```

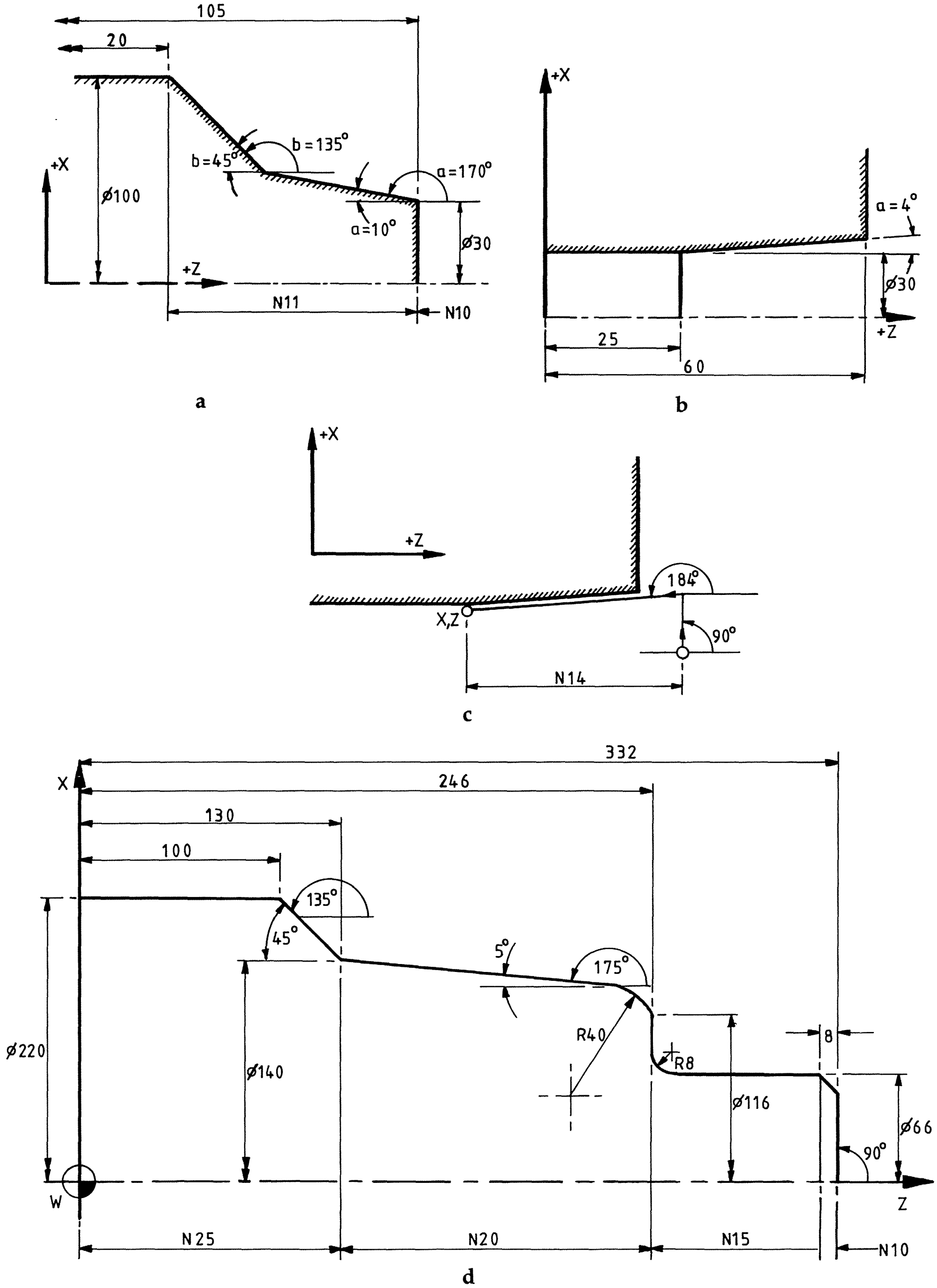


Fig. 5.19. "Blueprint programming" for turning operations. **a** Contouring – external machining. **b** Contouring – internal machining. **c** Drawing dimensions. **d** Contour cycle programming for a turning centre. [Courtesy of Siemens.]

5.4.12 The Structure of Tool Offsets and their Compensations

Tool Offset Number

In most CNC controllers the geometrical tool data for the tooling is usually stored under the tool offset number "D", where the:

Length ± 999.999 mm
Radius ± 999.999 mm

Depending on the controller type, the "T-number" is usually 4–8 decades. Typically the controller has its tool offset block sub-divided into 8 columns: P0–P7. The format of the tool offset block may be identified by the tool type (P1) (see Fig. 5.20). On one popular controller, either 99 or 128 tool offset blocks are available to the user, or a number may be selected via the machine data. The tool offset can be called up in up to three decades, via D1 to D... addresses, with its cancellation being with a D0. The tool offset is not rescinded, however, until the corresponding axis is programmed.

The tool number, type, geometry and the wear of all active tooling are stored in the tool offset area of the controller. The tool geometry together with its associated wear is updated by, for example, the measuring cycles in the CNC. Such wear when it occurs, is summated in the controller in accordance with the machine data.

Tooling Classification

The following example shows the breakdown of the tool type P1:

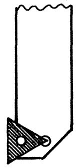
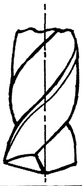
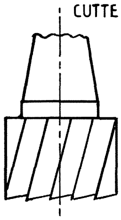
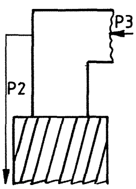
Unqualified: Type 0 Tool not defined
Type 1 . . . 9 Lathe tools
Semi-qualified: Type 10 . . . 19 Tools with active length compensation only (e.g. drills)
Qualified: Type 21 . . . 29 Tools with radius and length compensation (e.g. cutters)
Qualified: Type 30 . . . 39 Tools with radius compensation and two length compensations (e.g. angle cutter)

Tool Offsets on Turning Centres without Using Tool Nose Compensation

The tool offset is effectively derived from the sum of the tool length compensation together with any external, additive compensations. Hence, the sum of such compensations would correspond with the dimension "XSF" or "ZSF" as depicted in Fig. 5.21a, where:

P = theoretical tool tip
S = tool nose centre
F = slide reference point

In Fig. 5.21a, the tool's path is determined from the programmed tool nose centre "S" and this type of length compensation is generally referred to as the "tool nose centre". Incorporating tool compensation into the "tool nose centre" causes differences between the old and new offset values if the tool offset number is changed. This poses the question as to whether the difference is traversed directly following the change, or not taken into consideration until the programmed traverse of the corresponding axis is resolved on start-up.

TOOL.	STRUCTURE OF THE OFFSET MEMORY.	PROGRAMMING.
1. Facing tool – turning. 	TOOL N° P0 / TYPE P1 / GEOMETRY P2, P3, P4 / WEAR P5, P6 Dn: 123....8 / 1.......9 / X / Z / Radius / X / Z	TOOL CALL: T100 D50
2. Grooving tool. 	Dn: 123....8 / 1........9 / X1 / Z1 / Rad 1 / X / Z Dm: 123....8 / 1........9 / X2 / Z2 / Rad 2 / X / Z	TOOL CALL: T100 D50 (e.g. for left-hand cutting edge) ⋮ D55 (e.g. for right-hand cutting edge)
3. Drill. 	GEOMETRY P2 / WEAR P5 Dn: 123....8 / 10 (.19) / Length / LENGTH	TOOL CALL: T100 ⋮ M06 G17 (D50) or M06 G16 U V+/-W (D50)
4. MILLING CUTTER. 	GEOMETRY P2, P4 / WEAR P5, P7 Dn: 123....8 / 20 (.29) / Length / Radius / Length / Radius	TOOL CALL: T100 ⋮ M06 G17 (D50) Length effective in Z, rad. effective in X/Y plane. or M06 G16 UV +/- W (D50) Length effective in W, rad. effective in U/V plane.
5. ANGLE CUTTER. 	GEOMETRY P2, P3, P4 Dn: 123....8 / 30 (.39) / Length1 / Length2 / Radius WEAR P5, P6, P7 Dn: Length1 / Length2 / Radius	TOOL CALL: T100 ⋮ M06 G16 UV +/- Z+/- U(D50) Radius effective in U/V plane, length1 effective in Z, length 2 effective in U.

N.B. G16 is purely a setting function; no traversing is possible in these blocks. D is not coupled to plane selection.

Fig. 5.20. The structure of the tool offset memory. [Courtesy of Siemens.]

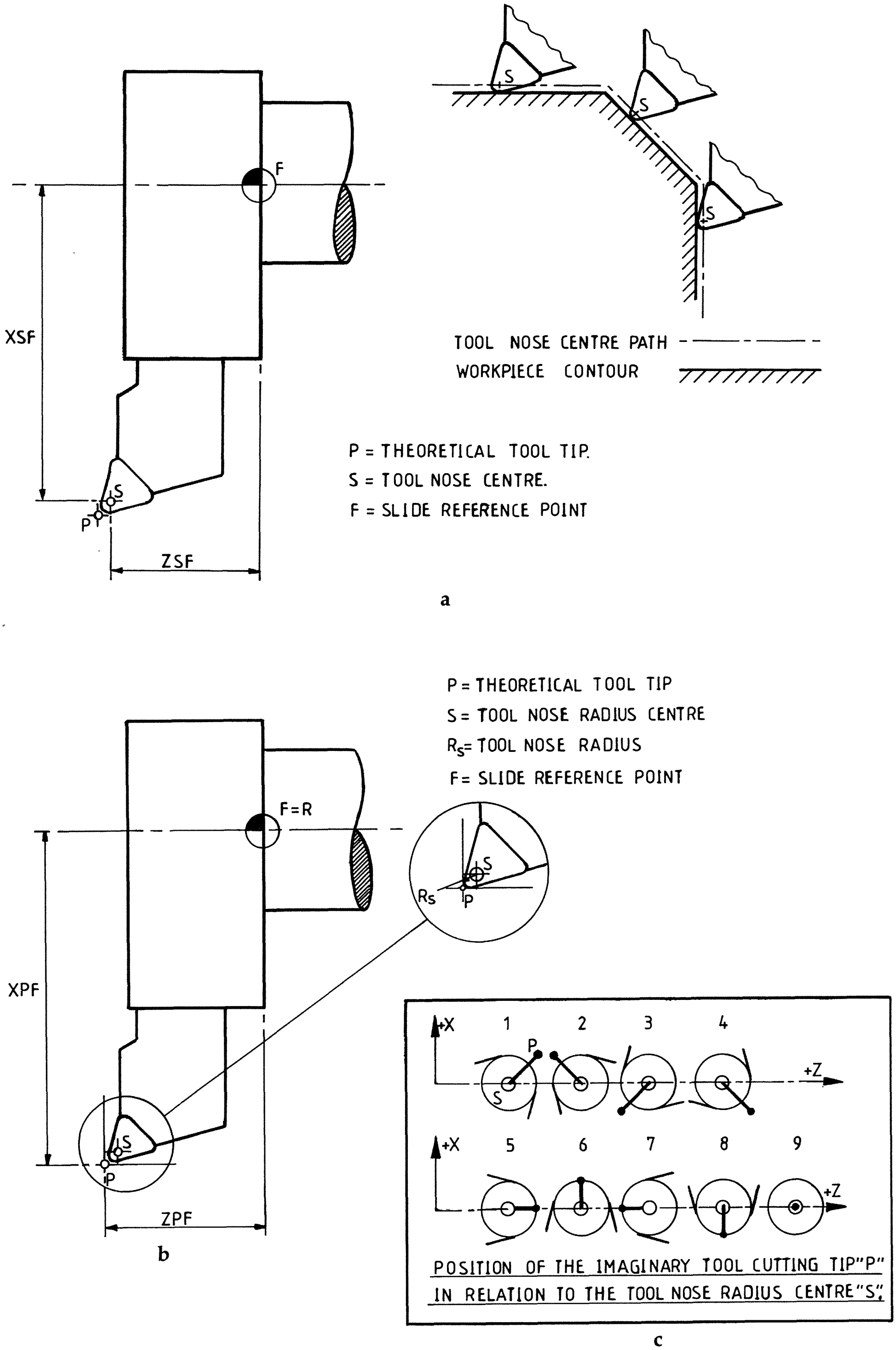


Fig. 5.21. **a** Tool offset without using tool nose radius compensation (TNRC). **b** Tool offset using tool nose radius compensation (TNRC). **c** Position of the imaginary tool cutting tip "P" in relation to the tool nose radius centre "S". [Courtesy of Siemens.]

NB: With TNRC (i.e. G41 or G42) the difference, in addition to the tool nose radius, is traversed in BOTH axes, no axis command being required for traversing the tool offset.

Tool Offset Using Tool Nose Radius Compensation

It is possible to program a workpiece contour in conjunction with tool nose radius compensation (TNRC), as illustrated in Fig. 5.21b. The length of compensation entered into the controller is termed "the cutting point" and is designated by point "P". With this point known in terms of "X" and "Z" axes, the controller will then compute the tool path to be traversed and, as such, no contour error occurs. The engagement of TNRC takes effect at the end position of the block in which it is called (i.e. G41 or G42), meaning that in the following block the compensation is fully engaged.

In order to calculate and engage TNRC correctly, the controller requires a code indicating the position of the "imaginary" tool cutting tip "P" in relation to the tool nose centre "S" (see Fig. 5.21b), a magnified illustration for greater clarity is given.

Whenever the "XSF" and "ZSF" are selected as the tool dimensions instead of the "XPF" and "ZPF", namely the dimensions of the tool nose centre/slide reference points, one of the 9 codes depicted in Fig. 5.21c must be used for all the tools, with this particular controller. This is the convention for a turning centre with the turret situated above the workpiece; if the second (lower) turret is to be programmed the codes are applied in the same manner, with the only difference being that the X-axis direction is reversed.

Machining Centre, Selection and Cancellation of the Length Compensation

Only when either the G00 or G01 is active can the tool length compensation be selected. It is necessary to select the plane which is perpendicular to the length compensation direction, such as:

N5 G00 G17 D.. Z.. LF

Only the tool's length compensation is written into the compensation memory using a "D-word"; this offset is always combined with the sign entered for its corresponding axis. To cancel length compensation, this is achieved with "D0", although the compensation is not removed unless its corresponding axis has been programmed. The following examples illustrate the effect of cancelling compensation with/without cutter radius compensation:

length compensation without cutter radius compensation:
N5 G90 G00 G17 D1 Z.. LF
.
.
N50 D0 Z.. LF
where: N5 = selection of length compensation (e.g. drill)
N50 = cancellation of length compensation

length compensation with cutter radius compensation:
N5 G90 G00 G17 G41 D2 X... Y... LF
N10 Z... LF

N50 G40 X... LF
N51 D0 Z... LF
where: N5 = automatic selection of cutter radius compensation

N10 = with length compensation
N50 = cancellation of cutter radius compensation
N51 = cancellation of length compensation

Intersection Cutter Radius Compensation

The compensation of the cutter radius is effective in any chosen plane, G16–G19, with the length compensation of the cutter always perpendicular to the selected plane, as we have seen previously. The G-codes for radius compensation are determined as follows:

G40 – no intersection cutter radius compensation

G41 – direction of tool travel to the left-hand side of the workpiece

G42 – direction of tool travel to the right-hand side of the workpiece

Whenever "mirror-imaging" is used, the path that might be travelled by the tool is depicted as follows, whilst taking the sign into consideration:

	Both axes mirrored or both axes without mirroring		One axis mirrored	
	(Sign of cutter radius compensation value)			
	+	−	+	−
G41	Left	Right	Right	Left
G42	Right	Left	Left	Right

Selection/Cancellation of the Intersection Cutter Radius Compensation

Tool compensation preparatory functions can only be selected if either a G00 or G01 is active. It is possible to program G40, G41, G42 in a block which does not contain tool path moves, providing the rapid/feed function has been previously programmed in at least one axis. The following example highlights this point:

N10 G01 G17 G41 D07 X... Y... LF
N15 Z... LF
where: N10 = at the end of this block the compensated path is reached in the selected plane – only the radius compensation value is incorporated
N15 = the tool length compensation has now been incorporated into the program as well.

Yet another technique for introducing compensation into the program is depicted below:

N10 G17 LF
N15 G41 D07 LF
N20 G01 X... Y... LF
N25 Z... LF
where: N10 = selection of the X–Y plane
N15 = selection of compensation
N20 = only the radius compensation has been selected at the end of this block
N25 = the tool length compensation has now also been incorporated.

Either cutter radius compensations, G41/G42, can be cancelled using G40, providing they are in linear blocks, G00/G01. So that the correct compensations are retracted, at least one plane must be programmed, with the length compensation being cancelled using "DO". This is, of course, assuming that its compensated axis was programmed. In the example given below, cancellation of cutter compensation is shown:

N30 G40 X... LF
N35 D0 Z... LF
where: N30 = cancellation of tool compensation – only the radius compensation value is retracted
N35 = the length compensation value = 0, is retracted.

Whilst not strictly a tool cancellation in the traditional sense, it is possible to swap one type of compensation for another, as the following change from G41 to G42 shows:

N10 G01 G17 G41 D12 X... Y... LF
N15 Z... LF
N20 G42 X... Y... LF
N25 Z... LF
where: N10 = incorporation of the radius compensation to the left-hand side of workpiece
N15 = incorporation of the length compensation
N20 = radius compensation changed to the right-hand side of workpiece, for example, when changing the direction of motion to the workpiece – traverse milling
N25 = no change in tool compensation

Finally, in the examples of offsetting tooling, it is possible to change the tool offset number, without the need to re-enter the G-function (as it is modal), as the following examples indicate:

N10 G01 G17 G41 D12 X... Y... LF
N15 Z... LF
N20 D10 Z... LF
N25 X... Y... LF
where: N20 = change in length compensation
N25 = change in cutter radius compensation

Whenever the cutter radius compensation has been selected, it is generally not permissible to program either G58, G59, or G33 in most controllers. The remedy for this is to program these functions before selecting the appropriate cutter radius compensation, or alternatively, cancel the cutter radius compensation – select G58 . . G33 – then select the cutter radius compensation again. If the cutter radius compensation has been selected, including the G40 block, the effective zero offset value must not be changed.

In the following milling examples we can gain an appreciation of the advantages of utilising tool compensations, as only the part's dimensional features need be considered, once the appropriate compensation/s has been engaged.

Example 1. Milling a profile utilising cutter radius compensation (see Fig. 5.22a):

```
N1 G01 G41 D1 G90 G17 X30 Y90 F500 S56 M03 LF
N2 G91 X30 Y30 LF
N3 G02 X30 Y-30 I0 J-30 LF
N4 G01 X30 LF
N5 G02 X30 Y30 I30 J0 LF
N6 G01 X-15 Y-30 LF
N7 X15 Y-30 LF
N8 X-30 LF
N9 X-30 Y-30 LF
N10 X-45 Y30 LF
N11 X-15 Y30 LF
N12 G40 G90 X0 Y90 LF
N13...
```

NB: As we can see (Fig. 5.22a), the milling cutter used a radius of 14 mm, with the cutter radius being entered under the tool offset number D1.

Example 2. Milling a circle utilising cutter radius compensation with scrolling – in/out – to avoid dwell marks (i.e. "witness") on the component (see Fig. 5.22b):

```
N1 G90 G00 G17 G41 D1 X80 Y30 LF
N2 G03 X130 Y80 I0 J50 LF
N3 G91 G02 X0 Y0 I50 J0 LF
N4 G90 G03 X80 Y130 I-50 J0 LF
N5 G00 G40 X70 Y80 LF
N6...
```

There is a whole host of virtually infinitely variable programming techniques that could be adopted in the machining of components. Just look how many there are and how they can vary. Even with individual part programs, there are many methods of programming motions – assuming the cutters take the same paths around the workpiece. If one decided to write a program using different tool motions for the same part, this would yet again produce considerable diversity in programs. There is no unique method for part programming a workpiece, only reasonable solutions, although it should be said that some programs can considerably reduce non-productive motions whilst machining the part, which can save seconds, or indeed minutes from the cycle time, depending upon how long, or complex the part. Not only can a more productive throughput result from optimum programming, but the length of blocks used in the memory might also be reduced, which is a further saving. A good part programmer can save a company considerable expense in reducing redundant work–non-productive cycle time to a minimum.

In the final section concerning the fundamentals of part programming we will consider further the effects of cutter and tool nose radius compensations, as their engagement needs to be fully understood and appreciated.

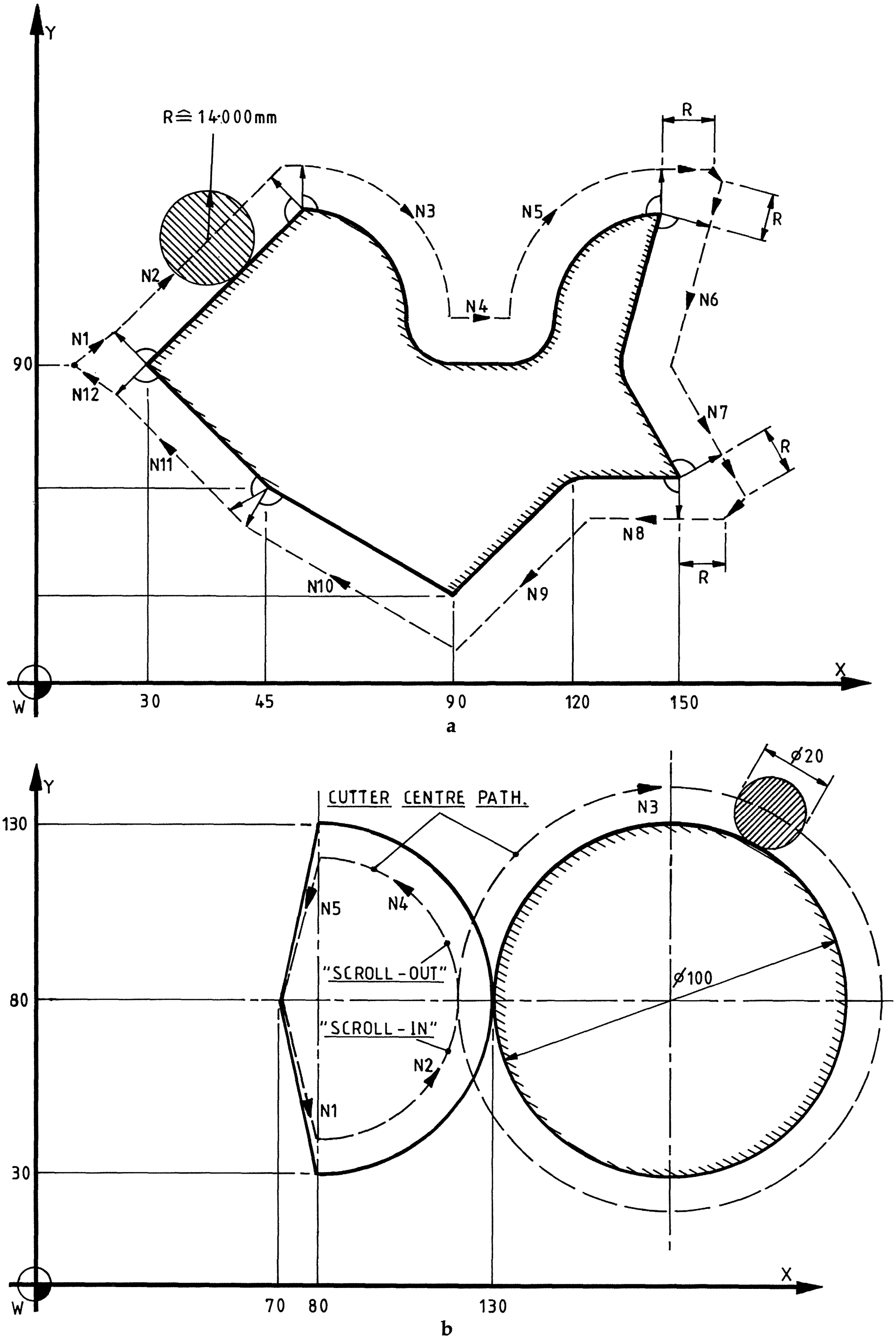


Fig. 5.22. a Milling with cutter radius compensation. **b** Full circle programming using cutter radius compensation. [Courtesy of Siemens.]

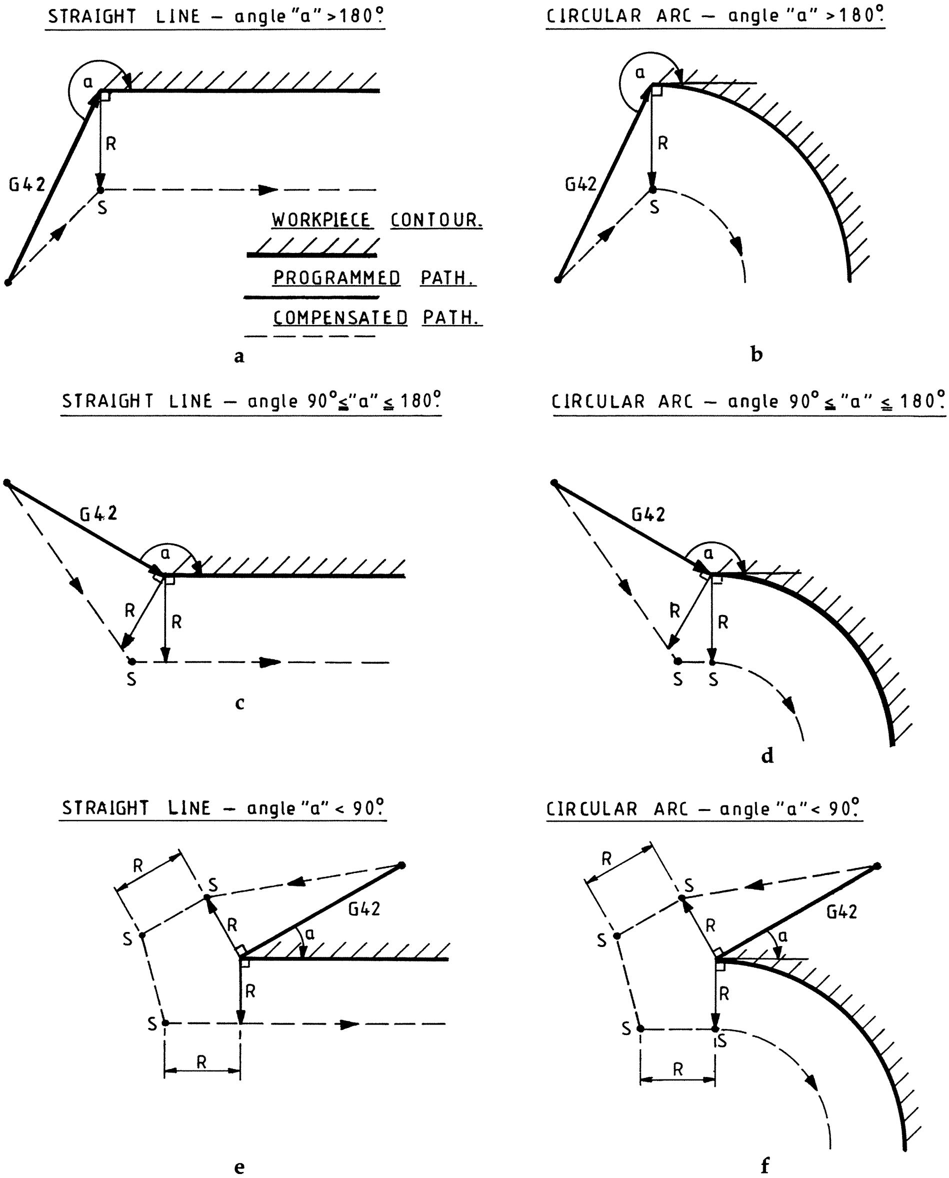


Fig. 5.23. The cutter compensation selected for various approach angles. [Courtesy of Siemens.]

5.4.13 Further Information on Cutter Radius Compensation (CRC)/Tool Nose Radius Compensation (TNRC)

The Selection of CRC/TNRC

We have seen how the compensation mode is selected for either CRC or TNRC previously (section 5.4.12) in the fixed plane, using either preparatory functions G41/G42, together with an offset number "D". The cutter compensation will either be to the left-hand side of the workpiece contour, in the traversing direction using a G41, or to the right-hand side of the component's contour with a G42. When selecting either CRC/TNRC, it is necessary for the controller to "look-ahead" – read two or three blocks ahead – in order to calculate the point of intersection. In the pictorial representations that follow, all the stop positions for single blocks are denoted by an "S", although we appreciate that in reality no such condition actually occurs in practice as we cut the part. In the following selection of typical cutter compensation engagements, a block start vector, denoted by the character "R", is created perpendicular to the programmed path, see Fig. 5.23a–f.

Obviously for the successful engagement of cutter compensation – which is always a problem for people new to CNC programming – certain rules must be adhered to:

the selection of the compensation mode can only be achieved in a block programmed with an "active" (i.e. modal) G00, G01, or alternatively either G02 or G03

the tool number D0 is assigned to the 0 compensation value and as such, no compensation is selected

CRC/TNRC in the Part Program

In the following schematic and tabulated examples (Fig. 5.24a–c), when using the selected CRC/TNRC, we have already mentioned how the controller, of necessity, must read two further blocks in advance during processing of the current block in order to calculate the intersection point for the compensated paths. These diagrams (Fig. 5.24a–c) illustrate just how such compensation is achieved for the various transitions:

straight line–straight line
straight line–circular arc
circular arc–straight line
circular arc–circular arc

NB: These geometric transitions of the various tool path vectors have been grouped according to the workpiece's included angle, denoted by the letter "a".

It is obvious from such pictorial representations that in order to generate successfully from obtuse to acute corner geometries (Fig. 5.24), the cutter's vectored path around these workpiece intersection points, is, of necessity, quite a complex motion.

NB: In Fig. 5.24 for all cases and for the sake of simplicity, the cutter compensation shown activated is G42, which as we now know, having the cutter to the right-hand side of the workpiece is in the traversing direction. It should also by now be appreciated that if G41 transitions had been applied, the same vectored paths would have resulted, except that the workpiece would lie on the left-hand side of the cutter's path.

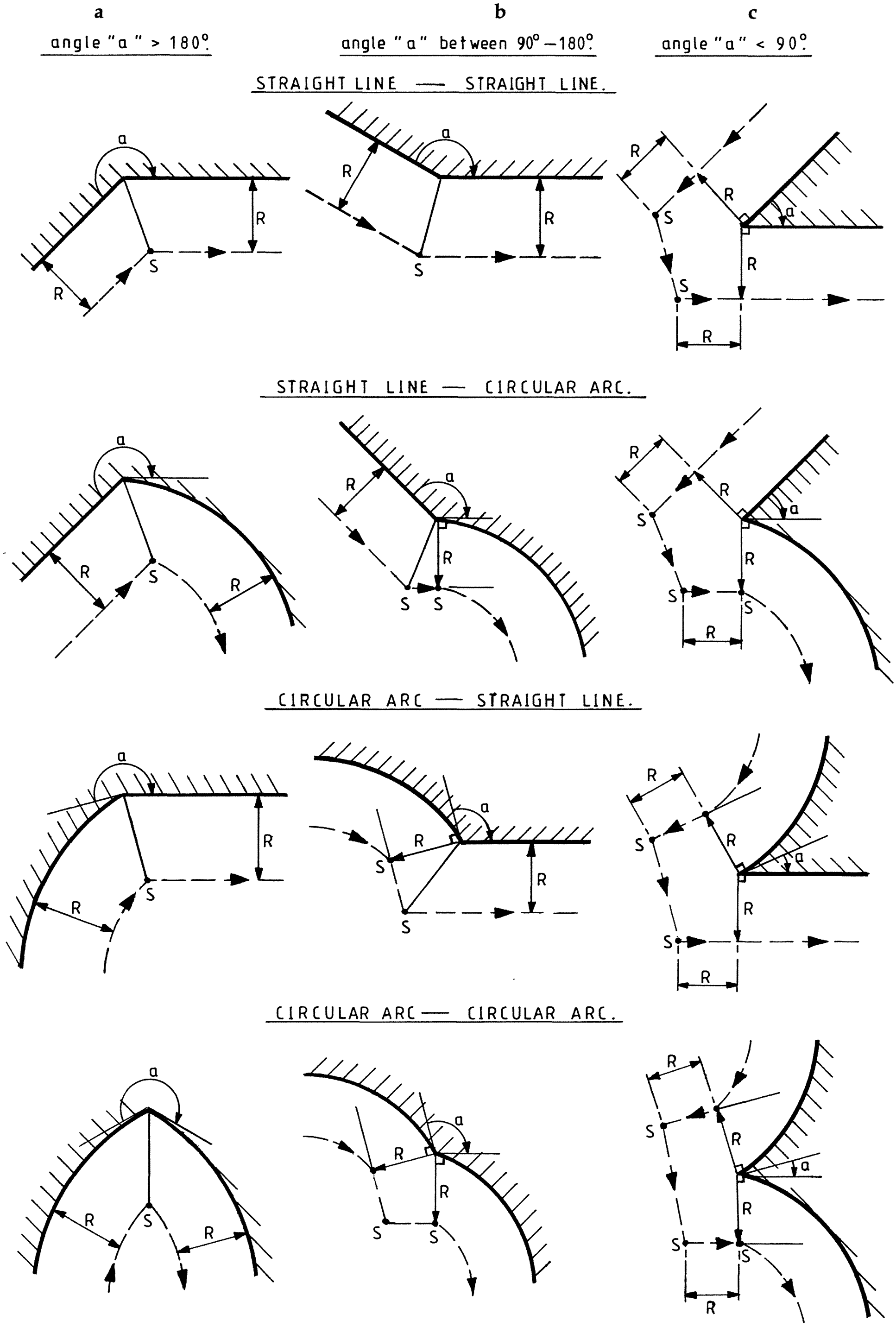


Fig. 5.24. Tool compensation for various workpiece geometric transitions. [Courtesy of Siemens.]

Cancellation of CRC/TNRC

Just as important as the successful engagement of cutter compensation is the cancellation of cutter compensation. In fact, it is even more critical to observe the rules of cutter compensation cancellation, than those for its engagement. This is because if we engage a cutter transition compensation incorrectly, the worst thing that can happen is that we will cause a vectored cutter path which might machine too much off the workpiece and lead to scrapping the part, or at best leave extra stock material behind – after the passage of the cutter – so that further machining would be necessary at some later stage. However, if cutter compensation cancellation is retracted at the wrong point in the part program, it can at worst cause a rapid sideways radial motion as it is cancelled. There is damage to both the workpiece and cutter, with the severity being dependent upon the magnitude of the cutter's radius. Therefore, extreme care must be used in determining the earliest point within the program at which cutter compensation cancellation can be successfully achieved.

It is apparent to the reader by now that the compensation mode is cancelled using the preparatory function G40. In the following selected examples (Fig. 5.25a–c), cancellation of cutter compensation is depicted for both straight line and circular arc tool path motions for varying workpiece included angles. As previously mentioned for the engagement rules of cutter compensation, the cancellation can only be achieved in a program block which is "active" with either G00 or G01 linear motions, or G02/G03 circular motions. Furthermore, the tool number D0 corresponds with a value 0, which allows it to be used to cancel the tool compensation also.

Changing the Direction of Compensation

There are many occasions when it is necessary to change the direction of cutter radius compensation within the part program, in order to machine a certain feature. A typical example of this is shown in Fig. 5.26a, where a top face has been milled and the compensation is changed to machine the chamfer. This diagram shows the perpendicular vector with a length "R" which is created in the appropriate direction of compensation at the end position of the old G-function block, in this case G42, and at the starting point for the new block with its respective G-function G41.

Changing the Offset Number

If we change the offset number at any point within the program, then the following logic applies (Fig. 5.26b):

there is no block start intersection calculated from the old compensation

a perpendicular vector with length "R1" is created at the end position of the block using the old offset number

the block end intersection is calculated with the new compensation value

Changing the Compensation Values

As the reader can appreciate, this modification to the radius compensation value (Fig. 5.26c) is similar in its function to that of changing the offset number described above (Fig. 5.26b). The compensation values may be changed at the:

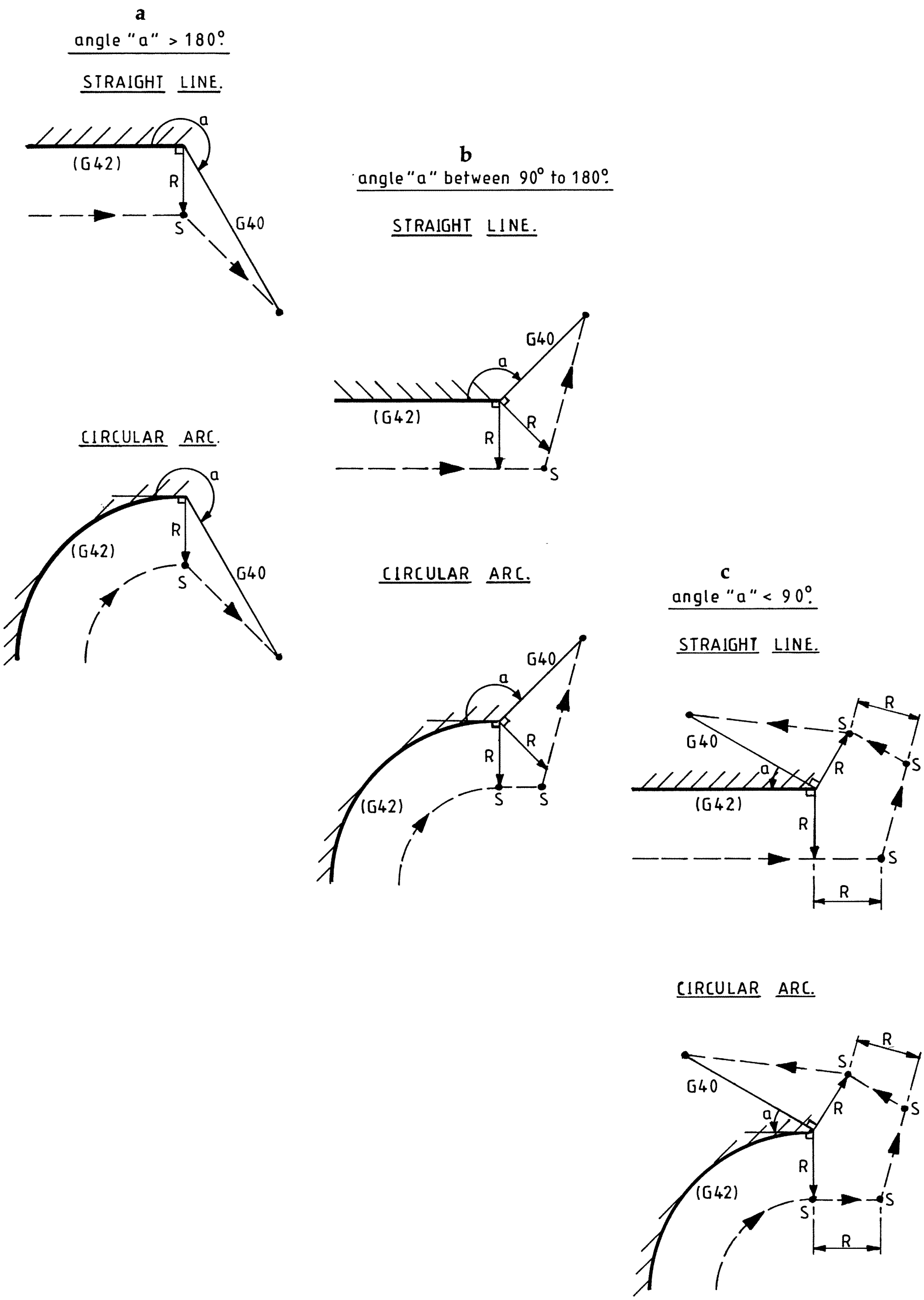


Fig. 5.25. Cancellation of tool compensation using the preparation function G40. [Courtesy of Siemens.]

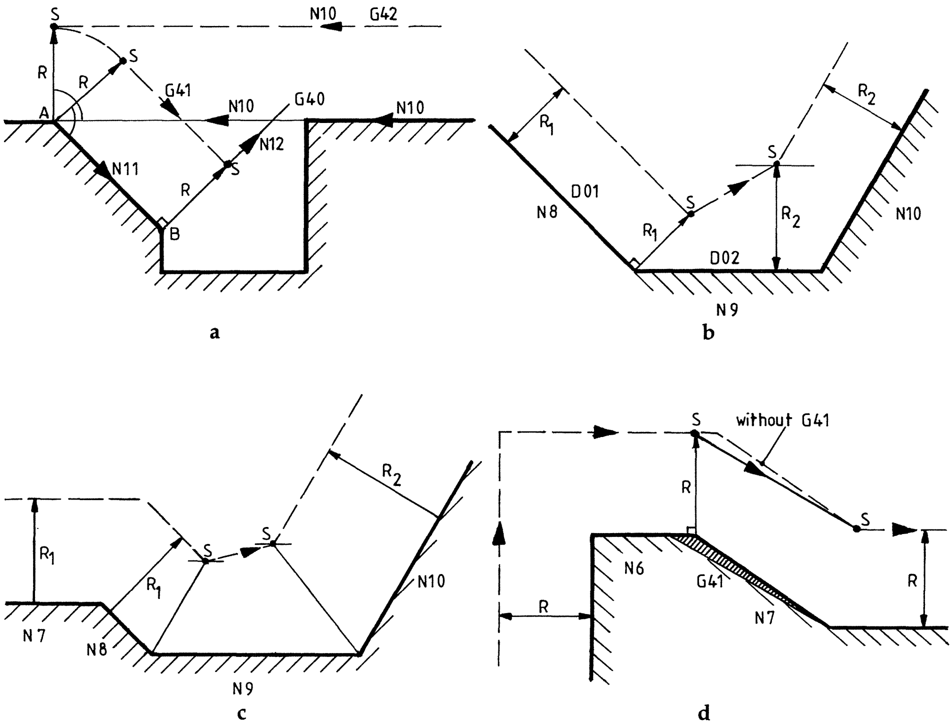


Fig. 5.26. Adjustment of cutter path. **a** Changing the direction of compensation. **b** Changing the offset number. **c** Changing the compensation values. **d** Repetition of the selected G-function (G41, G42) with the same offset number. [Courtesy of Siemens.]

operator's panel
using an external tool offset, or in the part program
tape reader – using an NC tape

The new compensation value takes effect in the next block of the part program.

Repetition of the Selected G-Function, with the same Offset Number

Assuming that either a G41, or G42 preparatory has already been programmed and is repeated, a vector with length "R" and perpendicular to the programmed path is created in the preceding block at the block end position (Fig. 5.26d).

The following example illustrates the block start intersection being calculated for the following block:

N4 G91 D10 G41 X...Y...LF
N5 Y...LF
N6 X...LF
N7 G41 X...Y...LF
N8 X...LF

NB: This extra G41 in block N7 being repeated from block N4, causes an error, thus, extra stock is removed and part is scrapped (Fig. 5.26d).

The Effect of Using M00, M01, M02 and M30 with either CRC/TNRC Selected

M00 and M01: the CNC stops, when this preparatory function is programmed, at the position "S" (shown in Fig. 5.26), for a single block.

M02 and M30: when these preparatory functions are active, the compensation is also retracted if it is cancelled in the last block with a G40, assuming that at least one axis address has been programmed. The following example shows the function M30 within the program:

```
.
N150 X...Y...LF
N200 G40 X...M30 LF
.
```

Obviously the compensation is not retracted if a cutter path has not been programmed.

CRC/TNRC with a Combination of Various Block Types and in Conjunction with Contour Errors

If one is programming in a contouring mode, special attention must be paid to the blocks without tool movement in order to prevent contour errors, as the following examples illustrate:

when tool path addresses are programmed, but there is no movement, since the distance is 0 – as the example below shows:

```
.
N...G91 X0 LF
.
```

auxiliary functions, such as a dwell, axis address outside the compensation plane, or a zero offset programmed in the compensation plane instead of path addresses, shown below:

```
.
N...M05 LF
N...S21 LF
N...G04 X100 LF
.
```

When one "auxiliary function block" is programmed between the tool paths in the compensation plane, no error occurs on the part:

```
N5 G91 X100 LF
N6 M08 LF
N7 Y-100 LF
```

However, when two "auxiliary function blocks" are programmed between the tool paths in the compensation plane, a corner error occurs. The part has an inappropriate tool motion, causing a chamfering to the corner:

N5 G91 X100 LF
N6 M08 LF
N7 M09 LF
N8 Y-100 LF
N9 X100 LF

NB: There are many examples that can be caused by incorrect usage of M-functions, leading to part scrappage by unanticipated and undesirable tool motions, so extreme care in when, where and how they are used, is urged.

Special Case CRC/TNRC Problems

In this final discussion about cutter compensation programming techniques, a range of "special case" problems for both CRC/TNRC will be highlighted. The first example chosen (Fig. 5.27a) illustrates how the controller logic always uses the next block to calculate the point of intersection of the compensated paths. Assuming that no axes in the compensation plane are programmed in the next block, the controller will automatically skip this block and use the following one. When this occurs there is a likelihood that a contour error will take place, if the intermediate block is less than the compensated value. Machining is not interrupted, although an alarm signal is indicated.

Fig. 5.27b shows the expected outcome of the toolpath motions when an intermediate block is too small for the selected compensation.

The illustration depicted in Fig. 5.27c shows the problem when the direction of cutter compensation of either CRC/TNRC is retained and the traversing direction is reversed. Note that the return path, shown by line N2, must exceed twice the cutter radius/tool nose radius, or the tool will proceed to move in the wrong direction.

The following diagrams (Figs. 5.27d–f) apply to external contours with circle transitions having obtuse angles:

Fig. 5.27d: in order to prevent a conditional stop in the contouring mode owing to intermediate blocks which are too small, the tool paths "AB" and "BC" can be omitted within the CNC

Fig. 5.27e: depending upon the tolerance "d" which is defined on start up – maximum being 32 000 μm, the path will be as follows:
if X1 and Y1 are less than "d", there will be a direct traverse from "A" to "C"

Fig. 5.27f: if X1, Y1, X2 and Y2 are less than "d", there will be no compensating movement and machining continues with a new radius at point "A", producing a machining error

The block numbers are interchanged whenever CRC/TNRC generates intermediate blocks – including those upon selection and cancellation – if an axis movement outside the compensation plane is programmed between these blocks.

In Fig. 5.27g, an indication of such programming problems can be seen, as the following logic shows:

N5 G00 Z100 LF
N10 X...Y10 LF
N15 G31 D01 X20 Y20 LF
N20 G03 X0 Y40 I-20 J0 LF

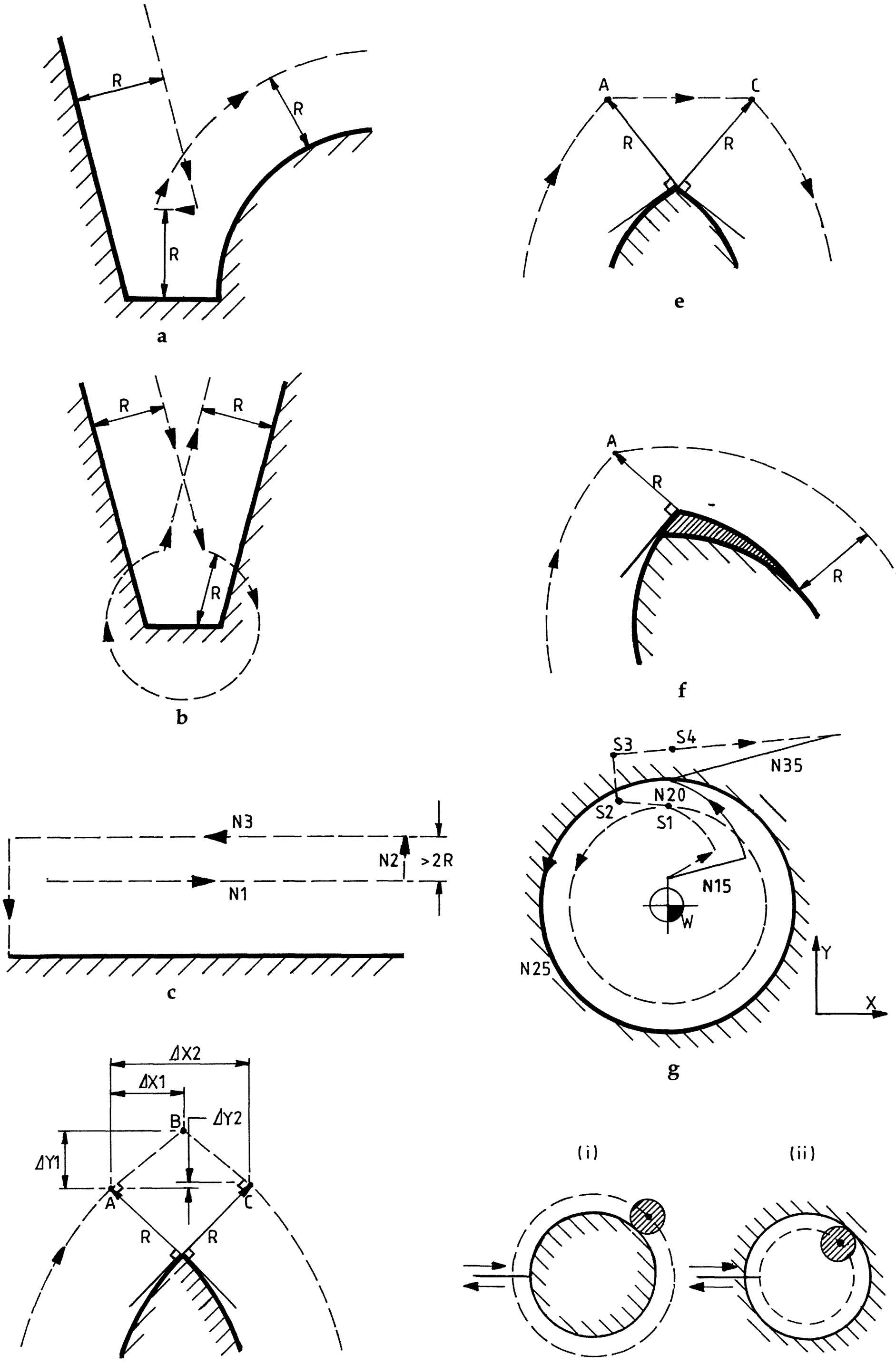


Fig. 5.27. "Special case" cutter compensation problems. [Courtesy of Siemens.]

