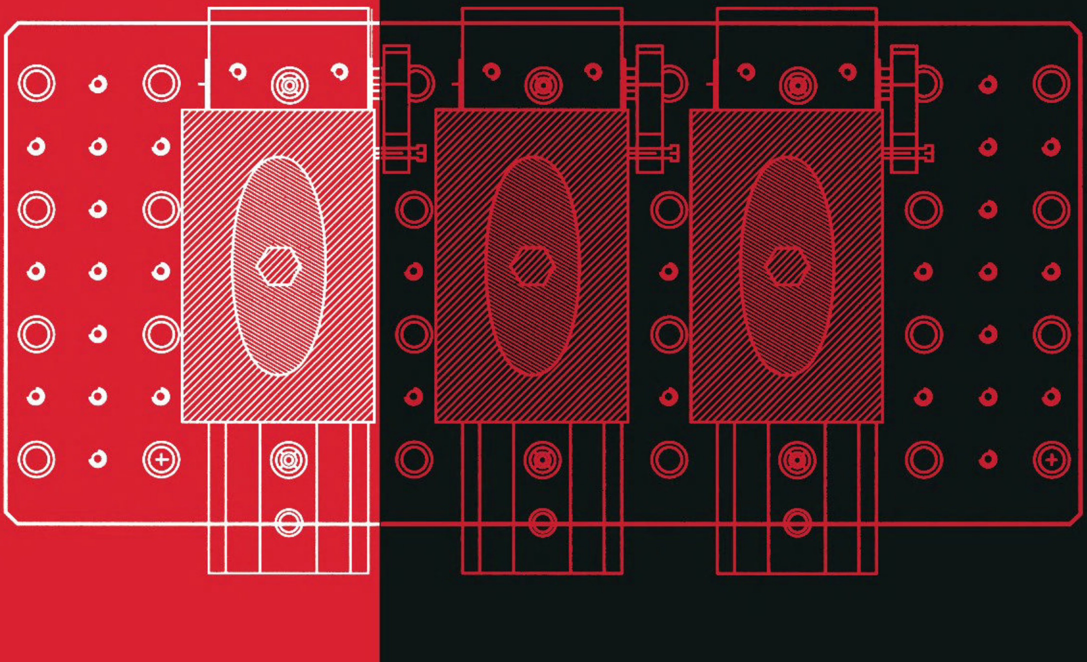
CNC MACHINING TECHNOLOGY

2 Cutting, Fluids and Workholding Technologies



GRAHAM T. SMITH

Springer-Verlag

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Volume II

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With 85 Figures

Springer-Verlag
London Berlin Heidelberg New York
Paris Tokyo Hong Kong
Barcelona Budapest

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Cover illustration: Ch.3, Fig.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.]

ISBN-13: 978-3-540-19829-1 e-ISBN-13: 978-1-4471-2053-7
DOI: 10.1007/978-1-4471-2053-7

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

Typeset by Best-set Typesetter Ltd., Hong Kong
69/3830-543210 Printed on acid-free paper

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

PLATO 428–348 BC

Contents

Preface

Each volume in this series of three attempts to explain the design of turning and machining centres and how they are operated through part programming languages. Furthermore, a discussion about how such stand-alone machine tools can be networked into flexible manufacturing systems is given along with the problems relating to such interfacing. These volumes were written as a companion book to the successful *Advanced Machining – The Handbook of Cutting Technology* published jointly by IFS and Springer Verlag in 1989. The individual volumes look at interrelated aspects of using turning and machining centres:

Volume I considers the design, construction and building of turning and machining centres, then goes on to consider how these individual machine tools can be networked together providing the desired communication protocols for flexible manufacturing systems, leading to a complete Computerised Integrated Manufacturing system. This latter philosophy is discussed in terms of a case study on the most automated factory in Europe, ironically manufacturing turning and machining centres. Finally, mention is made of the efforts given to ensure significant advances in both ultra high-speed machining design and sub-micron operation, which is sure to have a major impact on general turning and machining centres in the future.

Volume II discusses the crucial point of ancillary activities associated with these machine tools, such as the cutting tool technology decisions that must be made in order to ensure that each machine is fully tooled-up and optimised efficiently. A brief review is also given on cutting tool materials development and tooling geometry considerations. Modular quick-change tooling is reviewed together with both tool and workpiece monitoring systems. A discussion follows on tool management, which becomes a major activity when a considerable tooling inventory exists within a manufacturing facility. Cutting fluids are an important complement to cutting tools, as they not only extend tool life but additionally enhance the workpiece machined surfaces; therefore it is important to choose the correct cutting fluid and handle it in the approriate manner to obtain maximum benefit from its usage. Workholding technology is an expensive burden that requires careful consideration to achieve an economic optimisation, particularly in a larger scale automated facility such as in an F.M.S. environment and a range of workholding strategies and techniques are reviewed.

Volume III is a highly focused text that discusses how a part program is generated – after a general discussion about controllers. Consideration is given to the fundamentals of CNC programming and this becomes a major part of the volume with a structured development of how to build programs and where and when the "word address", "blueprint/conversational" and "parametric" programs are utilised. High speed machining fundamentals are considered along with the problems of servo-lag and gain for both milling and turning operations. A section is devoted to "Reverse Engineering" using digitising/scanning techniques – allowing replicas to be used to generate part programs, as these techniques are becoming popular of late. Finally a discussion ensues on the design of CAD/CAM systems and how they might be used for multiple-axis machining, through a direct numerical control link.

Graham T. Smith
West End
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January 1993

Chapter 1

Cutting Tool Technology

1.1 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.

1.2 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.

1.3 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.

1.4 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.

1.4.1 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.

1.4.2 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. 1.1):

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.

1.4.3 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.	DIRECTION OF INCREASE IN CHARACTERISTIC:- CUT.	CARBIDE.
BLUE.	P01	Steel, steel castings.	Finish turning & boring, small chip section, dimensional accuracy & vibration – free.	↑ INCREASING SPEED. ↓ INCREASING FEED.	↑ WEAR RESISTANT. ↓ TOUGHNESS.
	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.		

Fig. 1.1. 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. 1.2a. 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. 1.2b). 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