N25 X0 Y40 I0 J-40 LF
N30 G01 Z0 LF
N35 G40 X80 Y60 LF

NB: The points S1, S2, S3 and S4 belong logically to block N25, with the machining sequence, visible in the single block, as follows:

. . . , N20, N25 (S1), N30 (tool withdrawn from the workpiece), N25 (S2), N25 (S3), N25 (S4), N35 . . . This sequence is also valid if N25 is a linear block.

Fig. 5.27h illustrates the effect of using negative compensation values. This means that a compensated path corresponding to a G42, with a positive compensation value, is implemented with a G41 – i.e. an analog internal contour is followed instead of the programmed external contour, or vice versa.

In Fig. 5.27h(i), the cutter centre path shown has a positive compensation value which has been entered, whereas in Fig. 5.27h(ii), a negative compensation value is illustrated in conjunction with the same machining program. If the program is generated as shown in Fig. 5.27h(ii), with a positive compensation value, it will have a negative compensation effect and produce machining as described in Fig. 5.27(i). Therefore, it is possible to implement two machining conditions using the same program and they are distinguished by entering either a positive or negative compensation value.

In the final section concerning CNC programming fundamentals we will consider the advantages to be gained from utilising programming aids termed "canned cycles".

5.4.14 Part Programming Using "Canned Cycles"

Canned cycles consist of a predetermined series of machining operations that direct the movements of all axes and the spindle. Canned cycles are intended to permit operations such as drilling, tapping, boring, pocket clearances and so on, without requiring repetitive programming of all data in each block of information. Many controllers have over ten canned cycles which can be called upon by the programmer. This allows the user to select the actions desired for these canned cycles. Each cycle is defined as a multi-step sequence of operations, with each step representing a departure mode, switching mode, or a mode of operation. For example, with a typical controller up to 28 actions are selectable allowing the programmer to customise a canned cycle, with up to 24 steps being used to define a canned cycle. In the following list, there is a typical range of actions available which can be user defined on a vertical machining centre:

00 – end of cycle
01 – rapid to R-plane
02 – start spindle
03 – stop spindle
04 – orientate spindle
05 – reverse spindle direction
06 – off-centre position
07 – remove off-centre position
08 – feed to depth
09 – incremental feed to depth
10 to 13 – dwell cycles
14 – return to R-plane at traverse rate

15 – return to R-plane at feedrate
16 – return to initial position at traverse rate
17 – return to initial position at feedrate
18 – programmed spindle direction
19 – turn on operator's feedhold
20 – distance to zero
21 to 28 – disable/enable and dwell cycles

NB: The programming manuals would offer a detailed description of each programmable action and how to engage them within the canned cycle.

In the following typical canned cycles for machining centres, the reader can gain an appreciation of how they operate. The first canned cycle we will consider is the standard drilling cycle, depicted in Fig. 5.28a:

rapid traversing to an X/Y position within the program
rapid traverse to a preselected R-plane, above which rapid motions can be safely made
feeding to the programmed Z-depth at a preselected feedrate
return to R-plane at feedrate, this being the end of the canned cycle
rapid traverse to the next X/Y position

In the second example of canned cycle programming this is used in conjunction with the drilling cycle (Fig. 5.28a) and is a spotfacing operation with a dwell (Fig. 5.28b):

rapid traverse to drilled hole at the X/Y position
rapid traverse to the pre-selected R-plane
feeding to programmable Z-depth
dwelling to clean up counterbore
return to R-plane at feedrate, end of canned cycle
rapid traverse to next X/Y hole position

After drilling the holes in the component using a canned cycle, it is often desirable to incorporate a tapping cycle (Fig. 5.29a) as a nested subroutine within the main program. A typical tapping canned cycle is shown in Fig. 5.29a:

rapid traversing to the X/Y position
rapid traverse to the preselected R-plane
feeding to required Z-depth
reversal of spindle rotation and return to R-plane
cancel spindle reversal and stop spindle
rapid to following X/Y hole position, as necessary

The final canned cycle, depicted in Fig. 5.29b, is a boring cycle having a dwell with feedrate return:

rapid traverse to hole position in X/Y plane
rapid traverse to R-plane
feeding to specified Z-depth
timed dwell
return to R-plane at feedrate
traverse at rapid to next hole position in X/Y plane as necessary

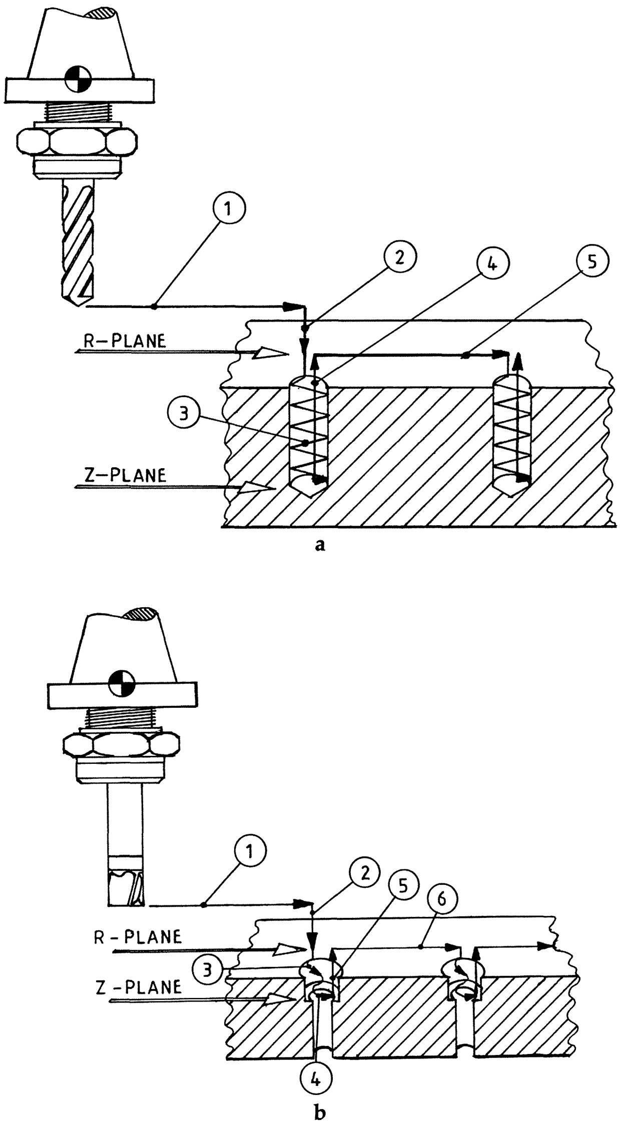


Fig. 5.28. Using "canned cycles" for drilling and spotfacing operations. **a** A standard drilling cycle (i.e. G81). 1, traverse to position (X/Y); 2, traverse to R-plane; 3, feed to programmed Z dimension (i.e. in-zone position); 4, return at traverse to R-plane (end of cycle); 5, traverse to next position (X/Y). **b** Drilling cycle with dwell – "spotfacing" (i.e. G82). 1, traverse to position (X/Y); 2, rapid to R-plane; 3, feed to programmed Z dimension (i.e. in-zone position); 4, dwell time; 5, return at traverse to R-plane (end of cycle); 6, traverse to next position (X/Y). [Courtesy of GE Fanuc.]

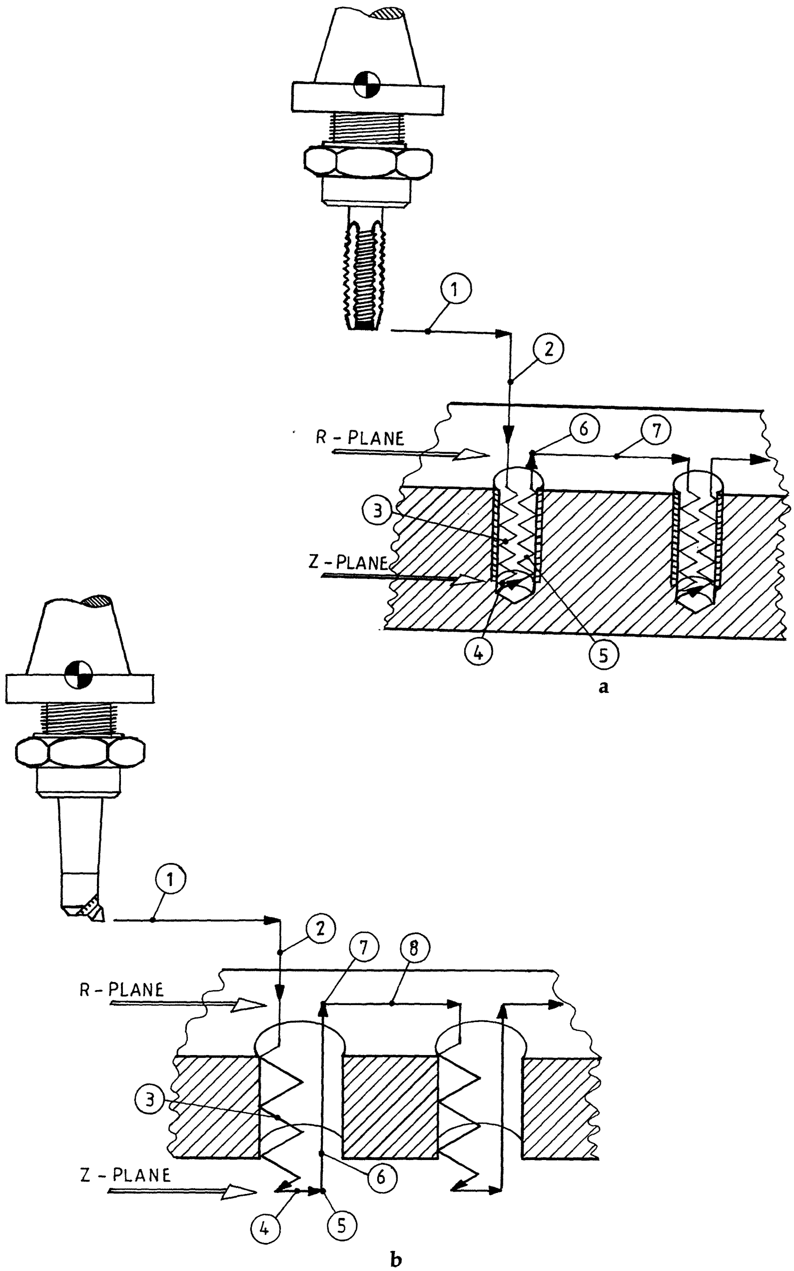


Fig. 5.29. Typical "canned cycles" for tapping and boring operations. **a** Tapping cycle (i.e. G84). 1, traverse to position (X/Y); 2, traverse to R-plane (i.e. in-zone position); 3, feed to Z dimension (i.e. distance zero position); 4, reverse spindle for return to R-plane; 6, remove spindle reversal and enable feedhold (end of cycle); 7, traverse to next position (X/Y). **b** Boring cycle with spindle stop, traverse return (i.e. G86). 1, traverse to position (X/Y); 2, traverse to R-plane; 3, feedrate to Z dimension (in-zone position); 4, dwell; 5, spindle stop; 6, return at traverse to R-plane (in-zone position); 7, spindle start (end of cycle); 8, traverse to next position (X/Y). [Courtesy of GE Fanuc.]

A User-Macro

Such individual machining operations as those listed above can be incorporated into larger canned cycles, often termed a "user-macro". Typical user-macros are shown in Fig. 5.30a,b for a linear and circular drilling pattern, respectively. By definition, a user-macro is used to repeat a series of actions at several programmed positions. The repeated actions are defined in the programming logic and once called, the execution of the series of blocks containing axis moves causes the macro to re-execute these repetitive operations until either cancelled, or another canned cycle is programmed.

In Fig. 5.30a, the linear drilling pattern consists of a row, column, or rectangular grid of hole centres which can lie at any angle from −360° to 360° relative to the horizontal axis – obviously on a vertical machining centre. In generating a drilling pattern, the machine tool traverses to all the defined hole centres in order, including any "don't drill" points. The currently active canned cycle is then executed at each hole centre unless it is defined by a "don't drill" point.

In Fig. 5.30a, the general form of linear pattern programming is to activate the desired canned cycle, then call for a linear pattern as depicted in the linear pattern of holes, where:

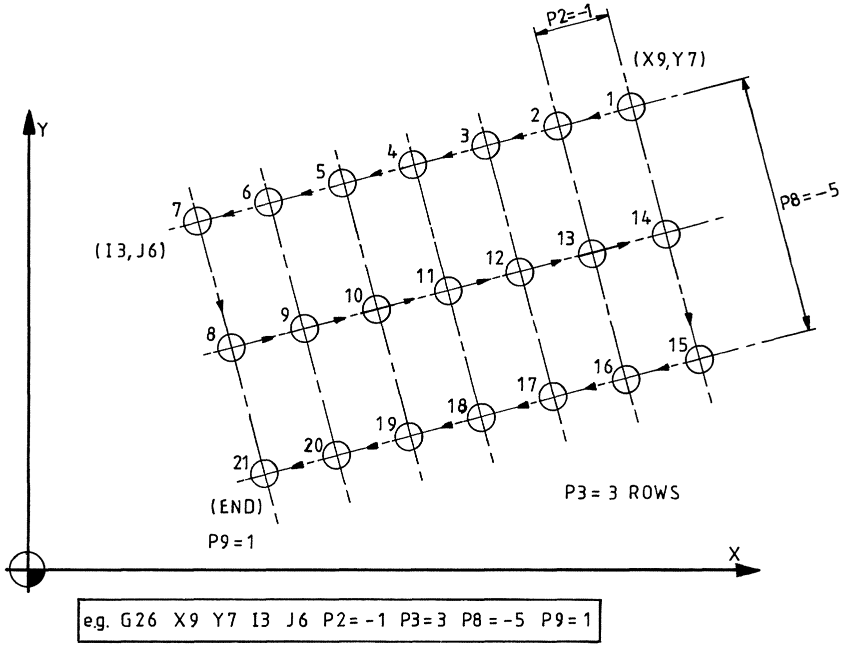
XY = start point of the pattern
IJ = signed increments from the start point to centre
P2 = signed incremental distance between holes
P3 = 3 rows
P8 = last row of holes from first
P9 = row spacing – last hole

A circular drilling pattern (Fig. 5.30b) consists of a set of equally spaced holes positioned around the circumference of a circle of given centre and radius. In generating the hole pattern the machine traverses to all the defined points in order, including those defined as "don't drill" points. The currently active canned cycle is then executed at these points unless defined as "don't drill" points. The general form for programming a circular hole pattern is to activate the desired canned cycle, then call the circular pattern (Fig. 5.30b), as follows:

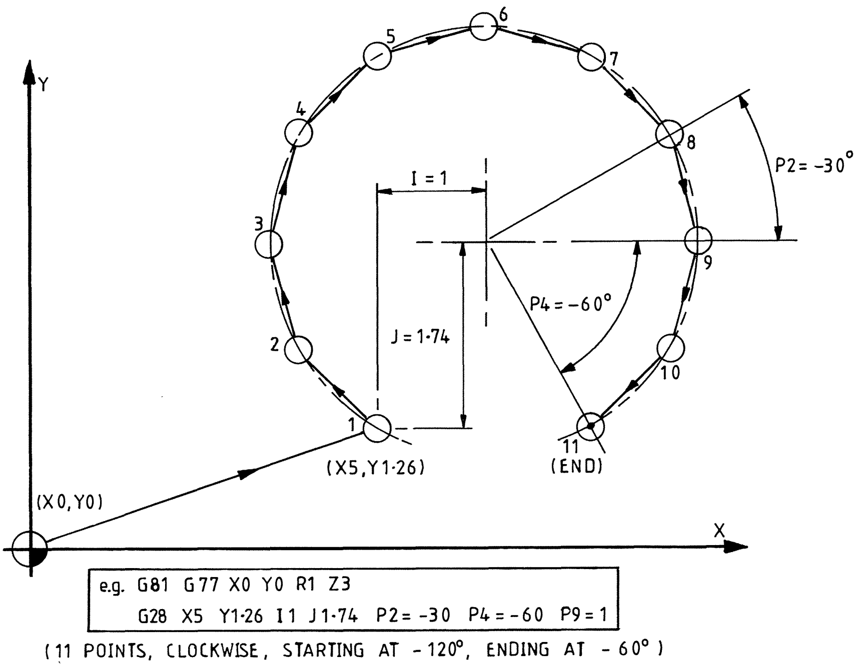
where G81 = standard drilling cycle
XY = start point of the pattern
IJ = signed increments from the start point to centre
P2 = signed incremental angular distance between holes
P4 = angle of last hole in pattern
P9 = finishing position indicator

NB: There is a whole host of different linear and circular drilling patterns that can be programmed and those just mentioned were only included to illustrate how the program logic for such specific holes is structured. Furthermore, this is not intended by any means to be an exhaustive account of the permutations of holes that it is possible to program within the part program, or indeed of any of the dimensional features that can be logically described using either "word address" or "parametric" programming. The intention with section 5.4 was simply to give the reader an appreciation of the programming aids and logical structures that may be called upon when writing part programs.

The final sections of this chapter will examine how a range of specialised CNC applications can be incorporated into such machine tools, which "open-up" the programming and manufacturing opportunities, further increasing the diversity of



a



b

Fig. 5.30. Typical "canned cycles" for drilling. **a** Linear drilling pattern (G26). **b** Circular drilling pattern (G28). [Courtesy of GE Fanuc.]

such CNC machines. The importance of such applications will become increasingly popular as companies come under commercial pressures in the years to come.

5.5 High-speed Milling Fundamentals

With the new developments in carbide, ceramic, polycrystalline diamond and cubic boron nitride tooling, cutting speed potential has dramatically increased on both turning and machining centres. Such tooling developments have led to the construction of high-speed spindles, improved bearing design and lubrication systems, advances in spindle cooling equipment, together with more rigid machine tool structures, and as such, allowing the exploitation of higher cutting speeds. Improvements in productivity, together with the elimination of chatter and longer tool life, have been the primary objectives of these developments. This has resulted in the current "state-of-the-art" machine tools, where the contouring speed is the limitation for profiling accuracy requirements, or the CNC's processing speed, rather than the physical metal removal rates.

In any high-speed machining operation, the principal factors affecting tool path accuracy, and hence the part geometry, are generally considered to be:

basic construction of machine tool, in particular its rigidity and accuracy

cutter design and stiffness

servo-lag

control processing speed

In the following sub-sections, we will consider each of these factors in turn along with their influence in a high-speed milling situation particularly.

5.5.1 Machine Tool Rigidity and Accuracy

In this section we will consider only two pertinent points: first, that high-speed milling is a dynamic process that can cause much higher stresses on the machine tool than would occur in traditional machining operations. This means that the machine, of necessity, must be much more rigid so that it can absorb these higher stresses without causing unacceptable deflection of its basic design, whilst simultaneously increasing the "dampening effect". Secondly, precise contour milling operations depend upon the basic machine tool accuracy. In the following sections we will discuss the factors that are unique to the generation of contoured surfaces at high speeds. The reader also needs to appreciate that the straightness and alignment of the axes, errors in positioning, plus the repeatability errors will be superimposed onto the finished part in addition to any errors that may be created by the dynamics of high-speed milling.

5.5.2 Cutter Design and Stiffness

Milling cutters can be designed that will run up to and over speeds of 40 000 r.p.m., but this is beyond the scope of this discussion. Their design must ensure that large chip gullets occur and that the cutter can be dynamically balanced in the radial and axial planes – dual plane balancing – to reduce vibrations at high speed and damp such tendencies, with cutter stiffness rigidity as a high priority. Normally, when any high-speed contour milling is necessary, the use of relatively small diameter cutters becomes desirable to reach into intricate three-dimensional surface features and as such they can easily be deflected. If we change either the feedrates or the amount of stock to be removed, this affects the cutter by varying the forces, which in turn influences its deflection. Cutter deflection may adversely affect the machine tool's ability to reproduce the programmed contour faithfully but owing to high speeds deflections are minimised.

One must always keep in mind that any potential cutter deflection is a function of the material, geometry and its length-to-diameter ratio. For example, a cemented carbide cutter is of the order of three times stiffer than its equivalent high-speed steel cutter, having the same size and geometry. We have already seen in chapter 2 that cutter deflection – when manufactured from the same material – does not vary as a linear function of its length but as a cubic function of it; therefore a 50 mm long cutter will potentially deflect eight times more than a 25 mm cutter operating under the same load. This leads to an obvious recommendation to utilise the shortest acceptable cutter to machine the part features, made from cemented carbide with "dual plane balancing" and having good chip evacuation abilities.

5.5.3 Servo-lag Problems Affecting the Machined Contour

Today, most CNC machine tools use "proportional servo-systems", where the axis velocity is proportional to the difference between the actual position and the command position (Fig. 5.31a). This "error signal" is used by the system to determine any acceleration/deceleration necessary as well as the steady-state velocities. As one can appreciate from Fig. 5.31a, the distance between the actual and commanded positions is commonly termed "servo-lag". This is taken a stage further in Fig. 5.31b, where the illustration depicts how a "proportional servo-system" is used to mill a sloping line. In this example, DX and DY are the total programmed changes in position on the X and Y axes, respectively, to go from point "A" to point "B", whereas DX_L and DY_L are the amount of lag on each axis at point "C" along the tool path from "A" to "B". Furthermore, in such a system the lag on the X-axis must be proportional to a similar lag on the Y-axis, in order to accurately follow the slope of the line. This can be represented mathematically by the following relationship:

$$\frac{DX_L}{DY_L} = \frac{DX}{DY} = \text{slope of the line}$$

In Fig. 5.31c, we can gain an appreciation of just what happens when the servo-lag on both axes is not proportional. As the machine travels from point "A" to point "B", the lag on the X-axis is proportionally less than the lag on the Y-axis. This might be the result of the servo-gains between the X- and Y-axes not being properly synchronised. Incidentally, "gain", or servo-gain in this case, is a measure of the servo's responsiveness – with the higher the gain, the lower the lag. Normally, gain can be expressed in mm/min (i.e. velocity)/mill (i.e. distance in 0.001) of lag. Lag can be found using the following relationship:

$$\text{Lag "L" (mm)} = \frac{\text{Feedrate (mm/min)}}{\text{Gain "G" (mm/min/0.25)}}$$

For example, if a slide is travelling at 2500 mm/min and the servo has a gain of 2, the lag will be 1.25 mm as shown by the calculation:

$$L = \frac{F}{G} = \frac{2500}{2/0.001} = 1.25\,\text{mm}$$

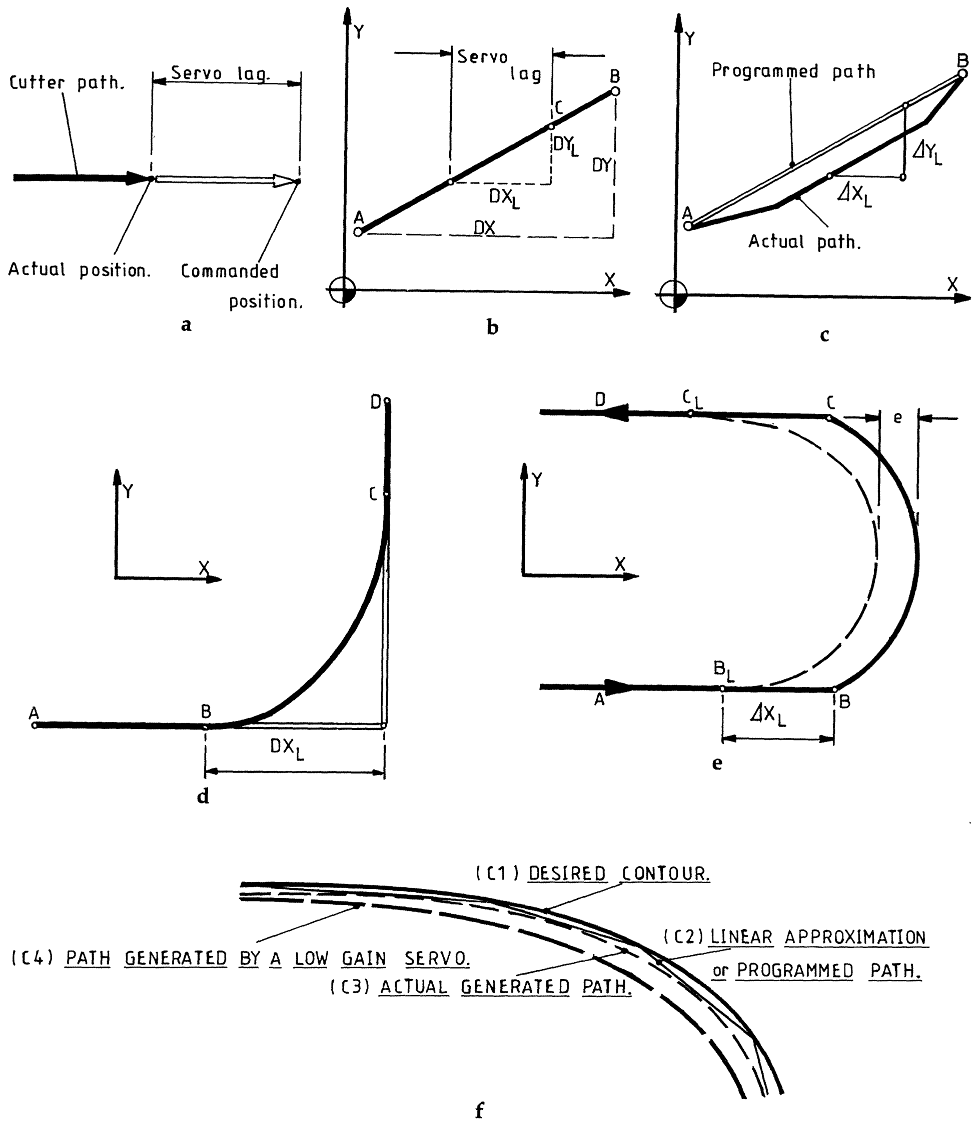


Fig. 5.31. The fundamentals of precision in high-speed milling operations. **a** A simple example of servo-lag. **b** How a proportional servo system mills a sloping line. **c** What happens if servo-lag on both axes is not proportional. **d** The effect of servo-lag and gain on corner milling. **e** The effect of servo-lag and gain on circular paths. **f** The impact of servo-lag when following a contour. [Courtesy of Boston Digital Corporation.]

The Effect of Servo-lag and Gain on Corner Milling

If two axes with correctly matched servo-lag can move in a straight line from point "A" to point "B", then to understand the effect of gain, let us consider what occurs when milling a right-angled corner at a constant feedrate without stopping (Fig.

5.31d). Whilst cutting the corner from "A" to "B" and then onward to "D", the servo develops a steady lag (DX_L), until sufficient command signals have been generated to reach point "B". It is at this position that the control begins to generate commands toward point "D", although the actual slideway has not yet reached point "B", owing to the servo-lag (DX_L). At this point the X-axis will begin to decelerate and, simultaneously, the Y-axis begins to accelerate, i.e. the velocity is proportional to the distance between the command signal and the actual position. It is not until point "C" is attained that the X-axis slide actually stops. Acceleration factors affect the slideway motions producing the result that the distance from "B" to "C" is always greater than DX_L. Furthermore, this is not a circular arc, but an exponential curve, with the amount of variance from the sharp right-angled corner being dependent on the magnitude of servo-lag, which itself depends upon the affect of feedrate and gain – according to the previous formula.

The Effect of Servo-lag and Gain Whilst Generating Circular Paths

For the reader to understand just what happens in milling complex contours, we will consider the case of two straight lines joined by a semi-circle (Fig. 5.31e). In this case, milling occurs at a constant feedrate from point "A" in a straight line until the command dimension reaches point "B". However, at this point, because of the effect of servo-lag, the slide will have only reached point "B_L". Therefore, as the control command is moving forward at a constant rate, it begins to generate commands toward point "C". This results in the slide beginning to move away from the desired path at point "B_L". The dotted line shows the actual path taken by the cutter and as we can see, from points "B_L" to "C_L" the deviation from the desired path is shown as "e".

In this example the magnitude of "e" is determined as a function of the feedrate and gain and the desired radius. When the radius error approaches the programmed radius, the resulting machined profile appears distorted and is hence impracticable. If one wanted to cut a 25 mm radius at a feedrate of 2500 mm/min with a machine tool gain being 25 mm/min/0.001, then the error generated would be approximately 0.125 mm; whereas if the gain is increased to 100 mm/min/0.001, the maximum error "e" will be reduced to approximately 0.008 mm.

A machined curve is an approximation on CNC machine tools, in that the profile is constructed from a series of short connected segments, or chords. The controlling factor on the length of such segments is the deviation between the centrepoint of any chord and a point at right angles on the programmed curve. The linear distance between these two points is usually termed the "maximum allowable chordal deviation" and is a function of the controller's executive software. Therefore the resultant machined curve is a combination of the chordal deviation and the servo-lag for a particular machine tool.

Illustrated in Fig. 5.31f, is the culmination of servo-lag when following a contour, with the curve "C1" being the desired contour, "C2" a linear approximation (the programmed path), "C3" the actual generated path resulting from servo-lag utilising a high gain servo and, finally, "C4" being the path generated by a low gain servo. Through servo-lag a smoothing of any contour occurs owing to the lagged cutter path; this causes severe contour problems with respect to part accuracy for simple arcs, as shown in Fig. 5.31e.

Clearly, servo-lag and gain promote a variety of effects on complex shapes depending upon their geometry and tolerance and these effects become still more complicated when considering three-dimensional contouring. In many circumstances, the cutting of three-dimensional profiles may necessitate utilising four or five axes of movement to produce the part. The servo-lag and gain on all axes must be considered when manufacturing complex and accurate parts. Regardless of part complexity, or indeed the number of axes utilised, there is one point that should be emphasised: potential errors created by servo-lag can exceed the errors in the basic positioning accuracy specifications for any machine tool.

5.5.4 CNC Processing Speed

Probably the main factor limiting contouring speed is the processing speed of the CNC, with each "stroke" generated for every axis which must be read, interpreted and activated. This is usually referred to as the "block processing time". The maximum allocated time for block processing of information is dependent on the length of the stroke and the feedrate. It is possible to calculate the maximum block processing time (T_b) as follows:

$$T_b = \frac{\text{Maximum stroke length}}{\text{feedrate}}$$

For example, if we require a chord length, i.e. stroke length, of 0.50 mm, in order to maintain contouring accuracy whilst milling at 3000 mm/min, or 50 mm/s, with the maximum block processing time it should be less than:

$$T_b = \frac{0.50}{3000/60} = \frac{0.50}{50} = 0.01\,\text{s, or } 10\,\text{ms}$$

Many CNCs have block processing times within the range of 60–80 ms, as we can see in this case the program would suffer from "data starvation", whilst the controller caught up on its data processing. Such "starvation" would cause hesitation in the slides, slow down the cutting time and leave dwell marks on the workpiece. Since this is unacceptable, a lower feedrate must be programmed and a longer cycle time will result. In this example, if the block processing time of the controller is 60 ms, the cut would take six times longer to generate the profile than a controller having a processing time of 10 ms.

In order to understand more fully the problems mentioned above, we will consider two widely differing applications, in the first instance the milling of a hob to manufacture a die used in producing intricate metal buttons. Such a hob will more than likely have fine detailed work on it, with radii as small as 0.25 mm requiring a tool tip radius of 0.025 mm. In order to machine features with such a small cutter, spindle speeds might reach 40 000 r.p.m. utilising feed per revolution of 0.008 mm giving a feedrate of 320 mm/min. Many people would not consider this as high-speed milling, but let us look more closely at this particular problem. If the controller has a servo gain of 4, with a feedrate of 320 mm/min, this means that the servo-lag would be 0.75 mm/min, which is consistent with producing radii of 0.25 mm/min. However, if the gain was one, this would cause a servo-lag of 0.320 mm/min and in this case it obviously could not machine the part. In such circumstances it would be necessary to reduce the feedrate to 75 mm/min to generate the contour and this means the cutting time increases by a factor of four.

Let us now consider the impact of block processing time under these conditions. To cut a radius as small as 0.25 mm, we would need to produce linear stroke lengths of 0.075 mm to reproduce acceptable detail. This requires a block processing of 15 ms. If the controller has a block processing time of 60 ms, then the feedrate must be limited to 75 mm/run which increases milling time by a factor of four.

The second example to be considered is the casting pattern for a large ECM electrode for a turbine fan, with the material being aluminium having very gentle three-dimensional curves. In this case, the spindle has a 250 000 mm/min capability and with adequate power to cut at a feed of 0.25 mm/rev. This would indicate a feedrate of 62 500 mm/min (i.e. 250 000 × 0.25 = 62 500 mm/min) would be possible. For accuracy, a chordal deviation (C_d) of 0.005 mm would indicate a stroke length of 0.75 mm if the minimum radius of curvature was 25 mm.

Assuming that a servo gain of one was available, then we would get errors as large as 0.125 mm; this would not produce an acceptable part; also at 62 500 mm/min, a block processing time (T_b) of 60 ms would require stroke lengths of 2.5 mm instead of the 0.75 mm we needed for the required accuracy. Therefore, in order to eliminate the effects of low gain or slow processing time, it is necessary to depress the feedrate, resulting in cutting time increased up to 400%.

In considering these two examples metaphorically, one method is like racing a go-cart on a small tight track, whilst the other is similar to a highly tuned sports car on a longer and smoother track. The go-cart may only reach 30 km/h, whereas the sports car may hit 200 km/h. The corner forces and the reaction times are similar, even though the speeds are vastly different. Looked at yet another way, we can say that the frequency of response of drive and car, i.e. servo gain and processing time, are similar in both examples even though the speeds (feedrates) are radically different.

In the day-to-day production environment, the duplication of specific and precise contours is the end result of a combination of inter-related factors. As the number of axes required to produce the part increases, the difficulty of obtaining the desired shape will increase proportionally. So, machine tools that produce excellent general purpose work may not be either accurate enough or efficient enough when machining contours. Therefore the machine tool described and partially illustrated in Figs. 5.31 and 5.34e, respectively, has been specifically designed so that that block processing time is as low as 10 ms, instead of the usual 60–80 ms. With this servo system, gains up to 4 instead of the more common 1 or 2 are provided.

This completes the review of the implications of high-speed milling operations and many of these problems of both the effects of servo-lag and gain are true in turning operations, with the exception being that workholding becomes the real cause for concern, as the following section shows.

5.6 High-speed Turning Operations

As was suggested above, servo-lag and gain are also crucial in any high-speed turning operations, as response time and data processing speed become paramount to any instantaneous vectoring of the tool around the workpiece, together with an advanced "look-ahead" capability.

However, turning operations at such ultra-high speeds differ fundamentally from high-speed milling, in that the workpiece revolves and this in itself is the major factor which must be addressed. When headstocks are rotated at or above 12 000 r.p.m. there is a limitation when using conventional contact bearing techniques for spindle rotations. It becomes necessary to incorporate air-bearing spindles, preferably with direct-drives that have the added benefit of removing from the system the transmission problems of conventional drives which can influence part geometrical features. Any workpieces having out-of-balance non-symmetrical features should be avoided, as their dynamic balance at speed will not only become a problem in terms of destabilising the cutting process, but can cause problems with safety when work-holding the part – possibly throwing the component from the chuck, between centres, expanding mandrel, etc.

The workholding techniques utilised can influence yet more problems, such as "bursting pressures" associated with centrifugal forces affecting the chucks, etc., so as the internal forces build up with rotational speed, if high-strength materials are not used then such devices can literally explode. When long, thin workpieces are revolved at high speed there is a tendency to "whipping" which may cause either damage to the machine tool or affect operator safety. There are many more such problems occurring owing to high speeds which do not readily arise at conventional rotational speeds, but a full description of such problems was not the intention here, only an appreciation of the influence of ultra-high speeds during turning operations.

5.7 "Reverse Engineering" – an Overview of Digitising on Machining Centres

Touch-trigger probes have been in general use on machining centres for well over ten years and during this period the process-related metrological applications of workpiece setup and tool wear compensation have occurred. A touch-trigger works by passing signals to the controller to record the points when the stylus makes contact with the workpiece and in so doing stops the machine's slide motions. Furthermore, a number of these points can be used for computing workpiece positions, diameters and angles. Any controller has to be able to accept an external signal as an interrupt to its motion and act accordingly with computation being possible whether it is instigated by the programmer, within the program, or by the controller's executive functions. Such touch-trigger probes are offered by the vast majority of machine tool builders and as such they form a basis for the digitising of the workpiece in the following discussion.

5.7.1 The Principles of Digitising

With any digitising technique it is necessary to position a model of the part to be digitised within a predefined envelope, or area, which is then scanned at discrete intervals. The positional data obtained from scanning the model can be used to construct a replica. The reproduction quality depends upon several factors, most of which are sourced through the digitising method chosen, whilst other influences include the software capability when building the model's replica.

It should be quite feasible to build a three-dimensional model using a mainframe computer, although a more limited two-dimensional model could be built with a desk-top computer. It is necessary for the system designer to choose either two or three dimensions at an early stage, since the cost of both computer and its respective software has a significant bearing on its cost-performance factors. Briefly then, to describe the differences between the two systems, it is necessary for the reader to visualise a wire-frame model (see Fig. 5.33c). In a two-dimensional system the computer can only be aware of the intersections on the wire frame, knowing nothing about the space between the points, whereas a three-dimensional system uses these points to construct surfaces, and as such knows a great deal more about the model's geometry. At present, the market values of cost ratios between these two systems is about 10:1, in terms of software costs alone – in favour of the two-dimensional system, of course. This two-dimensional system forms the basis for discussion here, with occasional reference to three-dimensional techniques.

Fig. 5.32a(i) shows a touch-trigger probe fitted with a stylus of a known diameter. It is shown in contact with a model being digitised at a given position in the X–Y plane and finding the Z-plane for that position. In order to cut an exact replica of the digitised model, a tool of identical proportions to the stylus (Fig. 5.32a(ii)) can be positioned by the machine tool to the same coordinates, reproducing the point of contact. Once the stylus is in contact with the workpiece surface, a series of points can be digitised and the coordinates of the surface contacted may be linked to form a cutter path (Fig. 5.32b) using these consecutive points.

The probe's path – hence the cutter path – is formed by defining a grid over which the probe must move (Fig. 5.32c) and by fixing this grid, two of the three coordinates are automatically known leaving the third to be captured by the probe. The grid must be defined in such a manner that the model (or relevant areas to be digitised) is covered. Therefore the probe moves to each point in succession and captures the data by its motion along a grid line automatically fixing one axis. The second axis coordinate is found by moving along that line in discrete steps, whereas the third axis is found by digitising at that point.

Using this basic principle, described above, it is manipulated through a software package and its performance has produced good results for the majority of digitising applications.

5.7.2 The Performance of a Digitising System

A digitising system's overall performance is the combination of several factors, each differing in performance, but taken collectively they offer the final result and can be categorised as follows (in no particular order):

touch-trigger probe and stylus performance
the CNC system performance
machine tool scale system
digitising performance

Touch Trigger Probe and Stylus Performance Factors

The definition of probe performance can be said to be "the repeatability of switching in a given direction", or to put this into perspective, this particular probe has an omnidirectional two sigma repeatability of just one micrometre. The basic contribution to the overall error performance is small, with the effect of the probe switching characteristics on accuracy being illustrated in Fig. 5.32d. There is some deflection of the probe stylus which occurs prior to the trigger signal being activated and this pre-travel is comprised of both the stylus bending and displacement – although it is repeatable in all directions to within one micrometre (i.e. two sigma) and does not vary with the direction of displacement. Owing to unknown workpiece surface characteristics, it is

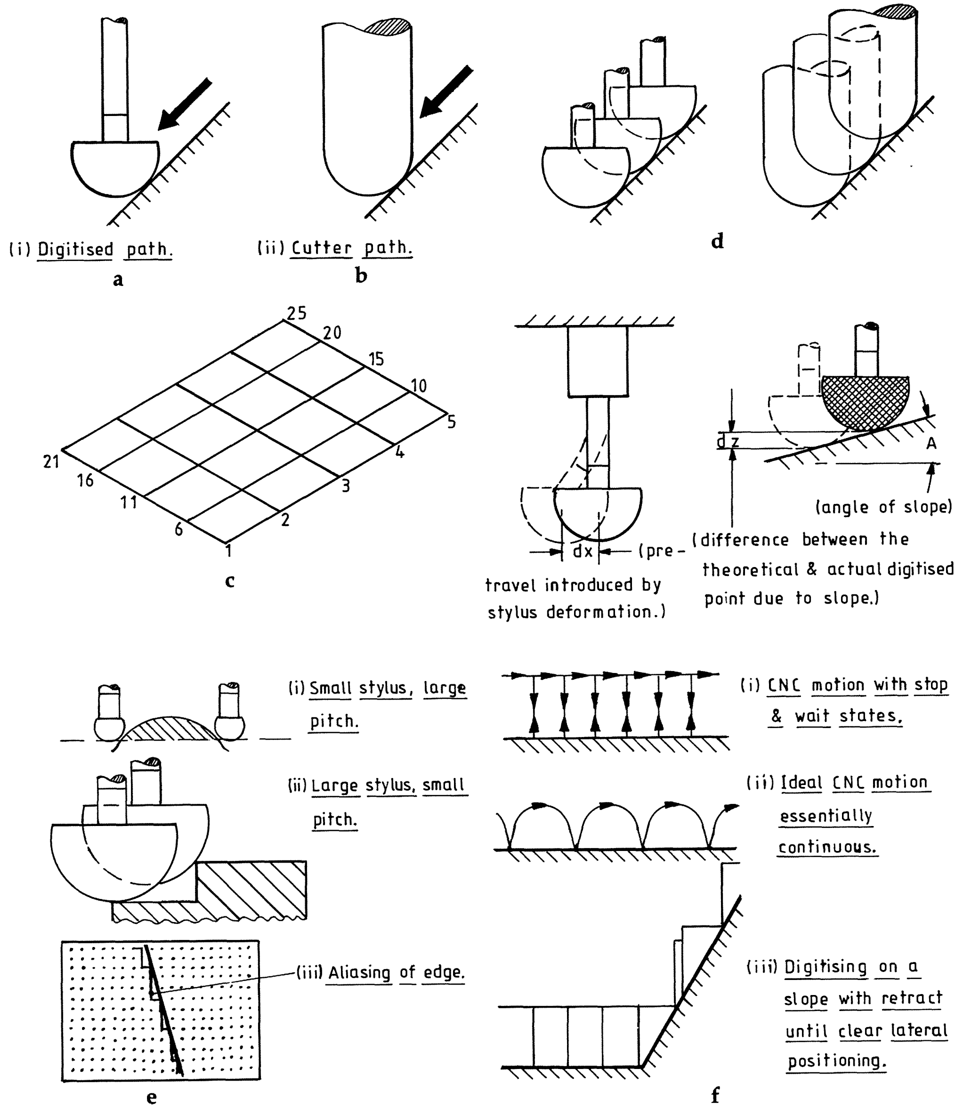


Fig. 5.32. Digitising a component on a machining centre – an overview of the operating principle. **a** The basic principle. **b** Consecutive points are used to form a cutter path. **c** The basic grid style and the order of digitising. **d** Causes of error by deformation and slope. **e** The effect of stylus and pitch variation. **f** Digitising motions. [Courtesy of Renishaw Metrology MAE.]

not possible to know the exact contact point between the stylus "ball" and the workpiece (Fig. 5.32d). Since the styli are not infinitely stiff, a small amount of bending occurs on contact with a part and this movement is termed pre-travel and occurs prior to the switching of the probe. The pre-travel variation cannot be accommodated by the probe's calibration and is shown as an error of surface duplication. In order to minimise the stylus pre-travel – due to bending variations – a range of stiff ceramic stemmed styli matching the diameters of commercially available ball-nosed endmills are available, with matching software. As an example of stylus bending of the stem, typical variations for a 50 mm long stylus are 0.038–0.050 mm.

As can be seen in Fig. 5.32d, the effect of pre-travel is to modify the theoretical point of contact. If "A" is the slope angle at the point of contact and "dx" is the pre-travel in the X–Y plane, the Z-plane value given will be lower by: dx/cos A. The solution is to use stiffer styli, and the shafts of 67% larger diameter than those previously used ensure that surface distortions are kept to a minimum.

The CNC System Performance

Any CNC system deals with the probe's signal in different ways and in real-time gauging, the controller can operate fast enough so that no delays in signal processing and recording the positional data occur. However, not all systems can be operated in real-time and errors through reading delays may occur. Such processing errors can be due to the sample time of the CNC; this is because these CNC systems scan external signals serially. Quite simply, the controller is not looking at the time a signal is given and as a result, the system does not respond until the signal has been "seen".

Assuming the worst case, the digitising has the following CNC error:

$$e = \frac{f \, . \, t_s}{60}$$

where:

e = error in µm due to sample time
f = feedrate of CNC at the time of signalling in mm/min
t_s = sample time of input in ms
60 = a-units coefficient

For a typical CNC, the values will be:

$$t_s = 6\,\text{ms}$$
$$f = 100\,\text{mm/min}$$

Thus: $e = \dfrac{6 \times 100}{60} = 10\,\mu\text{m}$

The interpretation of this value is that there is a maximum error value of 10 µm owing to the sample time of the CNC and as this is a maximum value, the mean will be lower and closer to 5 µm which will affect the system resolution.

Normally, there should not be any other CNC performance factors associated with data capture, but other errors exist in the controller's system.

The final cutter path is a series of points to be linked by linear interpolation. To provide smooth motion, a CNC system buffers data and instigates the execution of a block of data just before the completion of the previous block. The zone in which this overlap occurs is dependent on the servo response of the machine tool – a heavy machine needs more time to change direction than a lighter one. Similarly, if the positions given by the program to the CNC system are very close, then in certain cases it may be seen that the final cutter path will deviate from the program path with less linearity than expected.

Machine Tool Scale System

Digitising techniques depend on the accuracy of the machine tool's positional measuring system. If this system is subject to errors then the digitising data will carry those errors.

Touch-trigger digitising is a relatively light-duty cycle for any machine tool. The greatest errors sourced in the scale system will be those due to changes in the ambient conditions during digitising – thermal effects within the machine tool. An encoder system mounted on the leadscrew itself – indirect feedback – will suffer directly from these changes, modifying the accuracy as a result, although the direct feedback linear scale systems are less affected by thermal growth problems. With the changes in response to market requirements, CNC system operation will also change and this will require the speed of digitising to increase. As the increased duty cycle of the servo systems increases, this promotes extra input into the machine tool and further distortions may be present within the encoder systems. Such increased heat input might cause the machine tool's geometry in addition to its linear accuracy to be affected.

Digitising Performances

For digitising techniques in two-dimensional operations, they operate at discrete intervals, with the probe being driven to a point in free space above its target and descending to the model's surface – this occurs irrespective of the part's slope, or geometry. Therefore there is a relationship between the original model and its digitised replica, which is dependent on the grid size and its pitch (see Fig. 5.32c). In the case of Fig. 5.32e(i), a large pitch is being used in conjunction with a small stylus. In such a case the surface definition will be lost, as the data cannot "see" between the discrete points on the grid. However, in Fig. 5.32e(ii), a larger stylus and a small pitch occur with this smaller pitch preventing overcutting, but the larger stylus diameter being unable to "see" small radii – in this condition a "metal-on" situation results.

Yet another digitising error occurs when the result of slopes lies within grids at indeterminate angles, as illustrated in Fig. 5.32e(iii). If a slope lies across the points of a mesh and meets along every point at this angle, such as 45° on a grid with pitches "x" and "y" being the same, then the line would be accurately defined. However, if the slope of such a line falls outside these parameters then "aliasing" will occur, such as the "saw-toothed" effect (Fig. 5.32e(iii)) produced instead of a line. Under these circumstances the solution is to reduce the grid size, increasing the chance of the line falling onto grid intersection points.

Model Stylus Considerations

If we appreciate that any digitising takes place within a predefined space and it can be applied to any model which may be placed within that space, with only certain limitations in the model's profile, this infers that there should be no re-entrant angles, or surface reversals which might prevent part removal from a mould.

Using touch-trigger probes the forces generated are light, being considerably less than those associated with the older technique of electronic tracing. Typical lateral forces are 50–100 g using a stylus with length of 50 mm, which can rise to 400–500 g in the vertical direction and, as a result, models should be rigid enough in structural integrity and the mounting to withstand these light loads.

An Efficient Digitising System

Clearly, digitising requires the system to store large quantities of data, and hard discs allow efficient mass storage in personal computers – meaning that the CNC system is capable of transmitting data whilst the part is digitised. Equally, a machining program will be generated from the same points and containing a number of passes; the program will be large – normally greater than that of most machine tool memories. It is anticipated that the controller should be able to receive the digitised program via an external source by "trickle feeding", on demand from the CNC. It is important that there is a provision for a suitable and efficient data communications channel which is accessible whilst the system is running.

Possibly the major consideration in digitising performance is the digitising speed, with the actual performance being controlled by the ability of the CNC to provide fast and continuous motion even when there are significant changes in direction. In Fig. 5.32f, some characteristics of digitising which are significant are illustrated. The motion of the machine from point to point should be continuous, without the delays associated with block read time and in position checking. The digitising sequence with "stop and think" states at the end of each motion can be seen in Fig. 5.32f(i); with this method, an average digitising time of 2.5 s is achieved. The ideal path occurs in Fig. 5.32f(ii), where the minimum of delays are present, offering significant reductions in processing time – about 1 s per point. Obviously the probe cannot contact the model prior to taking a reading, with the software noting the collisions in the X–Y plane before taking a reading in the Z plane. The final diagram showing digitising motions (Fig. 5.32f(iii)) highlights how the probe retracts as it collides with the model's surface before meeting its X–Y coordinate targets; with efficient processing this reduces the delay that might otherwise occur resulting from "stop and think" decision making.

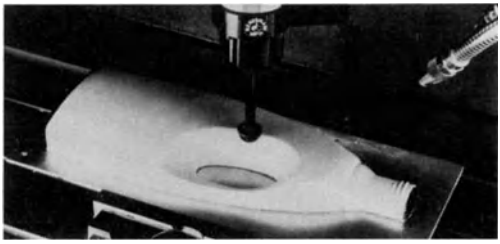
The Development of Digitising for Mould Work

Several factors are predominant when digitising moulds on CNC machines. These factors relate to how data is used by the personal computers and software, so by utilising a computer effectively the database can be manipulated. For example, what was inconceivable when tracing moulds with hydraulic copying techniques, are now straightforward operations. With computer software, the data can be adjusted allowing for shrinkage factors which can be altered separately for each axis, with the computer insensitive to whether the shrinkage factor is 1% or 50%; however, families of parts based upon dimensional scaling are possible. Yet another advantage of using software is the "mirror-imaging" capability, which complements the scaling function; this "scaling" can produce "families" of related parts. As all these functions are common to one database, the digitising operation need only be performed once with the computing creating the necessary "data model" from which the mould is cut.

The operating principle for digitising, highlighted in Fig. 5.32, is shown practically in Fig. 5.33 on a vertical machining centre. This system is $2\frac{1}{2}$-dimensional rather than 3-D and to produce male/female mould transforms using $2\frac{1}{2}$-D geometrically is extremely difficult. However, the solution to this desirable capability is found by investigating linear data transformation techniques and a mathematical routine gives the desired transforms within practical limits.

This completes our review of digitising, with just one technique of digitising discussed amongst the variety of methods currently available. Digitised models offer a realistic means of "reverse engineering" which can offer competitive production

a



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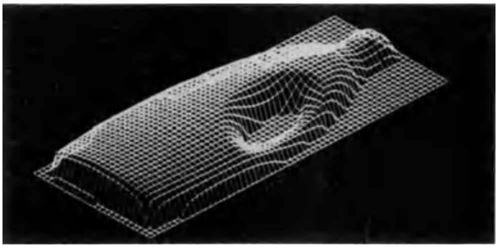

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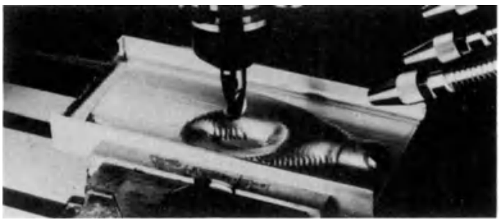


d

advantages, when companies are faced with either one-off or small batches. In the final section of this chapter a brief excursion into CAD/CAM will be presented, illustrating the benefits that accrue from its implementation.

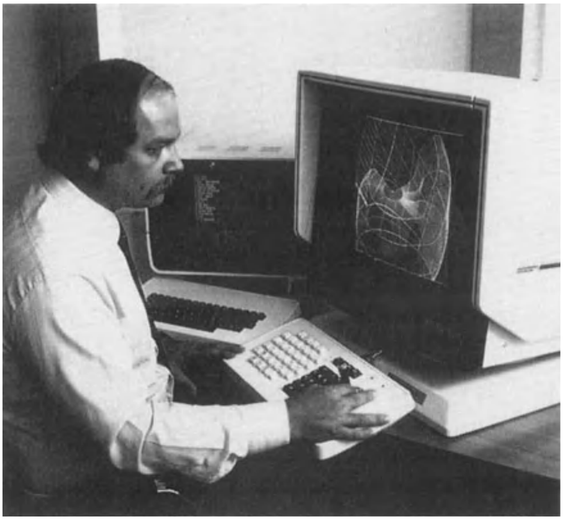
5.8 Computer-aided Design and Manufacture

If companies decide upon the feasibility of purchasing CAD/CAM systems, inevitably they are governed by the software developed which determines the hardware that can be adopted. This software will have been written to run on a specific range of computers, although one might have some control over the available options for a particular computer. Prior to a discussion about the various aspects when choosing a computer suitable for a company's needs, there are several general questions which need consideration. A CAD/CAM system must be continuously developed, with improved software becoming available periodically. Therefore the software supplier must ensure that future "upgrades" will be available on the hardware for a realistic period of time. Certainly, a company having purchased the CAD/CAM system will rely heavily upon it and in the event of a breakdown, a hardware maintenance service that is readily available is essential.

Any calculations performed by the computer occur via the central processing unit, or CPU, with processor speed being measured in millions of instructions per second, or MIPs. The speed at which the processor achieves its calculations is an important factor, which determines how fast the applications software performs its task, although this is by no means the only factor requiring consideration. The applications software speed depends on how well it utilises the hardware capabilities, graphics software and operating system software. Furthermore, it will also depend on the memory available, together with the hard disk's access speed. With this in mind, the only way of obtaining a realistic comparison between computers is to run a "benchmark test", which typifies the work expected to be performed by the CAD/CAM in-service. Typically, the creation of toolpaths when machining a complex three-dimensional surface might suffice (see Fig. 5.34d).

Whenever we attempt an exercise in mental arithmetic, we hold the numerical values in our memory whilst performing the calculation. We also know how to achieve these calculations. A computer memory, or random access memory (RAM) has similarities to our mental capabilities, but it can retain significantly greater numbers in its memory. The expression used to determine a computer's memory is "megabytes", or millions of characters and by way of illustration, the *Concise Oxford Dictionary* might occupy about 5 megabytes of memory. The amount of memory

Fig. 5.33. Digitising techniques for milling dies and moulds. **a** A low cost digitising package. It allows the manufacture of dies and moulds from an original sample: a "digital replica". **b** A touch-trigger probe is moved to pre-determined points, e.g. in the X and Y plane, taking readings in the Z-axis. Probing density is programmable, each reading taking typically 2.5 s. The resulting data is transmitted to the on-line computer. **c** Once digitised, the data can be examined using wire frame graphics, either in part section, or section, or whole. Points can be reviewed, edited and redundant data eliminated. The data transform can be made on simple command, e.g. mirror image, scaling in 1, 2 or 3 axes, male/female transform. **d** The machining centre is set up with the required size cutter to make the replica. High accuracy means that little hand finishing is necessary. [Courtesy of Renishaw Metrology MAE.]



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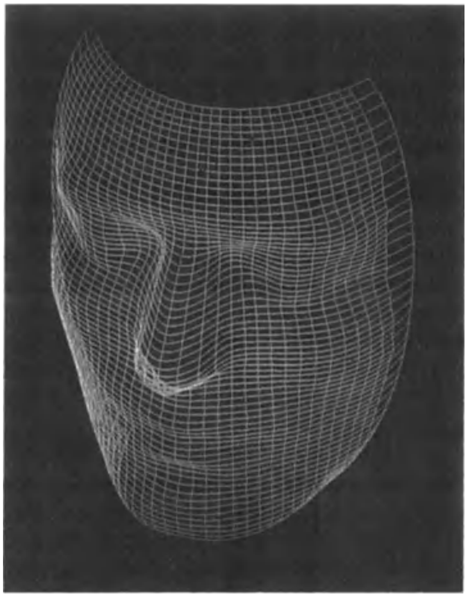

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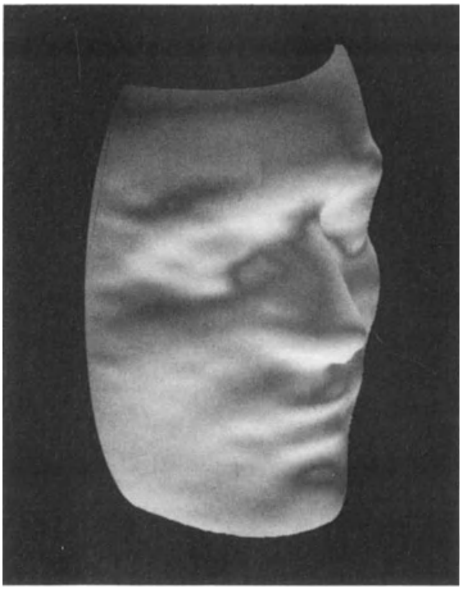

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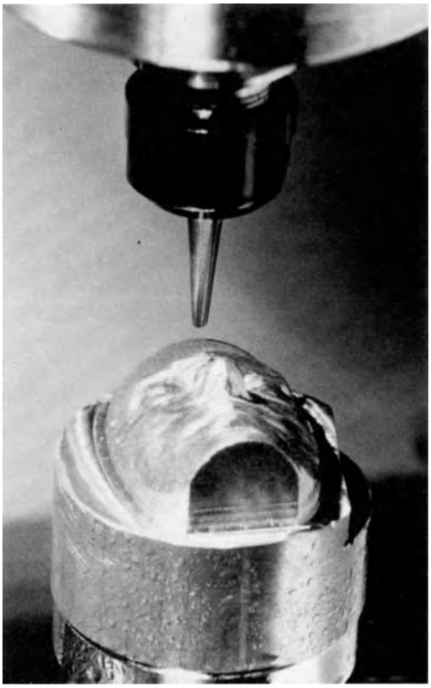
Fig. 5.34. The approximate stages in machining "sculptured surfaces". **a** A twin-screen CAD/CAM workstation with the sophisticated software necessary for 3-dimensional applications. **b** Isoparametric curves plotted for two different parameterisations of the same patch – the "Coon's patch", often termed a "wire-frame model". **c** Continuous tone picture using Painter's algorithm – illumination computed; "Lambert's law model". **d** Tool path graphics, illustrating cutter motions superimposed on a "wire-frame model". **e** Machined profile, using a 5-axis machining centre. [Courtesy of McDonnell Douglas/Boston Digital Corporation.]



e

Fig. 5.34. Continued

required is variable and will depend on the computer and the software it is currently running. Generally, we can say that the greater the memory capacity, the faster it runs – up to a point – as the "law of diminishing returns" applies and one must decide whether increased expenditure is worth the performance improvements.

A computer system must have adequate hard disk capacity which is used to store the CAD/CAM software and, additionally, to store the data created by the user, typically geometry files, or tape files to be sent to a machine tool via DNC, or similar. The important question for the user is not how much total hard disk capacity there is, but how much user space is available, as this depends on the area occupied by both the operating system and applications software. Naturally, it would be obvious to assume that the more disk space the better, but any data on the disk must be managed carefully to ensure it does not become cluttered with "old files". An important safeguard is to obtain "back-up files" kept separately either on a floppy disk, or tape, as hard disk failures can arise occasionally and lost data could prove disastrous to the company. It is usual to keep these "back-ups" in a fire-proof safe, ideally in a separate building to the CAD/CAM system. When a user only has sufficient disk space for the present needs, rather than for long term storage, then regular "back-ups" will allow tape files to be kept in order.

Clearly, it is necessary to discuss computer hardware requirements in conjunction with the software it is to run, and, to use a musical analogy, if the hardware is a violin then the software is the musical score, neither is of any use without the other. CAD/CAM software may be considered in three categories:

operating system software
graphics software
applications software

Let us briefly review these software applications in turn, considering probably the most important aspect – the operating system software – first. The software comprising the operating system controls the routine functions of the computer and as such influences how efficiently the computer performs its task. Typical operating systems such as UNIX and VMS tend to be more complex then MS-DOS. For example, both UNIX and VMS can perform several operations simultaneously, typically running the CAD/CAM system, post-processing and sending files to machine tools – usually termed "multi-tasking". The graphics software creates screen images, shaded pictures (Fig. 5.34c), line drawings and pop-up menus. Lastly, the applications software is the actual CAD/CAM software together with any associated software for either post-processors, DNC links, etc.

The quality of the screen graphics is an important feature for any visual representations such as CAD/CAM systems and one describes this aspect in terms of the maximum resolution of the monitor. A typical high-resolution monitor with a 19 inch screen has 1024×864 pixels (picture elements). Hence, the greater the number of pixels per inch of screen area, the better the picture resolution. Obviously, in order to obtain the monitor's maximum resolution, the computer and its software must be able to support such capability.

Earlier, we talked about the need to keep a "back-up" copy and just as important is the ability to accept data from other systems. Data can be stored either on $3\frac{1}{2}$ inch or $5\frac{1}{4}$ inch floppy disks, or, alternatively, via tape cartridges, or cassettes. Floppy disks can only hold up to 1.5 megabytes of memory, whereas tapes can conveniently hold large amounts of data. A limitation of tape storage is that the data can only be accessed sequentially and tapes tend to be large and unwieldly, with long programs taking time to read. Conversely, floppy disks allow quick access to files and at any point on the disk. A company's customers may have their own CAD/CAM facilities, so compatibility of each other's systems might figure as a high priority when the company considers its hardware requirements – particularly if both need to access each other's files.

Peripheral devices such as plotters and printers are obviously desirable elements in any CAD/CAM system, together with the need to "down-load" programs to the machine tools. Sufficient communication ports to which these peripheral devices can be linked is essential. Long CNC data files are often "down-loaded" to the machine tool's controller by a variety of means, but typically in a "block-to-block" fashion – particularly whenever enough "buffer storage" is not available to hold the complete program: termed "drip-feeding". In order to achieve uncorrupted data transfer of programs from one hardware device to another, efficient and compatible "hand-shaking" is essential, but more will be said on communications in chapter 6.

Finally, once the company has decided which CAD/CAM system they feel will offer them the best compromise in the initial stages of implementation, they must bear in mind that at some later stage they may require to up-grade the system as their needs change. It is important that any system expansion can take place without a complete and costly overhaul of this system. Therefore, if it is envisaged that later up-grading is likely, this point should be addressed at an early stage of any feasibility assessment of prospective CAD/CAM systems.

5.8.1 Choosing Computerware – the Process of Elimination

As with many things in life, there is inevitably no clear-cut answer when one decides to purchase either hardware or software for a CAD/CAM system, as any final choice may depend upon many factors. Inevitably, the decisions taken about both hardware and software are often interrelated, with the suitability of one being dependent on the efficiency of the other. By the well-tried process of elimination, one can compromise to find a particular system which best suits a company's work, business set-up and staff. Generally, it is necessary to examine six areas when coming to a decision, namely:

functionality
software
applications
software
support
supplier

"Functionality" – computer jargon to explain its difference from "function" (which has other connotations in the computer world) – clearly refers to the purpose of the system. For example, does one require a computer-aided draughting and design (CADD) system having a 3-dimensional modelling capability, or conversely, would a 2-dimensional draughting system be adequate? Obviously, the system chosen limits the range of appropriate software. "User-friendliness", compatibility of suppliers'/ customers' systems, trained personnel available, proposed future system developments and a company's business requirements should all be investigated when deciding the best software system for the company.

A typical "application" factor might include whether a system is for a "single-user", namely for one terminal, or if it is to be for "multi-use" such as interfacing with other computers. Therefore, will one need either a central database, or perhaps terminals at other locations? This means that application considerations in conjunction with the software chosen for a company's needs will influence the hardware purchased.

A major, but often underrated, consideration should be "support", as even the most suitable system can be a liability when poorly installed, or not accompanied by software up-dates and quick repairs to hardware. Yet another "support" area which should be considered is the relative practical training of a vendor's staff, as if this is not effectively given, together with appropriate documentation, then this can influence the CAD/CAM's impact within the company at large.

The choice of supplier will be made simpler by highlighting these critical factors as only a few suppliers will meet the company's objectives. Often the computer firms short-listed will have a specific knowledge of a company's manufacturing enterprise and their previous experience will be invaluable, as this saves both time and expense. Often such CAD/CAM suppliers know more about the scope of this equipment for a specific company's applications and can advise them accordingly and, in this way, obtain the most cost-effective equipment. This is not always the case, however, as the choice of software may lead to only a single supplier – possibly with a limited hardware option. If the company purchasing the CAD/CAM system is a "first-time user" they should act with caution, as the temptation might be to obtain a "limited" system owing to its lower cost.

Sometimes corporate aspirations can be important at the initial feasibility stage in the purchase of a CAD/CAM system, because both the scope and function of such equipment can influence its effectiveness within the company. It is possible to implement such systems gradually within a company and it is worth considering obtaining the advice of an experienced consultant in the field. Such people could map out a strategic program of the functional implementation of a computer system over the complete spectrum of a company's operation in stages over a two-year time period. This should be considered the maximum time for the original CAD/CAM system, as the technology is changing so fast that any initial choice will be obsolete five years later.

Any initial implementation program to choose the software should simultaneously consider the potential links at future stages to process planning, manufacturing and metrological considerations. Such manufacturing philosophies will inevitably lead to choosing some form of multi-user system using either a mini-computer, or a workstation network – this latter approach is possibly more flexible, but here we must leave the subject, as it becomes highly "user-specific" to a company's needs.

Once a system has been chosen, whether it is a workstation network or a standalone system, there are several additional pieces of hardware available which improve and enhance the system still further. Occasionally a company's software needs will dictate that "extras" are required; some investigations into the options are necessary and are described below:

mathematical co-processor – this speeds up calculations
additional memory – i.e. random access memory (RAM)
extra storage facilities – e.g. disk
back-up and archiving options
high resolution colour monitors
input devices – tablet, mouse, etc.
output devices – plotter, printer, etc.
document management
historic data handling – scanning
security

Increasingly, choices in back-up and archiving techniques are becoming popular and as systems become larger, more data is created, so an important security feature must be the ability to provide back-up files speedily. As an example of this importance, we can consider that a network of six personal computers having produced a day's work necessitates an hour a day attended loading of files on floppy disk space, or half an hour unattended loading using a magnetic medium. Similarly, most cartridge tapes are limited to 40–60 Mb of data, although some can hold more, up to 300, or even 2300 Mb (i.e. 2.3 Gb). It can be appreciated that both the selection and implementation of any back-up and archive unit can seriously impede the productivity and security of a CAD/CAM system.

Once the system has been chosen it is possible to enhance the equipment and improve its efficiency still further by additional "refinements". Using twin screens (see Fig. 5.34a) improves user performance, by allowing one for detail and the other for the overall picture; a third screen can be employed for text only. If the second screen is just a "text only" version, it cannot cope with high-resolution presentation. Graphics monitors should always be coloured, as even very basic CAD/CAM software allows a palette of around sixteen colours, whereas more extensive colour capabilities can rarely be justified in engineering applications – some systems offer 256 discrete colour shades out of a potential palette of 64 million.

Further, the geometric design and draughting benefits – aesthetically allowing circles to appear as round and lines straight, from increased resolution capacities up to 1024 × 786 pixels (i.e. points of resolution displayed) offer a more realistic visual interpretation, but in general do not aid in their improved interpretation to any great extent. It should be pointed out that higher-resolution screens do help us appreciate surfaces (Fig. 5.34c), whereas schematics (Fig. 5.34b) do not justify such high resolution to gain a visual understanding of the displayed artefact. With the improvements in the effective use of "window" technology for most software CAD/CAM systems, the use of a multi-button mouse has largely superseded the menu tablet, which should be avoided if possible.

When selecting printers/plotters, one should aim for the level of print quality suitable for a company's particular text presentations and a plotter capable of coping with the maximum size of paper used. Plotter speed varies with cost and this becomes an important consideration as more operators use the system.

Document management is a relatively recent concept with most CAD/CAM systems with the advent of quality assurance procedures becoming a dominant factor in most trading companies of manufactured goods. Any CAD/CAM system of late must conform to the quality assurance system of presentation, EN29000 (previously BS5750 part 2), but this can be open to a degree of interpretation by the software companies with reference to what level of detail is required and what security options to adopt, together with techniques in retrieving them.

Finally, the skill in choosing any "computerware" for CAD/CAM applications lies in selecting both software and hardware which gives the best facilities at present and the greatest scope in the future, whilst obviously having the optimum value for money. Therefore, it is essential to select the system according to a company's present and specific business needs and their future plans.

In the final section of this chapter we will briefly consider both the problems of representing sculptured surfaces on screens and just some of the techniques used to machine them.

5.8.2 Sculptured Surfaces and their Machining Problems

In CAD/CAM systems, curves and subsequent surfaces result in two functional demands of the system:

curve fitting
curve design

In "curve fitting" the fitting of a curve, or surface, is called for through a set of defined points having a smooth transition from one point to the next. "Curve design" entails the modification of the curve equation parameters either directly or indirectly, to observe what shape may be developed.

Most sophisticated 3-dimensional CAD/CAM systems have "curve fitting" capabilities, often using a modified cubic equation-based technique. Such methods mean that in the equation defining the curve there are individual sums – including cubed factors – which, when added to squared factors and more sums them finally to an individual number, representing the curve mathematically as exemplified below:

$$U^3a_3 + U^2a_2 + Ua + a_0 = r$$

As each equation is developed, this produces a discrete curve which can be more easily defined with respect to its start and end points, in addition to the curve's slope at each point.

This technique of "curve fitting" is not new and such indirect methods were devised in the early 1960s, making it relatively easy to manipulate these curves – without recourse to modifying the different equation parameters. In a typical system, a complicated curve would be comprised of several discrete curves – termed "spline" – whereas a surface is simply a curve with an extra dimension. For a "curve fitting" the cubic method is particularly suited, although a modified cubic approach that can accommodate the uneven spacing of "nodes" – the curve start and end points – has particular benefits when digitising surfaces.

It was a Frenchman, Bezier, who, whilst working for Renault was intrigued by car body design and found the "point and slope" technique rather inconvenient for curve design. His philosophy was to find a way of manipulating the individual parameters contained within the basic equation in an easier manner also using the indirect method. Bezier used an open polygon – a plane figure of many angles and straight sides by which a curve approximating to it passes through the start and end point of the open polygon: resulting in a designer changing the polygon and, as such, achieving different results. Having more defined points in the polygon gives more flexible control for surface manipulation; furthermore, the curves generated are formed by equations comprised of parameters raised to higher powers than the cubic varieties, having longer and more complex mathematical expressions. Such a curve is a discrete segment in a complex curve and these segments must be joined together.

With the Bezier technique the transition between curve segments, or patches – the surface equivalent to a line segment – requires close study by the designer. A further refinement not developed by Bezier, but incorporating Bezier mathematics, was the "B-Splines", which ensure a smooth transition between segments/patches. Yet another, later, development was the non-uniform "B-Splines" which catered for the uneven spacing of nodes.

Terminology which is not very common but is associated with the term "NURBS" includes the rational and non-rational parametric surfaces, which we will define shortly. Returning to the rational parametric surface, this may be represented in many forms with mathematical precision. The cubic non-rational variety cannot express a 90° arc with mathematical precision, although it has adequate accuracy for any machining requirements. Most CAD/CAM systems have a variety of other software techniques to define such elements as circles, spheres and cylinders with the desired precision. However, rational parametrics have a single bias for form generation, which provides a tidy programming solution by eliminating different pieces of software, although whether this helps or hinders the user is an open debate.

This brings us back to "NURBS", referred to earlier, which is the amalgamation of rational parametric surfaces together with non-uniform B-Splines resulting in Non-Uniform Rational B-Splines – "NURBS".

Whenever a data file is transferred between two CAD/CAM systems having different surface definition methods, including equations with one incorporating parameters higher than cube orders, the receiving CAD/CAM system can break down the surfaces into smaller patches and as such they can be redefined using cubic form. Any differences that might occur through this redefinition of the mathematical expressions are so small as to be insignificant, for the practical purposes of machining contour. It should be said that nearly all today's systems have graphical interfaces, with the actual curve/surface profile manipulations being indirect, but the underlying theories and attributes still apply.

It is not possible in the space provided to discuss the process of surface construction and software manipulation for all CAD/CAM systems available. Even on just one system there are a variety of techniques that can be utilised to achieve similar machining results. As an example, we will consider one problem that may occur in the machining of a bottle mould cavity (Fig. 5.33d), at the portion where a "gouge" situation could be present at the transition between the main body and the neck. Assuming that a CAD/CAM system has "multi-surface" capability offering "gouge avoidance" of the cutter, the complete cavity might be machined successfully employing this facility – although this would be time consuming, owing to the complex computations required looking for "gouge" situations. Possibly the best solution in this case might be to machine the main body and neck without "gouge avoidance", then apply it to a small selection of the neck/body transition. In order to reduce the user input time for "multi-surface" machining operations through many "keystrokes", "macros" have been developed – capturing a sequence of "keystrokes" in a simple command, in conjunction with APT (i.e. Automatically Programmed Tool) techniques.

So far we have briskly described the philosophy and mathematics used to develop sculptured surfaces which are becoming an increasingly important feature in manufacturing today. Typical processes requiring sculptured and smooth surfaces are die cavities, aerofoil sections, impeller blades, foundry patterns, body-panel pressings, etc. Inevitably, this means that in order to produce such free-form shapes a CNC milling technique should be adopted, in order to minimise tooling costs. Obviously if the part is to be manufactured on the machining centre it is necessary to produce a path for the cutter to follow (see Fig. 5.35) although the problems in determining the strategy when machining such sculptured surfaces are not simply restricted to the manufacturing operation alone. In order to verify the desired shape for our part, it is often prudent to cut a model from either remeltable wax, or foam, but this becomes impractical for large components.

When machining any 3-dimensional/sculptured surface, this is achieved by line milling along the contour, with the precise adaption of the tool geometry around the contoured profile being dependent upon both the tool geometry and its guidance. The tool's path can be evaluated in terms of the scallop width and height, whilst the tool guidance mode might be established using model scanning/digitising (see section 5.7.1).

If three-axes milling is used for machining contours, it means that we can only guide the tip of the tool within our "working envelope", as the tool's axis is maintained in a constant relationship to the profile. Often ball-ended milling cutters are used, or alternatively, either barrel-shaped cutters or indeed "fully-defined" APT cutters may be utilised. However, if we confine our comments to the ball-ended cutters, it is possible to use three different cutting modes when three-axes milling:

plunge cutting
constant-depth cutting
reverse cutting

The tool engagement modes will vary depending upon the curvature of the surface shape. The fixed cutter axis in three-axes milling operations produces unfavourable cutting conditions, whereas favourable tool geometry adaptions are possible with respect to the workpiece contours using five-axes milling techniques. As such, five-axes milling implies simultaneous technological advantages through control of both the tool's cutting point and the cutter's axis. Furthermore, five-axes milling represents the general case with respect to the milling process, as there are no additional restrictions that can influence the potential degrees of freedom for the rotating cutter. This infers that the cutter's orientation with respect to the workpiece contour offers favourable cutting conditions, and along many sculptured surfaces an exact relation-

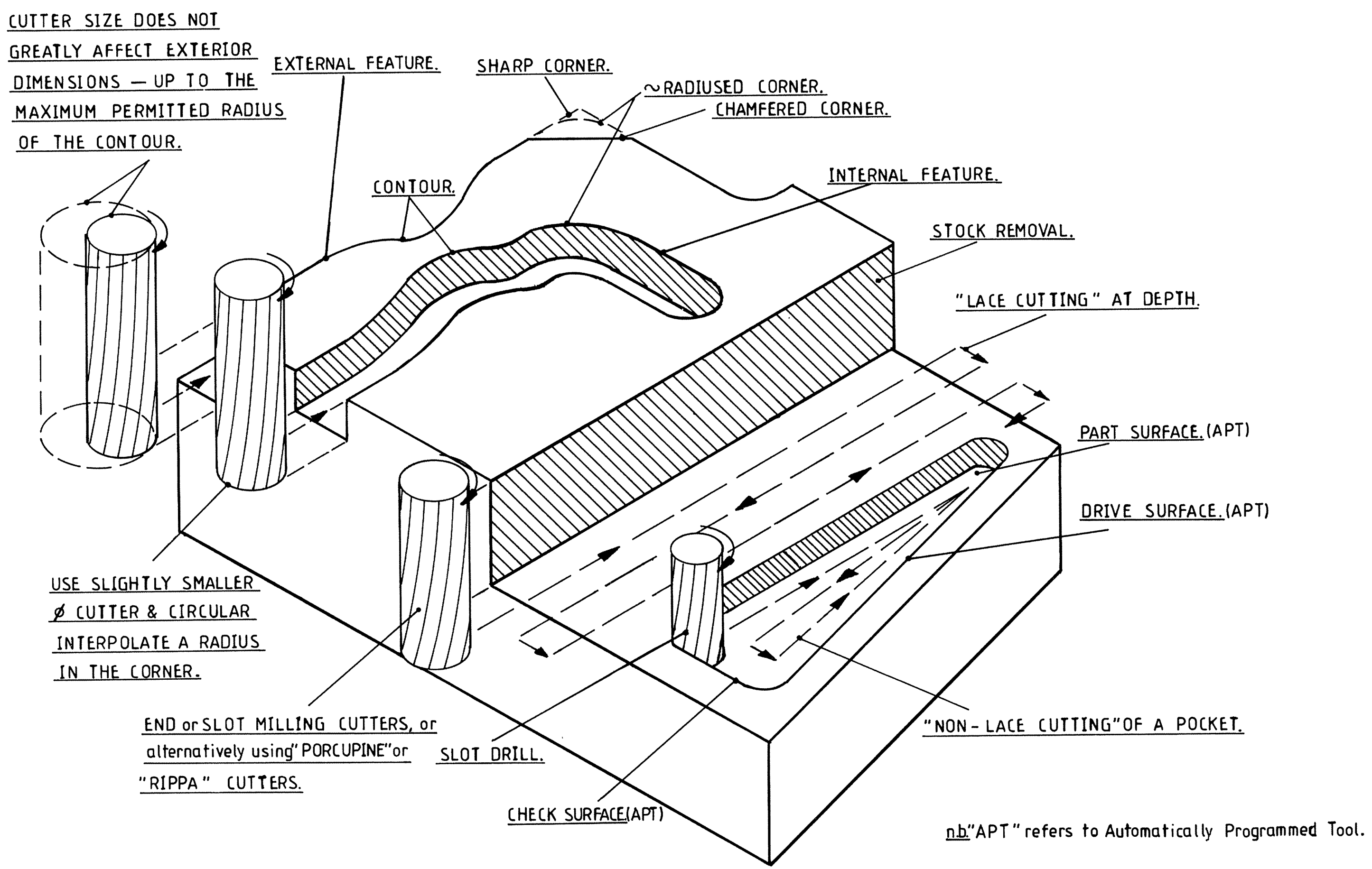


Fig. 5.35. A representation of just some of the milling operations and tool paths possible on a machining centre.

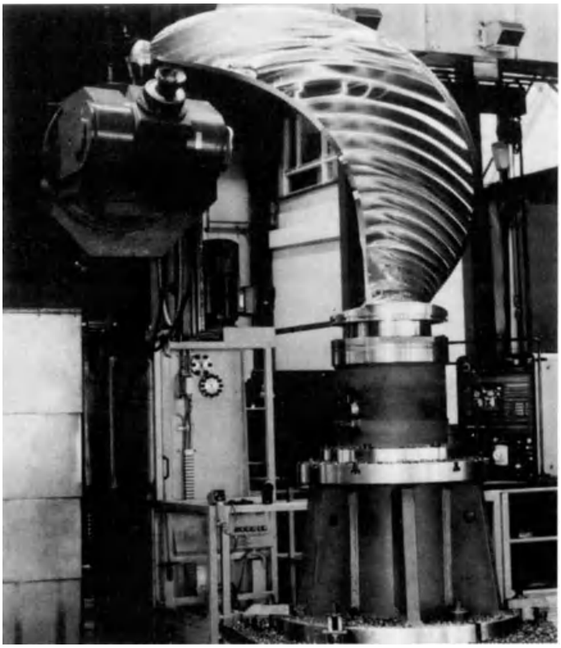


Fig. 5.36. The complete machining of an impeller, by utilisation of a 5-axis horizontal machining centre in conjunction with a high-level programming language. The "sculptured surfaces" are produced with great form accuracy and at optimum metalcutting efficiency. [Courtesy of Scharmann Machine Ltd.]

ship is established. Utilising five-axes, or three-axes milling techniques for sculptured surfaces causes a scalloped surface topography, as shown in Fig. 5.36 for five-axes impeller milling. As one can appreciate from Fig. 5.36, a greater overlapping of the milled paths results using five-axes face milling whilst maintaining the same scallop height as for three-axes milled contours. As a consequence, there will be a reduction in the number of milled paths over the profile leading to a reduction in the time taken to machine the part.

By using CAD/CAM systems, a feature available with the more sophisticated software is the ability to machine the surface profile within prescribed workpiece tolerances automatically. Using five-axes allows the machining to occur with constant, or variable, "tilt angles". The "tilt angle" can be defined by the surface normal to the tool axis at the point of contact with the part's surface. Using variable "tilt angles" alleviates possible cutter collisions during feeding when normal to the contour of the part, whilst achieving the greatest permissible scallop width – for improved stock removal and optimum scallop/cusp height reductions, further aiding the effort in part finishing.

Not only does five-axes milling offer the ideal cutter/workpiece geometric relationship during sculptured surface manufacture, it improves the tool wear characteristics considerably, resulting in extended tool life over three-axes profiling methods and greater protection to the tool by minimising the forces on the cutter. However, whatever cutting strategy is employed, care must be taken to avoid the cutter "gouging" other features on the workpiece, typically when machining re-entrant angles on the part. Using APT, or NMG (i.e. Numerical Master Geometry) provides for the definition of ''check surfaces'' (see Fig. 5.35) which are surfaces beyond which the cutter's tool path cannot exceed – ''gouging avoidance''. Such techniques effectively provide a means of blending one contour (patch) to another, smoothly. This means that as a ball-nosed cutter cannot get into a corner between the surface being cut and the ''check surface'', a radius will be developed. Using the ''check surface'', facility means that it becomes much simpler to implement than to define the blend explicitly.

It would have been quite easy to expand our thoughts and ideas considerably in this chapter on virtually every topic covered, but it was not the intention to explain all of the problems and solutions to turning and machining centre programming. Indeed, it would have been totally impossible. Therefore a concise and generalised treatment has been given, simply to give the reader the essence of programming.

In chapter 6, we will discuss the various merits of Flexible Manufacturing Cells and Systems and describe just some of the problems that must be overcome for their effective utilisation within a company. Lastly we will go on to consider the latest trend in turning/machining centres – ''sub-micron'' machining techniques, whilst explaining the technological problems that must be overcome to machine at such highly accurate levels of manufacture.

Chapter 6

Current Developments in Flexible Manufacturing Cells and Systems, Leading to Complete Computer Integrated Manufacture

6.1 Introduction

In previous chapters we have, in the main, been concerned with a discussion about stand-alone turning and machining centre technology and related activities, such as tooling, workholding, and cutting fluids. This final chapter will consider how best to achieve a degree of automation using equipment and looking into the relative merits and drawbacks of such implementations. Prior to discussing the role of currently available FMC/S solutions, it is probably worth defining what we mean by "Flexible Manufacture" – whether one is describing either a cell, or a system. The definition favoured by the author is a modification to that proposed by an early investigation commissioned in America by the US Task Force Study: "Two or more machines coupled to either a robot, or an automatic transfer mechanism for the machining of parts". This loosely describes, in the most basic terms, the requirements for a flexible manufacturing cell; in fact we must qualify this definition by saying that, according to an FMS builder, such systems must be "as rigidly flexible as possible!". This means that either a cell or system should have a degree of flexibility within rigid constraints in order to perform in anything like a flexible manner.

During the early 1980s, companies were investing in large-scale FMS and often these were doomed to failure, principally because lack of rigid constraints of either part handling, tool management, compatible communication protocols plus error-recovery procedures were not strictly formalised – this is where our rigid constraint is essential. As a result of the above, many manufacturing departments became somewhat disenchanted with such complex FMS solutions to their variable production scheduling needs and in recent years have been more inclined to favour the cell approach, or the progressive integration of stand-alone machine tools into cellular configurations. This latter technique of a step-by-step approach to FMC integration, allows a company to not only build up their production capabilities in a proven and steady manner, but also to minimise the capital expenditure. It is then spread over a longer time-scale, whilst simultaneously gaining experience and confidence in the assurance that each machine tool element within the FMC offers real benefits to the manufacturing capabilities, rather than the possibly dubious merits of an ill-conceived and executed feasibility plan. Any feasibility study must be carried out utilising computerised simulation techniques in order to obtain a realistic appraisal of both current and future manufacturing capabilities, but more will be said on this, and other related topics affecting production, later in this chapter. Such highly productive equipment placed into a conventional manufacturing department, without thought to the logistical problems associated with its implementation, leads inevitably to, at best, bottlenecks disrupting the harmonious flow of parts, to, at worst, complete failure and chaos within the company, with "loss of face" for all concerned.

In the following pages, we will try to alleviate such disastrous and ill-fated implementations, by attempting to describe not only the range and scope of FMCs presently available, but some of the systems that lead to complete computer integration of the manufacturing factory, as depicted in the case-study towards the end of the chapter. Lastly, we will look at how part accuracy is becoming the most important manufacturing characteristic and the steps a machine tool builder must be prepared to go to achieve ultra-high precision workpieces. During our discussion, frequent mention will be made throughout the chapter, to such topics as "logistics", computer integrated manufacturing and so on, in order to attempt to give an overview of not only flexible manufacturing strategies, but integration themes.

6.2 The Importance of "Logistics" in a Flexible Manufacturing Environment, its Feasibility and Simulation during the Development

In any highly productive environment such as a flexible cell, or system, the throughput time and capital turnaround are major factors that influence the cost of production. Quite simply, the machine tool is just a link in the total chain: from receiving an order, to part supplying and then invoicing the customer. When considering investment, it is appropriate in most cases to rearrange and organise any existing manufacturing facility, in small steps and over an extended time, rather than building a so-called "green-field site", as this objective is much less drastic whilst increasing the utilisation of our present manufacturing equipment in conjunction with the considerable reduction of throughput time. Clearly, this is not a simple task, especially if one considers that during the amortisation time for such investment, any in-house production will need to be adapted to an ever more rapidly changing market condition. This fact is true, whether the company is investing in: stand-alone machines, cells, or systems. The crucial problem is always how this new production facility can be organised and harnessed to the existing overall manufacturing capabilities. Such a problem might be compared with a surgical transplant, where all that we know is that it can only succeed if the body does not reject the new organ, accepting it as a harmonic unit of the system. Seen another way, we are confronted with interfacing and communication problems that need to be planned and solved with care, to ensure that everything will remain compatible after any subsequent investments.

Not only do we expect compatibility from our current and future plant needs, but also from the human involvement in the manufacturing facilities. From a company's design, organisation and planning departments the personnel at all levels interpose control restrictions between the planning/manufacturing areas, whether computer support is available, or not. Often, in many production shops there may still remain several conventional machine tools and associated methods/sequences that are primarily dependent on man, resulting in workpiece calculations for the whole facility being strongly orientated towards the labour rates. Even when a company has taken steps towards computer-integrated manufacturing (CIM) methods, the effect of man still plays a part, albeit a minor role. Man is at the focus of any traditional manufacturing facility and it is the function of computer-integrated manufacture to minimise human activity within the day-to-day control process. Furthermore, by utilising CIM it is possible to reorganise everything in such a manner that computer algorithms can be used purely for the planning and mechanised sequences of manufacture.

It is not only the management that must be trained appropriately to cope with changes in manufacturing, but shop-floor level employees also – in the same way as it is necessary to train somebody in programming aspects when involved with CNC machines. So far, companies involved in computer-assisted manufacturing have found that the demands on operating personnel do not reduce, but can be considerably higher than for conventional routes of manufacture – often termed "job-enrichment" in the United States. This term encompasses the concept that an enriched quality of working life results from operators being associated with flexible manufacturing systems. There are many more aspects of responsibility for the operator in an FMS system than for the operator running just one machine tool. As a result, FMS operators need to have a broader view of manufacturing. Instigating a third shift together with some weekend working will only be viable from a sociological point of view if the manufacturing system can be successfully buffered in the first and/or second shift, then run with limited manpower on the third. A third shift cannot yet be run in an unmanned "lights-out" operation. That situation is still a few years away, in terms of total integration of hard/software functions. As a result, the unattractive night shifts will perpetuate, together with weekend working, for some time to come, requiring certain key personnel for either supervisory or maintenance tasks. Such working arrangements mean that problems will remain in terms of the pay structure and social politics area until these points are resolved.

Formulating a manufacturing facility into an unmanned environment is limited by the amount of additional and out-of-proportion expenditure; particularly when short part-cycle times exist, the costs for fixtures, pallets, buffer stations etc. will, in most instances, prove uneconomical. This point is thought to be relevant when one considers the personnel savings – or lack of them – as a result of much manpower effort being expended simply loading and unloading parts in the preceding and subsequent shifts, respectively. This makes a nonsense of our reasons for automating the manufacturing process in the first place.

Many companies deciding to invest in flexible manufacturing cells or systems would normally instigate such technological innovation in a step-by-step expansion – unless a "green-field" site was chosen for this new production facility. About 30% of all flexible manufacturing systems are planned as an integrated and "overall" concept in a single or double expansion stage. Companies investing in such systems are normally "batch-producers", who have the advantage of being able to take the step to flexible manufacture clearly and decisively, leaving behind the concept of rigid manufacture. Without question, these companies adopt this manufacturing strategy basing their investment strategy on the unequivocal desire to be able to react in a more rapid and flexible manner to fluctuations and changes in market conditions. It is also apparent that company investment strategies consciously accept certain cost increases which arise through this demand for flexibility. The diagram shown in Fig. 6.1 illustrates that as far as "pure" manufacturing costs are concerned, the route towards greater flexibility will inevitably lead to higher production costs. Although these additional costs incurred can, to some extent, be offset by new disposal strategies typified by "just-in-time" inventories.

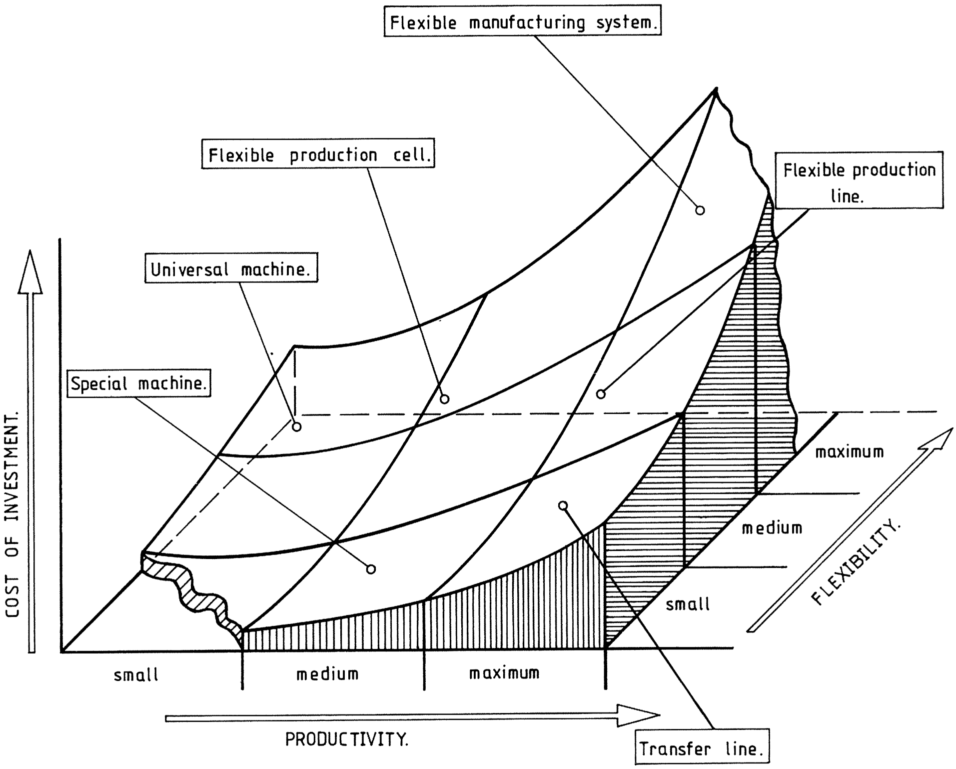


Fig. 6.1. A comparison of manufacturing systems based on the following criteria: automation level, productivity and investment costs. [Courtesy of Scharmann Machine Ltd.]

Logistics as a Company Strategy

In any company, solving the logistical problems requires a series of basic decisions to be taken, with possibly the crucial one being to purchase integrated software for all the technical and commercial fields of planning. The corporate decision to standardise software will ensure high data topicality together with simultaneous and redundancy-free data keeping. In essence, what this means is that for both production planning and control, we are in a perpetual state of readiness for information regarding: delivery deadlines; order status; parts availability; through-put time; capacity loading; costs. However, logistical problems can only be consistently overcome, if such responsibility is singularly authorised for all activities affecting orders and the establishment of organisational rules is centrally instigated.

Any logistical activity begins long before a customer places an order and in terms of the context of production program planning, the turnover target for the financial year must be established and any rough planning at this point helps. With the manufacturing aim being to ensure a balanced capacity peak in the bottleneck area, basic deadlines can be established for orders. Allocation of delivery deadlines in the offer phase is a second function of rough planning, with possibly the most important third-stage function being the periodical follow-up of the order once it has been placed. The

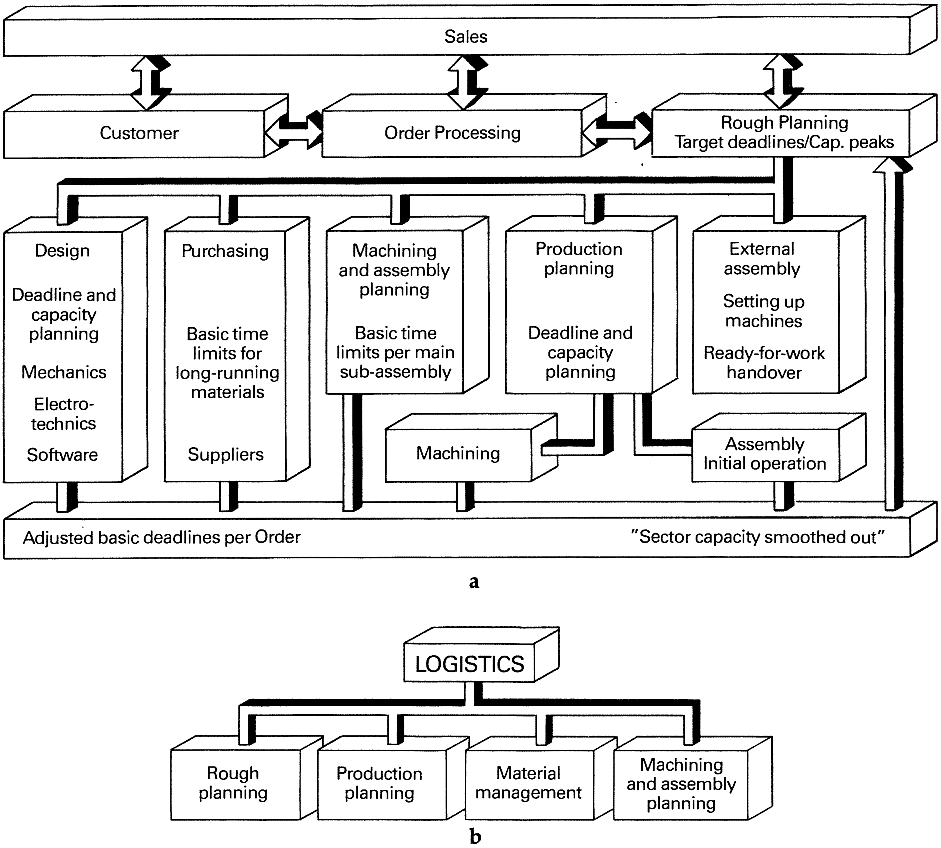


Fig. 6.2. The importance of logistics as a company strategy. **a** The concept of integrated logistics. **b** The "key" sectors of logistics in manufacture. [Courtesy of Scharmann Machine Ltd.]