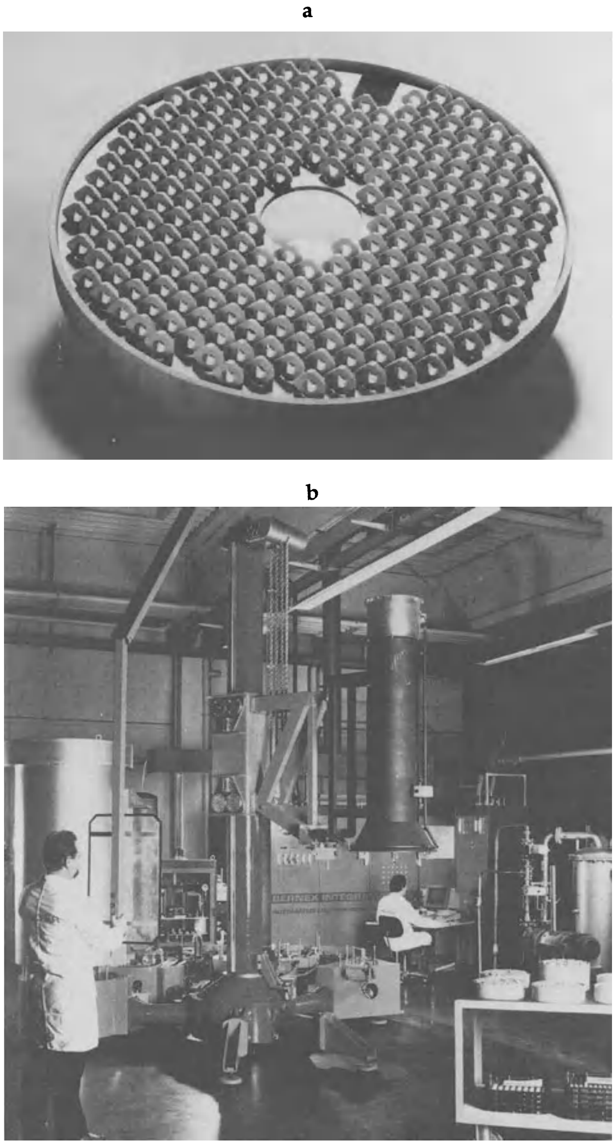


Fig. 1.2. Inserts can be coated using either the CVD or PVD process. **a** Sintered inserts prior to multi-coating. **b** Plant used for coating the cutting inserts. [Courtesy of Walter Cutters.]

(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. 1.3, 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 –

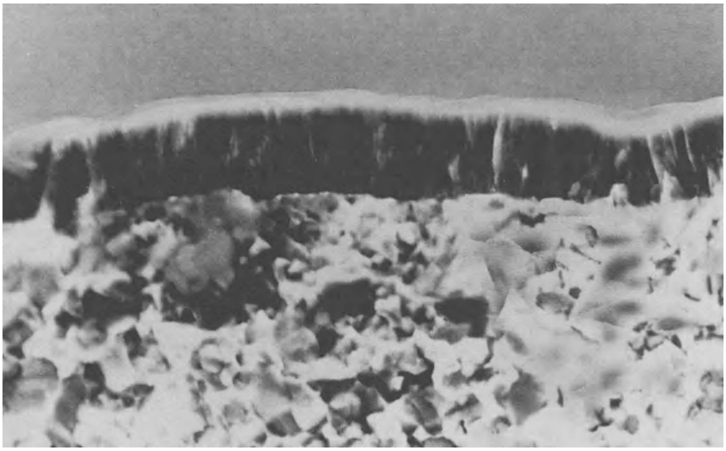


Fig. 1.3. A carbide insert clearly showing the metallurgical composition and construction of the tin deposited layer on the tungsten carbide substrate. This could have a very complex metallurgy with up to 13 coatings produced by either the PVD or CVD process. [Courtesy of Walter Cutters.]

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.

1.4.4 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 $Si_{6\cdot Z}$ $AlzOzN_{8\cdot Z}$ 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.

1.4.5 "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.

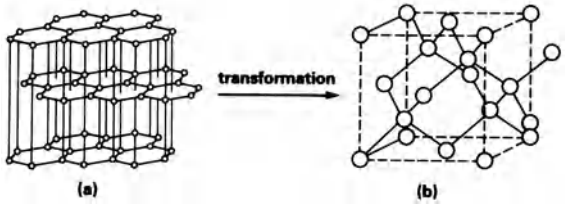


Fig. 1.4. Polycrystalline diamond (PCD) development. **a** The hexagonal arrangement of atoms in graphite. **b** The cubic arrangement of atoms in diamond. [Courtesy of Debeers PLC.]

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. 1.4a) and when subjected to heat and pressure application they can be transformed into cubic diamond structure (Fig. 1.4b). 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. 1.5 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.

1.5 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

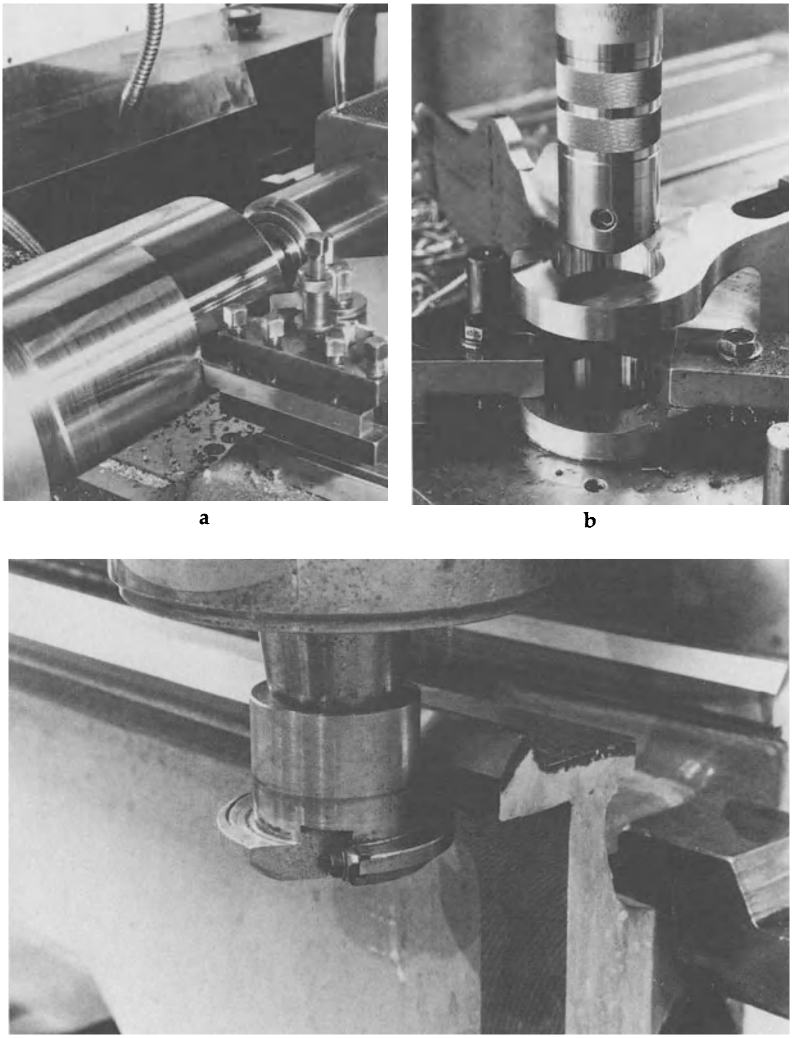


Fig. 1.5. Machining applications are many and varied using ultra-hard cutting tool materials like PCD and CBN. **a** PCD turning copper printing rolls. **b** PCD boring alloy engine support struts. **c** CBN fly-cutting induction hardened cast iron lathe beds. [Courtesy of Debeers PLC.]

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.