block diagram in Fig. 6.2a highlights the theme of integrated logistics as conceptually realised by a machine tool manufacturer.

In logistical terms, for all departments participating in processing the order, basic deadlines must be calculated in terms of network plans. Simultaneously, the projected estimated capacities are loaded into these bottlenecks and a position plan is produced for the optimum exploitation of the manufacturing space. Such deadlines are repeatedly matched with those in specialist departments, until an agreed schedule has been defined and area capacities have been smoothed out. The established basic deadline framework is the binding target for all participants and the reference for all alterations. Acknowledgement of these scheduled activities will ensure that an immediate follow-up of the order occurs. Therefore, if deadlines are exceeded, methods are directly sought to compensate for any delays in the schedule. Such rules ensure that it is not left to the final (assembly) stage before attempts are made to reduce delays, but that prompt action occurs early on and at every stage of order processing. From a customer's point of view, this means that information about an actual order status is always available and in general guarantees the meeting of their anticipated delivery dates.

More precise planning normally occurs in the areas of production planning and materials management, with the basis here being the part list's orientation and its influence on final assembly of product. In a similar fashion – in terms of material requirements – it provides a clear description of the order relating to deadlines and capacities in the working schedule for, say, a mechanical fabrication, or the coordination of detail for assembly activities. It is, of course, very important to have a homogeneous transition from a rough to precise planning stage, for there to be an acceptable overall planning strategy. Furthermore, any activities that have been specified at the rough planning stage will be progressively replaced by precise plans once the period of order processing has begun.

When an order network has been derived from the parts list, any fabrications and assembly orders belonging to a customer order are related to each other and this will immediately highlight any mutual dependency of products. It follows that the consequences of any interruptions in the run of work can be easily established and countermeasures introduced.

The organisation of CNC activities, such as preparing, administering, and distributing all the information necessary for such machine tool operations, is largely concerned with either the production of individual, or job-lot manufacture. Integration of CNC activities can be incorporated still further into the logistical strategy by having computer-aided production planning with a CNC programming system – possibly CAD/CAM integration, with direct numerical control links established to both the machine tools and tool preparation facilities.

Finally, for new and modified designs, it is of the utmost importance that in the early stages of a product's design any work is closely supervised, with effective communications established in order to eliminate possible sources of error and therefore difficulties, before one gets to the final manufacture and assembly stages.

The importance of logistics in the company's manufacturing strategy is shown schematically in Fig. 6.2b, where it acts as a focus for integration of rough and production planning, material management, machining and assembly planning. This coordination of multiple planning functions highlights problems prior to and during manufacture, smoothing-out bottlenecks, minimising errors whilst manufacturing, and considerably shortening product development times. By incorporating the theme of integrated logistics within a company, a framework is provided for a "simultaneous" – or as it has recently been termed a "concurrent" – engineering strategy to be developed. This technique has shown conclusively that it will drastically reduce and simplify new design concepts and shorten product lead to the market, with all of the implied cost savings.

Before a company decides to purchase a flexible manufacturing cell, or system, it must carry out a feasibility study, considering not just the parts (and their costs) to be manufactured within such a facility, but the implications of placing highly automated plant into the current production area and how it might affect the harmonious flow of parts through the factory. As such, it is often necessary to simulate the plant within the constraints of the manufacturing department to gain an appreciation of likely problems. These topics we will now address, before looking in detail at typical automated installations to be found in most advanced countries in the World today.

6.2.1 The Feasibility Study – a Vital Element in any Advanced Manufacturing Strategy

Any company embarking on the purchase of highly productive equipment such as a flexible manufacturing system must, of necessity, conduct a feasibility study in order to be assured that such a large capital outlay will considerably improve the company's performance for its perceived market. The design, its development and installation, can be thought of in three distinct stages:

project planning and realisation
system integration into manufacture
project responsibility

In order to achieve a successful implementaion, the feasibility study can be subdivided into three further categories:

first stage – a quotation planning study
second stage – an order planning and FMS quotation
third stage – ordering the FMS and its project management

Let us now look more closely at each stage to try and build up a picture of how one might instigate and develop a successful flexible manufacturing system.

The Quotation Planning Study

First, we must consider the amount of work involved in the logistical implementation, which would take into account an analysis of the expected workpieces to be manufactured, normally grouping parts of similar geometries, or processes, together – termed "group technology". It is then important in the preparation of the concept to document in some detail, all pertinent facts. Simultaneously, a team of interdisciplinary engineers is chosen who will embrace a range of technologies, system planning, and the computer systems to be utilised within the perceived FMS. Once these factors have been established, it is possible to calculate the costs, draw up a quotation and present it to the company's management for acceptance.

An Order Planning Study and FMS Quotation

From now on, feasibility activities become more inter-related and a detailed examination of workpieces to be machined occurs with part families being firmly established – the "group technology" theme again. Part fixturing concepts are explored and if necessary pallet sizes are decided. Concurrent activities of mutual interest concerning the workpieces are collated and data relating to the whole machining process – including the means of manufacturing part features are determined, together with the concept of their storage: pallet pools, stillage stations, buffering and the part transportation system to be incorporated – either rail- or wire-guided AGVs, flexible flow systems, robots (floor, or gantry types). Simultaneously, peripheral equipment (subsystems) is specified which will influence both the FMS layout and its productive capabilities. Machining times, together with the computer and transport systems, will have a considerable impact on the prospective plant layout, and their preselection at an early stage is necessary. This will focus our attention towards possibly two, or at most three, potential systems that can be "modelled" by simulation (see section 6.2.2). The critical stage has now begun where one attempts to establish a representative "model", around which all our final decisions are made. The alternative simulation "models" will define: the system layouts, material supply routes, tool handling strategies, and compare the chosen "models" under realistic production conditions, running them over specified time-scales to assess potential "bottlenecks" in the system.

Once the alternative "models" have been simulated, their respective documentation is produced in order that a final manufacturing decision can be made, taking into account capital costings, manufacturing output, flexibility of production and amortisation cost factors. Furthermore, the documentation generated includes not only anticipated quotation costs and a description of the chosen system's performance, but also the plant layout's and their respective specifications.

The Ordering of the FMS and its Project Management

By now, the team involved in the feasibility study will know all the relevant facts, enabling them to be in a position to award a contract, with the assurance that such a study has highlighted the expected advantages and weaknesses in the manufacturing concept. Hopefully, the latter problems are only of a minor nature and will not unduly affect the project. With the contract awarded to either a single-source vendor, or a multi-sourcing with overall project supervision by a specified company, such details as production planning and system design can be developed from the functional specification. Whilst this is being undertaken, training and, later, works acceptance will eventually occur – usually on the vendor's site. Sometimes when a large system rather than a cell is built, it would be installed at the company's manufacturing facility, which would have the correct infrastructure by now in place, with foundations and services prepared at an earlier stage in the project.

Assembly of the complete installation including machine acceptance trials, peripheral equipment acceptance and computer system integration, is established and as usually expected, a direct numerical control link to the in-house CAD/CAM system occurs. Lastly, a complete justification for the whole manufacturing facility installed is initiated, where run-offs of parts within the system are compared with the master schedule laid out during the project's conception, so that the company is assured that the installation is meeting its productive requirements. After acceptance by the company, a close working relationship will have been established between the customer and vendor and this continues into the guarantee time and often beyond.

Any prudent company deciding to install such highly sophisticated and comprehensive equipment must, of necessity, conduct a well-disciplined and planned feasibility study in order to ensure that the project achieves its manufacturing objectives. Such a study will then be sure to come in at cost, on time and having the desired production capabilities. We have seen that possibly the key element in any prospective dynamic part-scheduling facility, namely a flexible manufacturing cell, or system, requires simulation to ensure that it meets the functional specification developed during the company's feasibility study. This can be "modelled" either with an in-house simulation system or, more usually, by the vendor's system. In the following section we will consider the "simulation modelling" in more detail, looking at two currently available systems.

6.2.2 Simulation Techniques, the Key to Successful System Integration

When a simulation "model" is developed the objective is to predict the effects of alternative actions – "what/if" conditions. It utilises the computer-driven electronic "models". Such "models" are created by the user producing graphical, or alphanumeric data illustrating situations expected within a proposed, or alternatively, "real-life" operation over an accelerated time-base. In recent years, there has been an increasing emphasis on integrated systems in which machines and peripherals are linked, thus reducing lead times and work-in-progress levels, and maximising resources. Simulation has many beneficial features and can be applied across a range of technologically innovated areas, such as:

a feasibility design tool

a preliminary study when making modifications to a current system

a method of capturing/studying a system's parameters then incorporating them into a "host" computer

showing the affects of altered time scales on the system

an aid to study the extremes of an operational system's capability without the risk and expense of disrupting production

a training tool for operators reducing the expense, or inconvenience, involved in using the actual system

Simulation comes into its own when there are indeterminate variables, typically queue times and breakdowns that preclude the exclusive use of mathematical techniques to predict the system's performance, or the result of a series of events. The aim when using simulation packages, is to attempt to achieve the right balance of resources – men, machines and work transportation – then to establish how they might be organised to obtain the maximum effect. The method by which the electronic "model" is created and manipulated is dependent upon the simulation language chosen for the software package; it is also influenced by the process to be simulated. Basically, three types of simulation language are used in the determination of a simulation "model":

"PROCESS"-based: these are primarily concerned with continuous processes – by which the resources pass through the plant – that are used exclusively in manufacturing activities

"ACTIVITY"-based, often termed two-phase programs, that are concerned with discrete time-periods and are best suited for "modelling", then simulating batch-type manufacturing systems

"EVENT"-based, known often as three-phase programs and can be used in a similar manner to the "ACTIVITY"-based methods, but with more modelling discrimination

In our discussion we will consider only the latter two languages – "ACTIVITY" and "EVENT"-based – as they apply specifically to the batch manufacturing found in flexible manufacturing production. Any "ACTIVITY"-based language considers the start, duration and end of an operation as just one activity, with the various resources coming together to undertake a sub-routine. Only after this sub-routine, such as loading/unloading the machine tool, has been completed will the clock advance. In the case of "EVENT"-base languages, each event is considered separately with the clock advancing at each time there is a change of state and with our last example, loading and unloading would be described as separate events.

The simulation process can be basically considered in three stages:

system definition and creating the model outline with captured data

writing/proving out the electronic "model" within the computer

operating and redefining simulation runs until acceptable results are obtained

As one would expect, creating a system "model" is the most demanding and critical stage of the simulation process; furthermore, as the computer simulates this "model" and not the system, successful operation depends on how accurately the "model" represents the system. The well-known saying "garbage in, garbage out!" means that our model developed is only as good as the data gathered. The "model" includes structural and physical relationships combined with the system's time-based interactions; so, by defining our problem and highlighting critical points whilst collecting data – this being difficult and time-consuming – then building/validating the "model", we will obtain a realistic representation of simulation.

When "model" building, the programs can range from those that are mathematically-based – having a complex structure developed with a knowledge of high-level computer languages, such as Fortran, enabling it to run using powerful simulation programs – to these running on microcomputers in such a way that "modelling" is invisible to the user. The more powerful discrete event simulation methods are usually used with mainframes/minicomputers, but some systems have specific hardware developed. These systems are more specifically used by expert programmers and are designed to handle any problem capable of being "modelled" in discrete event form. Such "modelling" is a long process requiring a thorough understanding of the system, although one system has reduced the keyboard input time using a front end code generator, which is an additional program enabling an interactive input of "model" data in English.

The number of visual interactive systems is increasing, allowing non-experts to use the programs, being in effect validated "models" into which the prospective system "model" is fed. As such, these systems are particularly relevant for "modelling" flexible manufacturing systems, or when tool management systems need to be simulated. This is not a limitation compared with the more sophisticated simulation packages, as it allows the non-expert to understand the software functions more easily, whilst gaining confidence in programming. For this reason, these data-driven visual systems are gaining acceptance – particularly since they cost a fraction of the high-level programs, whilst being much easier to use. Possibly the main benefit of the visual interactive systems is that they give the user an easy means of explaining the system "model" to the decision-makers within the company. This on-screen pictorial mimic which has an interactive ability is much more acceptable to management than the more common but traditional tabular output of simulation results.

As we have seen, the more powerful systems require experts, taking time and requiring proficiency in programming ability; this inevitably confines such systems to areas where cost-effectiveness becomes paramount. Whatever simulation system is chosen for the task, whether the manufacturing project is complex or relatively simple to simulate, then the preliminary planning should not account for more than 1% of the project's capital cost. The preliminary model created would be appropriate for additional detailing in order to fully test and optimise the proposed system. Any further detailing to the simulation depends upon the complexity of the system, but also the "law of diminishing returns", meaning any direct savings found by further enhancement of the model, must be levied against greater costs. Typically, the cost of gaining proficiency in the simulation system and its annual running costs can approach £30 000 – for an advanced system that is fully capable of general use, and whose cost must be taken into account.

With some companies, having an in-house simulation system is vital, but whenever a company needs to "model" only occasionally, then it might be more appropriate to use a consultant. Using a consultant to build the simulation "model" can be achieved at a fairly low cost, prior to the heavy investment needed to assess the feasibility of the project.

In Fig. 6.3 a range of simulation "models" can be seen, depicted in either cells or systems, produced by two of the leading simulation software companies. The "models" shown in Fig. 6.3a–c are presented to the user in a plan form, whereas the "models" shown in Fig. 6.3d–f are oblique views of the simulation. In both cases a range of colours can be used to identify the dynamic moving elements, such as pallets, or automatic-guided vehicles and at any time the machine utilisation rate, personnel utilisation, product routing and quality control objectives can be assessed in a real-time sense. By running the "models" over a specified time-base it is possible to see if "bottlenecks" occur at certain times and by amending the layout – introducing either new machine tools, or re-routing parts – "what/if" conditions can be assessed.

Therefore let us consider the logic used in Fig. 6.3a–c; the "models" are described in terms of "entities" which engage in "activities. An "entity" represents a resource, such as a CNC machine, robot, conveyor, or palletised part, whose behaviour is being simulated, whereas an "activity" is the state in which an "entity" remains whilst an operation takes place over a period of time. The time of the "activity" is previously calculated and once it has begun it continues for the time duration, unless the logic of the "model" allows the process to be interrupted. For example, a machine tool and its associated workpiece might be engaged in a specific machining operation which could be interrupted by, say, a breakdown. When an "entity" is not involved in an "activity" it waits in a "queue"; thus a machine might wait in a "queue" when there is no part for it to currently machine. With any "entity", attributes can be used to describe it in greater detail, for example, a machine tool's attributes would be its speed, range of operations it can perform, and the last time it has been maintained. The life of a typical "entity" might consist of several "activities" and "queues" and the manner in which "entities" travel around the "model", from one state to another, can be represented in an activity cycle diagram (not shown).

When one requires to change the status of the "model", then by cycling through the three dynamic conditions of "start", "time" and "end", further what/if conditions will result and help the programmer to assess the "models" viability. Let us look a little closer at these three phases:

"start" – checks the conditions of each "activity" in turn to see if any can start. The "activity" number establishes the checking sequences and obviously the priority between competing "activities". The logic dictates that an "activity" may only start if the approprate "entities" are available in the correct "queues". If an "activity" can begin, the "entities" are moved from their respective "queues" to the "activity", with the time being written next to this "activity"

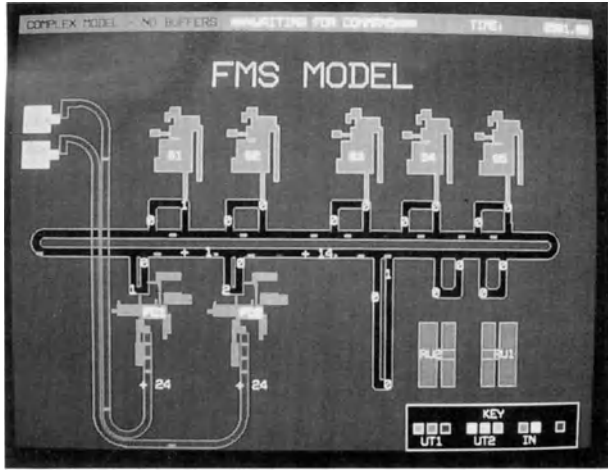
"time" – this is needed to locate the "activity" or multiple "activities", with the earliest end time and advances the simulation clock to this time

"end" – the "activities" due to finish at the new simulation clock time; it moves the "entities" to the destination of the "queues". At this point, the "activity" returns to the "start" phase

Such simulation practice proceeds for as long as necessary, to verify the logic, observe behaviour of the "model", or to collect statistics.

The simulation "models" depicted in Fig. 6.3d–f, allow a dynamic simulation package to be used, producing complex and realistic "models" through a "building block" approach, making a knowledge of programming unnecessary. "Models" are built using a series of "blocks" which prompt the user to input information that accurately represents the process to be simulated. These "blocks" take the form of a logical sequence that makes the "models" easy to read and understand, with on-

a



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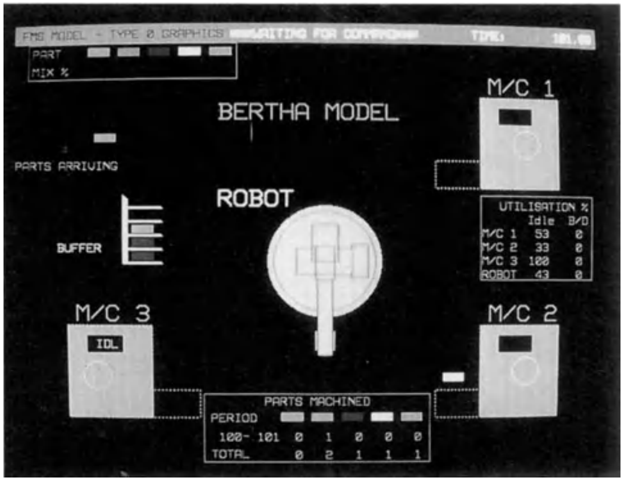

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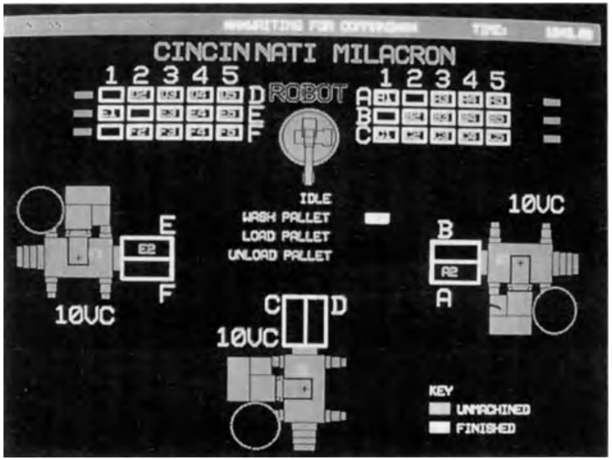
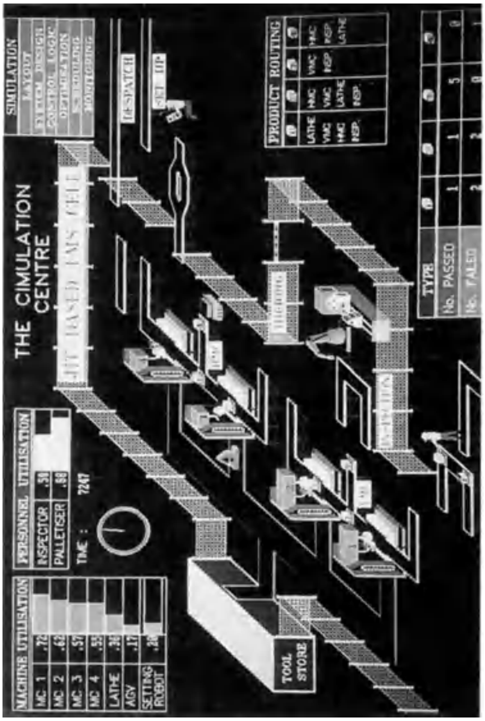


Fig. 6.3. Two simulation software packages illustrating how the efficiency and potential feasibility of prospective FMS/C can be assessed and then run over a preselected time-base to determine "what/if" conditions in a dynamic situation. **a–c** This package highlights a range of plan views of both FMS/C models. **d–e** Oblique simulation of an FMS, showing the dynamic time-base changes in manufacture and its "zooming" capabilities. [**a–c** Courtesy of P-E Consulting Services. **d–f** Courtesy of Cimulation Centre.]



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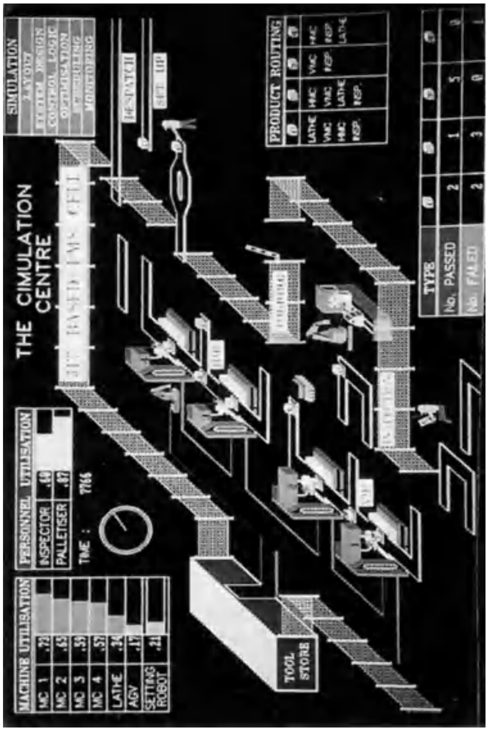

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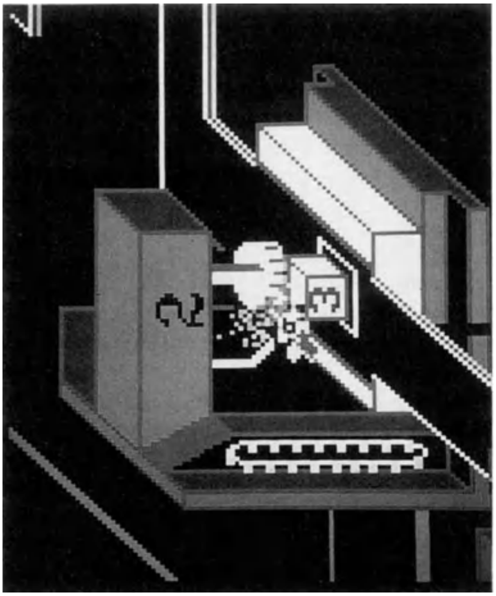

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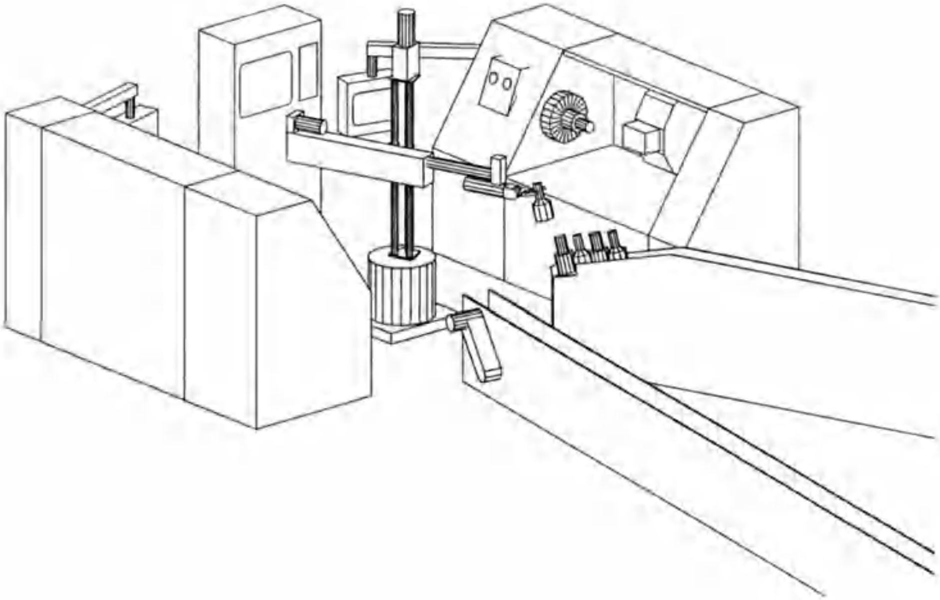


Fig. 6.4. A simulated robot-loaded turning cell with "hidden line removal", used in feasibility studies for cells/systems. [Courtesy of BYG Systems Ltd.]

screen prompts to further enhance the documented flowchart. Once the "model" has been completed, then what/if experimental data is read prior to performing a simulation run.

The graphics are so designed that even a novice can develop 3-dimensional colour layouts, allowing the user to see the process in operation relatively quickly. An interactive feature can be called-up to help analyse what is happening to the "model", allowing the user to step through the "model" whilst watching the graphics being continuously up-dated. Alternatively, the simulation can be run until a certain condition occurs, then halted to establish the reasons for occurrence. A menu generator can be used allowing the "model" builder to develop a series of menus, enabling the simulation to be operated by an unskilled user. Such menus allow variables to be modified, then the data collected and stored for subsequent analysis. Data can be read from existing computer files so that a simulation "model" can be loaded with an up-to-date start position. If a user has a knowledge of computer languages, there are interfaces for Fortran and "C" subroutines. CAD drawings can be displayed onto the screen so that movement can be superimposed onto the most complex of backgrounds.

A partial view of the dynamic simulation model can be seen (see Fig. 6.3d,e) and where an area of special interest occurs, then a zoom facility enables the user to observe the "workings" of the model in greater detail (Fig. 6.3f). The complex "model" can be observed at any time and the "model" will continue to run in real-time, even when one moves ahead to a new time-frame to see what might be happening at that time to the "model".

Before we leave this theme of computer simulation, it is worth briefly describing one of the three-dimensional advanced "modelling simulation of mechanisms" – such as robots and their tasks – that are currently available.

The system shown in Fig. 6.4 is an advanced kinematic "modelling" technique that is used in conjunction with an integrated three-dimensional-solid "modeller" to simulate both mechanisms and manipulators, as well as for conventional robots. Although a robot is depicted in both Figs. 6.3b and 6.3c, it does not have a truly "modelled" kinematic design which is necessary for the detailed analysis for actual implementation, whereas the "model" shown in Fig. 6.4 is a detailed scaled model of the true working environment. Such "models" are created using textural, or interactive graphical techniques and can be displayed as either a wire-framed form or with the hidden lines removed (Fig. 6.4), or optionally with full solid shading. New structures can be readily "modelled" and added to the system in complex relationships, enabling animation to detect clash problems between kinematic members automatically. This enables the user to verify that the "model" has collision-free operation, often within restricted areas.

By using such dynamic and realistic "models" of the actual working environment, the optimum placement of the moving elements and their relationship to the fixed elements can be achieved, which reduces the planning and design cycle considerably. Typically, a feasibility study of an FMC takes days rather than months and is certain to work, as the verification has been proven off-line and away from the production environment. This eliminates the costly mistakes that could arise if such a "model" had not been simulated and keeps the project time to a minimum. As with the previous simulation "models" discussed, the relative time frame can be moved to any point in the cycle and many further enhancements on the robot's optimisation within a cell can be achieved. Typically, the robot "modelled" can highlight the motions of the elements in terms of their range of angular/linear movement and how often they are activated during the simulation task. If in the case of a six-axis robot, only four axes are being used at almost 100% motion, then by modifying, or changing the layout slightly, all axes can be utilised at less than their theoretical motional limits. This allows a much better working relationship of the robot to its environment to be established, improving its optimisation.

Once the user is content with the proposed robotic cell, and all of the logical and positional information has been established – including input/output signals to control any peripheral equipment, the processing of sensory inputs, path control data, and high-level programming structures such as loops, branches and wait instructions – then it is possible to down-load the program to the robot controller. Once the program has been accepted by the robot's controller, then assuming the peripheral devices have been adjusted accordingly, the robotic cell can be run in its working environment.

This completes our review of some of the simulation packages available and their potential in removing the uncertainty when considering the prospective feasibility of an FMC/S. In the following section we will consider some typical plant layouts of cells and systems, before going on to mention how communication between machine tools and peripheral devices is achieved and look at some typical configurations of such communications.

6.3 Flexible Manufacturing Cell and System Configurations

The machine tools and peripheral equipment discussed so far function more than adequately in a "stand-alone" form which is by far the most popular method of production layout used by companies today. If this is the case, why do we need to invest large capital sums and increase the complexity of manufacture by using an FMC/S? There are some important reasons why such a plant configuration is necessary, not least of which being the opportunity to increase the company's profits whilst gaining a return on capital; possibly even more important is allowing the company a degree of flexibility to react to market and design changes. It is true to say that only certain production environments can truly gain from the implementation of such automation (see Fig. 6.1). Furthermore, this statement can be qualified by maximising the main advantages to be gained from total flexibility – a difficult test at best – and focusing upon a "Group Technology" (GT) approach to manufacture. Using this "GT" philosophy to obtain maximum benefit from the plant, processes are either grouped together in the form of a cellular manufacturing facility, or workpieces – where common features require similar production methods – further improving the cell's efficiency. Possibly the major advantage of such a flexible approach to the manufacture of parts is the unprecedented opportunity to drastically slash the hidden costs of production such as: work-in-progress, overheads and indirect labour. Any inroads that can be made into such areas will be a significant saving within the company, with the additional benefits being:

untended operation on third shift, or minimal manning on day shifts – reducing labour costs
improved machine tool utilisation
50% reductions in any work-in-progress
setting up times reduced
workpiece accuracy of more consistent quality
production techniques standardised
delivery times shortened
planned maintenance procedures – giving capital equipment a longer life
less floor space for plant – as manned access is minimised
opportunities for part/tool inspection during the machining cycle
part scheduling and re-routing of workpieces during planned maintenance, or unanticipated machine failure
interfacing to: MRP, MRPII and CAD/CAM peripherals through DNC links

6.3.1 Flexible Manufacturing Cells (FMC)

In recent years, more companies are seeing that the cell approach to untended machining is the way forward, as it can be developed using a step-by-step build-up of the major elements and in such a manner spreads the capital costs and hence risk, over a longer period. Secondary to this point, but some may feel just as important, is the experience and confidence gained by the company starting with a smaller and less complex cell – often beginning with a "stand-alone" machine tool – then progressing through stages to a larger FMC layout. Typical of this strategy is the FMC shown in Fig. 6.5, where it can be seen that two horizontal machining centres and one turning

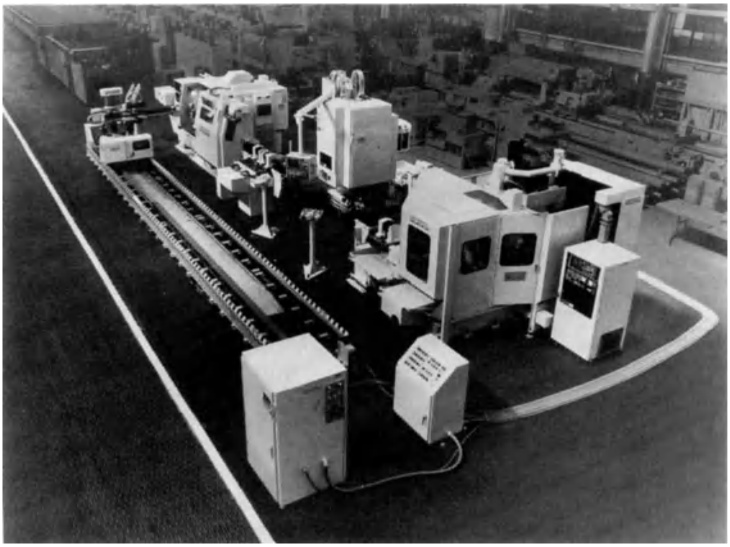


Fig. 6.5. Turning and vertical/horizontal machining centres in an FMC configuration together with robot-loading rail-guided vehicle. [Courtesy of Cincinnati Milacron.]

centre have been connected together by a rail-guided vehicle (RGV). This RGV has the ability to supply preset palletised parts by the carrier via the pallet stocker, or tooling from the tool centre. There is a two-way dialogue between the machine tools, peripherals and the system computer at all times, which up-dates, or re-routes work (in the case of an anticipated shut-down of one of the machining centres) with continual part tracking and tool scheduling/up-dating. In such a manner high machine tool utilisation can be achieved – over 90% efficiency is possible throughout the working day.

This type of FMC can be seen throughout many of the industrialised countries of late and gives a degree of flexibility of production within reasonably rigid constraints, in that such systems have often been called "prismatic cells" – but even here one must be careful to qualify this statement, as some rotational features can always be accommodated using either interpolation techniques, or special-purpose "U-centre" milling heads. Such cells can start with just two machine tools, then be progressively built up to a complete machining complex, comprised of six, or more, machining centres. However, when one reaches this level of complexity then it becomes important not only to utilise floor space effectively – often if this is to be the case, then staggering machine tools on alternate sides of the rail is necessary – but in addition, adding further RGVs to serve the extra machining centres. It is advisable by now to have completed a simulation of the enlarged cell layout, to obtain the maximum benefit from not only the extra machines, but the best utilisation of the RGVs proposed to service these machines (see section 6.2.2).

If a company is predominantly machining parts complete from bar stock cut to prescribed lengths, rather than the general machining of prismatic features, then a cell with a configuration similar to that shown in Fig. 6.5 might be the answer. Here, a rail-guided vehicle has a load/unload robot situated upon it and it is free to move up and down the track supplying parts to the turning centre, or the vertical/horizontal machining centres. Normally such an FMC would be fully guarded in the vicinty of the track and robot's moving elements, but for clarity this has been removed. As parts to be made by such a cell often differ only marginally in detail – the "GT" philosophy again – then the cell controller (shown in the foreground) can be of a much simpler design and of relatively low-level sophistication. This is prudent, as it reduces both the cost of the overall supervision, often needing only a programmable logic controller (PLC) to fulfil the production requirements, whilst having the major advantage of simplifying error-recovery – one of the greatest problems associated with down-time on FMCs – but more will be said on this topic later.

The pre-cut bar stock is stacked onto a workstation in such a manner that the robot's gripper can grip the parts easily – a range of delivery solutions can be used here to simplify either programming of the robot, or identify differing stock diameters and lengths – such as gravity feed chutes for parts, or flexible flow systems with automatic size identification and buffering incorporated into the equipment. Part delivery is not the major problem, however, as component fixturing, scheduling, monitoring and robot delivery is more critical – but even here, if both the dynamic simulation layout in combination with robotic simulation has been previously undertaken, this latter problem will have been addressed.

Whenever a company is likely to embark upon the development of a cell into a totally integrated system often covering a considerable floor space within the production facility, then there is some justification for elevating the supervisory control room over the plant so that engineers are positioned strategically above the facilities and have a clear view of the equipment. Usually such an environment is clean, relatively quiet and air-conditioned, which is an important point, as such personnel must spend considerable time within this area. Equipment in this control room will not only monitor the immediate and everyday functions performed on the machine tools – tool management, part status, scheduling, SPC – but is connected to the "outside world", to other departments, through communication links – ethernet, manufacturing automation/technical office protocols (MAP/TOP) – or even to other companies involved in Just-in-time (JIT) or similar activities.

The strategic placement of the centralised and elevated control room is critical to any further plant to be added to the cell at a later stage, as visual confirmation of machine tool and peripheral equipment status can be verified accordingly. However, even when the most well-planned floor layout has been built, there comes a time when the simple visual confirmation of a manufacturing activity becomes counter-productive and under such circumstances the real-time dynamic simulation takes on a greater significance for part status confirmation within the control room.

Often when a company is involved in a "highly-focused" production activity, then it is important to obtain the most advantageous machining capability possible by linking similar manufacturing processes together. In order to minimise possible work-in-progress activities, parts might be palletised and conveyed around the cell, then loaded by a gantry robot to a turning centre. This machining philosophy is used in the two machine turning cell described below. The workpieces might be loaded onto "coded" Europallets – several at a time and then delivered to each machine tool. Part scheduling is accomplished by a supervisory cell computer situated on one of these machines and can be used to a range of work-related activities such as: machine control, logistical part handling, tool strategy and management, together with machine monitoring. Such a controller, as one might expect, is MAP compatible and is not only easy to understand and use, but offers significant advantages in any error recovery situation.

Not only does the cell have the ability to automatically load workpieces into the turning centres, but a gantry robot can be used to change complete chucks for another rescheduled part without stopping the manufacturing process. It might also be used to load/unload quick-change tooling at will. By utilising a very universal and robust gantry robot it could also transfer workpieces to a part monitoring stage where a range of automated metrological equipment can be accommodated to inspect critical dimensional features of the component. Such an on-machine inspection facility would inspect the parts such as rotational features, using an automated caliper gauge which up-dates tool offsets during its inspection and can generate statistical process control (SPC) data to control the machining process, whilst production continues on the following part.

The major advantage of utilising another machine tool of similar specification, is that a balanced production flow between these two machines can be more readily achieved and in so doing, the overall utilisation rate is improved. Furthermore, if for any reason one machine tool is taken out of commission through either a preventative maintenance procedure, or unexpected machine failure, its work can simply and speedily be switched to the other machine tool, without too much lost production. In such a manner, down-time is drastically reduced and a vast improvement in the overall cell utilisation rate occurs.

The final cell to be discussed in this section is depicted in Figs. 6.6 and 6.7. The author has had the unique experience of designing this cell and taking it through the commissioning stages and final acceptance, in conjunction with a large machine tool builder in the UK. It was envisaged as a "turn-key" package – where specific parts were originally designed and the cell was brought on-line to machine such components. In this way, the total concept of flexible manufacturing could be addressed from the initial feasibility study, through to conception. The Southampton FMC comprises the following hardware:

two axis turning centre, supplied with modular (block) quick-change and "sister" tooling, programmable tailstock and chuck, with swarf conveyor

three/four axis vertical machining centre, with modular (varilock) tooling, programmable vertical chuck, tool breakage detection, adaptive control and touch-trigger probing, with swarf conveyor

coordinate measuring machine of cantilever design, with motorised touch-trigger probing which can be controlled through either a micro-vax, or PC, for full colour graphics programming

six-axis electrical robot, having a special purpose back-to-back (offset movable jaws) gripper, hydraulically operated

cell controller with built-in CRT, having both a "QWERTY" keyboard for programming cell production requirements and special-purpose controls for: interrupting program cycles, inspection calls, changes of batch sizes, etc.

optical tool presetter with on-line tool offset facilities

direct numerical control link to CAD/CAM equipment for completely automated design, manufacture and inspection

Customised software was developed and communications are orchestrated via the cell controller, through the robot controller, to trip input/output devices on the various machine tools and peripherals, such as to: open doors, close grippers, load parts into workholding devices, etc. The network topology used for communications is the "star" configuration (see Fig. 6.9a).

In order to obtain a realistic understanding of how such a cell operates, it might be prudent to run through the making of some typical parts during a conventional production cycles. Each of the machine tools within the cell can be operated in a "stand-alone" mode, so if one requires to run the system untended the supervisory

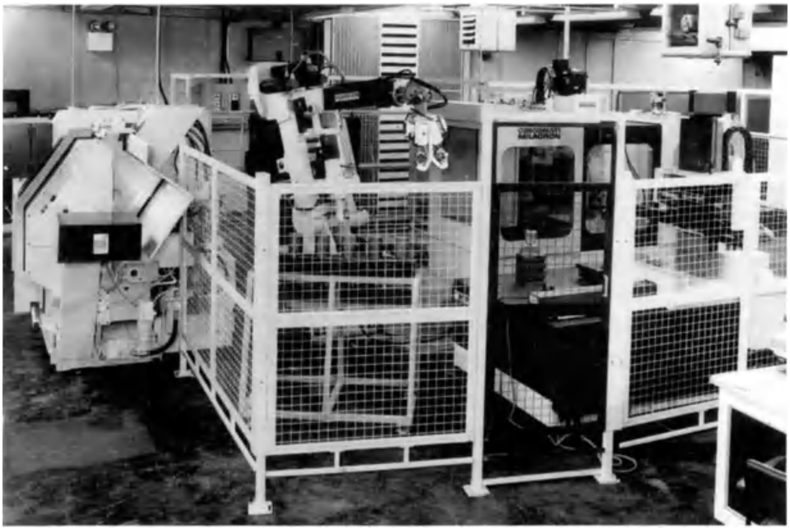


Fig. 6.6. A typical FMC installation (developed by the author and a machine tool manufacturer) at "commissioning stage" during the late 1980s. Initially, the cell was comprised of a slant-bed turning centre, a vertical machining centre, a 6-axis robot and a coordinate measuring machine. Later additions included an optical tool presetter and modular quick-change tooling, together with a CAD/CAM DNC link. [Courtesy of Southampton Institute/Cincinnati Milacron.]

Fig. 6.7. Detail of the robot's gripper in the "Southampton cell" designed by the author. The hydraulically operated and offset back-to-back gripper has synchronised movable jaws, enabling fast load/unload of the parts (i.e. of varying diameters) and close access to the workholding equipment. NB: Jaw faces/ends can be quickly changed. [Courtesy of Southampton Institute/Cincinnati Milacron.]

control must be managed through the cell controller. This necessitates operating the equipment in the "cell mode", which is achieved by simply pressing the suitable button; however, before the cell can run, it is necessary to ensure initially that both machine tools are in "cell mode" and their axis and other peripherals are set to zero. The robot axes need to be datumed and set to zero and this is achieved at the cell controller by simply holding down a button whilst all six axes are set. Confirmation of each axis appears on the CRT display. Assuming that an appropriate number of pre-cut billets have been loaded onto the workstation, then the batch size can be stated and confirmed in the controller – assuming the respective part numbers have been called up from the CNCs on each machine tool. It is possible to identify over thirty discrete part programs for mixed batch manufacture within the controllers and these are assigned by the operator at will. Once these preliminary details have been established then the robot will move to pick up the first billet once the run command has been activated (Fig. 6.7). If the part requires turning, then the robot picks up the billet and moves toward the turning centre whilst signalling the turret to retract which opens up an access hole for the gripper at the back of the turning centre. At the same time, the programmable tailstock " latches-up" and a compressed air pipe connected to it blasts a stream of high velocity air at the chuck. This chuck, in turn, slowly rotates in order to remove any unwanted swarf trapped from a previous machining cycle. The robot gripper will move to load a billet into the chuck – the tailstock having previously "latched-down" and the air blast ceased and chuck stopped – the billet is gripped by the chuck and the robot retires from the working envelope. The turret comes forward and closes the hole at the rear of the machine and the part program generates the desired features on the part. Simultaneously, the robot returns to the workstation, picks up another billet for this batch and waits whilst the initial component is machined. At the end of the machining cycle the controller signals the robot to advance into the working envelope of the turning centre – having previously withdrawn the turret for access by the gripper; the gripper supports the part whilst the chuck jaws open and retires a short distance. The tailstock "latches-up" and the chuck rotates under the air blast, then lowers again, ready for the robot gripper to load the next billet, as before. It then retires from this vicinity, through its access hole and the machining of the second part begins.

It is worth pausing here to consider a problem that might have been difficult to overcome if it had not been anticipated. As the bar stock has had its "gripping diameter" reduced, this could mean that a very complex robot program needs to be developed to cater for a range of differing turned diameters, as the centreline of the robot will have changed with respect to the part. However, owing to the fact that both gripper jaws can move in synchronisation, the "gripping diameter" will not influence the robot's program. Furthermore, with the back-to-back offset design of this gripper (Fig. 6.7), it has the ability to get close to the chuck jaws, enabling it to manipulate small parts adequately. Finally, owing to the application of hydraulic pressure, it is possible to restrict the flow of oil and in this manner control the pressure applied by each jaw on the part, minimising damage on thin-walled components.

The robot will now swing around to face the side of the machining centre (Fig. 6.6) and the sidedoors are signalled to open, whilst the machine's table with its automatic vertical chuck will be in the desired position to accept the workpiece. The robot reaches into the working envelope of the machine tool and loads the turned features into the vertical chuck, which once again is hydraulically operated and of variable clamping pressure. It then retires and the doors are closed allowing the part program to machine the necessary prismatic features and some rotational features, utilising circular interpolation, if necessary.

Whilst this activity is continuing, the robot picks up its third billet and waits whilst the turning centre completes the second workpiece. It then goes through the identical unload/load sequence previously mentioned and with the third component machined, it now has the option for several activities:

waiting whilst this part is completed and then unload/loading the part into the machining centre – assuming it is the final part in the batch

picking up a fourth billet and waiting whilst the turned part is completed and loading that into the turning centre, whilst placing the second partially completed component onto the workstation. This is assuming, of course, that the machining centre cycle time is much longer than that of the turning center's. In fact, it may require several parts to be buffered in this manner, whilst the machining centre is still operating

loading a partially completed part into the coordinate measuring machine, if an "inspection call" has been activated. This could have been done to the first component as a "first-off" inspection procedure, if required

an interruption to this batch could have been decided to be necessary by the operator at the cell controller and different part programs would have been called-up from the unique identifiers within the turning centre's controller and the robot would load another billet when the third part had been completed

NB: The buffered partially machined components can be completed at will, whenever necessary, as it simply requires them to be picked up and machined to the desired part program. The position of each part is known within the cell's logic by the unique software developed for this cell.

Such flexibility of production and the options performed at any and every stage of the part's manufacture, gives one the capacity to respond quickly and efficiently to changes in production, quality problems on the machine tools (i.e. using touch-trigger probing), or alternatively, at the post-machining stage using the CMM. There are many more subtleties of both production and monitoring of either parts, or tools, that could have been mentioned, but not in the space provided. It should be clear to the reader by now that there are highly productive advantages to be gained by such a flexible manufacturing cell installation.

6.3.2 Flexible Manufacturing Systems (FMS)

The flexible manufacturing cells discussed so far have either been built up in a "step-by-step" approach, or as "turn-key" installations. FMSs, by their general nature, tend to be of greater complexity, whilst being situated over a larger area of the manufacturing facility. Such a large and complex installation means that either part- or tool-delivery systems to the individual machine tools need to be considered. A typical method of delivery used is that of the AGV (automated-guided vehicle, Fig. 4.26) previously mentioned in section 4.8.1. In such an FMS environment, the freedom gained in situating plant in the optimum configuration within the geographical layout of the manufacturing facility can be achieved, which would be much more difficult to attain using RGVs (rail-guided vehicle delivery systems; see Fig. 6.5).

A workpiece can be located onto its respective "coded" pallet and loaded through the machine tool's pallet-changing mechanism into the working area of the machine using an AGV. It is also possible to transfer simultaneously a part previously machined on its "coded" pallet back to the AGV and away for either further machining, or back to the centralised load/unload station. It is worth restating at this point, that such

Fig. 6.8. An FMS illustrating "pallet pools" strategically positioned for easy access of the wire-guided AGVs. Note the elevated control room. [Courtesy of Cincinnati Milacron.]

"coded" pallets need to be uniquely identified in order that the desired part is loaded onto its anticipated machine tool and that the correct part program is down-loaded from the machine control unit into the "active" memory area of the CNC controller. Such scheduling of parts, tooling, programs and so on, are the task of the host computer, which can dynamically schedule and re-schedule parts within the FMS as dictated by the contingencies of the "master schedule", or anticipated/unanticipated machine tool interruptions. Pallet "coding" for efficient workpiece tracking within the FMS can be uniquely identified in a number of ways and just some of these ways were described in section 4.8.1.

AGVs can also be used to unload a magazine, or chain magazine of tools to either replenish a "sister" chain, or present a "new" range of preset tooling to the machine for further jobs, whilst simultaneously removing the "old" tool chain magazine and transporting it back to the presetting facility. In such a manner, tooling/workpieces can be quickly and efficiently loaded and unloaded to the FMS machine tools and other devices, such as: wash-stations, coordinate measuring machines, pallet-pools, servicing facilities, etc., according to the dynamic dictates of the scheduling requirements demanded by the host computer.

The machine tool just discussed, might well be part of a large-scale FMS as depicted in Fig. 6.8. In this installation in Phoenix, Arizona, USA a large-scale "turn-key" facility has been installed with numerous machine tools, having AGVs, "pallet-pools" and so on, controlled from an elevated control room, where the minimum of staff can supervise the smooth running of this FMS. Obviously, during the running of such plant, it is necessary for a certain amount of support staff to be present for tool-kitting and maintenance, but whenever practicable the facility can be minimally-manned during the night shift, as parts will have been buffered at the "pallet-pool" stations, together with additional "sister" tooling delivered to the machines as production demands dictate. This system is particularly noteworthy in that one major machine tool company was responsible for the complete FMS, from feasibility, through to customer acceptance/commissioning. This is an important point in a fully integrated and operational FMS, as one company has overall responsibility for the project from inception, through to completion. This means that the customer knows exactly who to contact with any queries regarding the day-to-day problems that might arise, whilst the machine tool supplier is in a position to fully support the customer's needs speedily and efficiently, without recourse to further dialogue with yet other companies involved in the FMS installation.

As one can by now appreciate, such a high level of computerised equipment necessitates considerable communication sophistication between the "host" and peripheral devices and when errors occur, through either faulty interlocks on moving elements within the FMS, or data corruption between the respective computers, then quick and easy "error-recovery" is the key to maintain optimum plant operation. It has already been alluded to previously that FMS "condition monitoring" sophistication is a critical element in the successful implementation of any FMC/S, however, more will be said on this topic later in the chapter.

In the following section the theme of system communications will be briefly touched upon, looking into the various "network topologies" and MAP/TOP techniques currently used, whilst attempting to identify the research direction that manufacturing systems "networks" are developing towards, in order that the reader might readily appreciate the levels of sophistication of present and future computer communication.

6.3.3 "Network" Topologies and their Use in CNC Machine Tool Applications

As we have seen in the previous section and more specifically in the case of the large-scale FMS depicted in Fig. 6.8, significant amounts of data transfer occur with such equipment having a considerable level of machine intelligence in order to perform the expected control functions necessary in such manufacturing environments. In recent years an almost limitless number of proprietary local area networks (LANs) have come to exist, or have been proposed, as some vendors have attempted to control standards in order to dominate their market positions. This has lead to a lack of industry standards and it is now clear that no single vendor can supply all of the communication needs desirable in an automated factory. Any vendor attempting to install translator boxes between peripheral devices within the FMS, to obtain successful communications, should be vigorously resisted by the customer, whilst it is also prudent to avoid single source suppliers of communication equipment. Furthermore, the systems limitations of the proprietary networks need to be stringently evaluated by the prospective client. Where standards do exist, they do not make the task of the engineer easy, as important decisions about modulation, access, media, topology, together with many other technical communication considerations must be made when producing a functional specification for an FMC/S. Let us consider these four primary independent variables in a little more detail:

Modulation
(i) baseband: typified by the telephone network
(ii) broadband: a typical cable TV installation

Access
(i) contention
(ii) token passing

Table 6.1. Characteristics of media transmission.

Transmission media	Bandwidth	Distance	Versatility of topology	Installation ease	Cost	Noise immunity
Twisted pairs	6 MHz (low)	Short	High	Moderate	Low	Low
Coaxial cable	300 MHz (medium)	Moderate	High	Easy	Moderate	Low
Fibre optics	300 MHz (high)	Long	Moderate ("bus" and "tree" Difficult)	Moderate	Moderate	Very high

(iii) frequency division multiplexing
(iv) time division multiplexing
(v) master-slave

(Transmission) Media
(i) twisted pairs
(ii) coaxial cable
(iii) optical fibres
(iv) microwave, etc.

NB: Let us look (Table 6.1) in more detail at the comparison between the first three types – transmission media being the most popular at present.

Topology (see Fig. 6.9)
(i) star (Fig. 6.9a)
(ii) ring (Fig. 6.9b)
(iii) bus (Fig. 6.9c)
(iv) tree (Fig. 6.9d)
(v) unconstrained (Fig. 6.9e)

These variables are by no means an exhaustive list and at present it would be possible to produce over three hundred possible combinations. The engineer is thus presented with a series of decisions: "How then can my choice be made?". The answer will depend upon the intended use and we might ask:

"How expensive is the system?"

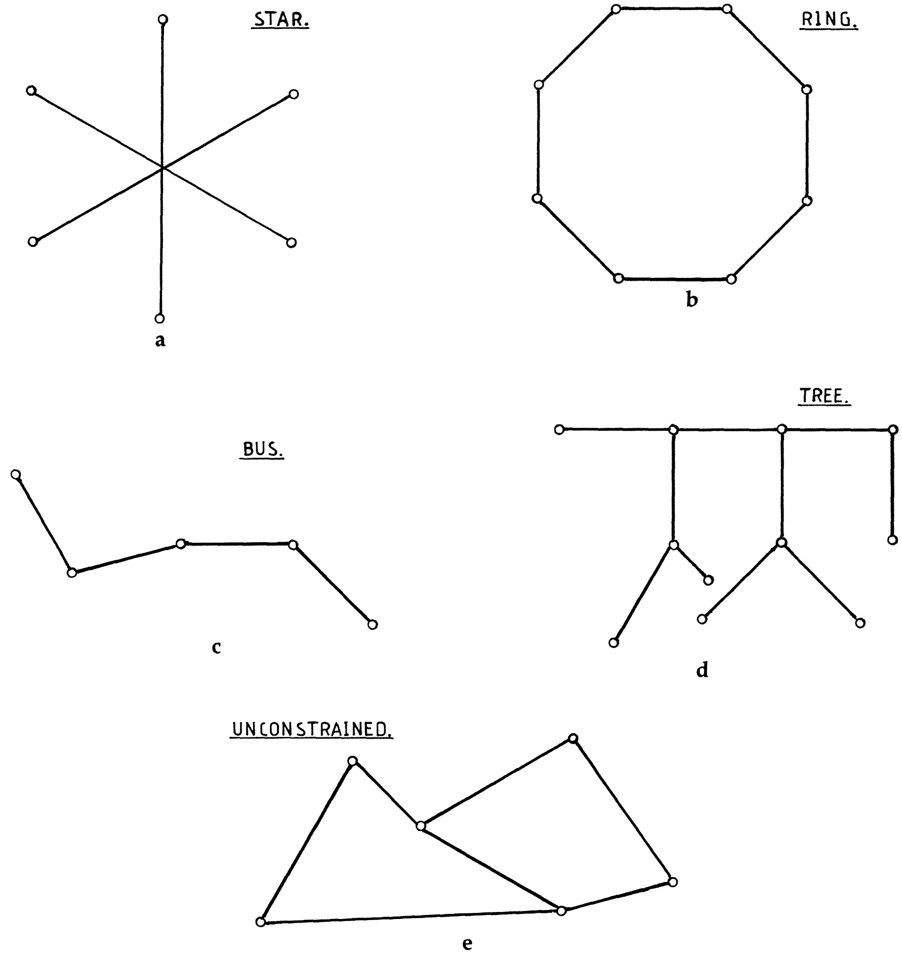
"What capacity is necessary?"

"What are the acceptable error rates?"

Such questions and many others must be answered if one is to obtain a successful integration of hardware/software devices within an FMC/S facility.

One local area network topology is a direct numerical link through a PLC to the "stand-alone" CNC machine tool. Even here, in this most simple communications link, many companies still have problems associated with data transfer from host's, or CAD/CAM workstations. Such problems become exacerbated when different makes of peripheral equipment are connected to other types of network topology. In fact, this problem has been partially addressed in recent years by the OSI seven-layer model which is more commonly known as MAP/TOP, but more will be said on this topic in the following section.

If we consider the "bus" network topology and its related software in more detail, this will give the reader an indication of just some of the functions necessary for successful software communications within an FMS. For a range of peripheral hard-



Topology	Reliability	Interface complexity	Modularity	Flexibility	Cost
Star	Poor	Simple	Moderate	Poor	High
Ring	Moderate	Simple	Good	Moderate	Moderate
Bus	Good	Moderate	Good	Good	Low
Tree	Good	Moderate	Good	Good	Low
Unconstrained	Very good	Very high	Moderate	Poor	High

Fig. 6.9. Typical arrangements of network topologies and their different characteristics.

ware devices connected to a "bus" LAN, for a CAD/CAM link via a DNC link to be successful, a range of software is required. Here we can see that a vast array of software functions is required and these FMS technology orientated functions might consist of:

production planning administration
master data administration
  system configuration (system parameters)
  tools (nominal data)
  workpiece carriers
control data administration
  CNC part programs
  workplans
  production orders
status data administration
  system status (plant status)
  tools (actual measured data)
  workpiece carriers (pallets)
  workpieces
connection to tape punch reader – if necessary
alarm/error messages
synchronisation
message handling and print functions
setup and clamping calculations – for tool "balance"
automatic material flow control
  including connection to a transport system
machine tool programs
  for serial link
  for LAN
automatic tool flow control
  single part (workholding)
  pallet-based transport systems
tool setting machine connection
special machine connections
  wash machines
  coordinate measuring machines, etc.
short term shutdown
shift reports
CIM interface

In order to achieve secure data transfer and compatibility between a range of software protocols, it is highly desirable to use MAP/TOP communications philosophies and this will be considered in the following section.

6.3.4 Manufacturing Automation/Technical and Office Protocols (MAP/TOP)

Manufacturing Automation Protocols (MAP)

As we have seen in the previous pages, and no doubt as we probably know from personal experience, the linking of so-called "islands of automation" – namely turning and machining centres – to workpiece transportation systems and other devices in the communication world of manufacturing, known euphemistically as FMC/S, has a technical flaw – it has, until recently, been almost non-existent between different vendors' products. This, however, has not been true when a "turn-key" system has been purchased from a single vendor source, which has meant that most successful automation systems were commissioned from the larger machine tool companies. The problem here is one of secure data transmission (communication) between different vendors' products, such as a turning centre made by one company and a robot by another. This problem of the successful two-way transfer of data between devices associated together in an FMC/S has been addressed by the Manufacturing Automation/Technical and Office Protocols, known more commonly as MAP/TOP, which have, in their various versions, been to a greater or lesser extent a success.

Prior to a discussion on the methods by which data communication is presently achieved between automated equipment, it is appropriate to consider the historical background in the development of MAP/TOP. The automotive industry was one of the leaders in adopting automation into manufacturing plants in order to improve their competitiveness, which meant that they were one of the first to experience the problems associated with the lack of multivendor communications. It is generally agreed that General Motors, and to a lesser extent Boeing, in the USA were the instigators behind these communications developments. In 1980, General Motors, the largest company in the World at that time, set up a study group after the company turned in a loss of $780 000 000, its first for sixty years. Their findings indicated that around 40% of the total automation investment in the plant at their factories was being consumed in communication costs. This meant that the company had to come to terms with this drain on capital resources and they declared their intention to press ahead with the establishment of their own rules for communications and insisting that once the rules were established, they would become mandatory for all suppliers of equipment to General Motors. Thus, the General Motors MAP Task Force was established and it was their original intention to take the best solutions of the existing standards from around the World and incorporate them into a new protocol. Unfortunately, they shortly established that the standards organisations had not considered the complex communications requirements for manufacturing, so General Motors had to use existing standards whenever possible and supplement them with its own where applicable.

Possibly the first practical MAP demonstration for the public occurred at the July 1984 "National Computer Conference" in Las Vegas, when General Motors, along with seven suppliers, demonstrated four of the seven layers in operation – more will be said on these layers shortly. In November the following year, at the Detroit "Autofact 85" exhibition, there was a more ambitious display by General Motors and other vendors. On this occasion, twenty-one other companies were present, including: AT & T, Digital Equipment Corporation, ICL, Motorola, Gould & Allen Bradley, together displaying a MAP network with six layers in operation reaching the 2.1 specification. The American lead was being followed in Europe, and in March 1985, the European MAP Users Group was formed, along with ESPRIT initiatives on similar lines. With the MAP specification being 2.1, a very impressive "CIMAP" show sponsored by the Department of Trade and Industry was held at the NEC in Birmingham, with about seventy companies taking part. The dynamic demonstrations of MAP/TOP were on show to a privileged audience of engineers and the biggest hall was filled with a single network. Since then, a further refinement of the standard has led to MAP 3.0, which was previewed for the first time at the "Enterprise Network Event" in Baltimore, USA, in 1988. Around this time, much disquiet was heard

Table 6.2.

User programs	Application programs (not part of the model)	Server machines
	Layer 7	
Application	Manages lower-layer services including application programs	Application
	Layer 6	
Presentation	Restructures data to/from the standardised format used within the network	Presentation
	Layer 5	
Session	Name/address translations, access security and synchronises and manages data	Session
	Layer 4	
Transport	Provides transparent reliable data transfer from end device to end device	Transport
	Layer 3	
Network	Establishes connections between equipment on the network	Network
	Layer 2	
Data link	Establishes, maintains and releases data links	Data link
	Layer 1	
Physical	Encodes and physically transfers messages between adjacent devices	Physical
	◄── **(Physical link)** ──►	

amongst the MAP vendors, relating to the frequent modifications to the standard and as a result MAP 3.0 was frozen for a period of six years, enabling some consolidation to occur.

So far, the reader has been introduced to the Open Systems Interconnection (OSI) seven-layer model adopted by MAP, but little detail has been given. Let us look a little deeper at these seven layers (Table 6.2), each handling different aspects of inter-computer communications.

If we consider each layer's application in turn, then at the bottom of the model one has:

1. *Physical.* This specifies the actual cable connecting one computer, or machine tool, to another and the type of signal that will pass over it – with General Motors specifying broadband. As we have discussed in section 6.3.3, broadband looks like a conventional co-axial aerial cable used in conjunction with television, being approximately 2 cm in diameter. Signals passed over it are analogue, modulated like radio waves to carry the digital information. The name broadband is derived from the fact that it is possible to transmit many different signals at a range of frequencies through the cable without interference.
2. *Data link.* This defines how messages are passed over the network, with each message entering the network being a package of information termed a "data-frame". This together with a specifying address is necessary to send it to the correct computer on the network. The problem here is in deciding when any particular "node" – this is a computer, or machine connected to the network – can transmit its message.

   Two common systems in use are "collision detection" or "token passing", with General Motors choosing the latter as being the more suitable for MAP. As its name implies, in "token passing" a "token" is passed from one "node" to the next. Only the "node" that holds the "token" may transmit messages and each can only hold it for a fixed period, before passing it onward.

3. *Network*. This decides the format of messages on the network and for this General Motors chose an existing standard termed "connectionless networking". In essence, this means that each message is self-contained, carrying its own address. By using this system, there is no need for one computer to form a fixed link with another to pass the message.
4. *Transport*. This contains the part of the protocol ensuring data integrity and unlike lower layers, a "node" establishes a notional connection with similar nodes at this level. When a message is sent, the transport layer at the transmitting "node" looks for an acknowledgement from its respective receiving "node". However, if it does not receive one, then it retransmits its message.
5. *Session*. This is a complete conversation between two "nodes", or computers and during this activity data may be exchanged between different programs running on each. As an illustration of this conversation, a host computer might be communicating with a programmable logic controller (PLC) in the plant. The communications link might be that the host is used to control production, but simultaneously it may be down-loading files, from the host, to the PLC, whilst receiving data from the PLC which may be used to maintain a record on the whole plant's database, held on the host computer.
6. *Presentation*. This handles the language each computer speaks. One computer might use a particular binary number to, say, represent the letter Z, whilst another binary number uses a different numerical value. Therefore, in order for them to be able to communicate with each other, they must both utilise the same data representation. Thus, the "node" that initiates the exchange of data will firstly ask if the recipient "node" uses its favoured representation. If the answer to this request is "no", then it tries a different approach until they obtain a common language understood by both.
7. *Application*. These are the programs that run on a computer and it is such programs that communicate with one another – the MAP objective being to enable them to exchange data. When General Motors initially attempted to instigate MAP, it had to develop its own protocols here as there was no International Standard, or group, to help them draw up such protocols. For example, in MAP 2.1 it included the following:

   "Manufacturing Message Format Standard" (MMFS), pronounced Memphis, which is a language allowing machine tools, that do not have sophisticated memory devices, to talk to one another

   "Common Application Service Elements" (CASE) which is used to set up communications with a remote "node"

   "Transfer, Access and Management" (FTAM) which was a protocol developed by Boeing for file transfer between "nodes" with devices such as disk drives

When MAP 3.0 was launched, all three protocols were replaced by the "Manufacturing Message Specification" (MMS). The logic behind the central concept of MMS, is the "Virtual Manufacturing Device" or VMD. With this protocol, every computer, or machine tool looks the same to the network through the MMS and it actually looks like the VMD. Thus, all the actual functions of the "node" are "mapped" onto the VMD.

This completes our summation of the seven MAP layers and their respective functions, but before we go on to consider Technical and Office Protocols (TOP) and their relationship with MAP in an FMC/S, it is worth briefly mentioning how MAP has been adopted by the manufacturing community so far. Across a range of motor manufacturers, such as: Jaguar, BMW, Renault, Mercedes, etc., MAP networks exist, although it is perhaps not the complete solution, as lower grade network topologies might be more applicable to some manufacturers such as "MINI-MAP". The MAP standard is now in the public domain and its development is controlled through MAP user groups – the largest being in the USA. There is a growing influence in Europe, principally via the European MAP User Group (EMUG) and others being developed both in Japan and Russia. Such user groups will determine the changes that will be made in the future to MAP 3.0. However, the growth of MAP is not solely in the automative industries, as automation companies, electronics firms, together with other interested concerns are also adopting the MAP philosophy of communications protocols.

Technical and Office Protocols (TOP)

In more recent times, a parallel pressure group for the standardisation of networks was established for applications in the engineering and office areas. The catalyst in this instance was the Boeing Company who introduced the Technical and Office Protocols (TOP), version 1.0 in November 1985. This, in turn, led to the formation of a TOP User's Group in December of the same year, together with the setting up of a joint steering committee for the two activities, so in most respects both MAP and TOP remain identical. Their differences lie in that they are designed to interface to different kinds of application software and also in the manner in which messages are sent around the network. As we have seen in the comments in the MAP section, this system uses a "token-passing" method, whereas TOP has chosen the IEEE 802.3 standard Ethernet-type CSMA/CD local area network, which has been implemented by many office systems manufacturers. Data transfer, however, can be interchanged between the two systems via a "bridge", or "router".

TOP protocols are more relevant than MAP in a design office, where data transfer times are less critical and the electro-magnetic environment less hostile. Furthermore, in the beginning, Ethernet networks cost about 80% less than the equivalent MAP network and even as MAP becomes cheaper, it is unlikely to undercut the cost of Ethernet. Alternatively, for a company involved in a substantial manufacturing operation, it may require a MAP broadband network and this could be extended into the design office, typically to the CAD/CAM system. There are many further options of configuring MAP/TOP networks – there are no firm rules and the theories on the optimum configuration change as MAP and TOP networks are implemented throughout industry. Finally, in recent years, both MAP and TOP have assumed the mantle of version 3.0 and in so doing, ensure the parallel development of these two standards.

6.3.5 Computer-Integrated Manufacturing (CIM) Networking Requirements

In general, the requirements which distinguish a CIM network from other applications can be loosely classified into three areas:

efficiency and flexibility of real-time multi-process communications
accommodation of equipment and environment heterogeneity
distributed network management and control

Let us consider each in turn in a little more detail, gaining a clearer picture of the technological problems to be addressed.

Efficiency and Flexibility of Real-time Multi-process Communications

Considering that computer networking technology is quite advanced for its specific application to a CIM task, it has not as yet been well characterised. Recently, a large body of analytical research has been produced for network control and communications in general, with the focus being upon "modelling" and performance analyses together with designing flexible manufacturing systems to accommodate future growth. However, this research has seldom considered the needs for real-time communications between the factory equipment such as multiple robots and multi-machine systems, where delays – as little as a few tens of milliseconds – might disrupt the process, causing losses in both production time and product quality. So, by producing formal characterisations and "modelling" of the entire manufacturing process, this will lead to efficient network architecture and more rapid error recovery.

Accommodation of Equipment and Environmental Heterogeneity

Computerised equipment for autonomous manufacturing, engineering design and office management may use their own specific languages, data structures and operating systems which may not be mutually compatible. Such problems of incompatibility can, in the main, be overcome by adopting a standardised layered network architecture, whereby individual computers can communicate to peer level counterparts in their own languages. To this end, the MAP/TOP seven-layer strategy seems the best solution in either a manufacturing or office environment, as has been mentioned in section 6.3.4.

Distributed Network Management and Control

From its inception, the objective of CIM is to unify the administrative, engineering, manufacturing processes, management and control functions of the integrated network which, of necessity, must be designed to support the distributed organisational structure within the company. Such a network should serve as the essential communication link for overall management of our integrated manufacturing process, whilst at the same time provide a degree of autonomy within local areas. The CIM network must, of necessity, continuously adapt to environmental changes resulting from: design modifications, reassignment of manufacturing processes, market demand, together with a host of other functions in a real-time sense. When attempting to provide timely communications between a large number of heterogeneous processes in a dynamic environment, the network management and control system must be aware of the status of all available resources over which decisions have to be made. Such decisions will include the efficient utilisation of resources of competing demand, together with: detection, isolation and recovery from failures – more will be said about this later. This can be partially achieved by incorporating human expertise into automated network management tools to provide: diagnosis, monitoring and dynamic adaption to failures, or planned changes in the CIM environment. The principal benefits of applying such artificial intelligence (AI) techniques to any network management control are the abilities to:

handle problems with ill-defined characteristics
assimilate/integrate information from a variety of heterogeneous sources

Conventional techniques such as the simulation experiments described in section 6.2.2, together with capturing program rules and heuristics would not be appropriate for knowledge and acquisition, unless sufficient expertise concerning network management had been developed. Under such circumstances, the "machine learning approach" – not relying upon heuristics – could probably provide the solutions to this problem. Yet another major concern to be considered is the security of the data, as networks provide electronic access to sensitive databases from remote modes. This problem cannot be over-emphasised when considering CIM network architectures; at all levels of information exchange, total security of data transfer must be achieved.

This completes our discussion about the networking requirements in CIM; it would have been easy to expand this section and look into current research activities in CIM networking, such as:

specification and analysis of network protocols
testing and standardisation of network protocols
lightwave and wireless communication
real-time communications, control and fault tolerance
network management and control

but this would necessitate considerable space and is, to some extent, outside the remit of the present text. In the following section we will consider the reasons why it is essential to have sophisticated condition monitoring techniques, to ensure that the plant is operating efficiently and that when faults occur, the type of error is speedily established and error recovery is quickly initiated.

6.4 Condition Monitoring of Untended Plant: FMC/S and CIM Installations

An unscheduled failure just for a stand-alone CNC machine tool can cause a loss of productivity averaging 11%. This problem is exacerbated as machines become integrated into an FMC/S; under such complex inter-relationships production losses can be up to 40%. When the theme of FMS was first introduced, extravagant claims were made for such systems and it is hardly surprising that experiences of failure bring them into disrepute, which may be the principal cause for the lack of installations in industry and discouragement of investment in these technologies. If industry is going to invest in integrated manufacturing systems across a wide area of application, then reliability and uptime must be improved. Let us now look at an advanced project associated with this topic, at present underway, by means of a case study to give the reader an appreciation of the general theme of machine monitoring.

In fact, a European "Esprit" project (504) has been running since the mid-1980s under the title "Development of fault tolerance in the control and management of a production system", with six companies involved. The multi-national companies include: AMTRI (Stewart Hughes Ltd) in the UK, Adersa (the French process control group), GRS (nuclear engineering specialists), the Technical High School in Darmstadt, Batelle Institute in Frankfurt and Ikerlan (the Spanish machine tool research centre). In December 1988 the £3.5 m "phase one" project was completed and this was followed by a more ambitious project (2349), with a budget of £7 m which is due for completion in 1992. Its "phase two" objectives were to build upon the hardware/

software techniques developed during "phase one", with particular reference to production environments within the automotive industry: namely improving the design of machines, acknowledging that faults cannot be completely eliminated, whilst attempting to improve the control and management of the plant.

One of the first tasks undertaken at "phase one", was a review of the trends in modern systems and determining how diagnostic monitoring might improve the plant in terms of availability, quality and reliability. The conclusion was that such performance monitoring as part of the overall real-time control structure of the plant will have a significant impact on its successful implementation and control. It became clear that in many instances of automated plant installations, little thought had been given to fault diagnostic concepts and when they were added, it was usually retrospectively and inadequately. The survey showed that integrated monitoring systems needed to consider the real-time status of all the plant: machine tools and associated equipment, the manufacturing process, together with raw material.

Therefore a major objective to control the machine operation was to use computer-based monitoring and diagnostics techniques, producing information which was fed around the control loop in such a manner that the system maintained control even under abnormal, or fault conditions. This concept was termed "fault tolerant control"

Fault Tolerant Control (FTC)

FTC conceptually means a system that is designed to tolerate faults and operates whilst these faults are being rectified. Such a system copes with abnormal conditions, by maintaining control whilst a recovery, or a shut-down program is implemented. FTC is related to adaptive control, depending upon a "bottom-up" application of advanced diagnostic monitoring to: machine tools, production processes and products. The speed at which the system collects/analyses the data required to maintain real-time control ranges from milliseconds, such as the case of tool breakages/collisions, to perhaps several days, when wear is detected in a machine tool gearbox.

This project's objective was to develop machine tools and methods necessary to build an FTC system suitable for use in a manufacturing plant, ranging from simply a stand-alone machine to a complex FMS facility. In order to achieve this level of control, it necessitated sophisticated data acquisition, analysis hardware and controlling software, in conjunction with sensors to support real-time process monitoring and in-process quality control.

First, a stand-alone experimental machine was used to determine the principles of fault diagnosis and computer "modelling" – highlighting the need to develop a fast, modular, multi-tasking computer for acquisition and analysis of real-time data and its synchronisation with the machine's operations. One of the major lessons learned from this stand-alone machine tool demonstrator, was the benefit to be gained from positioning sensors at the "heart" of the machine – hence the advantages gained from placing electrical transducer sensors at the hydrostatic oil spindle – providing direct tactile sensing signals. Secondly, a more ambitious demonstration was developed by Ikerlan in Spain – providing access to an existing FMC, comprised of a turning centre, machining centre, six-axis robot for loading/unloading tools and parts to the lathe, with an AGV providing palletised workpieces to the machining centre.

Initially, the principal task was a technical audit to define how the cell operated, establishing what sensors already existed, the failure modes in operation, communication used and how the cell was controlled. The FMC was activated upon the arrival of a workpiece blank, this being identified by a vision system which triggered the selection of programs, tools, robot grippers and other functions associated with this part's manufacture. The "host" computer had a database restricted to tool information, machine status, tool and billet positions, with very little in the way of fault recognition – this being confined to readily serviced items: blocked filters, malfunctioning switches, etc. In response to any error, the "host" simply shuts the machine down and in so doing severely limits the functional operation of the cell. Therefore a Data Acquisition and Analysis System (DAAS) computer was situated at each machine and interfaced with its controller and through the network to the "host". Software for interpreting fault conditions and planning the actions to correct them had to consider the viability of the machine tool's operating routine. Data needed to be collected only at the appropriate times relative to the machining program. As an example, vibration data collection was not taken during a heavy roughing cut, but under more steady-state machining conditions. This meant developing a new operating environment, which linked the software of the DAAS computer to the machine's operating programs – it is known that "synchronisation" is the key to success in diagnostic monitoring. This may be achieved by linking the DAAS computer to either the CNCs or PLCs, so that one can determine the context in which the machine is operating. Thus, it could be stopped, run, begin cutting, or activate a probing cycle, or similar, so that once we know the context of the machine's status, we can incorporate relevant monitoring. If, say, the spindle was running but not in cut then it might be more appropriate to monitor the spindle vibration data.

The DAAS computer runs a "mimic" of the part program in parallel with the actual programmed machining cycle and in this manner, keeps in step ensuring the correct acquisition and analysis of data. This technique permits a very fast reaction to data, indicating when a serious fault condition arises, such as that which is likely to cause tool/workpiece damage. At the machine level, the DAAS software generates indicators of the machine tool's health. Such indicators are interpreted using a ROM-based fast interpreter, taking the form of a simple "logic tree". Using "expert systems" at this level of monitoring/control, was considered appropriate for reasons of size and speed. The "logic trees" are defined by the manufacturing engineer and represent the logic progression from symptoms to identified error states and their associated actions, such as an unscheduled tool change, or operator intervention initiated by the DAAS through the controller link. Other indicators of the cell's status come from the "host" and for this higher level of interpretation an expert system is essential.

This cell's role as a demonstrator of condition monitoring is made operational by means of a simulated material requirements planning (MRP) work plant, with the FTC system integrated into the cell. In summary, this sophisticated FMC will always attempt to fulfil its production task, regardless of conditions. If faults develop, or are introduced, the cell will always attempt recovery by initiating action automatically, where they are within the scope of the control. When this is not possible, it will pass actions on in message form for defined manual intervention. Where recovery is not possible, the cell shuts down under control until such time as the fault is logged as being cleared and at such a time, it will initiate restart automatically and attempt to return to a normal schedule to achieve its original production goal. Where such a goal is no longer achievable, then it generates its "best target", making this information available to the MRP planner. During cell operation, the "host" maintains a graphical mimic of the status and prognosis based on the continuous interrogation of the database – manual intervention is also prompted from the "host" terminal.

Such condition monitoring sophistication is imperative in cells/systems, if a company is to benefit from high productivity, through the minimum of down-time due to error – recovery and maintenance scheduled/unscheduled within the plant. Efficient utilisation is the key element in a truly productive high capital cost plant, so that a company remains competitive, economic and flexible in their manufacturing demands against intense competition from rival manufacturers.

In the following section, we will consider just some of the monitoring systems necessary in order to obtain high quality parts and minimal scrappage, during untended or minimally manned production.

6.5 The Monitoring Systems Necessary for High Part Quality During Untended Machining

As one might expect when machine tools are utilised in the "stand-alone" condition, this invariably infers that an operator is present, whose prime task is to monitor the functions concerned with satisfactory part manufacture. In a typical production situation, the operator will be concerned that the tooling is performed satisfactorily, so will monitor the tools for:

identification
offset measurements
life
breakage detection

In a similar fashion, the operator will monitor/identify workpieces:

identifying the next part to be machined
set up fixturing and arrange clamping for the component
accurately locate the workpiece holding device on the maching tool
position the part in the correct relationship to the part program, by manually adjusting the workpiece, or program, accordingly – unless computerised workholding techniques are in use (see section 4.9).

Still other features require the operator's attention, including:

monitoring of the machine tool's cutting efficiency by sight and sound
part program adjustments, as the machine's operating temperature changes, e.g. from cold to its normal operating temperature
speed and feed adjustments, to optimise the best cutting conditions during the running of the part program

6.5.1 Untended Machine Tool Monitoring in an FMC/S

In an FMC/S environment, this implies that the plant is unmanned or, at worst, minimally manned machining occurs. The operator's absence for lengthy periods of time creates a considerable number of manufacturing problems that must be conquered if the machining system is to perform its production functions satisfactorily. These problems occur when attempting to monitor and service the operations normally associated with an experienced operator. Such tasks include monitoring the cutting tool's performance and condition, together with the other human-related

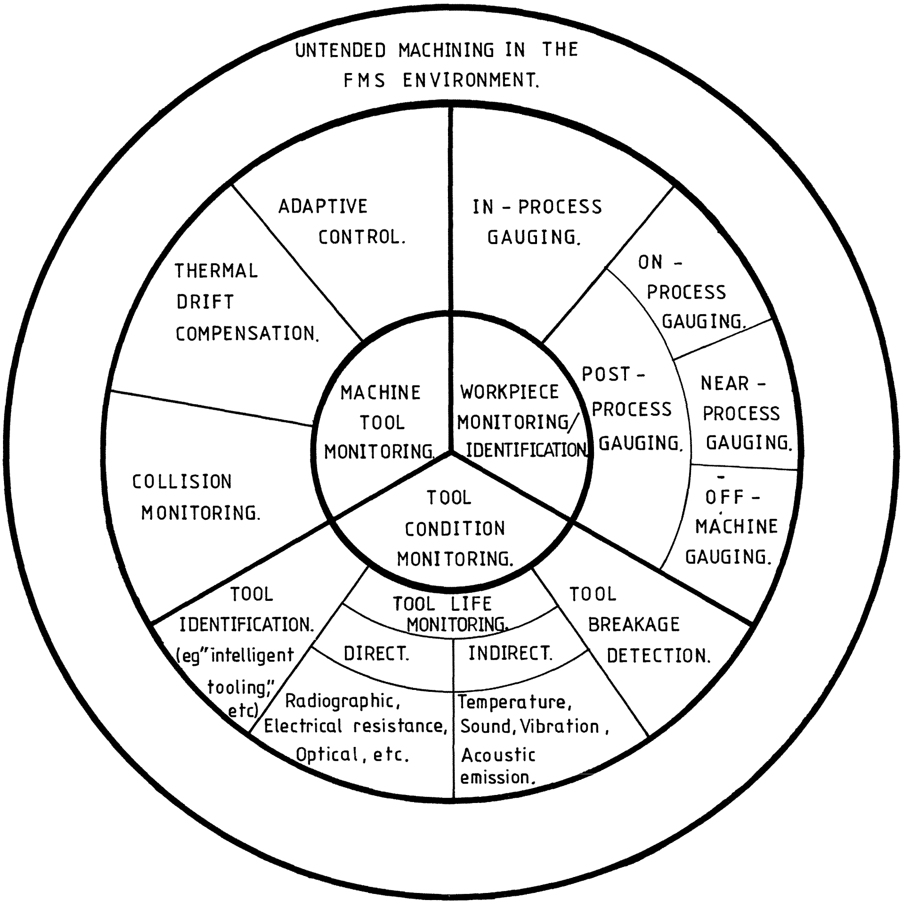


Fig. 6.10. The monitoring systems desirable for successful untended machining in the FMS environment.

tasks. Hence, in the unmanned condition normally associated with FMS plant, the monitoring system provides a degree of artificial intelligence (AI), necessary to mimic operator experience and to a lesser degree, provides instinctive reactions to changes in the plant running normally associated with human involvement.

A considerable array of monitoring systems is necessary to compensate for the lack of human presence on an FMC/S (see Fig. 6.10). In broad terms, they can be classified under three headings – with obvious sub-divisions as shown:

workpiece monitoring
machine tool monitoring
tool condition monitoring

Let us now look at each of these essential monitoring systems found in untended environments in a little more detail.

Workpiece Monitoring

In chapter 4 a review of workholding techniques was given and here we are primarily concerned with the automatic monitoring of the plant with respect to an FMC/S, although it is quite feasible to use such systems on minimally manned stand-alone machine tools. Essentially, workpiece monitoring is concerned with:

workpiece identification
automatic workpiece set-ups
workpiece gauging

The first requirement prior to machining the parts is to select them from the random mixture as they are either held on pallet stands/pools, or supplied via some other delivery system. With the variety of existing methods available for delivering the parts to the machine, the workpiece monitoring system must cope in an effective manner, such as radio transponders, bar coding, binary pins, etc., for say, machining centre palletised systems. Such indirect workpiece recognition – where the pallet is coded and it is assumed that the correct part/s will be held on this pallet's fixture – uniquely identifies it and calls up the desired part program in the CNC. Having identified the part and its associated part program, the component's orientation needs to be confirmed and this is established by the workpiece/holding monitoring system in the desired relationship and position to this part program. Whilst the machining operation is in progress there are several techniques available to assess part quality (see section 2.8.2):

in-process gauging – where information is gathered during the actual machining process – this is difficult to achieve in reality, owing to the practical problems of real-time measurement and control, so offers little potential, but in theory would seem an "ideal" technique

in-cycle gauging – commonly associated with turning and machining centres whether in "stand-alone" or cell form – using the popular touch-trigger probing techniques not only to assess the part quality between operations, but prior to this, to interrogate the fixture for accurate part alignment

near-machine post-process gauging – this technique has found particular favour on turning centre applications, where a receiver gauge is positioned adjacent to the machine tool and a part is automatically loaded and the established feed-back loop to the machine up-dates/corrects as the critical features being assessed change owing to either tool wear, thermal drift, or both. Such gauging equipment might be either contact (LVDT transducers) or non-contact (laser/light path systems), sampling at, say, 10% intervals to 100% inspection

off-machine gauging – using Coordinate Measuring Machines (CMM) coupled to a Statistical Process Control (SPC) package – allows a diverse range of parts to be inspected; alternatively, if short runs are the requirement, then greater flexibility can be accommodated, but at the expense of considerably slower part processing times

Yet another method (strictly speaking outside this discussion on untended monitoring, yet worthy of a mention) is the technique known as "deterministic metrology". This controversial method predicts and corrects for part errors based upon attempting to anticipate any machining errors in real-time and subsequently corrects them. This philosophy assumes that we will always try to cut a good part and as such, eliminates the need for further inspection. Thus a detailed mathematical model is developed in which the error-producing parameters – effects/interactions of machining – are accurately described.

Machine Tool Monitoring

If we ignore the diagnostic sensing devices used in determining the machine's health (previously alluded to in section 6.4) and concentrate on the protection that can be offered to the machine tool as a result of either variations occurring whilst cutting, temperature and protecting against collisions, then three monitoring devices seem necessary:

$\left.\begin{array}{l}\text{adaptive control}\\ \text{collision monitoring}\end{array}\right\}$ both having been described in section 2.8.1
thermal drift compensation

If we ignore both adaptive control and collision monitoring systems here as they have been dealt with adequately elsewhere (see section 2.8.1) – and concentrate on the latter system of thermal drift compensation, we will gain an appreciation of some of the problems associated with the influence of ambient temperature changes, the variations caused by the machine tool's structural modifications promoted by differential temperature effects and how they influence the part quality.

Whenever a machine tool is used as part of an FMC/S, or in "stand-alone" mode, and subjected to variable conditions of usage at or near its process capability (i.e. "for stable manufacturing process, it is the capacity to reach a certain level of quality" e.g. $C_p < 1.33$) which frequently is the case of late in precision engineering companies, then an uncompensated machine tool is likely to produce some scrap components. Simply, the rise in ambient temperature in the shop plays a significant role in causing the machine's structural elements to move. It has often been the case that the author has visited a company during the heat of the summer and found the ambient room temperature in excess of 30 °C around midday, with this problem being compounded by the fact that direct sunlight is present, further exacerbating the local temperature on the machine tool. In many manufacturing companies with such fluctuating temperature conditions, it seems impossible to maintain a consistent part dimensional quality. Even when the temperature within the workshop is stable and an air-conditioned environment exists, irregular usage of the plant causes differential temperature effects to influence the machine's structure and induce part variations at high relative precision indexes (i.e. $C_p < 1.33$). What often makes matters worse is that the machine tool's calibration – using laser interferometers, or similar methods, probably either occurred some months ago at best, or was undertaken when the machine was cold. Recently, a ball-bar system has become available to obtain a quick check for both turning and machining centres and to a lesser degree, CMMs within the precision manufacturing facility, allowing for speedy and efficient daily re-calibration of a range of geometric and linear features within the volumetric envelope of the machine tool.

Returning to the theme of differential temperature effects produced by irregular usage, typically a turning centre headstock can grow owing to a temperature increase in the bearings/motors by 20 °C. This problem can be minimised by the machine tool builder, with careful design of the structure and incorporating "heat sinks" at "hot spots", controlling thermal growth uniformly at the centreline and away from the spindle nose. However, a more significant thermal problem arises in the differential growth in the ballscrews – often of less temperature magnitude (4 °C) but this affects the positioning accuracy of the machine – particularly for indirect feedback closed-loop monitoring systems (i.e. with rotary encoder/motor designs). On the "C-type" frame typically found on vertical machining centres, the problem of thermal growth on the larger column machines can cause dimensional variations, and thermal sensors are often positioned in the bed, throat (column) and head of the machine tool. In order to obtain a degree of uniformity in controlling the thermal growth, the machine is run in hot/cold and intermittent conditions and plotted values are obtained for each thermal sensor, with software controlling and compensating the machine tool continuously in the X, Y and Z axes. Therefore by the judicious use of thermal sensors positioned at strategic points around the machine's structure, coupled to customised compensation software, it is possible to minimise the effects of thermal growth.

Tool Condition Monitoring

Previously we reviewed the range of monitoring systems used for tool:

$$\left.\begin{array}{l}\text{identification}\\ \text{life monitoring}\\ \text{breakage detection}\end{array}\right\}\text{ in section 2.8.1}$$

As we can see from Fig. 6.10, there is a range of monitoring techniques for controlling either the tool management functions of tool tracking, identification, life monitoring and breakage detection, with the express aim of optimising the tool's efficiency both in and out of cut. So, by utilising "intelligent" tooling, discrete data items can be stored on embedded capsules on each tool holder and a range of cutting data can be transferred back-and-forth to the controller/toolholder – in the case of read/write microchip systems – this improves the cutting tool optimisation. Incorporating adaptive control sensing devices – whether of the torque-controlled (TCM), or acoustic emission (AE) varieties – will offer significant improvements in cutting potential over those machines without such monitoring. For example, with TCM, as the main spindle is protected from overload, this in turn prevents damage to either the workpiece, or cutter. As the level of monitoring sensitivity is increased, this has the additional benefits of obtaining optimal stock removal rates under steady-state conditions and utilising a constant cutting power with the cutting/feed forces.

Tool life is improved and the fastest possible feedrate is selected at all times, without over-shooting of power during machining operations. Even more sensitive to minute cutting force/power fluctuations are the acoustic emission (AE) systems, but as they monitor the elastic stress waves created during cutting they are more difficult to isolate from the machine's "noise", particularly when light cutting conditions such as finish machining operations occur.

Much more detail appears in chapter 2 on tool condition monitoring systems with adequate descriptions of how tool identification, life monitoring and breakage detection are achieved along with the benefits to be gained from such tool/workpiece protection. In the following section we look at just some of the problems that must be overcome when considering the factors that affect part quality in an FMC/S, with particular relevance to the machining centre.

6.5.2 An Overview of the Features Affecting Part Quality in an FMC/S

Regardless of the machine tool that is used for the manufacture of a component, the most important criterion is "will it repeatedly produce a part of satisfactory quality?".

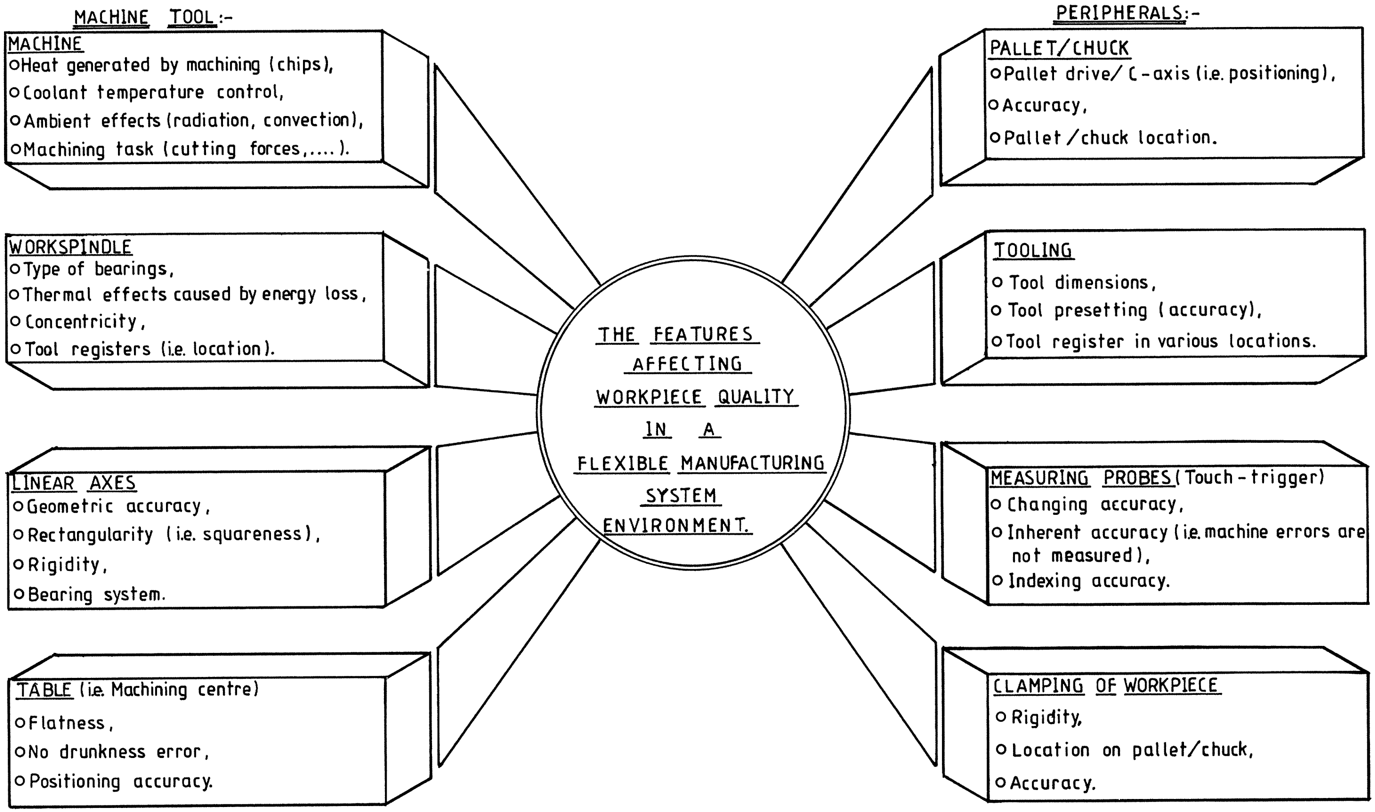


Fig. 6.11. The part quality produced by an FMS depends on the machine tools and peripherals. [Courtesy of Scharmann Machine Ltd.]

There are a number of closely allied factors that influence our ability to manufacture parts, most of which are depicted in Fig. 6.11, in this instance for a machining centre. If we consider the two basic hardware groups, they can be further subdivided as follows:

machine tool:
- machine
- work spindle
- linear axes
- table

peripherals:
- pallet/chuck
- tooling
- measuring probes (touch-trigger)
- clamping of workpiece

Let us now briefly review each of the above in turn beginning with the "machine"

Machine Tool

Machine. On a machining centre, or for that matter any machine tool where large stock removal rates are currently being undertaken, the volume of hot swarf generated must be quickly and efficiently removed from the working envelope and flushed into the swarf conveyor. If swarf is allowed to build up in the cutting vicinity then the hot tempered chips will cause a degree of thermal growth to the machine's structure, locally modifying and distorting the structure, which in turn affects the dimensional characteristics of the part. The same can also be said about coolant temperature control and on many of the larger installations, oil coolers and greater volumes of coolant are used to minimise the heat induced into the coolant during cutting. If this were not the case, then warm coolant during a machining operation might have a significant effect on expansion of the workpiece during its manufacture. As we have seen in section 6.5.1, the ambient room temperature and its fluctuation during the working day can play a role in influencing dimensional characteristics of the part. Yet another influential feature – but this time not a temperature induced one – is how the cutting forces generated can either distort the part, cutter, or both, during machining at high accuracy, particularly where workpiece/cutter rigidity is suspect.

Workspindle. The workspindle's accuracy plays a crucial role in the forming/generating machining tasks employed in the manufacture of parts. Bearings should be designed to allow for thermal growth and alignment modifications during the machine tool's working life. Rigidity must be maintained with bearing wear kept to a minimum and machine tool builders expend considerable effort ensuring that concentricity and alignment are controlled by sophisticated design, lubrication and cooling – often using refrigerated spindles, or heat absorbent materials (heat sinks) at strategic positions around the spindle. However, spindles are not of much use if the tool's location in it is of a small contact region and the tool's adaptor has insufficient register in the taper. As one might expect, the general rule in machine tool building is, the larger the machine the greater its spindle taper. This ensures that with the greater forces generated in larger machine tools during cutting, the spindle nose taper is of sufficient size to accommodate the cutter body whilst machining occurs.