1.5.1 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. 1.6. 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. 1.6a) and negative inserts (Fig. 1.6b). 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. 1.6c) or negative geometry (Fig. 1.6d). 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. 1.6d) in order to preserve

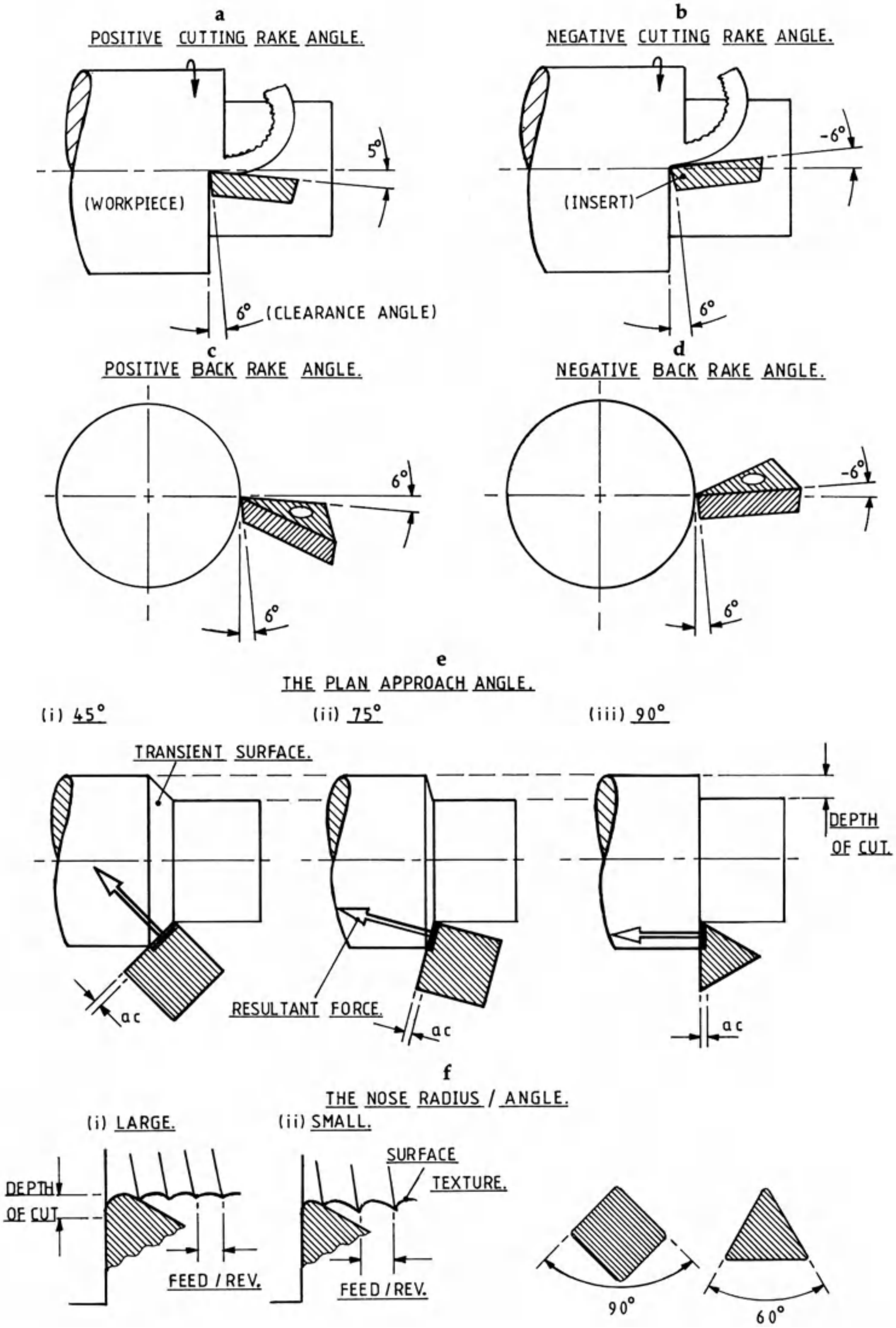


Fig. 1.6. The insert geometry in turning operations.

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. 1.6e). When a 45° large plan approach angle is used (Fig. 1.6e), 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. 1.6f) 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.

1.5.2 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.

1.5.3 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. 1.7a); alternatively, if the milling cutter rotates against the workpiece feed it is termed conventional, or up-cut milling (Fig. 1.7b). In either case the cutting action is best illustrated when side-and-face milling, as shown in Fig. 1.7a,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

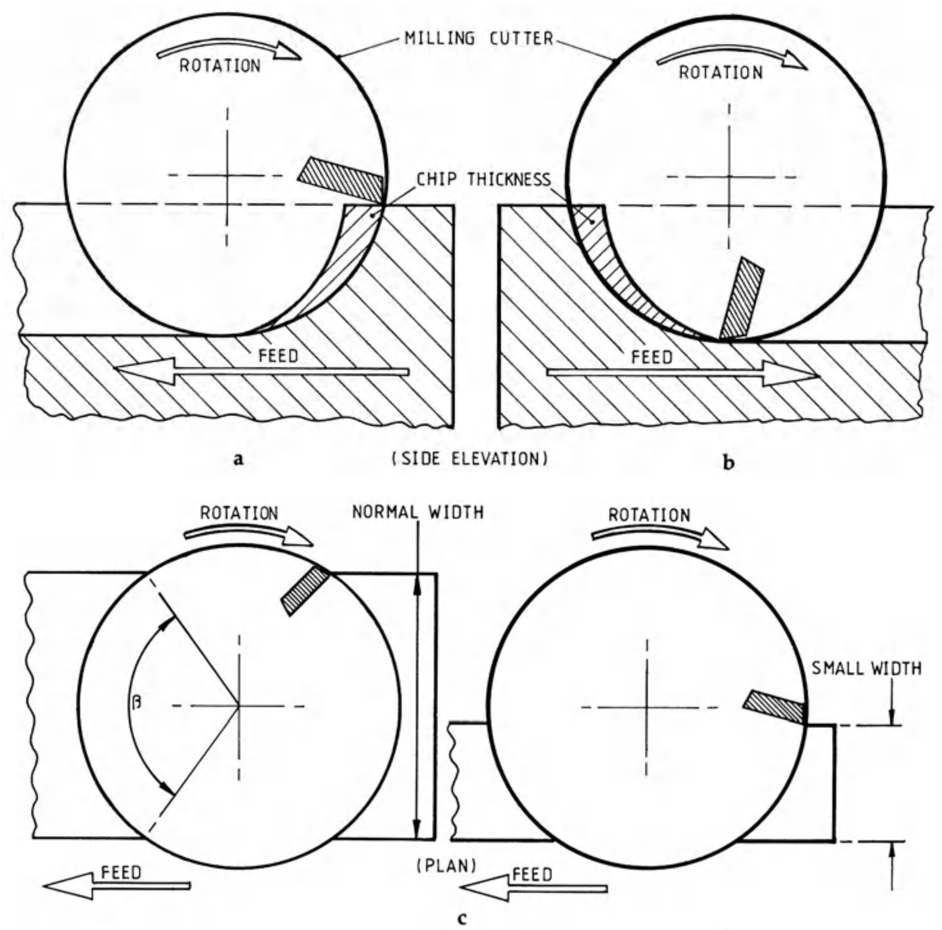


Fig. 1.7. Typical milling techniques adopted for either peripheral (**a**, **b**) or face milling (**c**) operations. **a** Climb- or down-milling. **b** Conventional or up-milling. **c** The effect of workpiece width on the cutter's performance. NB: Use a cutter diameter 30% larger (at least) than the 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. 1.7b). 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. 1.7c (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. 1.8b)
positive radial and axial (Fig. 1.8c)
negative radial, positive axial (Fig. 1.8d)