Linear Axis. As with any metrological equipment, machine tools are designed around kinematic motions of translation/rotation, but with extra emphasis upon restraint and location of the moving elements – slideways. The geometric accuracies of one axis with respect to another are crucial when designing a machine tool, as they have a direct effect on the subsequent part quality. A number of geometric features need to be considered by the "builder" – not least of which is the positioning and rigidity of the ways. As moving elements must respond to the motor drive commands issued by the CNC part program during the manufacture of the part, then low-friction rigid and well-spaced ways ensure the smooth transmission of motion. Such geometric features that the construction must account for are:

squareness of the axes with respect to one another
straightness of ways
parallelism of way guides
flatness
other geometric influences: "yaw, pitch and roll" tend to be, in the main, concerned with the moving element upon these ways, as does "backlash" in the ballscrew assembly

Table. Many engineers concerned with the manufacture of components on machine tools rarely consider the fact that even with a new machine the table is not flat. This does not become a problem worthy of consideration unless a company needs to be manufacturing at the highest levels of precision of the machine tool (C_p 1.33). At high relative precision not only is a machining centre table not flat, but as it moves along the ways, either locally or traversing its full axis length, it is subjected to "yaw, pitch and roll". The "yaw" occurs owing to the "crabbing effect" (i.e. sideways movement) in the main, resulting from the positioning of the ballscrew with respect to the ways and any lateral movement within the ways. "Pitch" is present owing to the undulations occurring in the ways, causing the table to rock back-and-forwards as it moves along ways. "Roll" is the twisting motion as the table moves along the ways. Returning to the flatness, it is a well-known fact that once the table has been calibrated – using either the "grid", or "Union Jack" technique – a region of relative flatness normally occurs and this is euphemistically termed "sweet spot" where higher accuracy machining can be achieved. It is worth stating that all the errors described herein will be present on any machine tool to a greater or lesser degree and their influence on part quality can be minimised by calibrating them out – incorporating compensated values into CNC software to override such errors. Lastly, regarding the machine tool's structural elements, we can improve the positional accuracy of the table, or any moving element by using linear direct-feedback scales for each axis. Not only does this minimise "backlash", but improves part quality as it is less influenced by "ballscrew windup" during cutting operations.

Peripherals

Pallet/Chuck. On a vertical machining centre, in particular, when the rotary table for pallets is incorporated the C-axis positioning accuracy will influence the prismatic angularity of the part features. Often a Hirth-coupling is used for location and positional accuracy is achieved through a rotary encoder. Pallet accuracy of the location on the table and working surface must be of a high order, so that when auxiliary workholding equipment is added – chuck, cube, tombstone – the extra height does not induce an accumulated angular or squareness error in situ.

Tooling. As we have seen earlier in the book, tooling can be classified under three headings: "qualified", "semi-qualified" and "unqualified". With "qualified" tooling we know all about its pertinent dimensions: length and diameter in the case of a new slot/endmill, whereas in "semi-qualified" tooling, we would simply know the drill's diameter with any surety. It follows that "unqualified" tooling is unique and as such, no true dimensional data is known. The point should also be made that at very high accuracy even new "qualified" tooling is made to certain high limits of precision and some companies (e.g. aerospace/optical) regrind their cutters to higher accuracy as a matter of course. Tool presetting plays a vital role in accurately building and setting up tool kits and on milling cutters, if each insert's setting in their respective location pockets is not achieved, then this can influence both the cutting behaviour and the subsequent dimensional characteristics of the workpiece.

Measuring Probes (Touch-Trigger). When in-cycle gauging of critical features is required in an FMC/S environment, the company often relies upon the "probing" accuracy on the machine tool, rather than using up valuable WIP time elsewhere: such is the case when a coordinate measuring machine, or receiver gauge is used. On machining centres the touch-trigger probe is held in the tool magazine and loaded into the spindle nose taper whenever it is decided to assess critical features. This may promote errors into the measurement cycle, as will the machine tool's inherent geometric inaccuracies, although in general they are of the order of micrometres – which may/may not be significant depending upon the level of accuracy demanded.

Clamping of Workpiece. As we have seen in Fig. 4.2 for workholding on turning centres and again, in Fig. 4.16 for machining centre workholding, the higher accuracy parts occur when using dedicated chucks, or fixtures. The major reason for this is their inherently higher accuracy of manufacture coupled with greater rigidity, which means that workpieces can be located in the required position more accurately and less flexure of the fixturing occurs – at the expense, of course, of more flexibility in accommodating differing part geometries.

As we can appreciate, there are a considerable number of mitigating errors that concern us when manufacturing parts either in a "stand-alone" or "system" mode. Each in itself is not too great a problem, but the significance magnifies as one approaches the process capability of the plant, where a compounding effect can present real problems during the part's manufacture.

6.6 Automated Auxiliary Equipment Necessary to Ensure Accurate Quality Assurance in an FMC/S Facility

Automatic Wash Station

Most of the larger "prismatic" machining and "rotational" cells used in industry today have some form of automatic part handling/transfer system incorporated within the facility. Normally, such plant is of high value and accuracy and, as such, many companies feel that using up in-cycle time assessing part quality is something of a waste of valuable productive capability. These companies recognising this point use an integrated and flexible metrology facility on line to assess the occasional preplanned part as deemed necessary by the host computer. Such a flexible metrological facility is a coordinate measuring machine (CMM). However, problems can arise when one tries to deliver this part to be measured straight after the completion of machining. The major problem is residual swarf and coolant adhering to the intricate and inaccessible features, or within the component. So, this usually means that an intermediate cleaning process is necessary, prior to inspection. Obviously, one would not want to manually clean each and every component destined to be inspected, as this would be labour intensive and boring, and not cost effective. Therefore, it is usual to include an automated cleaning facility within the system.

A typical washing station has an AGV loaded double pallet "paddle wheel" cleaning facility controlled through a DNC link to the "host" computer and it is possible to run a range of washing strategies – with any changes in these strategies being effected via a terminal in, for example, the control room. A number of washing/drying strategies can be utilised, such as:

number of paddle wheel stopping positions
paddle wheel position – angle unit
dwell in washing position – seconds
dripping time – seconds
washing time – seconds
blowing time – seconds

As an alternative, a six-axis robot equipped with high-pressure wash/degrease facilities – suitably protected and fully guarded – has proved well up to the task of cleaning components automatically, albeit an expensive but highly flexible solution to the problem.

Once the part has been thoroughly washed and dried, it is in an acceptable state to be loaded onto a CMM for automatic inspection.

An Integrated Coordinate Measuring Machine (CMM)

In the highly productive and flexible manufacturing environment found on FMC/S plant, it is essential to be able to automatically inspect parts on a specified basis, e.g. 5%–100% capability. This means that in a large-scale FMS a washing station should be incorporated prior to inspection of the parts. An AGV can load and unload parts to the CMM via the double-pallet buffer. The CMM with its integral computer is coupled to the "host" via a communications interface. This allows the "host" computer to instigate process strategies appropriate for the parts to be inspected. It also has the ability to inform the CMM as to what measurements are to be undertaken, with this information being based upon statistics previously achieved by measuring results.

If an inspected part exceeds its predefined limits, the "host" receives a feed-back message and the computer then passes this information to the storage/transfer system, making sure that the rejected component is precisely recorded. An operator at the setup station is in the position to make a decision on whether to reject the component, or send it for future re-working.

If such equipment is incorporated from the original feasibility study plan, then it can be an economic method of both cleaning and inspecting parts, without undue delays in work-in-progress (WIP). However, it is essential that when producing our planned integrated FMC/S, such equipment is specified, otherwise undue bottlenecks

Fig. 6.12. One of the most modern factories in Europe, in Worcester, England. A fully integrated CIM facility, producing 100 machines/month by 240 staff on 14.5 acres. [Courtesy of Yamazaki Mazak Ltd.]

in production will arise, upsetting the harmonious flow of production necessary in untended, or minimally manned plant.

The following computer-integrated manufacturing facility has been included as a look at the latest trends in advanced manufacture, whilst giving the reader an appreciation of the type and level of sophistication in an automated factory engaged ironically, in the manufacture of both turning and machining centres – the theme of this book.

6.7 Computer Integrated Manufacture (CIM) in the Automated Factory – a Case Study

It is arguable that the Yamazaki Mazak factory at Worcester, England is the most advanced in Europe. The factory began production in mid-1987 and is based upon Flexible Manufacturing Systems concepts of which it had previous knowledge from several sites outside of Japan, although the original site at Oguchi in Japan was developed some years previously. The UK was chosen because of its English-speaking advantage and the idea of building the factory at the birthplace of the industrial revolution appealed to Mr Teruyki Yamazaki – son of the founder. A green-field site was chosen for the factory (Fig. 6.12) on a 14.5 acre site, with an initial building area of 16 500 square metres. The whole complex was designed to be controlled as a highly advanced CIM system, that is, complete production control ensuring that manufacture is achieved in an optimum time, with minimum inventory. When the site was initially commissioned in 1986, it cost £35 m to build and it was designed to manufacture a range of turning and machining centres – with their own machine tools used to manufacture them. The complete factory has been laid out as a giant shop window, so that visitors (around 3000 per year) can see how the machine tools function within the factory and how the parts are made, tested and assembled.

The plant runs an MRP II system called "Magnet", originally written in Cobol for use in Japan, but heavily modified for the UK factory. The system operates at three distinct levels – using a different computer at each level – for scheduling, process control and specific machine control. An IBM mainframe computer processes any orders entered by the sales department into a sequence of operations involving the purchase of required components and the insertion of the individual order into the master schedule. Twice per day information updates are received from the factory floor and the computer is able to monitor the arrival of the required components and initiate the machining process. It receives data on current progress, distributing instructions based upon product mix optimisation going through the plant via a PC linked to three operational DEC Micro Vax computers – with each Micro Vax having a separate area of responsibility. One is used primarily to control the automatic warehouse, together with movements of four AGVs. A second channels instructions to the three CNC automated machining lines, whilst the third is dedicated to tool management, creating life-cycle maintenance for each tool and scheduling automatic replacements.

The machining activities run as a CIM system with automated delivery to the various machine tool lines from banks of pallets, which have the ability to continue working unmanned for the night shift in a "lights-out' situation. However, it is still cost effective to have a degree of manual operation when painting and welding, and for final assembly, owing to the relatively small volume of work undertaken during such activities. The "host" computer informs the MicroVax responsible for the machining lines when work is to be processed on a particular line, with its respective pallet being delivered to a specific machine according to the dictates of the master schedule. Whilst this is being initiated, the part program is called-up and downloaded to this machine tool, the software being written in Fortran, ready for the machining cycle to commence, once the previous part has been completed. As we have seen in the previous chapter, the part program prescribes not only the cutting sequences and effects the necessary tool changes, it also programs and monitors the feed and speed requirements of the cutting tools to ensure a standard and repeatable performance. It is worth pausing here to discuss the Japanese philosophy to manufacturing, alluded to earlier. They are not concerned with running cycle times at the theoretical 100% efficiency, but more interested in obtaining a longer and more predictable tool life, less stress on the machine tool, fixture and part, whilst enhancing part quality by cutting at around 80% of the capacity. This differs from the manufacturing philosophies adopted by both European and American companies in general and one might wonder how they can achieve such an efficient production throughput? The answer is by exceptional attention to the organisational elements of plant layout, work-in-progress, just-in-time/Kanban philosophies in practice, in a realistic manufacturing environment – this is where the real savings are made. Furthermore, the allocation of discrete functions to different computers working on various levels is the key to a successful CIM implementation, with the old adage to "keep it simple".

Yet another advantage of utilising the CIM strategy using the FMS philosophy is that machine tool building requirements are inherently cyclical in nature – often a high attrition rate occurs where customers might collectively decide to cancel, or postpone new capital goods purchases as recession pressures affect potential orders – allowing the machine tool builder to minimise such unforeseen circumstances. Similarly, CIM strategies can cater for demand peaks, which would otherwise create major problems both in terms of delivery on time and maintaining quality. Thus, using the CIM

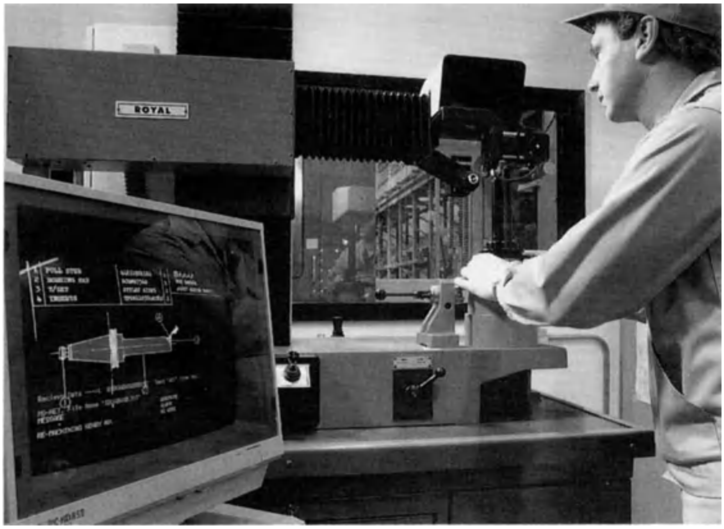


Fig. 6.13. The tool presetting area with on-line tool management/monitoring. [Courtesy of Yamazaki Mazak Ltd.]

approach limits the cyclical consequences of sharp contractions and expansions, by taking advantage of its inherent greater flexibility. Furthermore, as the significant proportion of value-added costs are created by the machinery rather than the labour force, problems of labour shortages, or redundancies are reduced – machines can easily be stopped, or started, without incurring additional costs. However, a more significant benefit is that production lead times can be slashed from the "industry average" of about six months to around eight weeks.

It is essential to maintain short lead times on such an automated facility, as they enable the factory's production schedule to be adjusted with considerable accuracy every month. This point encourages the customer to request the non-standard features – at higher cost – without incurring any additional delays, ensuring that there is no costly and extensive stockpiling of expensive bought-in components.

Prior to a "pictorial tour' around the manufacturing facilities at the Worcester plant, it is worth stating that up to 73% of these machine tools are sourced from European companies, with only the CNC and servo motors coming directly from Japan. Of the total workforce of around 200, about 60 are office and sales staff – with around 15 Japanese workers included in this overall number of employees. The proposed machine tool output is set to rise to about 100 (maximum) machines per month – this being a mixture of a range of turning and machining centres.

Finally, with regard to the working practices within the factory, all employees wear a standard issue overall and the company runs an apprenticeship scheme providing continuity of skills within the plant. Even the managing director must "clock in" using computerised bar-code readers, and all staff have staff status, monthly pay cheques, life insurance/private pension and health-care plans. All employees work a 40 hour week, with the shift workers receiving an additional unsocial hours' allowance, with overtime available to the staff. Not only are the manufacturing facilities clean, bright and exceptionally well laid out, there are some "novel touches" in that visitors can view the whole of the manufacturing facility from an elevated walk-way, running around the factory, but a large range of machines is always on display in the showroom. Just adjacent to the showroom, is a large expansive coffee lounge and informal meeting place, overlooking a traditional Japanese garden. Formal teaching and conference facilities are also present in this vicinity, with specialist engineering and sales staff in attendance at all times, to answer customer enquiries.

This gives the reader an overview of the facility at the Yamazaki Mazak, Worcester, plant; let us now discuss the factory in more detail.

6.7.1 The Layout of the CIM Factory

The manufacturing plant consists of discrete areas such as:

tool presetting and management facility, with automatic tool distribution highway
workpiece fixturing/palletisation
small prismatic line
large prismatic line
rotational parts line
automatic warehouse and delivery systems
sheet metal working and painting
quality control and superfinishing
clean room for precision sub-assembly
final machine tool assembly

Tool Presetting and Management Facility, with Automatic Tool Distribution Highway

A strategically positioned tool presetting facility beside the overhead distribution highway (Fig. 6.13) allows for tooling requirements to be administered via a MicroVax which is on-line to the "host". It organises the entire range of tool management activities including tool offsets, life and replenishment. When present tooling is required the setter has visual confirmation of the tool-build requirement (Fig. 6.13) highlighting the parts necessary and the offsets to be present for the respective cutting edge/s. All tooling is thus "qualified" on the tool presetter and placed into a known position in the "tool hive" pocket, ready for the overhead tool delivery robot to replenish the respective machine tool on demand. When the unmanned night shift arrives, a stock of previously stored preset tooling is buffered in their designated pockets in the "tool hive". This caters for any "sister tooling" – duplicate tools at the end of their tool life – to be replaced in the machine's tool magazine at the appropriate time and in so doing, increasing the tooling capacity to almost infinite lengths, ensuring that tooling is always available. At the end of the night's machining, when the day shift arrives, a stock of worn tools is buffered in identifiable pockets in the "tool hive" and they are broken down and rebuilt as required by the tool management software requirements – in line with production demand.

Obviously, such a complex set of tasks as tool replenishment, distribution and service, across the large tooling library necessary in the FMS lines, needs to be identified by a suitable tool tracking technique. Therefore, each tool holder has an embedded microchip capsule positioned in the end of the pull stud. This microchip carries the information (see section 2.7 on "intelligent/tagged" tooling concepts) allowing each tool to be identified and tracked around the system and continuously updating the tool life data whilst in-cut by the tool management computer.

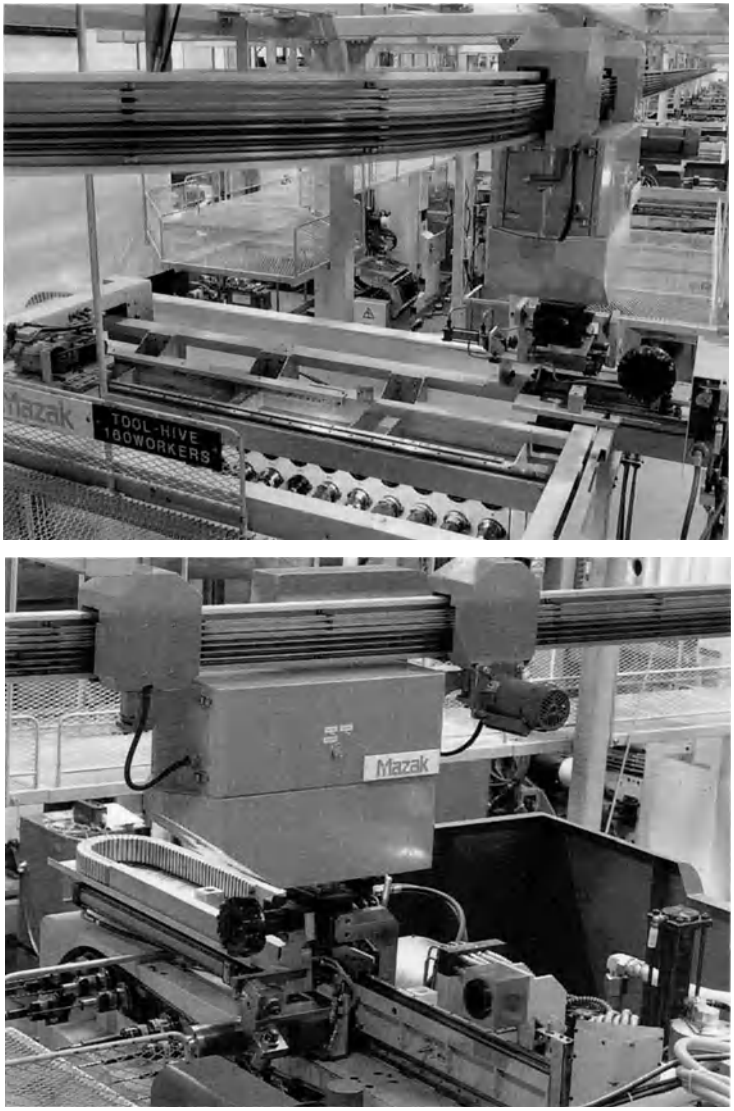


Fig. 6.14. Preset tools are automatically distributed along the U-shaped overhead monorail termed a "tool highway". [Courtesy of Yamazaki Mazak Ltd.]

When the preset life of a tool has been reached, or a new tooling library is needed on one of the machine tools, the tool robot will pick up a replacement from the buffer "tool hive" and transport it to the machine which will unload/load the old/new tool respectively (see Fig. 6.14). This tool highway straddles over both the small and large prismatic lines and is a U-shaped monorail, connected to the tool presetting facility by the adjacent "tool hive". When preset tools are required they are identified by the tool management software on the CPU for selection and delivery via the distribution highway. The highway distributes the tooling demands to the respective machine tools using a random access order and in so doing, optimises its travel along both the highway arms to the respective machining lines. Speed of delivery is not an essential requirement here, as efficient utilisation of resources is all that is needed.

Workpiece Fixturing Palletisation

If all one had to do was load/unload preset "qualified" tooling into the machine tools in their respective FMS lines, then the demands on the micro-computer would be quite small. However, not only must the cutting tools be tracked, assembled/broken down and cutting data determination managed as part of the overall tool management function, but the workpieces require similar attention. This is necessary to ensure that at all times codified pallets can be similarly built up and buffered onto pallet stands, awaiting either return to the pallet assembly area after machining, stored for further machining, or simply awaiting delivery to a machine tool. In Fig. 6.15, we can see an operator accessing information about a pallet build assembly. The isometric assembly mimic present on the screen, informs the operator not only how to assemble the workpiece on the pallet in this visual display, but identifies all the equipment necessary to assemble the fixture and which part should be used, whilst simultaneously noting/storing the pallet's code in the computer.

This workpiece palletisation is undertaken for both the large and small prismatic lines and in an adjacent area an automated palletised facility was built, for some unmanned pallet assembly operations. However, this is still at the proto-type stage of development and may/may not be brought on-line, depending upon the production pressure in the future and it is expected that up to 30% of components could be fixtured in such a manner.

Small Prismatic Line

As mentioned previously, the tool highway serves to load and unload cutting tools, on demand, to these machining centres, whilst palletised workpieces are delivered by a "stacking" RGV to any of the machine tools. This FMS line consists of seven horizontal machining centres of 800 mm pallet size, each equipped with an 80 tool magazine (see Fig. 6.14 for a restricted overhead view of the line). These machines are used, in the main, for the machining of the gearbox components, etc., and are fed components – mainly castings – by two auto-stacking cranes (RGVs) from the two-tier buffer pallet pool running the length of the track. In this manner, a 150 pallet stocker is located beside the RGV rail, with further buffering for 70 pallets, often used during the "lights-out" night shift. Toward the end of this small prismatic line is positioned an automatic wash station where the palletised parts are washed and then transported to a CMM for automatic inspection of critical features as necessary, with feedback of information to and from the "host". In fact, so accurate have the machines in the various FMS lines proved to be that the touch-trigger probing in-cycle has proved, in most cases, to be more than adequate. Probing is used not only for offset updates within the machines, but also for interrogation of the palletised workpieces, undertaken to exactly align the part with respect to the program before machining commences – a desirable check to ensure that dimensional quality is maintained. After machining the pallets are replaced in either the main pallet stocker, or loaded into the buffered stocker.

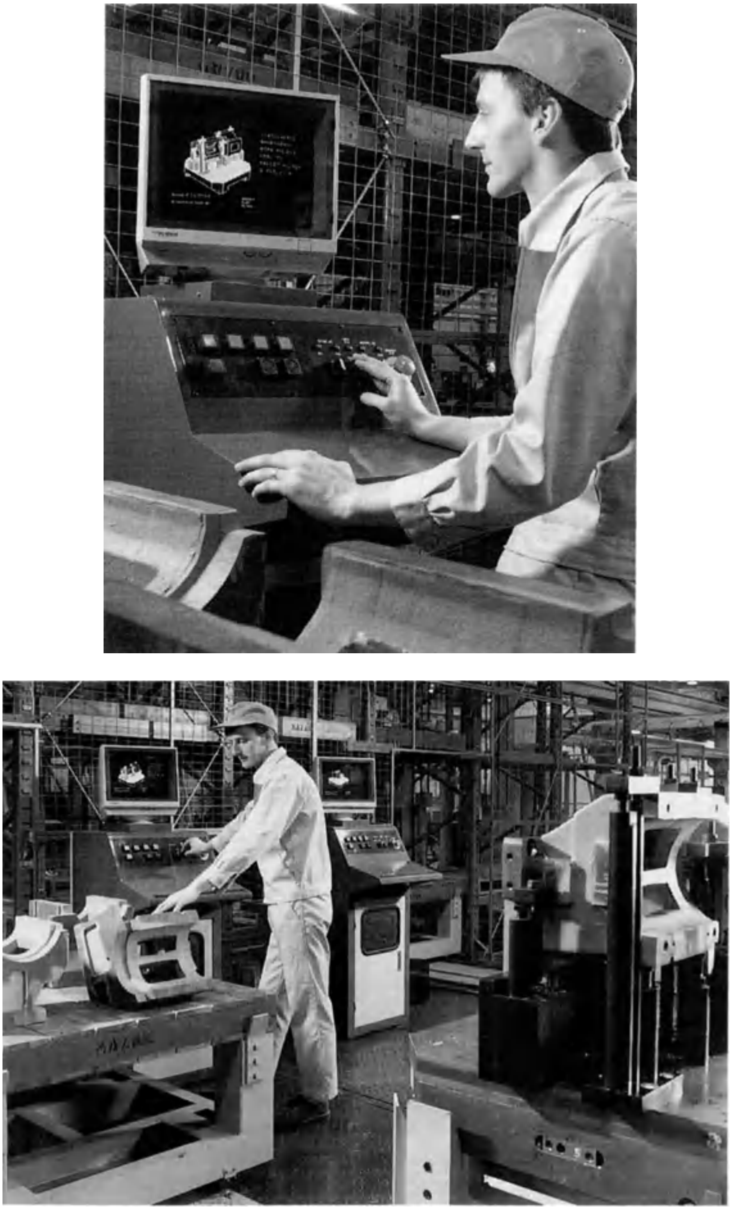


Fig. 6.15. Fixtures are scheduled by the host computer and all of its assembly details are displayed on the screen, allowing the assembler to speedily and accurately build up the part on its fixture. [Courtesy of Yamazaki Mazak Ltd.]

It is worth making the point that each machine tool has in situ a range of condition monitoring equipment: tool breakage/collision devices, tool life monitoring and adaptive control features ensuring that the cutting process is fully monitored during the part/s manufacture.

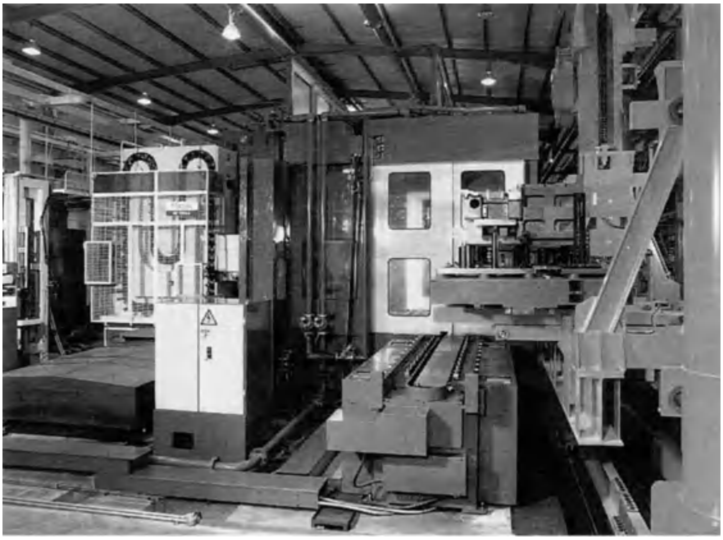


Fig. 6.16. The large prismatic machining line, consisting of travelling column machining centres (three). Pallets are transferred by rail-guided vehicle with "coded" programmable microchip pallet identification. [Courtesy of Yamazaki Mazak Ltd.]

Large Prismatic Line

This FMS line consists of three travelling column horizontal machining centres, with rectangular pallets 3500 mm long by 1600 mm wide. An 80 tool magazine is attached to each machine tool and old/new cutting tools are delivered by the other "arm" of the tool highway – both the small and large FMS lines run parallel to each other. A single auto-stacking crane runs as an RGV, alongside each machining centre and pallets are loaded from a 36 tiered pallet pool (see Fig. 6.16). At the end of this FMS line a large bedway grinder is positioned, and after machining the ways on the castings they can be ground with the minimum of work transportation.

Pallet identification is operated in the same manner as on the small prismatic FMS line, using programmable micro-chip coding systems on each pallet for appropriate identification of workpieces. If, for any reason, a machine tool is taken out of service – for essential/planned maintenance – the "host" tells its respective MicroVax to reschedule the work destined for this machine to a duplicate machine in the line, with the minimum of disruption to the production schedule, and in this manner, unanticipated or undesired breaks in manufacturing capacity are minimised. Only when manufacturing systems are designed around "rigidly flexible" strategies can they hope to gain some measure of efficiency.

As one might expect with such a large metal cutting facility, the disposal of swarf and coolant control requires particular attention to detail. In fact, a shared underground coolant and chip system was developed carrying 30 tonnes of coolant, with the capacity to handle and dispose of 20 tonnes of swarf per day. This underfloor coolant/chip disposal system carries the used coolant to a collection tank where the swarf is separated and automatically transported outside the building for collection.

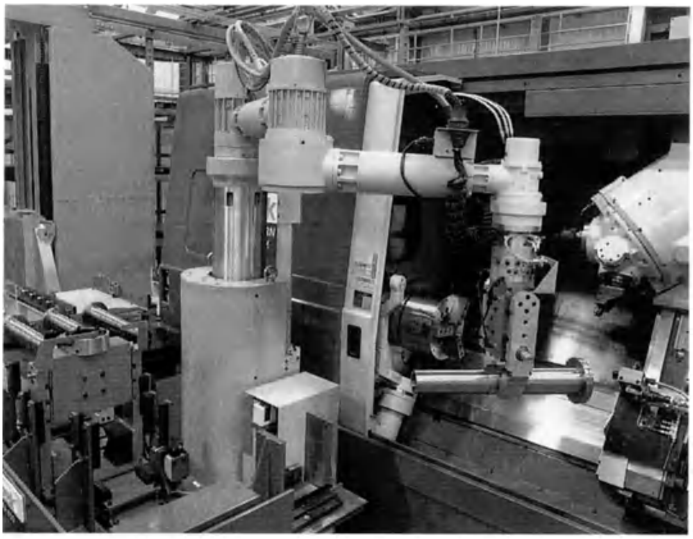


Fig. 6.17. The rotational parts line, consisting of three "mill-centres" fed by robots from stacked pallets. NB: Chucks have an automatic jaw changing facility. [Courtesy of Yamazaki Mazak Ltd.]

Rotational Parts Line

The rotational parts line is somewhat of a misnomer, in that on such machines it is possible to not only turn features, but mill, drill, cut splines, etc., by utilising a fully programmable C-axis and driven tooling. The line consists of three "mill-centre lathes" (turning centres) each with an 80 tool magazine, because a turret has a smaller tooling capacity. A fully programmable robot is situated next to each machine tool and can load parts from a 60 pallet stacking crane RGV (see Fig. 6.17). A novel feature of these turning centres is their ability to automatically change jaws to accommodate a range of part sizes and features. Jaw-changing is achieved by indexing the chuck to the change position and from a position above the headstock, jaws are unloaded and loaded by sliding the jaws out and then indexing the chuck to the jaw-change position. This automated facility increases the versatility of these turning centres considerably, allowing untended turning operations to be continued across a large range of part diameters/geometric features.

Tool presetting and calibration are achieved by utilising the "tool eye" situated on the machine and an automatic recalibration can be programmed when necessary; sister tooling is used so that either when the number of prescribed parts has been machined, or if tool wear has reached a predefined limit, the tool is changed.

This virtually completes our review of the metal-cutting capabilities within the factory, but it is worth stating that apart from a few grinding machines on the shop floor (where, incidentally, the overall temperature throughout the machining/assembly areas is maintained at $\pm 2\frac{1}{2}$°C) there is the jig-boring and super finishing area yet to be described.

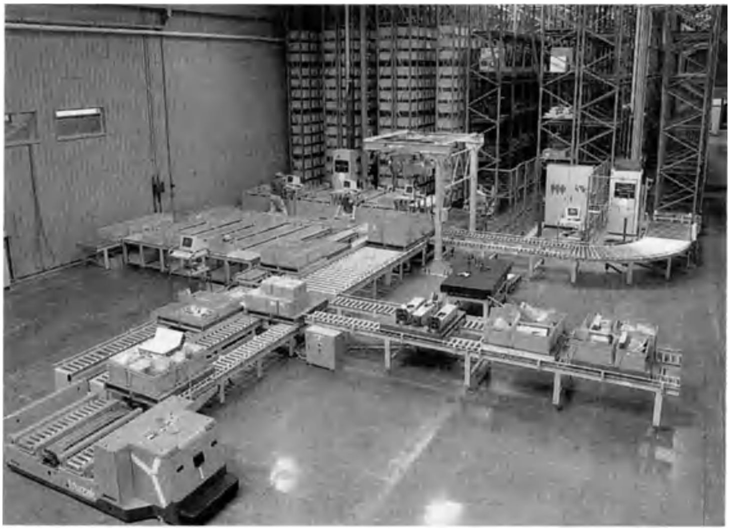


Fig. 6.18. The automatic warehouse under the "host's" control, with two AGVs to distribute parts to assembly areas. [Courtesy of Yamazaki Mazak Ltd.]

Automatic Warehouse and Delivery Systems

Although a limited number of parts are held in stock, the larger castings are sourced on a "just-in-time" (JIT) philosophy so that at any time a relatively small number of major items are carried on the inventory. The parts are held in the automated warehouse (Fig. 6.18) with the parts loading centre controlling the passage of work from the machining to the assembly departments. The "host" controls all the information appertaining to machined parts, purchased goods and assembled units, held in the automated warehouse. As dictated by the "host", they are distributed to their required destinations by two wire-guided AGVs (see Figs. 6.18 and 6.19).

The "host" can easily cope with the 4420 varieties of parts that are held in the factory and can be loaded onto pallets, or held in trays in the vertical stacks and sourced by the automated stacking RGVs (see Fig. 6.18). Two further AGVs of larger size and capacity are used to transport castings/loads up to 1000 kg around the manufacturing facility and are also under the control of the "host" as it processes work according to the dictates of the production schedule.

In Fig. 6.19, we can see one of the AGVs involved in unloading parts at the end of the rotational parts line prior to stacking in the tiered buffer, awaiting delivery to the turning centres by RGV and subsequent loading into the machine by the robot (Fig. 6.17).

Sheet Metal Working and Painting

As anticipated by the reader, the sheet metal working facility is fully computer-controlled. Sheet metal working is performed in approximately half the time it takes in a conventional factory. This speed of production of sheet metal parts is achieved using

Fig. 6.19. An AGV delivering parts ready for palletising into pallet store for the rotational parts line. [Courtesy of Yamazaki Mazak Ltd.]

Fig. 6.20. Sheet metal working – laser path cutting machines, CNC folding and bending machines, together with automatic welding machines. [Courtesy of Yamazaki Mazak Ltd.]

two laser path cutting machines, CNC folding and bending machines, automatic welding machines and a storage facility for 180 part varieties. The laser path cutting machines have the sheets loaded automatically from stacks onto their beds and the parts are cut out accordingly (Fig. 6.20). However, if some buffering of stock is required, then the laser leaves the parts attached to the parent sheet at prescribed intervals, by less than 1 mm, allowing for flat stacking – fully cut out (like a jig-saw

Fig. 6.21. Automated transportation of parts to either one of two painting systems, one for cast components and the other for sheet metalwork. [Courtesy of Yamazaki Mazak Ltd.]

puzzle) – then broken out when needed. In this manner, the area needed to hold any buffer stock is kept to a minimum.

At the end of the sheet metal facility is the painting bay, where two systems are provided: one for cast iron and heavy products and another for sheet metal spraying (Fig. 6.21). Both systems are automated and the transport of parts through the spraying booths and drying stages is fully controlled, but unlike automotive factories where robotic spraying and dipping are used, the actual spraying is completed manually. Once again, it is worth pausing here for a moment to discuss the reasons for this manual spraying operation. With such a diverse range of parts to be sprayed – of relatively low volume – it would be unwise to expend great amounts of money and effort in fully automating a robotic spraying facility of this type. Such plant would be hard to justify in terms of equipment, capital and effort. Furthermore, with the well-proven Japanese philosophy of "keeping it simple", manual spraying will produce a satisfactory quality and at minimum expense. The final point of being able to know when, why and by how much, to automate, is why the Japanese have become so successful in terms of both production throughput and quality.

Quality Control and Superfinishing

The superfinishing/jigboring facility on the shop floor has had special attention paid to it in terms of the installation of the machine tools. Not only are the foundations extra deep, they are isolated from the remainder of the shop floor to minimise vibrations. The special-housed machines are in a closely controlled-temperature environment, to within $\pm 1\,°C$, as this ensures that the precision can be maintained to within $0.5\,\mu m$ tolerances, where applicable. The machine tools range from high accuracy surface and cylindrical grinders to two of the Yamazaki Mazak's Jig Centre ATC machines. Such equipment is essential when high accuracy roundness, dimensional and geometrical tolerances are to be consistently held.

Fig. 6.22. The quality control of parts – temperature-controlled environment with a comprehensive range of metrology equipment. [Courtesy of Yamazaki Mazak Ltd.]

The quality control of high precision parts is assessed in the metrology laboratory adjacent to the superfinishing facility. Here (Fig. 6.22) in the temperature-controlled room, spindles, bearings, housings, etc. are inspected for roundness, surface finish, dimensional/geometrical features on a range of high accuracy equipment: Talyrond (roundness) and Talysurf (surface finish) instruments, Zeiss CMM (linear and geometric features on prismatic/rotational parts) and other metrological equipment. The quality information is fed back to the respective MicroVax for logging of data and quality control action.

Clean Room for Precision Sub-assembly

Not only is it essential in a "clean room" (Fig. 6.23) to maintain high accuracy and stability of temperature, but in order to avoid ingression of dust/debris particles in the air, contaminating the precision surfaces, it is important to purify the air to "class 10 000", i.e. as clean as the air above the middle of the Pacific Ocean. The workforce in the clean room wear special overalls and it is in here where assembly of the spindles and headstocks for turning centres and spindle cartridges for machining centres occurs. All sub-assemblies are then continuously tested/monitored on programmed "trial runs", to ensure that the spindles/cartridges within their housings are operating satisfactorily.

Final Machine Tool Assembly

The assembly hall (not shown) is where the sub-assemblies, machine beds and bought-in components are all delivered via the large AGVs. Typical machine assemblies include: spindle units, tool magazines, control units, etc., which are all subjected to exhaustive run and test procedures for 24 hours, prior to final assembly. The results

Fig. 6.23. The clean room and sub-assembly area for critical parts, such as spindles and headstocks (turning centres), also spindle cartridges (machining centres) prior to complete machine tool assembly. [Courtesy of Yamazaki Mazak Ltd.]

are continuously monitored and recorded. Machines thus assembled can be directly despatched, or moved, to customer "prove-out" areas where fixturing and tooling are fitted by the user, if necessary.

This completes our tour of the manufacturing facility at Yamazaki Mazak's CIM factory and it is worth concluding with some final comments on total quality management (TQM). TQM within the factory not only relates to every aspect of quality – not just one of the machines and its mechanical components – but also, the quality of the people and procedures adopted in maintaining/improving quality levels. In 1989, this factory produced about 1000 machine tools, worth then around £70 m, giving a theoretical turnover per employee (180 production people) of just under £400 000. Not only this, but in a recent survey conducted by a consultancy company, they were the top company in terms of automation, productivity, quality and ideas.

Such a technological approach to the manufacture of goods must surely be a lesson to us all, in that there are no mystical thoughts/philosophies in reaching these levels of production, only well-proven ideas that are efficiently carried out in a practical common-sense manner. Many companies can achieve similar productive potential within their existing plants – obviously to a lesser degree – with a clearly defined strategy of implementation, improvement and capital expenditure. If this is not the case, then more energetic and expansive companies will steadily, but surely, take over a staid and complacent competitor.

6.8 Present and Future Trends in Turning and Machining Centre Development

Increasingly, as companies are approaching the process capability of their machines, machine tool builders are being asked to improve their products, offering the customer still higher accuracy/precision. This will entail a range of modifications to current production machine tools. They will need to be able to resolve axes to higher levels than currently available, whilst monitoring the performance in real-time and correcting errors present during machining. In essence, the major problems to be addressed when attempting to improve production machine tools falls into several categories:

improving the machine's linear resolution
speedy recalibration of volumetric envelope
the increasing importance of condition monitoring
improving inertial response of slideway motion
thermal drift and damping improvements
ultra-high speeds for non-ferrous/metallic machining operations

The objective in high precision production machine tools is to produce a "zero defect" part, which no longer depends upon the skills and capabilities of the operator. We know that even with CNC performing a programmed sequence to faithfully manufacture parts with dimensional precision, it is still not possible to build the perfect machine tool. Every production machine today has varying degrees of in-accuracy present and adverse physical effects will, of course, be inevitable. In the following section we will look at the means by which these errors can be minimised, in a commercial sense, and attempt to describe how one might re-engineer machine tools for almost sub-micron accuracy and precision.

6.8.1 Approaching Sub-micron Levels of Accuracy and Precision on Turning and Machining Centres

It is well known that "direct" feedback monitoring systems, utilising linear scales, offer much greater axis resolution than their open/closed-loop "indirect" feedback counterparts. Even here, resolution of the latest scales can only be maintained with any predictable determination over small linear ranges, when approaching micron levels of precision. The major reason for this is the structural changes in-cycle, promoted by differential thermal expansion of the structure influencing the attached linear axis scales. This non-uniform thermal growth can be minimised by attaching laser interferometers coupled with suitable optics for each slideway. Such high resolution, around 40 nanometres (10^{-9} m), has already been incorporated onto diamond turning lathes in production environments and it is only a matter of time before they are incorporated onto commercially available ultra-high accuracy machine tools.

Laser transducers offer high resolution and are less influenced by thermal growth characteristics, as thermal and humidity sensors can compensate, to some extent, for non-linearity of axes and differential thermal growth. The major problem that exists on such machine tools when used at ultra-high accuracy/precision, is that the machine tool's structure will have present, in greater or lesser degrees, the following errors, axes and geometric misalignments:

straightness
flatness
parallelism
positional accuracy
angular: yaw, pitch and roll

repeatability
backlash – to some extent, even with ballscrews
velocity – promoted by feedrate (inertial and CNC interpolation errors)

All these errors can combine to influence the volumetric envelope of the machine tools. It is, however, possible to reduce these interactive elements by incorporating an "adaptive error compensation" unit. This equipment minutely adjusts the axes in "real-time" and the axes/geometric errors are minimised. In such a system, sensors monitor changes in the machine tool structure and software algorithms developed during the machine's initial calibration – via a total error-mapping of the volumetric envelope – can be used to modify each axis motion independently during workpiece machining.

Yet another contributor to errors on machine tools is the product of vibrations promoted during machining and to a lesser extent the machine tool's damping characteristics. Recently, to improve both the thermal growth and damping effects during machining for highly accurate machine tools, "Granitan" has found much favour. This is the product of crushed granite and thermosetting resins bonded to improve thermal expansion by five times and damping by ten times, although such advantages mean a more expensive and heavy machine tool structure.

6.8.2 Ultra-high Speed Cutting Operations on Machining Centres

One of the first questions one might ask is, "Why do we need to machine at ultra-high speeds?". There are a number of important production benefits that can be gained by such an approach:

increased productivity
minimal changes in material properties
distortion of workpiece reduced
burr-free improved finish
thin-section machining potential
tool life improvements
reduction in cutting tool varieties
fixturing of simpler design

Prior to a discussion on these important benefits, it is worth making the point that the term ultra-high speed machining refers to peripheral speeds in excess of 1500 m/min.

Increased Productivity

Obviously it is necessary to optimise the feed to this increase in rotational speed to obtain greater productivity. Typical cutting data might be a spindle speed of 20 000 r.p.m. with a roughing feedrate of 12 m/min, giving a saving in machining time three times greater than that found using conventional spindles.

Minimal Changes in Material Properties

Conventionally machined workpieces at and near the surface exhibit a degree of hardening, promoted by rupture of the slip planes as chip formation occurs causing higher temperatures and heat transfer to the workpiece owing to the action of cutting, inducing sub/surface residual stresses. The research has shown that once we obtain ultra-high speeds, the chip's deformation and its compression approach zero; it follows that minimal heat transfer into the workpiece occurs causing little in the way of work hardening at the surface. During cutting trials it has been demonstrated that the workpiece's temperature rise is normally less than 3 °C above ambient, when ultra-high speed machining. Furthermore, when "ramping" into a surface close to its underside – feeding down whilst simultaneously traversing along – this thin section does not "burn" as is often the case during conventional cutting operations.

Burr Free and Improved Finish

With more energy efficient and "cleaner" machining available from ultra-high spindle speeds, improvements in both surface finish (arithmetical mean roughness) together with burr-free edges occur. Burrs always present problems during the production of parts, as in many cases costly hand finishing becomes the only real alternative with larger components. Such extra manual intervention adds value to the part whilst increasing lead times.

Thin-section Machining Potential

By utilising ultra-high rotational speeds, the cutter forces are reduced significantly, which allows very thin wall and base sections to be machined. Typically a part feature might be a deep pocket to be machined from solid at ultra-high speed: roughing out using a 25 mm diameter slot drill and finish machined with a 12 mm diameter endmill in a very fast time, having a wall thickness of 1 mm and height of 33 mm. However, thickness can be down to 0.3 mm wide and of greater heights than the machined part just mentioned typically an 18:1 ratio (i.e. depth:cutter ratio), which would be impossible, in terms of geometric/linear tolerances, when using conventional milling rotational speeds.

Tool Life Improvements

The improvement in machining efficiency results in much lower cutting forces on the tool and, consequently, less wear occurs. Such wear reduction at ultra-high speeds is quite considerable and the in-cut machining improvements, between either regrinds or replacement, can be up to 80%.

Reduction in Cutting Tool Varieties

The improvement in efficiency of the cutting process means that we can dispense with a large tooling inventory held in the magazine. Often just one slot drill might be used for roughing, with possibly two endmills needed for finishing – this being dependent upon the part's corner radii, etc. Other cutters might be needed to produce features such as angles on the part, or barrel milling cutters may be required to machine contours, minimising cusp height effects. The ultra-high speed machining action ejects the swarf from the cutting vicinity, when tooling is correctly designed, and, in so doing, eliminates any secondary cutting promoted by trapped chips. Therefore, the need to be continuously changing to different diameter cutters, to provide better swarf clearance, is reduced, improving in-cut and tool changing times.

Fixturing of Simpler Design

The many benefits of ultra-high speed machining (force reduction, lower workpiece distortion and so on) combine to allow simpler and cheaper fixturing. Often all that is necessary are simple base plates for component location and restraint, with the need for costly fixturing only being necessary very occasionally.

It follows that if these are the benefits to be gained when ultra-high speed machining, then there must also be some problems that must be addressed when utilising this technique for milling/drilling on machining centres.

Problems Associated with Ultra-high Speed Milling

In order to gain the significant benefits when milling at ultra-high speed, several problems not associated with conventional rotational speeds must be overcome:

machine tool's accuracy and rigidity
cutting spindle performance
tool holder and cutter design
axis drive control capability
controller processing speed

Machine Tool's Accuracy and Rigidity

With the higher acceleration/deceleration and speed requirements needed to obtain the optimum performance when ultra-high speed milling, there are considerably greater stresses induced into the machine tool's structure. Therefore the machine must be designed to overcome stick/slip problems – giving high acceleration/deceleration response – coupled with higher rigidity and damping capabilities.

Cutting Spindle Performance

Possibly the greatest design problems are naturally associated with the spindle, with these high rotational speeds being fundamental to the success for ultra-high speed milling operations – more will be said on this topic shortly. However, for now it is worth mentioning that the spindle needs to maintain performance for extended times at high speed and critical to its operation is the design of bearings, their pre-load, lubrication, etc. Such a spindle needs to be able to accelerate/decelerate quickly, otherwise the savings will be lost for short cycle operations, whilst transmitting high power, not just at high speed but lower in the range for either drilling/tapping, or face milling operations. Bearings must be such that when they are transmitting high power, the heat generated does not cause thermal instability, which would not only reduce bearing life but influence machining accuracies.

Tool Holder and Cutter Design

As the rotational speed increases the spindle nose taper must be reduced in order to overcome the high cantilevered rotational masses and the centrifugal forces influencing cutter/holder stability. Therefore at just over 20 000 r.p.m. the 40 International (or its equivalent) taper is satisfactory, but when over 30 000 r.p.m. the 30 international taper is preferred and so on; it needs to be of short length whenever possible. Both spindle nose and tool adaptor tapers are made to a tolerance, which in turn can cause a radial out-of-balance, owing to the cutting forces, to occur. Not only will it be necessary to minimise radial out-of-balance effects, but axial balance, along the tool's and adaptor's length, needs to be addressed similarly if the cutting action is not to be de-stabilised during machining. At present, most companies machining at these speeds have only been "single-plane" balancing – for radial balance – whereas "dual-plane" dynamic balancing is the requirement. Such "dual-plane" balanced tooling is very difficult to achieve at present and further work on high-speed dynamic balancing, prior to use on these machines is necessary if their full cutting potential is to be realised. As an example of radial out-of-balance, if a cutter/holder is to be rotated at about 25 000 r.p.m., then only several micrometres of radial motion can be tolerated, otherwise it becomes unbalanced. Yet another problem occurs at high rotational speeds – the spindle nose taper swells owing to centrifugal force and Z-axis positioning is influenced as the cutter body is pulled back by the draw-bar. Not only is out-of-balance a product of rotational speed, cutter balancing and its fit in the spindle nose, but it is also affected by driving dog design, when present. However, this is outside the remit of the current discussion.