We will consider each combination individually, beginning with the double negative insert geometry (Fig. 1.8b), 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. 1.8c), 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. 1.8d. This design offers the advantages of both the previously discussed types, where the negative radial rake

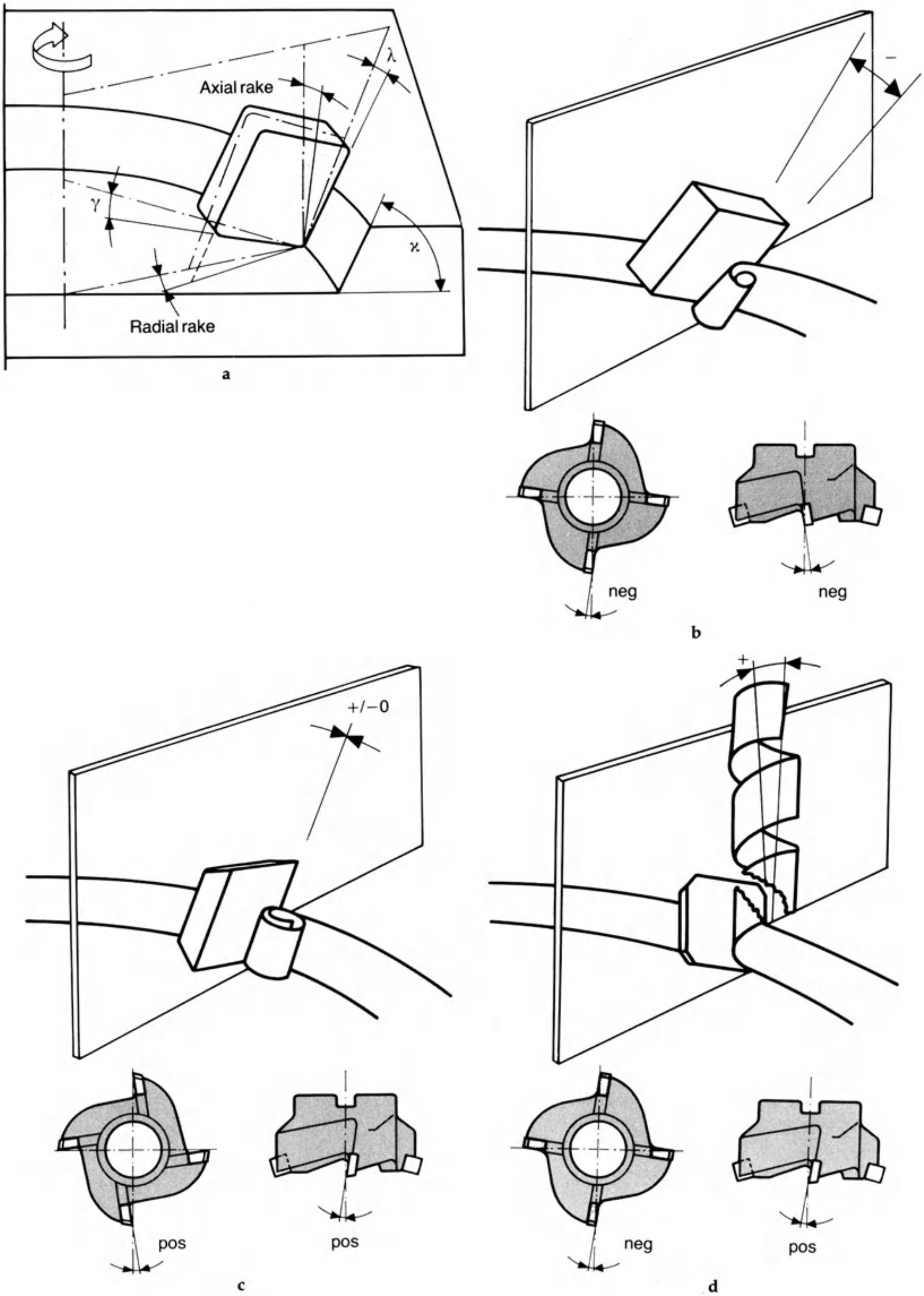


Fig. 1.8. Cutter insert geometry and terminology in milling operations. **a** Cutter insert geometry. **b** Negative/negative. **c** Positive/positive. **d** Negative/positive. NB: The angle of inclination of the insert generally termed "plan approach angle" and denoted by the Greek letter λ, has a significant effect on the cutter's performance and the workpiece. [Courtesy of Seco.]

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. 1.8a. 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.

1.5.4 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. 1.9a. 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. 1.9b), 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. 1.9b), 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

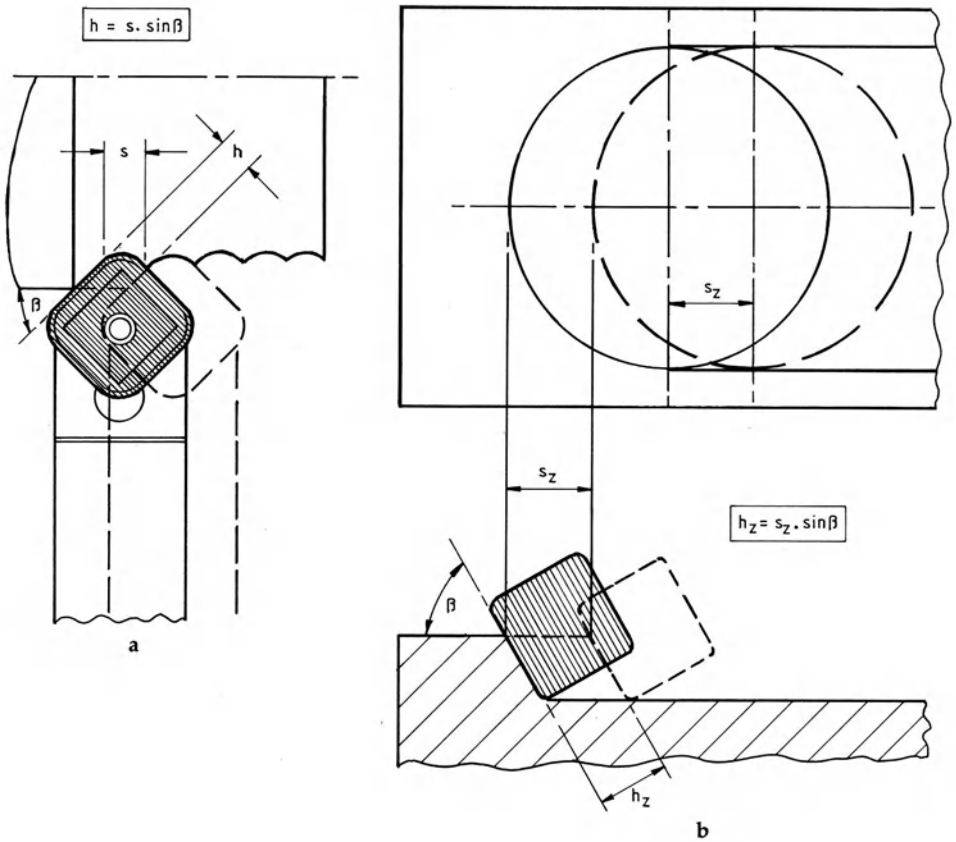


Fig. 1.9. Chip thickness in **a** turning and **b** milling operations. [Courtesy of Seco.]

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.

1.6 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. 1.10. 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. 1.11, 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

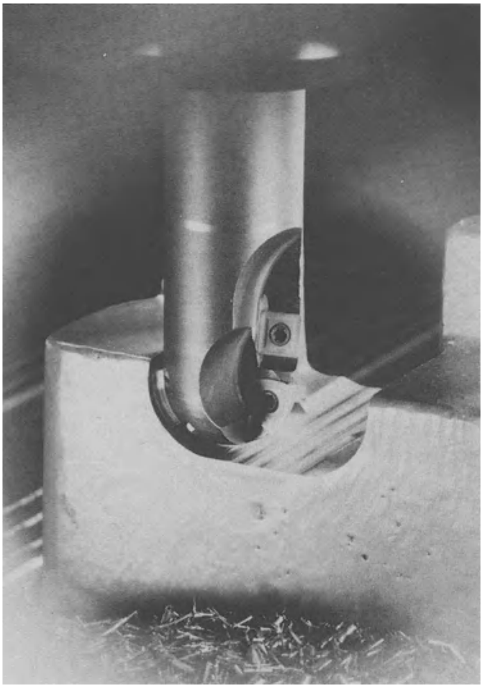


Fig. 1.10. A ball-nosed cutter with inserts positioned such that a swept volume occurs upon rotation. A wide range of materials can be machined simply by changing the grade of insert, which is true to a certain extent for all inserted-toothed cutters. [Courtesy of Walter Cutters.]

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

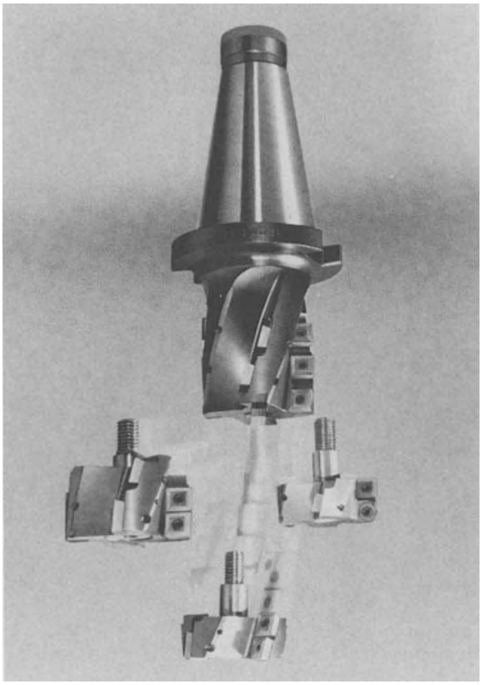


Fig. 1.11. An inserted-toothed end mill, known as a "porcupine cutter", with interchangeable ends as they are prone to damage in use. This also allows the cutter length to be modified. Notice how the strategic placement of the inserts on the cutter's periphery allows cutting along the whole length of 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.

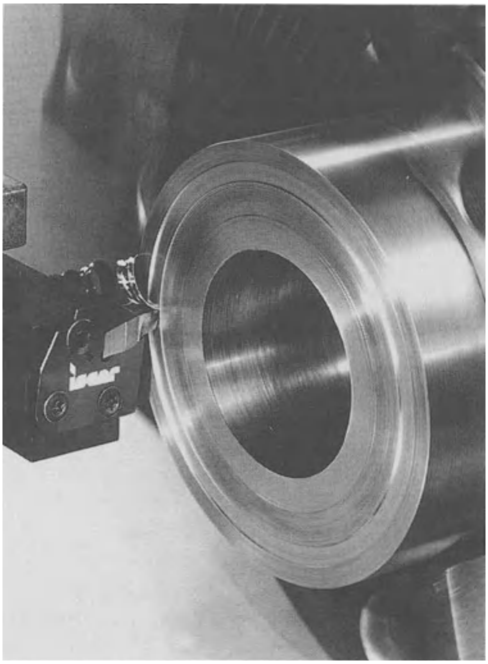
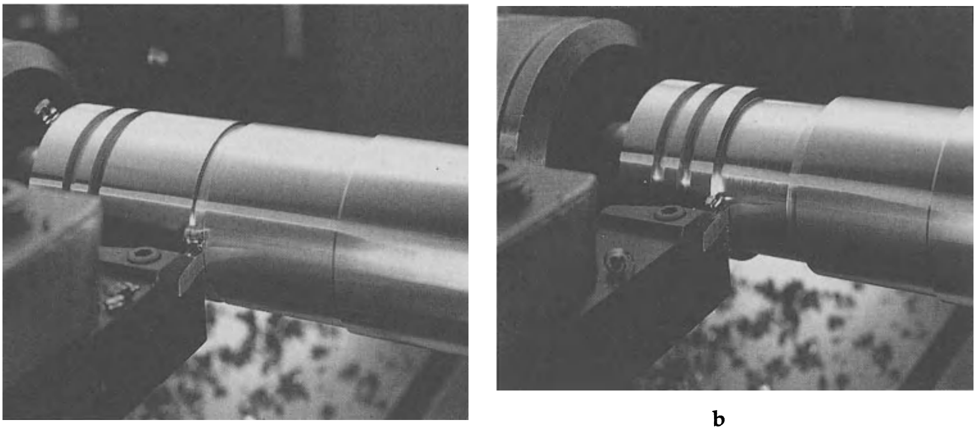


Fig. 1.12. A face-grooving operation using a sophisticated insert geometry for good chip control. [Courtesy of Iscar Tools.]

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. 1.12 and 1.13 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. 1.14 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. 1.13. 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.]

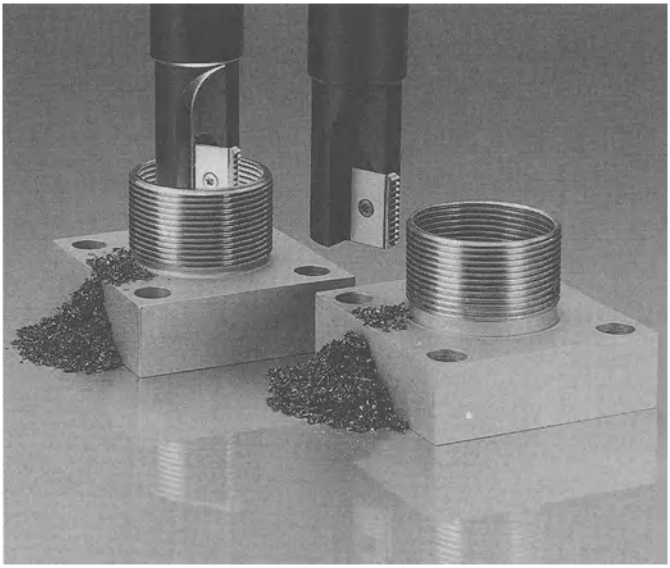


Fig. 1.14. External and internal thread milling. [Courtesy of Seco.]