Axis Drive Control Capability

We have seen in section 5.5 on "High-speed milling fundamentals", that servo-lag can cause geometric and linear errors in our workpiece. These are not too great a problem for general machining tolerances at conventional speeds, but become very significant as part accuracy increases and are further exacerbated by fast feedrates associated with ultra-high speed machining applications. Block "look-ahead" capabilities approaching 64 blocks are desirable here to maintain appropriate control.

Controller Processing Speed

What was said about ultra-high speed milling in the previous statement is equally true for processing speed when machining with fast feedrates (see section 5.5).

Not only should the "look-ahead" capability of the controller be enhanced, but the processing speed should ideally be in the region of 2–8 ms in order to minimise potential "data starvation", which causes hesitation in cutter/slideway response.

By now the reader should have gained an appreciation of not only the benefits to be gained from utilising machine tools equipped for ultra-high speed milling applications, but some of the problems that need to be addressed by both the builder and

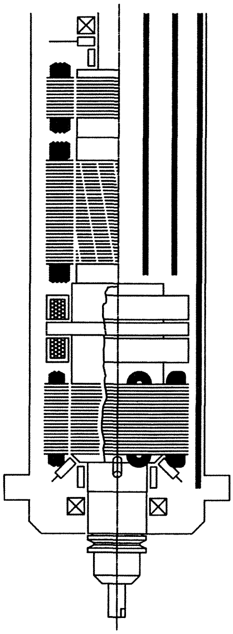


Fig. 6.24. Ultra-fast high-frequency spindles with "active" magnetic bearings. $80\,000\,\text{min}^{-1}$, 10 kW, SKI 25; $60\,000\,\text{min}^{-1}$, 20 kW, SKI 30; $40\,000\,\text{min}^{-1}$, 40 kW, SKI 40. [Courtesy of Rudolfe Carne Ltd/IBAG.]

tooling supplier. In the following pages, let us look at two potential direct-drive spindles currently available, that could be fitted for such work:

magnetic "active" spindles
pneumatic spindles

Magnetic "Active" Spindles

Once ball bearings reach an upper velocity of 80 m/s they tend to lose contact with the journal's wall and begin to skid, which means they rapidly wear out, owing to a combination of factors: centrifugal force, frictional effects and roundness modifications. Under such high rotational speeds, magnetic bearings become a viable alternative, as not only can they be used at ultra-high rotations, but, owing to their design, the power is available for lower speed milling applications. A typical magnetic bearing spindle is shown in Fig. 6.24 and has a speed range of 4000–40 000 r.p.m., delivering 40 kW continuous power, with a peak power of 52 kW, being assembled into a 200 mm diameter housing. The spindle was jointly developed between the company and Zurich University and has two radial and one bi-directional axial magnetic type bearings, with the high-frequency motor located about midway along the spindle housing. The bearing system is active, with the spindle position being maintained within 1 μm maximum run-out by digital control of the current to the magnets – initiated by radial and axial sensors which monitor position 10 000 times a second.

Under normal operation, the bearing control centralises the shaft prior to rotation, then continues to compute the necessary magnet current values until rotation ceases.

Table 6.3.

Machining data	Conventional spindle	Active magnetic bearing HF spindle
Rev/min (max)	6 000	40 000
Feedrate (mm/min)	2 400	10 000
Stock removal (cm^3/min)	480	2 000
	Costs (in \$)	
CNC machine	600 000	600 000
Additional spindle	–	150 000
Labour costs (5 years): 10 000 h @ \$50/h	500 000	500 000
Machine + labour cost	1 100 000	1 250 000
Cost per hour	110	125
Amortisation cost for 1000 cm^3 stock removal (\$)	3.82	1.04
Overall saving	–	72.8%

In the event of a malfunction, two small angular contact "catch" bearings – 0.2 mm clear of the shaft – provide emergency support. To maintain control of the spindle at all times requires an: electrical/electronic frequency converter for the high-frequency spindle drive; water tanks, pumps and heat exchanger for spindle jacket cooling, pneumatic filter regulator for hydropneumatic tool clamping; spray coolant and filtration system and finally, a separate electronic regulation and computer unit.

In order to minimise the tool balancing problem (alluded to earlier) at high rotational speed, a taper/contact face system was developed. This tool holding system utilises a Belleville spring tensioned drawbolt which engages the holder bringing it into the taper and, as it does so, a small elastic distortion of the spindle nose housing allows the toolholder shoulder contact.

Although these spindles cost approximately double the conventional ball bearing models, the real savings can be appreciated in Table 6.3 for a comparison of milling aluminium with a solid carbide cutter, 20 mm diameter having two flutes, with a depth of cut 10 mm and a feed per tooth of 0.2 mm.

Pneumatic Spindles

The air-lubricated bearing has been with us for some time and new applications are being identified as these bearings become more widely known and understood. In principle, the nature of an aerostatic bearing consists of a cylindrical bush having two rows of gas feed holes spaced evenly around the bearing circumference. The bearing is surrounded by a reservoir, into which gas is fed at pressure. The bearing carries a cylindrical shaft and, in operation, gas flows from the reservoir through the feed holes into an angular space between the shaft and bushing. From here, it flows axially (see Fig. 6.25b), escaping to atmosphere from the ends of the bearing. The pressure falls as the gas flows through the feed holes and enters the bearing clearance. It falls still further, as the gas flows towards the ends of the bearing, before finally exhausting to air. If we assume the condition of a weightless shaft occurs, then it will float concentrically within the bearing and all pressure forces will balance.

When a load is applied to the shaft, then the clearance between the shaft and the bushing diminishes in the direction of the load. The effect of this change in clearance is to increase the resistance to air flow at the zone of smallest clearance, resulting in an increase in air pressure. Conversely, where the clearance has increased, then the resistance to flow is diminished and the pressure falls. Thus a new equilibrium position is established, where the pressure difference across the shaft balances the applied load.

The aerodynamic bearing is capable of generating the necessary load balancing forces within itself, by virtue of rotation alone, enabling the bearing system to operate without the need for an external pressure supply, thus offering the potential for air-lubricated bearings without external air supply.

The hybrid bearing is basically an aerostatic bearing where advantage is taken of the inherent self-generating load capacity of the aerodynamic bearing. Therefore, we thus have an aerostatic bearing which, when operating at the design speed, can have between two to three times the static load capacity. Such characteristics are of particular significance if they are to be used for ultra-high speed machining spindles.

Typically, in Fig. 6.25a, can be seen an aerodynamic thrust bearing with spiral grooves and a commercially available spindle might offer the following benefits:

high rotational speeds – 10 000–30 000 r.p.m.

powerful electric motor – 15.5 kW at 30 000 r.p.m.

large bearing load capacities – these increase dramatically with speed for high table feedrates

low vibration and high bearing stiffness, offering excellent surface finish

minimal maintenance and indefinite working life – owing to non-contacting rotational parts

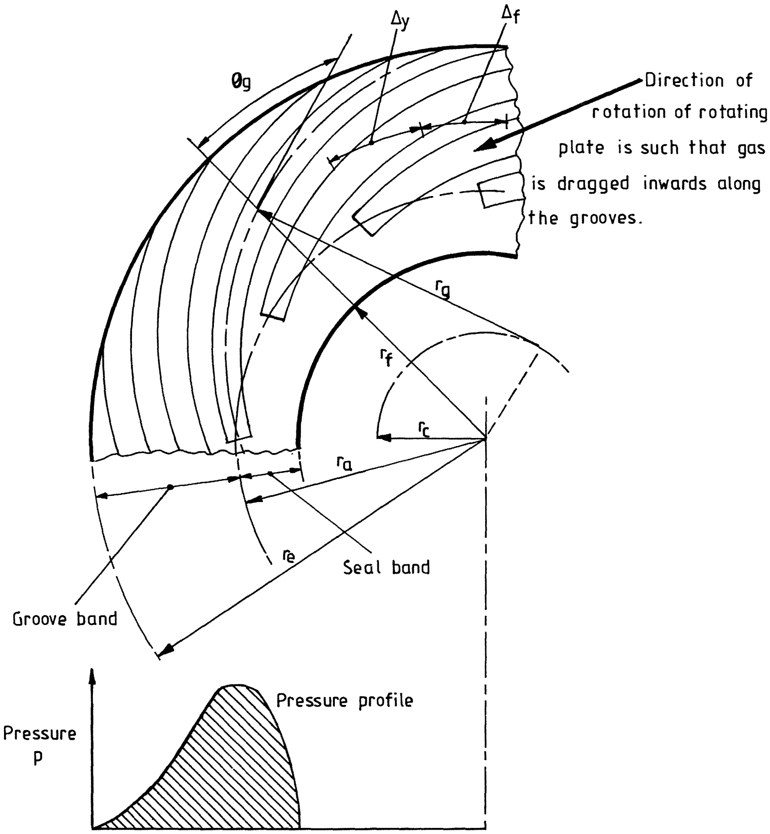
The future of ultra-high speed machining will allow us to approach the theoretical optimum cutting volume for, say, high-grade aluminium. This means that it should be possible to remove stock up to 120 cm^3/min/kW. Currently, the best machine tools can mill at around 73 cm^3/kW and shortly one Japanese machine tool manufacturer will be achieving stock removal rates of 80 cm^3/kW at 40 000 r.p.m. So, in summary, we can say that "true" high speed machining is now a practical reality for machining non-ferrous and many non-metallic materials and work is continuing in the development of cutting steels and more exotic materials for the aerospace industries.

6.8.3 Higher Accuracy on Turning Centres Using Direct Drive Spindles

With the continuing development in machining centre spindles, for greater speed, accuracy, thermal stability, damping capacity and so on, there has been a similar advance in the latest turning centre headstocks. Direct-driven headstocks are now beginning to appear on the more advanced machines (typical of such a headstock is that depicted in Fig. 6.26a) as their belt-driven cousins are now beginning to "show their age". Just why these direct-drive headstocks are replacing the traditional belt-driven varieties can be seen in Fig. 6.26b, where the combination of spindle motor plus drive (belts) cause an undulating and irregular harmonic rotational motion. The influence of this irregular harmonic belt-driven rotation can be appreciated by the schematic representation in Fig. 6.26c, where a tumbling three-lobed-harmonic-shape is reproduced on the workpiece by the action of the headstock's rotation and the linear motion of the cutting tool.

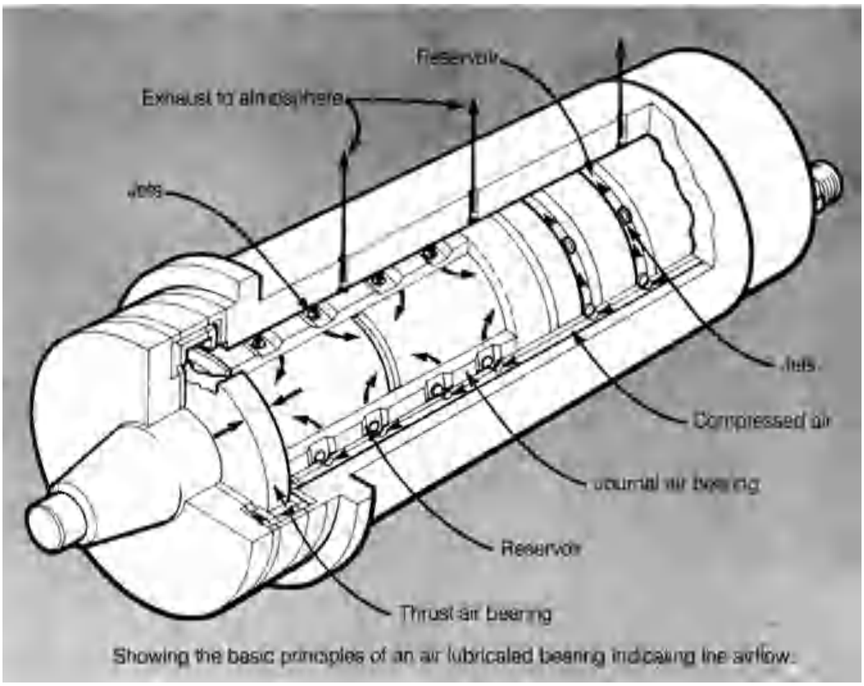
In Fig. 6.26d, there is virtually no harmonic influence on the workpiece using a direct-drive spindle and a much more consistent part results, in terms of both its geometrical and linear dimensions. Yet other benefits accrue when using direct-drive

a



Δ_y
Δ_f
θ_g
Direction of rotation of rotating plate is such that gas is dragged inwards along the grooves.
r_g
r_f
r_c
r_a
r_e
Seal band
Groove band
Pressure p
Pressure profile

b



Reservoir
Exhaust to atmosphere
Jets
Jets
Compressed air
Reservoir
Thrust air bearing
Showing the basic principles of an air lubricated bearing indicating the airflow.

c

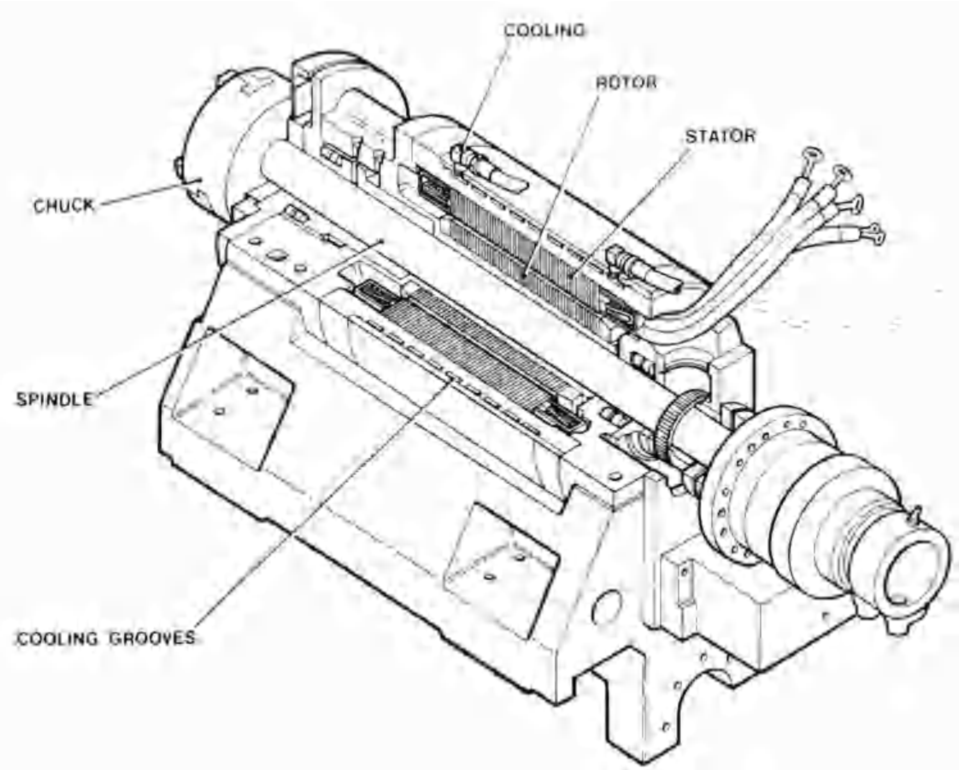
Fig. 6.25. Details of air-driven high-speed spindles used in milling applications. **a** A typical aerodynamic thrust bearing with spiral grooves. Air is dragged into the grooves by virtue of the relative motion of the plates and a pressure rise is caused by the restriction of the sealing band with consequent load generation. **b** A cutaway diagram of an air-driven spindle. **c** An ultra-high speed milling operation on an aluminium component. [Courtesy of Westwind Air Bearings Ltd.]

spindles, which include lower maintenance (no belt-tensioning problems and a more uniform load on the bearings), better thermal growth characteristics, higher spindle accuracy and improved damping.

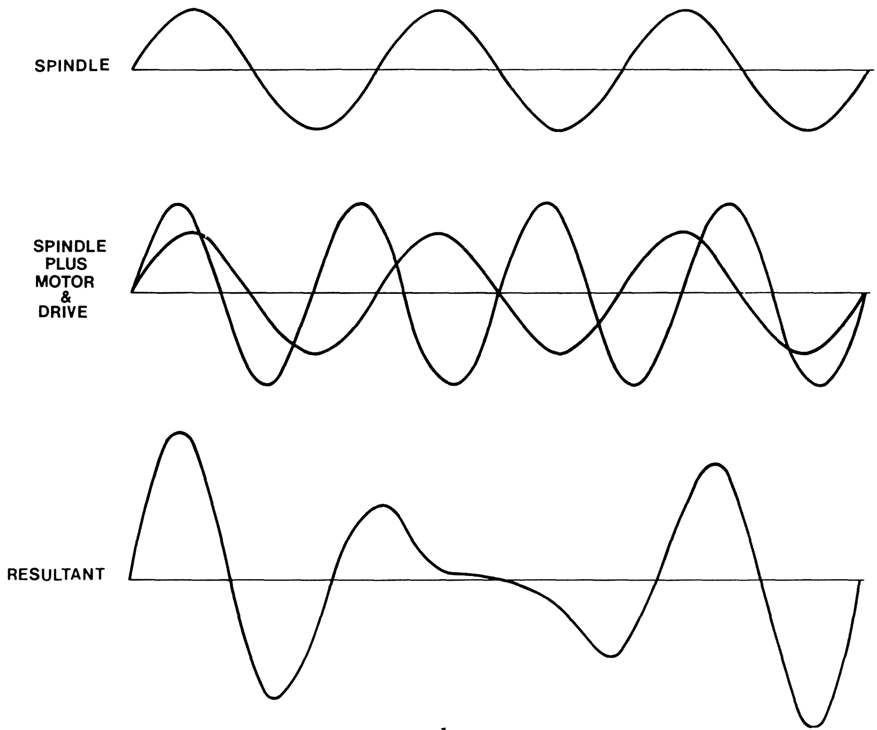
6.8.4 Diamond Turning and Machining – for Ultra-high Accuracy, Precision and Surface Finish

In recent years there has been pressure to achieve not only consistent dimensional and geometrical tolerances on high precision parts, but also superior surface finishes. Probably the "driving force" behind this development has been the optical industry, where diamond-lapped surface configurations used to take days, if not months, for the large monolithic mirrors used in the optical industry, or for astronomical telescopes. With the advent of diamond machining techniques, such large removal of stock, via coarse lapping, has been virtually eliminated, as these machine tools can generate a very close approximation to the tenths of wavelengths of light configurations needed in the final optical product. Hence, finish lapping with micron/submicron diamond pastes is all that is required to complete the product to its best optical configuration.

Not only is the optical industry in need of faster methods of production, but other exacting precision parts (of diverse shape, size and complexity) requiring superior finishes are being demanded by industry.


COOLING
ROTOR
STATOR
CHUCK
SPINDLE
COOLING GROOVES

a


SPINDLE
SPINDLE PLUS MOTOR & DRIVE
RESULTANT

b

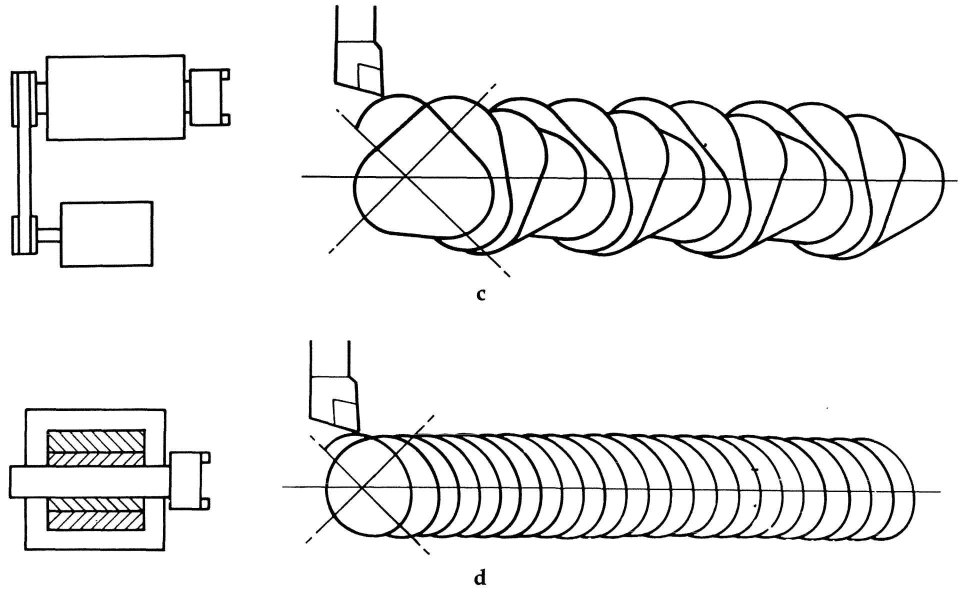


Fig. 6.26. The component quality is improved by using direct-drive spindles, rather than belt-driven headstocks on turning centres. **a** Direct-drive spindle cartridge for a turning centre. **b** The sinusoidal influence of component elements on a belt-driven headstock. **c** The harmonic effect of a belt-driven headstock on a turned component. **d** The harmonics virtually disappear on the component when direct-drive spindles are utilised. [Courtesy of Yamazaki Mazak Ltd.]

Diamond Turning Machines

The inherent hardness of many of the components machined on diamond turning lathes has, in the past, meant that natural industrial diamond tooling had to be used. Such tooling meant that the machine tool had to be inherently very rigid, with no play in the bearings, whilst offering high damping capacity, otherwise the tooling would easily fracture along its planes of weakness. Such "build philosophy" has been carried over to the latest diamond turning machines, despite the fact that often synthetic polycrystalline diamond (PCD) tooling can be utilised.

In a typical example where chucking tends to be simple, the part is often held in situ by pneumatic application. This type of machine has relatively unsophisticated tooling requirements and the main attention is placed upon a very high precision headstock and rigid bed, coupled with high resolution axes control. Obviously, a CNC controller is used to generate the necessary tool vectors for machining the part and a "direct" closed-loop laser-controlled positional feedback system is fitted to accurately monitor axis slideway motion.

Recently, a cutting tool company in Indianapolis, USA, has been producing some of the most accurate tool nose geometries, based upon chemically machining synthetic diamond cutting tools. In the past, most diamond tooling has been abraded away to form the correct tool geometry, and this was acceptable when one was prepared to spend time diamond lapping the surface profile to the correct configuration. However, as companies are demanding faster production and throughput of diamond machined parts, this has meant that post-machining operations must be kept to a minimum. The

Fig. 6.27. Possibly the most accurate and advanced diamond turning/grinding centre at present available. [Courtesy of CUPE Ltd.]

problem with conventionally abrading the diamond tooling to obtain the desired geometry, has meant that the irregular form of the tool nose radius has, when cutting, produced scratches in the surface of the component that need to be polished out later. The technique of chemically machining the edge away – by automatically removing the tool's surface atom-by-atom exposing an ultra-smooth planar face that is substantially co-planer with the naturally occurring crystal plane within the crystalline structure of the diamond – produces a super-smooth cutting tool edge which, when magnified optically ×10 000 still looks smooth. When machining this molecular-level chemically machined tool profile, significant savings in post-machining finishing are offered and will become more important as diamond machining applications expand.

Fig. 6.27 shows possibly the ultimate in advanced machine tool design in terms of diamond turning and grinding capacity currently available today. Let us look in some detail at what makes this machine tool so special. It has a three-axis CNC controller, using a "T-type" base and bridge construction, providing high loop stiffness between the tool and workpiece. The "T-base" is constructed from Granitan S100, giving excellent stiffness and high damping characteristics. Vibrations are minimised by supporting the base on a three point, self-levelling pneumatic vibration isolation system. The work spindle is built into the bridge carriage, which moves at 90° to the spindle axis and the toolpost is mounted on a separate carriage moving parallel to the spindle axis.

Carriage ways utilise hydrostatic bearings providing smooth motion with good damping, high stiffness and load carrying capacity, with freedom from "slip-stick" – essential requirements when servo positioning slides down to 1.2 nm. Oil temperature is controlled to 0.01 °C, ensuring thermal stability of the machine. The drive systems to both carriages incorporate direct drive frameless d.c. torque motor/tachogenerators mounted directly. Linear displacement for each axis is via laser interferometry (based upon heterodyne interferometry) with He–Ne lasers and the total system has been designed to minimise Abbé offset errors. The environmental effects on the laser path are corrected by an optical wavelength compensator, built into the system.

The workspindle is an oil hydrostatic bearing type, designed for high stiffness and low error motion. Once again, thermal stability is maintained through careful material selection and construction, coupled with oil temperature control to ±0.1 °C. The spindle is driven by a high performance brushless d.c. motor, directly mounted onto the spindle, with rotary encoder for fast tool servo applications; a stepless variable speed with bi-directional motion, having dynamic balancing capacity, vacuum work-holding and a temperature-controlled drive motor is utilised.

The B-axis rotary table allows the cutting tool tip to always be at a tangent to the surface being cut, i.e. normal to the cutting surface. Having the tool at such an orientation to the part eliminates errors due to tool tip irregularities. To maximise tool life, the B-axis can present an unused portion of the tool tip (by a small angular offset), furthermore, permitting versatility when machining Fresnel optics, as well as allowing the table to be indexed for the fly-cutting of optical polygons. The table is supported by hydrostatic bearings and a direct-drive frameless d.c. torque motor/tachogenerator is mounted directly onto the table with a rotary encoder.

A critical element on a diamond turning machine is the toolholder, with the tools having an 8 × 8 mm cross-section tool shank, closely supported to minimise tool overhang and improve rigidity. Tool setting is by a "station" located to the right-hand side of the workhead and utilises two air-bearing Linear Variable Differential Transformers (LVDT) gauge heads – one to determine the X-offset and the other the Z-offset for height adjustment. Tool setting is a fully automated function under CNC control and can be initiated at any time during machining. Later, a non-contacting optical tool setting station will be available for this machine tool.

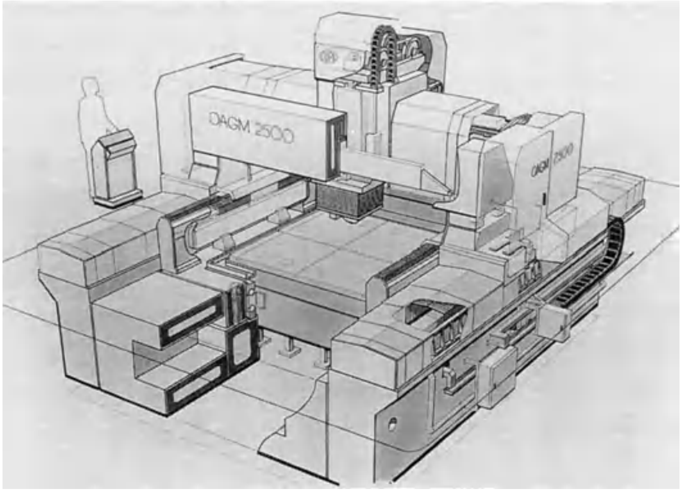
The machine utilises one of the most advanced CNC systems with its "electronic gearbox" capability, ensuring "zero following error" performance. The controller offers exceptional tool path accuracy by virtue of its unique high resolution, fast feed forward techniques – eliminating servo following errors. Yet another unusual feature of this controller is its on-line cubic spline interpolation facility. This allows data of the path definition to be input by either the equation of shape for the component surface – entered at the operator's control panel, or via a personal computer – or using the minimum number of datapoints. Both techniques eliminate the need for conventional post-processing of data. Other features available with this CNC include:

software error compensation
- tool error mapping
- error compensation for: B-axis, rotary motion and scale error
- volumetric error compensation for: cubic lattice and parametric errors

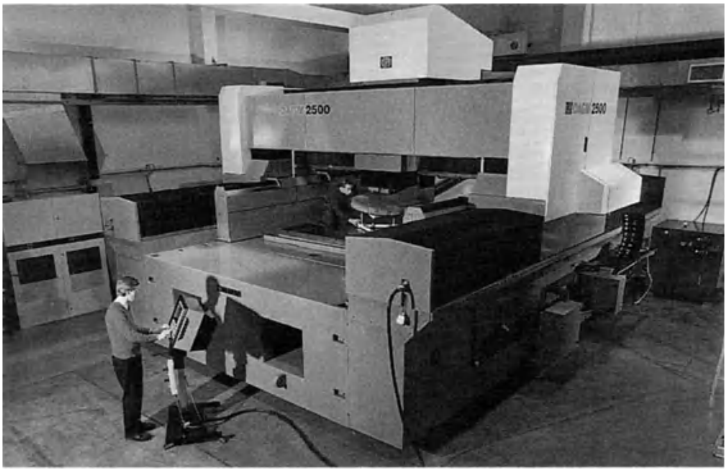
dynamic error compensation
- thermal growth, e.g. in spindle
- refractive index. e.g. laser interferometry
- fast tool servos
- metrology frame methods (see final section in book)

diagnostics
- fault indication
- performance monitoring for safety

Finally, let us turn our attention to possibly the most expensive and accurate machine tool ever made, utilising the latest trends in machine tool technology.



a



b

Fig. 6.28. The most sophisticated machine tool currently available with the ability to machine optical curvatures on large monolithic mirror blanks. There is an in-situ interferometric probe used adjacent to the spindle for surface evaluation. **a** A sectional diagram illustrating the major elements in the 3-axis machine tool. **b** The large Granitan structure with ultra-precise straight edge ways. The machine incorporates laser-controlled slideways and hydrostatic bearings. [Courtesy of CUPE Ltd.]

Diamond Machining for Optical Components

In recent years, the design trends in large optics – the most accurate/precise components currently manufactured – have progressed towards systems incorporating large, off-axis, aspheric optical elements. Such segments can be used in groups forming a single large parent optical surface. These segmented mirrors have found applications in space where it is possible to launch a folded mirror array, then deploying it providing a reflector larger than the diameter of its launch vehicle.

The machine tool shown schematically in Fig. 6.28a and actually in Fig. 6.28b, has been designed and built in the UK to generate and measure off-axis elements prior to final polishing. This machine tool weighs approximately 130 tonnes, having a component capacity of 2.5 m × 2.5 m × 0.6 m, but its overall length being 8 m × 6 m × 5 m. An advanced three-axis CNC controller is used together with an in-situ probe; also incorporated is a multiple path laser interferometer system to achieve the required component quality.

This machine tool incorporates polystyrene cores surrounded by Granitan S100 structure, suitably supported by light steel weldments, offering high stability and internal damping. The base is made in four sections, each weighing approximately 17 tonnes, with outer guideway members mounted on either side of the two centre spacing sections. To ensure precise re-assembly in the USA (Kodak), the base unit mounting faces were scraped flat. A 2.5 m × 2.5 m cast iron worktable was kinematically mounted onto the base structure in such a manner that any deflections caused by gantry motions did not produce table distortion. Weight relieving systems were fitted to minimise excessive loading on the kinematic location positions. The surrounding metrology frame was kinematically connected to the worktable – with its own weight relieving systems. The table and metrology frame were designed to compensate for thermal changes in the structure and were closely linked to the fabricated optical reference flats (Corning ULE 7971 titanium silicate material) in the metrology frame; each reference flat being 2.75 m × 0.3 m × 0.1 m. The travelling gantry – Granitan filled weldments – carried the spindle and in-situ metrology system.

Torque motor DC drives on the X and Y axes were by traction–friction, with each drive unit being mounted directly, driving a "vee" roller which in turn operated against a rigid circular section drive bar. Sagging of the drive bar was prevented by spring-loaded devices positioned at intervals along its length. Slippage of the gantry (caused by machining forces or acceleration) was prevented using a preloaded roller, providing sufficient force to maintain the drive rollers in contact with each traction bar at all times. The shorter Z-axis was controlled via the conventional ballscrew system, but with a backlash-free non-influencing nut. The ballscrew had a directly mounted d.c. torque motor which was mechanically counterbalanced.

To obtain the desired accuracy and resolution for each axis motion, the reference measurement system was via the "metrology frame concept" – this being utilised in the past on a number of high-precision machines. The basic reference frame is by three precision glass reference bars, principally for the control of the Z-axis. In practice, two reference bars are mounted either side of the worktable in the X-direction, which are nominally parallel and coplanar to the table. The third reference bar is mounted above and at right angles to the "X-bars", forming the reference for motions in the Y-direction, but all are mounted at the "Airy points", providing, in this case, the "points of minimum deflection" required for straight edges. In order to control the machine to the desired accuracy/precision, a built-in multi-path laser interferometer system is provided. Using three lasers and associated optics, the output beam is split three ways providing a comprehensive monitoring system for each axis. Furthermore, if any changes in environmental conditions occur such as temperature/humidity, these are immediately detected and compensation is actioned automatically. The laser resolution is to 2.5 nm across the volumetric envelope of the machine tool.

The in-situ gauging head alluded to earlier, can be used for the in-process inspection of any large three-dimensional optical elements. The form of the surface profile can be determined from the vertically acting measuring probe mounted adjacent to the spindle. The workpiece's optical surface can be completely scanned, providing a global evaluation of the machined surface. Surface data can be analysed using proprietary interferometry evaluation software developed by Kodak. The retractable probe can be sealed in a protective housing during machining operations. The probe's contact stylus is manufactured from "Zerodur" – having virtually a zero coefficient of linear expansion – which minimises errors caused by thermal changes. This probe's spindle is carried in an externally pressurised air-bearing, with a suitable counter-balance system providing a low and adjustable contact force. A retro-reflector referencing the Y-references straight-edge in conjunction with suitable optics, performs the vertical (Z) displacement measurement function. In order that the Z-axis can stay within the small stroke of the probe, the Z-axis slideway is under servo-control and caused to operate such that the null-seeking feedback device built into the probe is kept centralised. Additionally, small movements of the stylus (up to 4 mm) can be performed by means of bias coils, electrically operated and built into the probe body.

Owing to the high loads carried by the larger moving members of this machine tool, they have their carriage bearings of fluid film – X and Y axes utilise hydrostatic bearings fed by temperature controlled oil, whereas the Z-axis bearings are aerostatic. The collection and return of the exhaust oil from the bearings is filtered and temperature controlled to $\pm 0.1\,^{\circ}\mathrm{C}$, prior to recycling back to the hydrostatic bearings. Total oil flow is very low for the X and Y axes (1.6 l/min with nominal separation gaps being 25 nm). Typical vertical stiffness of each X-axis guideway is 9500 N/μm and horizontaly 8000 N/μm, with the Y-axis values being approximately half those of "X".

At present this machine tool utilises an air-bearing grinding spindle, operating at 3000 r.p.m. (electrically powered), but it would be quite feasible to use PCD rotating tooling on such a machine in a similar fashion to that described for the diamond turning lathe (Fig. 6.27).

What the reader should be able to appreciate by now, is that machine tools are approaching the absolute limits of accuracy/precision available either today, or for some considerable time in the future. They are operating in cutting environments which until recently were the domain of metrology instruments – in terms of workpiece resolution; meaning that not only are the part's qualities (dimensional and geometric features) influenced by the design, build and calibration procedures adopted on the machine (frequent calibration) but also its operating environment: temperature/humidity control, together with isolated and deep foundations. The general approach today is for greater and more consistent part quality on turning and machining centres in industry and this book has attempted to follow the latest trends in terms of advances in machine tools, cutting tool technology, workholding technology and cutting fluids.

Appendix

National and International Machine Tool Standards

Determination of Accuracy and Repeatability of Positioning of CNC Machine Tools

Date of issue	*Standard*	*Country of origin*
1972	NMTBA	USA
1977	VDI/DGQ 3441	Germany
1985	BS 4656: PART 16	Great Britain
1987	BS 4656: PART 16 (AMENDED)	Great Britain
1988	ISO 230–2	International
1991	BS 3800: PART 2	Great Britain

BS3800: General Tests for Machine Tools

PART 1: 1990 Code of practice for testing geometric accuracy of machines operating under no load, or finishing operations;
- geometric and practical test methods,
- definitions,
- use of checking instruments,
- explanation of tolerances,
- description of preliminary checking operations,
- description of accuracy of instruments required.

PART 2: 1991 Statistical methods for determination of accuracy and repeatability of machine tool;
- linear and rotary positioning errors applied to CNC machine tools,
- angular (pitch, yaw and roll) and straightness positioning errors applied to CNC and manually controlled machine tools.

PART 3: 1990 Method of testing performance of machines operating under loaded conditions in respect of thermal distortions;
- thermal distortion of structure,
- thermal drift of axis drives.

Glossary of Terms

A

A AXIS – The axis of rotary motion of a machine tool member or slide about the X axis.

ABSOLUTE ACCURACY – Accuracy as measured from a reference which must be specified.

ABSOLUTE DIMENSION – A dimension expressed with respect to the initial zero point of a coordinate axis.

ABSOLUTE POINT (Robots) – Equivalent to absolute coordinates in NC machines. The coordinates of a data point are defined in relation to an absolute zero.

ABSOLUTE PROGRAMMING – Programming using words indicating absolute dimensions.

ABSOLUTE READOUT – A display of the true slide position as derived from the position commands within the control system.

ABSOLUTE SYSTEM – NC system in which all positional dimensions, both input and feedback, are measured from a fixed point of origin.

ACCANDEC – (Acceleration and deceleration) Acceleration and deceleration in feedrate; it provides smooth starts and stops when operating under NC and when changing from one feedrate value to another.

ACCEPTANCE TEST – A series of tests which evaluate the performance and capabilities of both software and hardware.

ACCESS TIME – The time interval between the instant at which information is: 1. called for from storage and the instant at which delivery is completed, i.e., the read time; 2. ready for storage and the instant at which storage is completed, i.e., the write time.

ACCUMULATOR – A part of the logical arithmetic unit for a computer. It may be used for intermediate storage to form algebraic sums, or for other intermediate operations.

ACCURACY – 1. Measured by the difference between the actual position of the machine slide and the position demanded. 2. Conformity of an indicated value to a true value, i.e., an actual or an accepted standard value. The accuracy of a control system is expressed as the deviation or difference between the ultimately controlled variable and its ideal value, usually in the steady state or at sampled instants.

ACTIVE CONTROL – A technique of automatically adjusting feeds and/or speeds to an optimum by sensing cutting conditions and acting upon them.

ACTIVE STORAGE – That part of the control logic which holds the information while it is being transformed into motion.

ADDRESS – A character or group of characters at the beginning of a word which identifies the data allowed in the word.

ADDRESS BLOCK FORMAT – A block format in which each word contains an address.

ALGOL – (Algorithmic Language) Language used to develop computer programs by algorithm.

ALGORITHM – A rule or procedure for solving a mathematical problem that frequently involves repetition of an operation.

ALPHANUMERIC or ALPHAMERIC – A system in which the characters used are letters A to Z, and numerals 0 to 9.

ALPHANUMERIC DISPLAY – Equipment, such as a CRT, which is capable of displaying only letters, digits and special characters.

AMPLIFIER – A signal gain device whose output is a function of its input.

AMPLITUDE – Term used to describe the magnitude of a simple wave or simple part of a complex. The largest or crest value measured from zero.

ANALOG – In NC the term applies to a system which utilises electrical voltage magnitudes or ratios to represent physical axis positions.

ANALOG DATA – The information content of an analog signal as conveyed by the value of magnitude of some characteristics of the signal such as the amplitude, phase, or frequency of a voltage, the amplitude or duration of a pulse, the angular position of a shaft, or the pressure of a fluid.

ANALOG SIGNALS – Physical variables (e.g., distance, rotation) represented by electrical signals.

ANALOG-TO-DIGITAL (A/D) CONVERTER – A device that changes physical motion or electrical voltage into digital factors.

AND – A logical operator which has the property such that if X and Y are two logic variables, then the function "X and Y" is defined by the following table:

X	**Y**	**X and Y**
0	0	0
0	1	0
1	0	0
1	1	1

The AND operator is usually represented in electrical rotation by a centred dot "·", and in FORTRAN programming notation by an asterisk "*" within a Boolean expression.

AND-GATE – A signal circuit with two or more inputs. The output produces a signal only if all inputs received coincident signals.

APPLICATION PROGRAMS – Computer programs designed and written to value a specific problem.

APT – (Automatically Programmed Tools) A universal computer-assisted program system for multi-axis contouring programming. APT III – Provides for five axes of machine tool motion.

ARC CLOCKWISE – An arc generated by the coordinated motion of two axes in which curvature of the path of the tool with respect to the workpiece is clockwise, when viewing the plane of motion from the positive ddirection of the perpendicular axis.

ARC COUNTERCLOCKWISE – (Substitute "Counterclockwise" for "Clockwise" in "Arc Clockwise" definition.)

ARCHITECTURE – Operating characteristics of a control system, or control unit, or computer.

ASCII – (American Standard Code for Information Interchange) A data transmission code which has been established as an American Standard by the American Standards Association. It is a code in which 7 bits are used to represent each character. (Also USASCII.)

ASSEMBLY – The fitting together of a number of parts to create a complete unit.

ASSEMBLY DRAWING – The drawing of a number of parts which shows how they fit together to construct a complete unit.

ASYNCHRONOUS – Without any regular time relationship.

ASYNCHRONOUS TRANSMISSION – The transmission of information in irregular sections, with the time interval of each transmission varying and each section being identified by a stop and start signal.

ATTRIBUTE – A quality that is characteristic of a subject.

AUTOMATED ASSEMBLY – The application of automation to assembly.

AUTOMATION – The technique of making a process or system automatic. Automatically controlled operation of an apparatus, process, or system, especially by electronic devices. In present day terminology, usually used in relation to a system whereby the electronic device controlling an apparatus or process also is interfaced to and communicates with a computer.

AUXILIARY FUNCTION – A function of a machine other than the control of the coordinates of a workpiece or cutter – usually on–off type operations.

AXIS – 1. A principal direction along which a movement of the tool or workpiece occurs. 2. One of the reference lines of a coordinate system.

AXIS (Robots) – A moving element of a robot or manipulator.

AXIS INHIBIT – Prevents movement of the selected slides with the power on.

AXIS INTERCHANGE – The capability of inputting the information concerning one axis into the storage of another axis.

AXIS INVERSION – The reversal of normal plus and minus values along an axis which makes possible the machining of a left-handed part from right-handed programming or vice-versa. Same as mirror image.

B

B AXIS – The axis of rotary motion of a machine tool member or slide about the Y axis.

BACKGROUND – In computing the execution of low priority work when higher priority work is not using the computer.

BACKGROUND PROCESSING – The automatic execution of computer programs in background.

BACKLASH – A relative movement between interacting mechanical parts, resulting from looseness.

BAND – The range of frequencies between two defined limits.

BASE – A number base. A quantity used implicitly to define some system of representing numbers by positional notation. Radix.

BATCH – A number of items being dealt with as a group.

BATCH PROCESSING – A manufacturing operation in which a specified quantity of material is subject to a series of treatment steps. Also, a mode of computer operations in which each program is completed before the next is started.

BAUD – A unit of signalling speed equal to the number of discrete conditions or signal events per second; 1 bit per second in a train of binary signals, and 3 bits per second in an octal train of signals.

BEHIND THE TAPE READER – A means of inputting data directly into a machine tool control unit from an external source connected behind the tape reader.

BENCHMARK – A standard example against which measurements may be made.

BILL OF MATERIALS – A listing of all the parts that constitute an assembled product.

BINARY – A numbering system based on 2. Only the digits 0 and 1 are used when written.

BINARY CIRCUIT – A circuit which operates in the manner of a switch, that is, it is either "on" or "off".

BINARY CODED DECIMAL (BCD) – A number code in which individual decimal digits are each represented by a group of binary digits; in the 8-4-2-1 BCD notation, each decimal digit is represented by a four-place binary number, weighted in sequence as 8, 4, 2 and 1.

BINARY DIGIT (BIT) – A character used to represent one of the two digits in the binary number system, and the basic unit of information or data storage in a two-state device.

BLOCK – A set of words, characters, digits, or other elements handled as a unit. On a punched tape, it consists of one or more characters or rows across the tape that collectively provide enough information for an operation. A "word" or group of words considered as a unit separated from other such units by an "end of block" character (EOB).

BLOCK DELETE – Permits selected blocks of tape to be ignored by the control system at discretion of the operator with permission of the programmer.

BLOCK DIAGRAM – A chart setting forth the particular sequence of operations to be performed for handling a particular application.

BLOCK FORMAT – The arrangement of the words, characters and data in a block.

BODE DIAGRAM – A plot of log amplitude ratio and phase angle as functions of log frequency, representing a transfer function.

BOOLEAN ALGEBRA – An algebra named after George Boole. This algebra is similar in form to ordinary algebra, but with classes, propositions, yes/no criteria, etc., for variables rather than numeric quantities, it includes the operator's AND, OR, NOT, EXCEPT, IF THEN.

BOOTSTRAP – A short sequence of instructions, which when entered into the computer's programmable memory will operate a device to load the programmable memory with a larger, more sophisticated program – usually a loader program.

BUFFER STORAGE – 1. A place for storing information in a control for anticipated transference to active storage. It enables control system to act immediately on stored information without waiting for the tape reader. 2. A register used for intermediate storage of information in the transfer sequence between the computer's accumulators and a peripheral device.

BUG – An error or mistake.

BULK MEMORY – A high capacity auxiliary data storage device such as a disk or drum.

BUS – A conductor used for transmitting signals or power between elements.

BYTE – A sequence of adjacent bits, usually less than a word, operated on as a unit.

C

C AXIS – The axis of rotary motion of a machine tool member or slide about the Z axis.

CALIBRATION – Adjustment of a device, such that the output is within a specified tolerance for particular values of the input.

CANCEL – A command which will discontinue any canned cycles or sequence commands.

CANNED CYCLE – A preset sequence of events initiated by a single NC command, e.g., G84 for NC tap cycle. Also fixed cycle.

CANONICAL FORM – A standard numerical representation of data.

CATHODE RAY TUBE (CRT) – A display device in which controlled electron beams are used to present alphanumeric or graphical data on a luminescent screen.

CENTRAL PROCESSING UNIT (CPU) – The portion of a computer system consisting of the arithmetic and control units and the working memory.

CHANNEL – A communication path.

CHARACTER – One of a set of symbols. The general term to include all symbols such as alphabetic letters, numerals, punctuation marks, mathematic operators, etc. Also, the coded representation of such symbols.

CHIP – A single piece of silicon which has been cut from a slice by scribing and breaking. It can contain one or more circuits but is packaged as a unit.

CIRCULAR INTERPOLATION – 1. Capability of generating up to 90 degrees of arc using one block of information as defined by EIA. 2. A mode of contouring control which uses the information contained in a single block to produce an arc of a circle.

CLDATA – Cutter location data (see CLFILE).

CLEAR – To erase the contents of a storage device by replacing the contents with blanks or zeros.

CLEARANCE DISTANCE – The distance between the tool and the workpiece when the change is made from rapid approach to feed movement to avoid tool breakage.

CLFILE – Cutter location file (see CLDATA).

CLOCK – A device which generates periodic synchronisation signals.

CLOSED LOOP – A signal path in which outputs are fed back for comparison with desired values to regulate system behaviour.

CNC – Computer (Computerised) Numerical Control – A numerical control system wherein a dedicated, stored program computer is used to perform some or all of the basic numerical control functions.

COMMAND – An operative order which initiates a movement or a function.

COMPATIBILITY – The interchangeability of items.

COMPILER – A program which translates from high-level problem-oriented computer languages to machine-oriented instructions.

COMPONENT – One of the parts of which an entity is composed.

COMPUTER – A device capable of accepting information in the form of signals or symbols, performing prescribed operations on the information, and providing results as outputs.

COMPUTER-AIDED DESIGN (CAD) – A process which uses a computer in the creation or modification of a design.

COMPUTER-AIDED DESIGN/COMPUTER-AIDED MANUFACTURE (CADCAM) – The integration of computer-aided design with computer-aided manufacture.

COMPUTER-AIDED ENGINEERING (CAE) – The use of computing facilities in the integration of all aspects of design and manufacture to create an integrated engineering facility.

COMPUTER-AIDED MANUFACTURE (CAM) – A process which uses a computer in the management, control or operation of a manufacturing facility.

COMPUTER PART PROGRAMMING – The preparation of a part program to obtain a machine program using a computer and appropriate processor and part processor.

CONFIGURATION – The manner in which items are arranged.

CONTINUOUS PATH OPERATION – An operation in which rate and direction of relative movement of machine members is under continuous numerical control. There is no pause for data reading.

CONTOURING – An operation in which simultaneous control of more than one axis is accomplished.

CONTOURING CONTROL SYSTEM – An NC system for controlling a machine (milling, drafting, etc.) in a path resulting from the coordinated, simultaneous motion of 2 or more axes.

CONTROLLED PATH (Robots) – The straight line motion of a defined offset tool point between programmed points. All robot axes are interpolated through the programmed span.

CONTROL TAPE – A tape on which a machine program is recorded.

COORDINATE DIMENSIONING – A system of dimensioning based on a common starting point.

COORDINATE DIMENSIONING WORD – 1. A word in a block of machining information that provides instruction for one of the machine's axes. 2. A word defining an absolute dimension.