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. 1.15a, 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

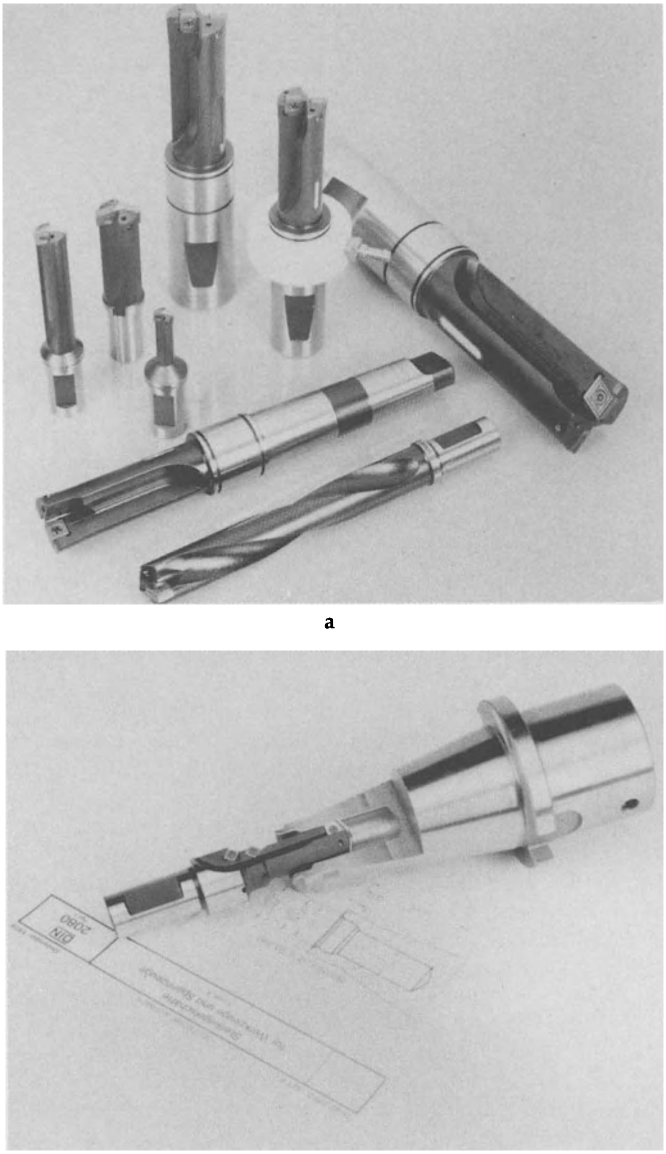


Fig. 1.15. **a** A small complement of the range and diversity of indexable-insert drills obtainable. **b** A spade drill in situ in a partially sectioned component. [Courtesy of Stellram Ltd.]

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. 1.15b) 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. 1.15b) 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. 1.15a). 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. 1.16) 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.

1.7 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

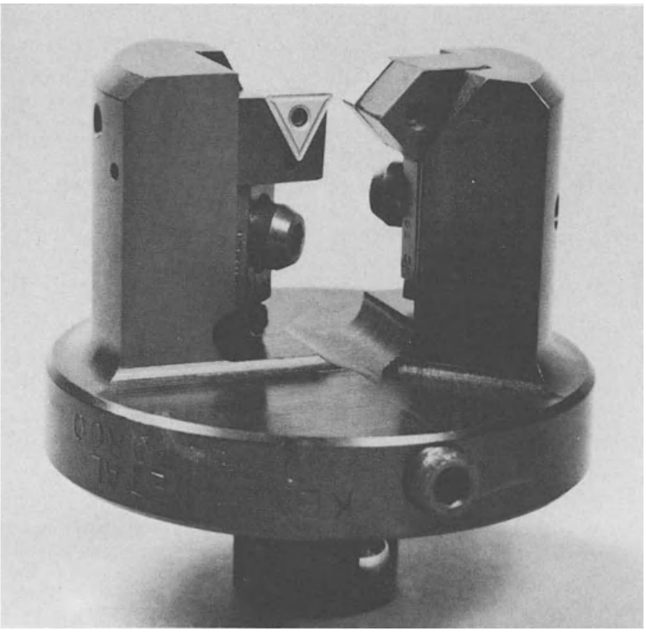


Fig. 1.16. A special engineered tool. [Courtesy of Kennametal (UK).]

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. 1.17. 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. 1.18) which are usually referred to as "block tooling". This method is designed around a replaceable clubhead, held in

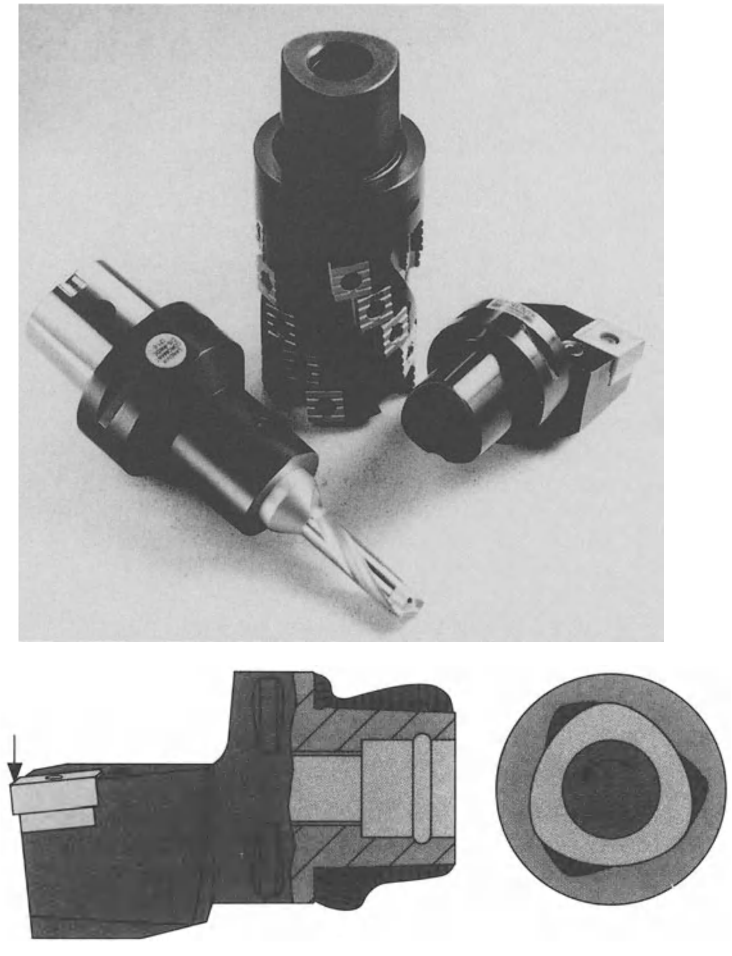


Fig. 1.17. The latest in modular quick-change tooling concepts: "Capto" (from the Italian "I hold firmly") based upon a tapered polygon coupling. The length of the taper and the precision contact surfaces of the Coromant Capto result in low surface pressures. This means long tool life and great repetitive accuracy. The stress curves lack peaks, avoiding the risk of vibrations or deformation. [Courtesy of Sandvik (UK) Ltd.]

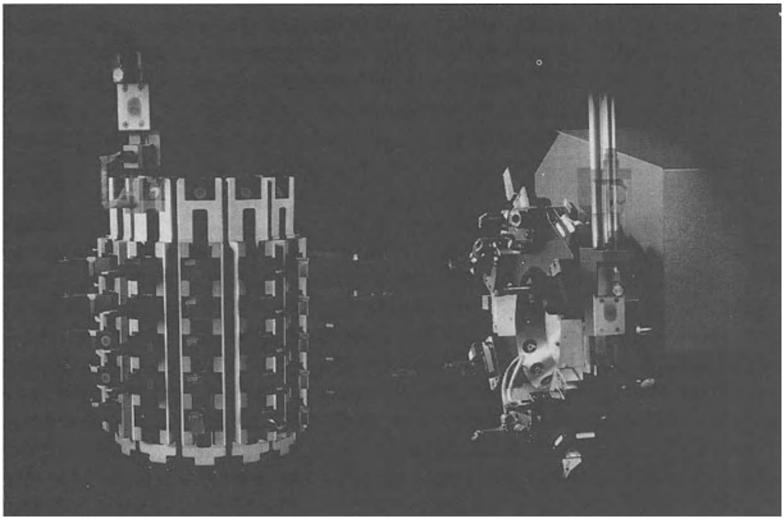


Fig. 1.18. The load/unload facility of an automatic block tooling arrangement for a turning centre turret (right) from/to the tool drum storage magazine (left). This reserve of tooling in the drum increases the machine tool's cutting capability and flexibility for unmanned machining considerably. [Courtesy 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. 1.18). 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. 1.19. 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.

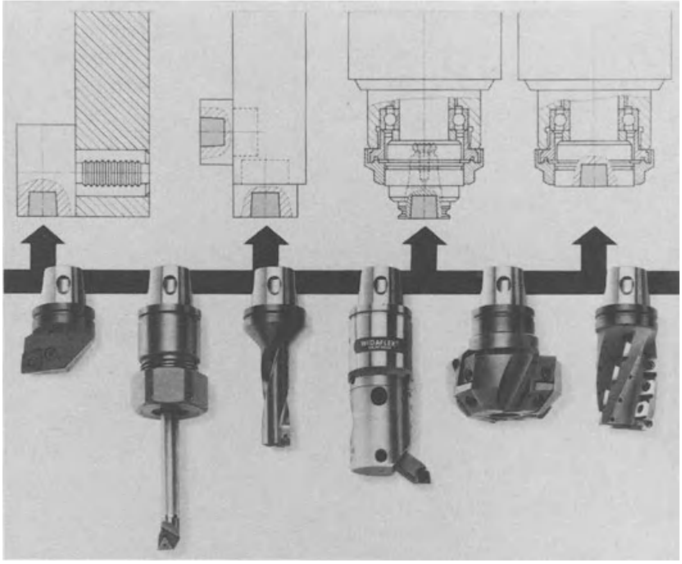


Fig. 1.19. A universal cutting adaptor for modular quick-change tooling. [Courtesy of Kruppwidia.]

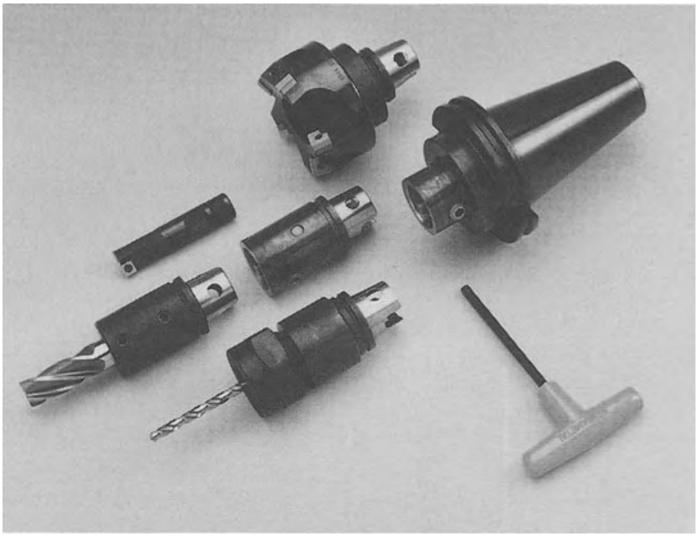


Fig. 1.20. The modular quick-change tooling for rotating tools on a machining centre or "driven" tooling on a turning centre. [Courtesy of Kennametal (UK).]

Fig. 1.20 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. 1.21) 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

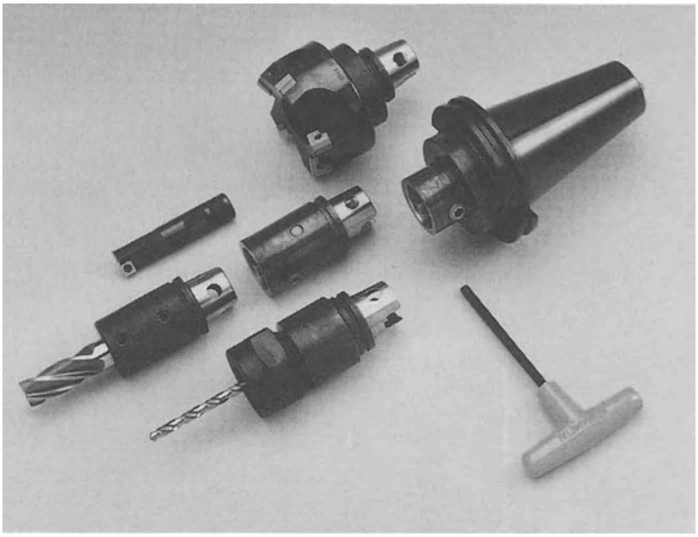


Fig. 1.21. These manual modular quick-change tooling units can be easily retrofitted to end-user's machines like the turning centre pictured. [Courtesy of Kennametal (UK).]