CORE MEMORY – A high-speed random access data storage device utilising arrays of magnetic ferrite cores, usually employed as a working computer memory.

CORE RESIDENT – Pivotal programs permanently stored in core memory for frequent execution.

COUNTER – A device or memory location whose value or contents can be incremented or decremented in response to an input signal.

CURSOR – Visual movable pointer used on a CRT by an operator to indicate where corrections or additions are to be made.

CUTTER DIAMETER COMPENSATION – A system in which the programmed path may be altered to allow for the difference between actual and programmed cutter diameters.

CUTTER OFFSET – 1. The distance from the part surface to the axial centre of a cutter. 2. An NC feature which allows an operator to use an oversized or undersized cutter.

CUTTER PATH – The path described by the centre of a cutter.

CYCLE – 1. A sequence of operations that is repeated regularly. 2. The time it takes for one such sequence to occur.

CYCLE TIME – The period required for a complete action. In particular, the interval required for a read and a write operation in working memory, usually taken as a measure of computer speed.

CYCLING CONTROL – A fundamental level machine control which programs the machine through dial or plugboard input.

D

DAMPING – A characteristic built into electrical circuits and mechanical systems to prevent rapid or excessive corrections which might lead to instability or oscillatory conditions.

DATA – Facts or information prepared for processing by, or issued by, a computer.

DATABASE – Comprehensive files of information having a specific structure such that they are suitable for communication, interpretation and processing by both human and automatic means.

DATA POINT – A programmed point which contains tool plant coordinate data and functional information.

DEAD BAND – The range through which an input can be varied without initiating response, usually expressed in percentage of span.

DEAD TIME – The interval between initiation of a stimulus change and the start of the resulting response.

DEAD ZONE – A range of inputs for which no change in output occurs.

DEBUG – To detect, locate, and remove mistakes from computer software or hardware.

DECADE – A group of assembly of ten units.

DECADE SWITCHING – Use of a series of switches each with ten positions with values of 0 to 9, in which adjacent switches have a ratio of value of 10:1.

DECIMAL CODE – A code in which each allowable position has one of 10 possible states. (The conventional decimal number system is a decimal code.)

DECODER – A circuit arrangement which receives and converts digital information from one form to another.

DEDICATED – Devoted to a particular function or purpose.

DEVIATION – The error or difference between the instantaneous value of the controlled variable and the setpoint.

DIAGNOSTIC ROUTINE – A program which locates malfunctions in hardware or software.

DIGITAL – Representation of data in discrete or numerical form.

DIGITAL COMPUTER – A computer that operates on symbols representing data, by performing arithmetic and logic operations.

DIGITAL-TO-ANALOG (D-A) CONVERSION – Production of an analog signal, whose instantaneous magnitude is proportional to the value of a digital input.

DIGITISE – To obtain the digital representation of a measured quantity or continuous signal.

DIRECTOR – A term used to designate an NC control unit.

DISCRETE – State of being separate or distinct, as opposed to a continuously varying state or condition.

DISCRETE COMPONENT CIRCUIT – An electrical circuit, implemented with individual transistors, resistors, diodes, capacitors, or other components.

DISK – A device on which information is stored.

DISK MEMORY – A non-programmable, bulk storage, random access memory consisting of a magnetisable coating on one or both sides of a rotating thin circular plate.

DISPLAY – Lights, annunciators, numerical indicators, or other operator output devices at consoles or remote stations.

DISTRIBUTED COMPUTER NETWORK – A collection of computers which can communicate with each other.

DISTRIBUTED PROCESSING – The processing of information on a distributed computer network in such a manner as to improve the overall efficiency of the task.

DITHER – An electrical oscillatory signal of low amplitude and of a predetermined frequency imparted to a servo valve to keep the spool from sticking.

DNC – (Direct Numerical Control) Numerical control of machining or processing by a computer.

DOCUMENTATION – The group of techniques necessarily used to organise, present, and communicate recorded specialised knowledge.

DOUBLE PRECISION – The use of two computer words to represent a number.

DOWNTIME – The interval during which a device is inoperative.

DRIFT – An undesired change in output over a period of time, which is unrelated to input, operating conditions, or load.

DRIVER – A program or routine that controls external peripheral devices or executes other programs.

DUMP – To copy the present contents of a memory onto a printout or auxiliary storage.

DWELL – A timed delay of programmed or established duration, not cyclic or sequential, i.e., not an interlock or hold.

DYNAMIC GAIN – The magnitude ratio of a steady-state output to a sinusoidal input signal.

E

EBCDIC – Extended binary coded decimal interchange code.

EDIT – To modify a program, or alter stored data prior to output.

EDITOR – A computer program which provides the ability to edit.

EIA STANDARD CODE – Any one of the Electronics Industries Association standard codes for positioning, straight-cut, and contouring control systems.

ELECTROMAGNETIC INTERFERENCE (EMI) – Unwanted electrical energy or noise induced in the circuits of a device, owing to the presence of electromagnetic fields.

EMULATOR – A device or program which behaves like another system, and produces identical results.

ENCODER – An electromechanical transducer which produces a serial or parallel digital indication of mechanical angle or displacement.

END EFFECTOR (Robots) – The general term used to describe a gripper or other tool used on a robot.

END OF BLOCK CHARACTER – 1. A character indicating the end of a block of tape information. Used to stop the tape reader after a block has been read. 2. The typewriter function of the carriage return when preparing machine control tapes.

END OF PROGRAM – A miscellaneous function (M02) indicating completion of a workpiece. (Stops spindle, coolant, and feed after completion of all commands in the block. Used to reset control and/or machine.)

END OF TAPE – A miscellaneous function (M30) which stops spindle, coolant and feed after completion of all commands in the block. (Used to reset control and/or machine.)

END POINT – An extremity of a span.

ERROR – The difference between the indicated and desired values of a measured signal.

ERROR DETECTING – A data code in which each acceptable term conforms to certain rules, such that if transmission or processing errors occur, false results can be detected.

ERROR SIGNAL – Difference between the output and input signals in a servo system.

EXCLUSIVE OR – A logical operator, which has the property such that if X and Y are two logic variables, then the function is defined by the following table:

X	**Y**	**Function**
0	0	0
0	1	1
1	0	1
1	1	0

The logical operator is usually represented in electrical notation by an encircled plus sign "+". There is no equivalent FORTRAN symbol.

EXECUTE – To carry out an instruction or to run a program.

EXECUTIVE – Software which controls the execution of programs in the computer, based on established priorities and real-time or demand requirements.

EXTENDED ARITHMETIC ELEMENT – A CPU logic element, which provides hardware implemented multiply, divide, and normalise functions.

F

FEEDBACK – The signal or data fed back to a commanding unit from a controlled machine or process to denote its response to the command signal. The signal representing the difference between actual response and desired response that is used by the commanding unit to improve performance of the controlled machine or process.

FEEDBACK CONTROL – Action in which a measured variable is compared to its desired value, with a function of the resulting error signal used as a corrective command.

FEEDBACK DEVICE – An element of a control system which converts linear or rotary motion to an electrical signal for comparison to the input signal, e.g., resolver, encoder, inductosyn.

FEEDBACK LOOP – A closed signal path, in which outputs are compared with desired values to obtain corrective commands.

FEEDBACK RESOLUTION – The smallest increment of dimension that the feedback device can distinguish and reproduce as an electrical output.

FEEDBACK SIGNAL – The measurement signal indicating the value of a directly controlled variable, which is compared with a setpoint to generate a correction command.

FEED ENGAGE POINT – The point where the motion of the Z axis changes from rapid traverse to a programmed feed (usually referred to as the "R" dimension).

FEEDFORWARD (ANTICIPATORY) CONTROL – Action in which information concerning upstream conditions is converted into corrective commands to minimise the effect of the disturbances.

FEED FUNCTION – The relative motion between the tool or instrument and the work due to motion of the programmed axis or axes.

FEEDRATE BY-PASS – A function directing the control system to ignore programmed feedrate and substitute selected operational rate.

FEEDRATE NUMBER – A coded number read from the tape which describes the feedrate function. Usually denoted as the "F" word.

FEEDRATE OVERRIDE – A variable manual control function directing the control system to reduce or increase the programmed feedrate.

FINAL CONTROL ELEMENT – A valve, motor, or other device which directly changes the value of the manipulated variable.

FIRMWARE – Programs or instructions stored in read only memories.

FIRST GENERATION – 1. In the NC industry, the period of technology associated with vacuum tubes and stepping switches. 2. The period of technology in computer design utilising vacuum tubes, electronics, off-line storage on drum or disk, and programming in machine language.

FIXED BLOCK FORMAT – A format in which the number and sequence of **words** and **characters** appearing in successive **blocks** is constant.

FIXED HEADS – Rigidly mounted reading and writing transducers on bulk memory devices.

FIXED SEQUENCE FORMAT – A means of identifying a word by its location in a block of information. Words must be presented in a specific order and all possible words preceding the last desired word must be present in the block.

FLIP FLOP – A bi-stable device. A device capable of assuming two stable states. A bistable device which may assume a given stable state depending upon the pulse history of one or more input points and having one or more output points. The device is capable of storing a bit of information; controlling gates; etc. A toggle.

FLOPPY DISK – A flexible disk used for storing information.

FLOW CHART – A graphical representation of a problem or system in which inter-connected symbols are used to represent operations, data, flow, and equipment.

FLUIDICS – The technique of control that uses only a fluid as the controlling medium. All control is performed without moving elements.

FOREGROUND PROCESSING – Execution of real-time or high priority programs, which can pre-empt the use of computing facilities.

FORMAT – The arrangement of data.

FORMAT CLASSIFICATION – A means, usually in an abbreviated notation, by which the motions, dimensional data, type of control system, number of digits, **auxiliary functions**, etc. for a particular system can be denoted.

FORMAT DETAIL – Describes specifically which words of what length are used by a specific system in the **format classification**.

FORTRAN – Acronym for Formula Translator, an algebraic procedure oriented computer language designed to solve arithmetic and logical programs.

FOURTH GENERATION – In the NC industry, the change in technology of control logic to include computer architecture.

FREQUENCY RESPONSE ANALYSIS – A method of analysing systems based on introducing cyclic inputs and measuring the resulting output at various frequencies.

FREQUENCY RESPONSE CHARACTERISTIC – The amplitude and phase relation between steady-state sinusoidal inputs and the resulting sinusoidal outputs.

FULL DUPLEX – Allows the simultaneous transmission of information in both directions.

FULL PROPORTIONAL SERVO – A system with complete proportionality between output and input.

FULL RANGE FLOATING ZERO – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. The control retains information on the location of "permanent" zero.

G

G CODE – A word addressed by the letter G and followed by a numerical code defining preparatory functions or cycle types in a numerical control system.

GAIN – The ratio of the magnitude of the output of a system with respect to that of the input (the conditions of operation and measurements must be specified, e.g., voltage, current or power).

GATE – A device which blocks or passes a signal depending on the presence or absence of specified input signals.

GAUGE HEIGHT – A predetermined partial retraction point along the Z axis to which the cutter retreats from time to time to allow safe X–Y table travel.

GENERAL PURPOSE COMPUTER – A computer designed and capable of carrying out a wide range of tasks.

GENERAL PURPOSE PROCESSOR – A computer program which carries out computations on the part program and prepares the author location data for a particular part without reference to machines on which it might be made.

GRAPHICS – The use of a computer to interactively create a drawing displayed on a terminal.

GRAY CODE – A binary code, in which successive values differ in one place only.

GROUP TECHNOLOGY – The grouping of machines and of parts based on similarities in production requirements such that the parts may be produced more efficiently.

H

HALF DUPLEX – Allows the transmission of information one way at a time.

HARD COPY – Any form of computer-produced printed document. Also, sometimes punched cards or paper tape.

HARDWARE – Physical equipment.

HEAD – A device, usually a small electromagnet on a storage medium such as magnetic tape or a magnetic drum, that reads, records, or erases information on that medium. The block assembly and perforating or reading fingers used for punching or reading holes in paper tape.

HOUSEKEEPING – The general organisation of programs stored to ensure efficient system response.

HYSTERESIS – The difference between the response of a system to increasing and decreasing signals.

I

IC – Integrated circuit.

INCREMENTAL DIMENSION – A dimension expressed with respect to the preceding point in a sequence of points.

INCREMENTAL FEED – A manual or automatic input of present motion command for a machine axis.

INCREMENTAL PROGRAMMING – Programming using words indicating incremental dimensions.

INCREMENTAL SYSTEM – Control system in which each coordinate or positional dimension is taken from the last position.

INDEXING – Movement of one axis at a time to a precise point from numeric commands.

INDUCTOSYN SCALE – A precision data element for the accurate measurement and control of angles or linear distances, utilising the inductive coupling between conductors separated by a small air gap.

INHIBIT – To prevent an action or acceptance of data by applying an appropriate signal to the appropriate input.

INITIALISE – To cause a program or hardware circuit to return a program, a system, or a hardware device to an original state or to selected points with a computer program.

INPUT – A dependent variable applied to a control unit or system.

INPUT RESOLUTION – The smallest increment of dimension that can be programmed as input to the system.

INSTABILITY – The state or property of a system where there is an output for which there is not corresponding input.

INSTRUCTION – A statement that specifies an operation and the values or locations of its operands.

INSTRUCTION SET – The list of machine language instructions which a computer can perform.

INTEGRATED CIRCUIT (IC) – A combination of interconnected passive and active circuit elements incorporated on a continuous substrate.

INTEGRATOR – A device which integrates an input signal, usually with respect to time.

INTELLIGENT TERMINAL – A terminal which has its own local processing power.

INTERACTIVE GRAPHICS – Ability to carry out graphics tasks with immediate response from the computer.

INTERFACE – 1. A hardware component or circuit for linking two pieces of electrical equipment having separate functions, e.g., tape reader to data processor or control system to machine. 2. A hardware component or circuit for linking the computer to external I/O device.

INTERFEROMETER – An instrument that uses light interference phenomena for determination of wavelength, spectral fine structure, indices of refraction, and very small linear displacements.

INTERLOCK – To arrange the control of machines or devices so that their operation is interdependent in order to assure their proper coordination.

INTERLOCK BY-PASS – A command to temporarily circumvent a normally provided interlock.

INTERPOLATION – 1. The insertion of intermediate information based on assumed order or computation. 2. A function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a defined geometric pattern, e.g., linear, circular and parabolic.

INTERPOLATOR – A device which is part of a numerical control system and performs interpolation.

INTERRUPT – A break in the execution of a sequential program or routine, to permit processing of high priority data.

I/O – (Input/Output) Input or output or both.

ITERATION – A set of repetitive computations, in which the output of each step is the input to the next step.

J

JCL – Job control program

JOB – An amount of work to be completed.

JOG – A control function which provides for the momentary operation of a drive for the purpose of accomplishing a small movement of the driven machine.

K

KEYBOARD – The keys of a teletype-writer which have the capability of transmitting information to a computer but not receiving information.

L

LAG – Delay caused by conditions such as capacitance, inertia, resistance or dead time.

LANGUAGE – A set of representations and rules used to convey information.

LAYOUT – A visual representation of a complete physical entity usually to scale.

LEVEL – 1. Formerly a channel of punched tape. 2. The average amplitude of a variable quantity applying particularly to sound or electronic signals expressed in decibels, volts, amperes, or watts. 3. The degree of subordination in a hierarchy.

LIGHT PEN – A photo sensing device similar to an ordinary fountain pen which is used to instruct CRT displays by means of light sensing optics.

LINEAR INTERPOLATION – A function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a linear (straight line) path.

LINE PRINTER – A printing device that can print an entire line of characters all at once.

LINKAGE – A means of communicating information from one routine to another.

LOCKOUT SWITCH – A switch provided with a memory, which protects the contents of designated segments from alteration.

LOG – A detailed record of actions for a period of time.

LOG OFF – The completion of a terminal session.

LOG ON – The beginning of a terminal session.

LOGIC – 1. Electronic devices used to govern a particular sequence of operations in a given system. 2. Interrelation or sequence of facts or events when seen as inevitable or predictable.

LOGIC LEVEL – The voltage magnitude associated with signal pulses representing ONES and ZEROS in binary computation.

LOOP TAPE – A short piece of tape, containing a complete program of operation, with the ends joined.

LSI – Large Scale Integration – A large number of interconnected integrated circuits manufactured simultaneously on a single slice of semi-conductor material.

M

MACHINE LANGUAGE – A language written in a series of bits which are understandable by, and therefore instruct, a computer. The "first level" computer language, as compared to a "second level" assembly language or a "third level" compiler language.

MACHINE PROGRAM – An ordered set of instructions in automatic control language and format recorded on appropriate input media and sufficiently complete to effect the direct operation of an automatic control system.

MACHINING CENTRE – A machine tool, usually numerically controlled, capable of automatically drilling, reaming, tapping, milling and boring multiple faces of a part and often equipped with a system for automatically changing cutting tools.

MACRO – A source language instruction from which many machine language instructions can be generated (see compiler language).

MAGNETIC CORE – An element for switching or storing information on magnetic memory elements for later use by a computer.

MAGNETIC CORE STORAGE – The process of storing information on magnet memory elements for later use by a computer.

MAGNETIC DISK STORAGE – A storage device or system consisting of magnetically coated metal disks.

MAINFRAME – See central processing unit.

MANAGEMENT INFORMATION SERVICE (MIS) – An information feedback system from the machine to management and implemented by a computer.

MANUAL DATA INPUT (MDI) – A means of inserting data manually into the control system.

MANUAL FEEDRATE OVERRIDE – Device enabling operator to reduce or increase the feedrate.

MANUAL PART PROGRAMMING – The manual preparation of a manuscript in machine control language and format to define a sequence of commands for use on an NC machine.

MANUSCRIPT – Form used by a part programmer for listing detailed manual or computer part programming instructions.

MEMORY – A device or media used to store information in a form that can be understood by the computer hardware.

MEMORY, BULK – Any non-programmable large memory, i.e., drum, disk.

MEMORY CYCLE TIME – The minimum time between two successive data accesses from a memory.

MEMORY PROTECT – A technique of protecting stored data from alteration, using a guard bit to inhibit the execution of any modification instruction.

MICROPROCESSOR – A single integrated circuit which forms the basic element of a computer.

MICROPROGRAMMING – A programming technique in which multiple instruction operations can be combined for greater speed and more efficient memory use.

MICROSECOND – One millionth of a second.

MILLISECOND – One thousandth of a second.

MISCELLANEOUS FUNCTION – An off–on function of a machine such as Clamp or Coolant on. (See Auxiliary Function).

MNEMONIC – An alphanumeric designation, designed to aid in remembering a memory location or computer operation.

MODEM – A contraction of modulator demodulator. The term may be used with two different meanings: 1. The modulator and the demodulator of a modem are associated at the same end of a circuit. 2. The modulator and the demodulator of a modem are associated at the opposite ends of a circuit to form a channel.

MODULE – An independent unit which may be used on its own or in conjunction with other units to form a complete entity.

MONITOR – A device used for observing or testing the operations of a system.

MOVABLE HEADS – Reading and writing transducers on bulk memory devices which can be positioned over the data locations.

MSI – Medium Scale Integration. (See LSI.) Smaller than LSI, but having at least 12 gates or basic circuits with at least 100 circuit elements.

MULTIPLEXER – A hardware device which handles multiple signals over a single channel.

N

NAND – A combination of the Boolean logic functions NOT and AND.

NAND GATE – A component which implements the NAND function.

NANOSECOND – One thousandth of one microsecond.

NEGATIVE LOGIC – Logic in which the more negative voltage represents the one (1) state; the less negative voltage represents the zero (0) state.

NIXIE LIGHT OR TUBE – A glow lamp which converts a combination of electrical impulses into a visible number.

NOISE – An extraneous signal in an electrical circuit capable of interfering with the desired signal. Loosely, any disturbance tending to interfere with the normal operation of a device or system.

NOR GATE – A component which implements the NOR function.

NOT – A logic operator having property that if P is a logic quantity then quantity "NOT P" assumes values as defined in the following table:

P	NOT P
0	1
1	0

The NOT operator is represented in electrical notation by an overline, e.g., $\overline{P}$ and in FORTRAN by a minus sign "–" in a Boolean expression.

NUMERICAL CONTROL (NC) – A technique of operating machine tools or similar equipment, in which motion is developed in response to numerically coded commands.

NUMERICAL DATA – Data in which information is expressed by a set of numbers that can only assume discrete values.

O

OBJECT PROGRAM – The coded output of an assembler or compiler.

OCTAL – A characteristic of a system in which there are eight elements, such as a numbering system with a radix of eight.

OFF-LINE – Operating software or hardware not under the direct control of a central processor, or operations performed while a computer is not monitoring or controlling processes or equipment.

OFFSET – The steady-state deviation of the controlled variable from a fixed setpoint.

ON-LINE – A condition in which equipment or programs are under direct control of a central processor.

ONE – One of the two symbols normally employed in binary arithmetic and logic, indicating binary one and the true condition, respectively.

OPEN LOOP – A signal path without feedback.

OPEN LOOP SYSTEM – A control system that has no means of comparing the output with the input for control purposes (no feedback).

OPERATING SYSTEM – Software which controls the execution of computer programs and the movement of information between peripheral devices.

OPTIMISATION – A process whose object is to make one or more variables assume, in the best possible manner, the value best suited to the operation in hand, dependent on the values of certain other variables which may be either predetermined or sensed during the operation.

OPTIMISE – To establish control parameters which maximise or minimise the value of performance.

OPTIONAL STOP – **A Miscellaneous Function** command similar to "Program Stop" except that the control ignores the command unless the operator has previously pushed a button to validate the command (M01).

OR – A logic operator having the property that if P and Q are logic quantities then the quantity "P or Q" assumes values as defined by the following table:

P	**Q**	**P OR Q**
0	0	0
0	1	1
1	0	1
1	1	1

The OR operator is represented in both electrical and FORTRAN terminology by a "+", i.e., P + Q.

OR GATE – A device which implements the OR function.

ORIENTATION (Robots) – The angular position of the wrist axes.

OUTPUT – Dependent variable signal produced by a transmitter, control unit or other device.

OUTPUT IMPEDANCE – The impedance presented by a device to the load.

OUTPUT SIGNAL – A signal delivered by a device, element, or system.

OVERLAY – A technique of repeatedly using the same area of computer store when actioning different stages of a problem.

OVERSHOOT – The amount that a controlled variable exceeds its desired value after a change of input.

P

PARABOLA – A plane curve generated by a point moving so that its distance from a fixed second point is equal to its distance from a fixed line.

PARABOLIC INTERPOLATION – Control of cutter path by interpolation between three (3) fixed points by assuming the intermediate points are on a parabola.

PARALLEL – The simultaneous transfer and processing of all bits in a unit of information.

PARAMETER – A characteristic of a system or device, the value of which serves to distinguish various specific states.

PARITY CHECK – A test of whether the number of ONES or ZEROS in an array of binary digits is odd or even to detect errors in a group of bits.

PART PROGRAM – An ordered set of instructions in a language and in a format required to cause operations to be effected under automatic control, which is either written in the form of a machine program on an input media or prepared as input data for processing in a computer to obtain a machine program.

PART PROGRAMMER – A person who prepares the planned sequence of events for the operation of a numerically controlled machine tool.

PASSWORD – A word the operator must supply in order to meet the security requirements and gain access to the computer.

PATCH – Temporary coding used to correct or alter a routine, or a term used in CAD.

PERIPHERAL – Auxiliary equipment used for entering data into or receiving data from a computer.

PERIPHERAL EQUIPMENT – The auxiliary machines and storage devices which may be placed under control of the central computer and may be used on-line or off-line, e.g., card reader and punches, magnetic tape feeds, high speed printers, CRTs and magnetic drums or disks.

PICOSECOND – One millionth of one microsecond.

PITCH (Robots) – A rotation of the payload or tool about a horizontal axis on the end of a robot arm which is perpendicular to the longitudinal axis of the arm.

PLANNING SHEET – A list of operations for the manufacture of a part, prepared before the part program.

PLOTTER – A device used to make a drawing of a display.

POINT-TO-POINT CONTROL SYSTEM – An NC system which controls motion only to reach a given end point but exercises no path control during the transition from one end point to the next.

POLAR AXES – The fixed lines from which the angles made by radius vectors are measured in a polar coordinates system.

POLAR COORDINATES – A mathematical system for locating a point in a plane by the length of its radius vector and the angle this vector makes with a fixed line.

POSITION READOUT – A display of absolute slide position as derived from a position feedback device (transducer usually) normally attached to the lead screw of the machine. (See Command Readout.)

POSITION SENSOR – A device for measuring a position, and converting this measurement into a form convenient for transmission.

POSITION STORAGE – The storage media in an NC system containing the coordinate positions read from tape.

POSITIVE LOGIC – Logic in which the more positive voltage represents the one (1) state.

POST-PROCESSOR – A computer program which adapts the output of a processor into a machine program for the production of a part on a particular combination of machine tool and controller.

PRECISION – The degree of discrimination with which a quantity is stated, e.g., a three-digit numeral discriminates among 1000 possibilities. Precision is contrasted with accuracy, i.e., a quantity expressed with 10 decimal digits of precision may only have one digit of accuracy.

PREPARATORY FUNCTION – An NC command on the input tape changing the mode of operation of the control. (Generally noted at the beginning of a block by "G" plus two digits.)

PREPROCESSOR – A computer program which prepares information for processing.

PREVENTATIVE MAINTENANCE – Maintenance specifically designed to identify potential faults before they occur.

PRINTED CIRCUIT – A circuit for electronic components made by depositing conductive material in continuous paths from terminal to terminal on an insulating surface.

PROCESSOR – A computer program which processes information.

PROGRAM – A plan for the solution of a problem. A complete program includes plans for the transcription of data, coding for the computer, and plans for the absorption of the results into the system. The list of coded instructions is called a routine. To plan a computation or process from the asking of a question to the delivery of the results, including the integration of the operation into an existing system. Thus, programming consists of planning and coding, including numerical analysis, systems analysis, specification of printing formats, and any other functions necessary to the integration of a computer in a system.

PROGRAMMABLE – Capable of being set to operate in a specified manner, or of accepting remote setpoint or other commands.

PROGRAMMED ACCELERATION – A controlled velocity increase to the programmed feedrate of an NC machine.

PROGRAMMED DWELL – The capability of commanding delays in program execution for a programmable length of time.

PROGRAM STOP – A **Miscellaneous Function** (M00) command to stop the spindle, coolant and feed after completion of the dimensional move commanded in the **block**. To continue with the remainder of the program, the operator must initiate a restart.

PROTOCOL – Set of rules governing message exchange between two devices.

PUNCHED PAPER TAPE – A strip of paper on which characters are represented by combinations of holes.

PULSE – A short duration change in the level of a variable.

Q

QUADRANT – Any of the four parts into which a plane is divided by rectangular coordinate axes lying in that plane.

QUADRATURE – Displaced 90 degrees in phase angle.

R

R DIMENSION – (See Feed Engage Point).

RANDOM ACCESS MEMORY (RAM) – A storage unit in which direct access is provided to information, independent of memory location.

RASTER DISPLAY – A display in which the entire display surface is scanned at a constant refresh rate.

RASTER SCAN – Line-by-line sweep across the entire display surface to generate elements of a display image.

READ – To acquire data from a source. To copy, usually from one form of storage to another, particularly from external or secondary storage to internal storage. To sense the meaning of arrangements of hardware. To sense the presence of information on a recording medium.

READER – A device capable of sensing information stored in off-line memory media (cards, paper tape, magnetic tape) and generating equivalent information in an on-line memory device (register, memory locations).

READ ONLY MEMORY (ROM) – A storage device generally used for control program, whose content is not alterable by normal operating procedures.

REAL TIME CLOCK – The circuitry which maintains time for use in program execution and event initiation.

REAL TIME OPERATION – Computer monitoring, control, or processing functions performed at a rate compatible with the operation of physical equipment or processes.

REFERENCE BLOCK – A block within an NC program identified by an "O" or "H" in place of the word address "N" and containing sufficient data to enable resumption of the program following an interruption. (This block should be located at a convenient point in the program which enables the operator to reset and resume operation.)

REFRESH – CRT display technology which requires continuous restroking of the display image.

RELOCATABLE POINT/SEQUENCE OF POINT (Robots) – A point or sequence in a robot which can be relocated in space.

REPAINT – Redraws a display on a CRT to reflect its current status.

REPEATABILITY – The closeness of agreement among multiple measurements of an output, for the same value of the measured signal under the same operating conditions, approaching from the same direction, for full range traverses.

REPRODUCIBILITY – The closeness of agreement among repeated measurements of the output for the same value of input, made under the same operating conditions over a period of time, approaching from either direction.

RESOLUTION – 1. The smallest distinguishable increment into which a signal or picture, etc. is divided in a device or system. 2. The minimum positioning motion which can be specified.

RESOLVER – 1. A mechanical to electrical transducer (see Transducer) whose input is a vector quantity and whose outputs are components of the vector. 2. A transformer whose coupling may be varied by rotating one set of windings relative to another. It consists of a stator and rotor, each having two distributed windings 90 electrical degrees apart.

RETROFIT – Work done to an existing machine tool from simply adding special jigs or fixtures to the complete re-engineering and manufacturing, and often involving the addition of a numerical control system.

ROBOT – An automatic device which performs functions ordinarily ascribed to human beings.

ROLL (Robots) – A rotation of the payload or tool about the longitudinal axis of the wrist.

ROUTINE – A series of computer instructions which performs a specified task.

RUN – The execution of a program on a computer.

S

SAMPLE AND HOLD – A circuit used to increase the interval during which a sampled signal is available, by maintaining an output equal to the most recent input sample.

SAMPLES DATA – Data in which the information content can be, or is, ascertained only at discrete intervals of time. (Can be analog or digital.)

SAMPLING PERIOD – The interval between observations in a periodic sampling control system.

SCALE – To change a quantity by a given factor, to bring its range within prescribed limits.

SCALE FACTOR – A coefficient used to multiply or divide quantities in order to convert them to a given magnitude.

SCHEDULE – A programme or timetable of planned events or of work.

SECOND GENERATION – 1. In the NC industry, the period of technology associated with transistors (solid state). 2. The period of technology in computer design utilising solid-state circuits, off-line storage, and significant development in software, the assembler.

SECURITY – Prevention of unauthorised access to information or programs.

SENSITIVITY – The ratio of a change in steady state output to the corresponding change of input, often measured in percentage of span.

SENSOR – A unit which is actuated by a physical quantity and which gives a signal representing the value of that physical quantity.

SEQUENCE (Robots) – Part of a robot program which consists of a point or series of points the performance of which will be dependent on defined input/flag conditions existing.

SEQUENCE CONTROL – A system of control in which a series of machine movements occurs in a devised order, the completion of one movement initiating the next, and in which the extent of the movements is not specified by numeric data.

SERIAL – The transfer and processing of each bit in a unit of information, one at a time.

SERVO AMPLIFIER – The part of the servo system which increases the error signal and provides the power to drive the machine slides or the servo valve controlling a hydraulic drive.

SETPOINT – The position established by an operator as the starting point for the program on an NC machine.

SIGN – The symbol or bit which distinguishes positive from negative numbers.

SIGNAL – Information conveyed between points in a transmission or control system, usually as a continuous variable.

SIGNIFICANT DIGIT – A digit that contributes to the precision of a numeral. The number of significant digits is counted beginning with the digit contributing the most value, called the most significant digit, and ending with the one contributing the least value, called the least significant digit.

SIMULATOR – A device or computer program that performs simulation.

SKEWING – Refers to time delay or offset between any two signals in relation to each other.

SOFTWARE – The collection of programs, routines, and documents associated with a computer.

SOURCE IMPEDANCE – The impedance presented to the input of a device by the source.

SOURCE LANGUAGE – The symbolic language comprising statements and formulas used to specify computer processing. It is translated into object language by an assembler or compiler, and is more powerful than an assembly language in that it translates one statement into many items (see macro).

STABILITY – Freedom from undesirable deviation, used as a measure of process controllability.

STANDBY POWER SUPPLY – An energy generation or storage system that can permit equipment to operate temporarily or shut down in an orderly manner.

STATIC GAIN – The ratio of steady-state output to input change.

STEADY STATE – A characteristic or condition exhibiting only negligible change over an arbitrarily long period of time.

STEPPING MOTOR – A bi-directional permanent magnet motor which turns in finite steps.

STEP RESPONSE – The time response of an instrument subjected to an instantaneous change in input.

STEP RESPONSE TIME – The time required for an element output to change from an initial value to a specified percentage of a steady state, either before or in the absence of overshoot, after an input step change.

STORAGE – A memory device in which data can be entered and held, and from which it can be retrieved.

STORAGE TUBE – A CRT which retains an image for a considerable period of time without redrawing.

STRAIGHT CUT SYSTEM – A system which has feedrate control only along the axes and can control cutting action only along a path parallel to the linear (or circular) machine ways.

SUB PROGRAM – A segment of a machine program which can be called into effect by the appropriate machine control command.

SUBROUTINE – A series of computer instructions to perform a specific task for many other routines. It is distinguishable from a main routine in that it requires, as one of its parameters, a location specifying where to return to the main program after its function has been accomplished.

SUMMING POINT – A point at which signals are added algebraically.

SYNCHRO – A transformer having a polyphase primary winding and single phase secondary winding which can be rotated. The voltage induced into the secondary may be controlled in phase by turning the secondary coil.

SYNCHRONOUS – A fixed rate transmission of information synchronised by a clock for both receiver and sender.

SYNTAX – The rules which govern the structure of words and expressions in a language.

T

TABLET – An input device which allows digitised coordinates to be indicated by stylus position.

TACHOMETER – A speed measuring instrument generally used to determine revolutions per minute. In NC it is used as a velocity feedback device.

TAPE – A magnetic or perforated paper medium for storing information.

TAPE LEADER – The front or lead portion of a tape.

TAPE PREPARATION – The act of translating command information into punched or magnetic tape.

TAPE TRAILER – The trailing end portion of a tape.

TASK – A unit of work.

TEACH (Robots) – The mode by which a robot is driven to required points in space for programming.

TERMINAL – A device by which information may be entered or extracted from a system or communication network.

THIRD GENERATION – 1. In the NC industry, the period of technology associated with integrated circuits. 2. The period of technology in computer design utilising integrated circuits, core memory, advanced subroutines, time sharing, and fast core access.

THRESHOLD – The minimum value of a signal required for detection.

TIME CONSTANT – For a first order system, the time required for the output to complete 63.2% of the total rise or decay as a result of a step change of the input.

TIME SHARING – The interleaved use of a sequential device, to provide apparently simultaneous service to a number of users.

TOGGLE – A flip-flop or two-position switch.

TOOL CENTRE POINT (Robots) – The real or imaginary offset point defined in relation to the tool mounting plate of a robot which moves in a straight line between programmed points and at the programmed velocity in controlled path machines.

TOOL FUNCTION – A tape command identifying a tool and calling for its selection. The address is normally a "T" word.

TOOL LENGTH COMPENSATION – A manual input means which eliminates the need for preset tooling and allows programmer to program all tools as if they are of equal length.

TOOL OFFSET – 1. A correction for tool position parallel to a controlled axis. 2. The ability to reset tool position manually to compensate for tool wear, finish cuts and tool exchange.

TOOLPATH – The geometry of the path a tool will follow to machine a component.

TOOLPATH FEEDRATE – The velocity, relative to the workpace, of the tool reference point along the author path, usually expressed in units of length per minute or per revolution.

TRACK – The portion of a moving storage medium, such as the drum, tape or disc, that is accessible to a given reading head position.

TRANSFER FUNCTION – An expression relating the output of a linear system to the input.

TRUNCATE – To terminate a computational process in accordance with some rule, e.g., to end the evaluation of a power series at a specified term.

TRUTH TABLE – A matrix that describes a logic function by listing all possible combinations of inputs, and indicating the outputs for each combination.

TUNING – The adjustment of coefficients governing the various modes of control.

TURNING CENTRE – A lathe type numerically controlled machine tool capable of automatically boring, turning outer and inner diameters, threading, facing multiple diameters and faces of a part and often equipped with a system for automatically changing or indexing cutting tools.

TURN KEY SYSTEM – A term applied to an agreement whereby a supplier will install an NC or computer system so that he has total responsibility for building, installing, and testing the system.

V

VARIABLE (Robots) – An ability to count events.

VARIABLE BLOCK FORMAT – Tape format which allows the number of words in successive blocks to vary.

VECTOR – A quantity that has magnitude, direction and sense and that is commonly represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

VECTOR FEEDRATE – The resultant feedrate which a cutter or tool moves with respect to the work surface. The individual slides may move slower or faster than the programmed rate; but the resultant movement is equal to the programmed rate.

VOLATILE STORAGE – A memory in which data can only be retained while power is being applied.

W

WINDUP – Lost motion in a mechanical system which is proportional to the force or torque applied.

WIRE-FRAME – A 3-dimensional drawing created by the projection of the points of intersection of the geometry.

WORD ADDRESS FORMAT – Addressing each word in a block by one or more characters which identify the meaning of the word.

WORD LENGTH – The number of bits or characters in a word.

WORLD COORDINATES (Robots) – The coordinate system by which a point in space is defined in three cartesian coordinates and three orientation or polar coordinates.

WRIST (Robots) – The element of a robot which applies orientation to a tool.

X

X AXIS – Axis of motion that is always horizontal and parallel to the work-holding surface.

Y

Y AXIS – Axis of motion that is perpendicular to both the X and Z axes.

YAW (Robots) – A rotation of a payload or tool about a vertical axis that is perpendicular to the pitch axis of the wrist.

Z

Z AXIS – Axis of motion that is always parallel to the principal spindle of the machine.

ZERO – One of the two symbols normally employed in binary arithmetic and logic, indicating the value zero and the false condition, respectively.

ZERO OFFSET – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. (The control retains information on the location of the "permanent" zero.)

ZERO SHIFT – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. (The control does **not** retain information on the location of the "permanent" zero.)

ZERO SUPPRESSION – The elimination of non-significant zeros to the left of significant digits usually before printing.

ZERO SYNCHRONISATION – A technique which permits automatic recovery of a precise position after the machine axis has been approximately positioned by manual control.

[COURTESY OF THE NUMERICAL ENGINEERING SOCIETY (UK)]

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Company Addresses

UK Head Office

William Asquith (1981) Ltd
Highroad Well Works
Gibbet Street
Halifax
W. Yorks
HX2 OAP
Tel: 0422 367771

Boko Machine Tools (UK) Ltd
Kingfield Industrial Estate
Kingfield Road
Coventry
West Midlands
CV1 4DW
Tel: 0203 228447/8

Bostomatic UK Ltd
7 Prospect Way
Butler's Leap
Rugby
CV21 3UU
Tel: 0788 73865

Bridgeport Machines Ltd
PO Box 22
Forest Road
Leicester
LE5 OFJ
Tel: 0533 531122

Butler Newall Ltd
(Electronic Accuracy Systems)
Westholme Road
Halifax
HX1 4JR
Tel: 0422 331144

International Head Office

Bohner & Kohle
GmbH & Co
Maschinenfabrik
Weilstrasse 4–10
D-7300 Esslingen/Neckar
Postfach 67
Germany
Tel: 0711-3901-0

Boston Digital Corp
Granite Park
Milford
MA 01757
USA
Tel: (508) 473–4561

Bridgeport Machines Inc
500 Lindley Street
Bridgeport
CT 06606
USA

UK Head Office	*International Head Office*
BYG Systems Ltd Highfields Science Park University Boulevard Nottingham NG7 2QP Tel: 0602 252221	
Carne (UFM) Ltd Swan Works 416–418 London Road Isleworth Middlesex TW7 5AE Tel: 081 5601182	**Ibag Zürich AG** Glattalstrasse 138 CH-8052 Zürich Switzerland Tel: 01 301 0020
Centreline Machine Tool Co. Ltd Newton Road Hinckley Leics LE10 3DS Tel: 0455 618012	
Cimcool Division Head Office Cincinnati Milacron Ltd Maybrook Road Castle Vale Industrial Estate Sutton Coldfield West Midlands B76 8BB Tel: 021 351 1891	**Cimcool Industrial Products** PO Box 463 3130 Al-Vlaardingen Netherlands 460 0660
The Cimulation Centre Avon House PO Box 46 Chippenham Wiltshire SN15 1JH Tel: 0249 650316	
Cincinnati Milacron UK Ltd PO Box No. 505 Kingsbury Road Birmingham B24 0QU Tel: 021 351 3821	**Cincinnati Head Quarters** Oakley Complex 4701 Marburg Avenue Cincinnati Ohio 45209 USA Tel: 513 841 8100
Cranfield Precision Engineering Ltd (CUPE) Cranfield Institute of Technology Cranfield Bedford MK43 0AL Tel: 0234 752789	
Crawford Collets Ltd Tower Hill Works Witney Oxfordshire OX8 5DS Tel: 0993 703931	

UK Head Office	*International Head Office*
Dean Smith & Grace Ltd Keighley West Yorkshire BD1 4PG Tel: 0535 605261	**Monarch M/C Tool Co** 615 North Oak Street PO Box 668 Sidney Ohio 45365 USA Tel: 513 492 4111
DeBeers Industrial Diamond Division Ltd Charters Sunninghill Ascot Berks SL5 9PX Tel: 0990 23456	
Devlieg Microbore Tooling Co Leicester Road Lutterworth Leics LE17 4HE Tel: 0455 553030	
Eclipse Magnetics Ltd Vulcan Road Sheffield S9 1EW Tel: 0742 560600	
Federal-Mogul Westwind Air Bearings Ltd Trading Park Holton Heath Poole Dorset BH16 6LN Tel: 0202 622565	
Ferranti Industrial Electronics Ltd Dunsinane Avenue Dundee DD2 3PN Tel: 0382 89311	
Flexible Manufacturing Technology Ltd (FMT) Carden Avenue Hollingbury Brighton BN1 8AU Tel: 0273 507255	
GE Fanuc Automation 1 Fairways Pitfield Kiln Farm Milton Keynes MK11 3EE Tel: 0908 260200	**GE Fanuc Automation Europe SA** Zone Industrielle Echternach Grand-Duche de Luxembourg Tel: 728372

UK Head Office	*International Head Office*
Gildemeister (UK) Ltd Unitool House Camford Way Sundon Park Luton LU3 3AN Tel: 0582 570661	**Gildemeister Aktiengesellschaft** Morsestrasse 1 D-4800 Bielefeld 11 Germany Tel: 05205 7510
Hahn & Kolb (GB) Ltd 6 Forum Drive Leicester Road Rugby Warks CV21 1NY Tel: 0788 577288	**Hahn & Kolb GmbH & Co** Bei Angabe Des Postfach 106018 W-7000 Stuttgart 10 Germany Tel: 49 711 945-0
Iscar Tools Ltd Woodgate Business Park 156 Clapgate Lane Bartley Green Birmingham B32 3DE Tel: 021 422 4070	**Iscar Limited** Box 11 Tefen 24959 Israel Tel: 0109724970311
AT & T Istel Industrial Systems Ltd Highfield House Headless Cross Drive Redditch Worcs B97 5EG Tel: 0527 550330	
Jones & Shipman PLC Narborough Road South PO Box 89 Leicester LE3 2LF Tel: 0533 896222	
Kennametal Europe PO Box 29 Kingswinford West Midlands DY6 7NP Tel: 0384 408010	**Kennametal Inc International** PO Box 231 Latrobe PA 15650 USA Tel: 412 539 4700
Krupp Widia UK Ltd 5 The Valley Centre Goron Road High Wycombe Bucks Tel: 0494 451845	**Krupp Widia GmbH** Münchener Strasse 90 D-4300 Essen 1 Germany Tel: 0201 725 0
KT-Swasey Ltd Stafford Park 2 Telford Shropshire TF3 3BO Tel: 0952 290200	**KT-Swasey** 11000 W. Theodore Trecker Way Milwaukee Wisconsin 53214-0277 USA Tel: 414 476 8300

UK Head Office	*International Head Office*
LK Tool Company Ltd East Midlands Airport Castle Donnington Derby DE7 2SA Tel: 0332 811349	
McDonnell Douglas Information Systems Ltd Boundary Way Hemel Hempstead Herts HP2 7HU Tel: 0442 232424	**McDonnell Douglas** Information Systems International 18881 Von Karman Suite 1800 Irvine California 92715 USA Tel: 714 724 5600
Micro Aided Engineering Ltd Bolton Business Centre 44 Lower Bridgeman Street Bolton Greater Manchester BL2 1DG Tel: 0204 396500	
NC Engineering Ltd 1 Park Avenue, Bushey Watford Herts WD2 2DG Tel: 0923 243962	
NCMT Ltd (Makino) Ferry Works Thames Ditton Surrey KT7 0QQ Tel: 081 398 3402	
P-E Information Systems Ltd (Hocus) Park House Egham Surrey TW20 0HW Tel: 0784 34411	
Rank Taylor Hobson Ltd PO Box 36 New Star Road Leicester LE4 7JQ Tel: 0533 763771	
Renishaw Metrology Plc New Mills Wotton-under-Edge Gloucs GL12 8JR Tel: 0453 844211	

UK Head Office	*International Head Office*
Renishaw Transducer Systems Ltd Old Town Wotton-under-Edge Gloucs GL12 7DH Tel: 0453 844302	
Ringspan (UK) Ltd 3 Napier Road Bedford MK41 0QS Tel: 0234 42511	**Ringspan GmbH** Schaberweg 30–34 6380 Bad Homburg Germany Tel: 06172 275-0
Röhm (GB) Ltd The Albany Boat House Lower Ham Road Kingston-upon-Thames Surrey KT2 5BB Tel: 081 549 6647	
Sandvik Coromant UK Manor Way Halesowen West Midlands B62 8QZ Tel: 021 550 4700	**Sandvik AB** 81181 Sandviken Sweden Tel: 026 260000
Scharmann Machine Ltd Cannon House 2255 Coventry Road Sheldon Birmingham B26 3NX Tel: 021 742 4216	**Dörries Scharmann GmbH** D-4050 Mönchengladbach 2 Hugo-Junkers Strasses 12–32 Germany Tel: 02166 454-0
Seco Tools (UK) Ltd Kinwarton Farm Road Alcester Warks B49 6EL Tel: 0789 764341	**Seco Tools AB** 77301 Fabest Sweden Tel: 022-340000
Siemens PLC Sir William Siemens House Princess Road Manchester M20 8UR Tel: 061 446 5740	**Siemens Aktiengesellschaft** Power Engineering & Automation Group Numerical Controls & Drives For Machine Tools Division PO Box 4848 8500 Nuemberg 1 Germany
SMG Ltd Industrial House River Dee Business Park River Lane Saltney Chester CH4 8QY Tel: 0244 681206	**SMT Machine Company AB** PO Box 800 S-721 22 Västeras Sweden Tel: +46 (0)21-805120

UK Head Office	*International Head Office*
Stellram Ltd Hercules Way Bowerhill Industrial Estate Melksham Wiltshire SN12 6TS Tel: 0225 706882	**Stellram SA** 1260 Nyon Switzerland Tel: 022-613101
System 3R (UK) Ltd 2 Duke Street Princes Risborough Bucks HP17 0AT Tel: 08444 4339	**System 3R International AB** Sorterargatan S-162 26 Vallingby Sweden Tel: 46(8)6202000
Tecnomagnetica UK Ltd 18 Riverside Estate Sir Thomas Longley Road Frindsbury Rochester Kent ME2 4DP Tel: 0634 715802	**Tecnomagnete SPA** Via Dei Cignoli 9 20151 Milano Italy
Thame Engineering Co. Ltd Field End Thame Road Long Crendon Aylesbury Bucks HP18 9EJ Tel: 0844 208050	
Walter Cutters & Grinders Ltd Walker Road North Moons Industrial Estate Redditch Worcs B98 9HE Tel: 0527 60281	**Walter AG** Postfach 2049 W-7400 Tuzbingen Germany Tel: 497071 7010
WDS Wharton LTD Marlco Works Hagden Lane Watford WD1 8NA Tel: 0923 226606	
Wix & Royd Ltd 77–81 Brighton Road Redhill Surrey RH1 6PS Tel: 0727 768823	
Yamazaki Mazak UK Ltd Badgeworth Drive Worcester WR4 9NF Tel: 0905 755755	

Index