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. 1.22. 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. 1.22 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

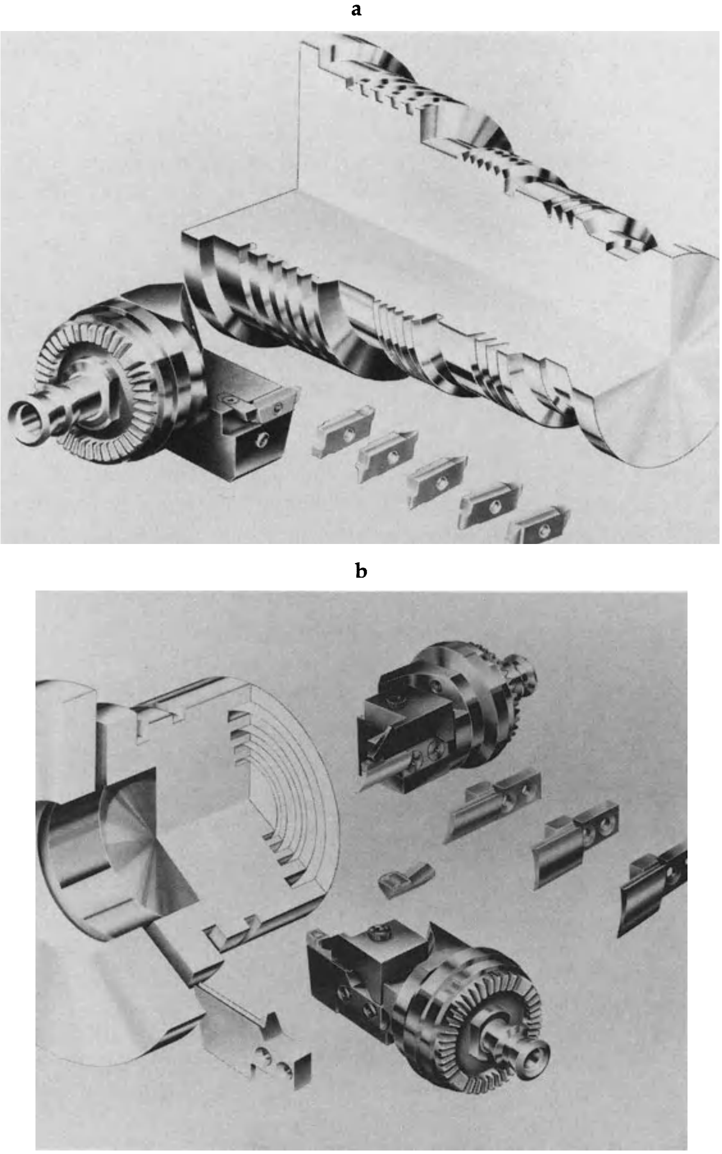


Fig. 1.22. **a** Grooving operations on diameters using a modular quick-change tooling system with a Hirth coupling adaptor. **b** Face and diametral grooving operations together with parting-off can be achieved with the minimum of tool holders. [Courtesy of Walter Cutters.]

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. 1.23 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. 1.24

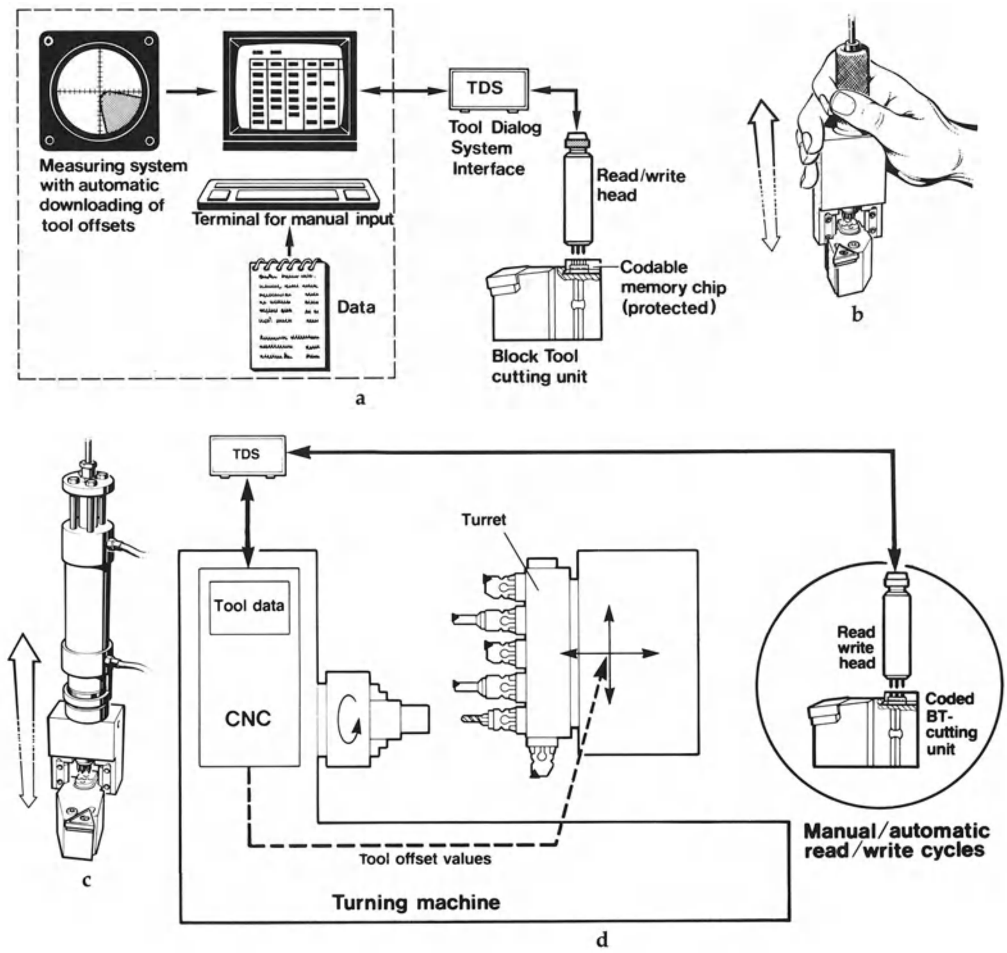


Fig. 1.23. Tool data processing using modular quick-change tooling on a turning centre via the "intelligent/tagged" tool concept. **a** Scheme of tool data input/output during tool preparation. Offsets are automatically downloaded. Tooling and other required data are entered manually and can be freely 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. 1.23.

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

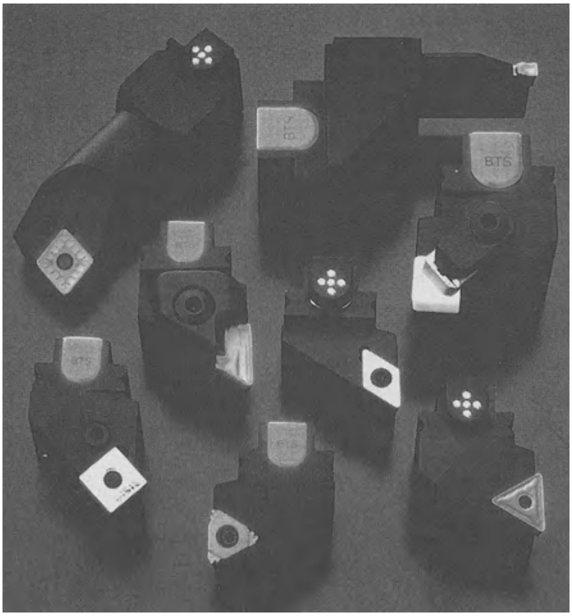


Fig. 1.24. A range of modular quick-change "block" tooling illustrating "intelligent/tagged" programmable clubheads clearly discernible by the five contact pins amongst standard units. [Courtesy of Sandvik (UK) Ltd.]

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.

1.8 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

1.8.1 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 1.7, 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. 1.25) and a turning centre application (Fig. 1.26) 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. 1.27 and has a variety of sources for the generation of sound waves during the cutting process (Fig. 1.27b). 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. 1.28). 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

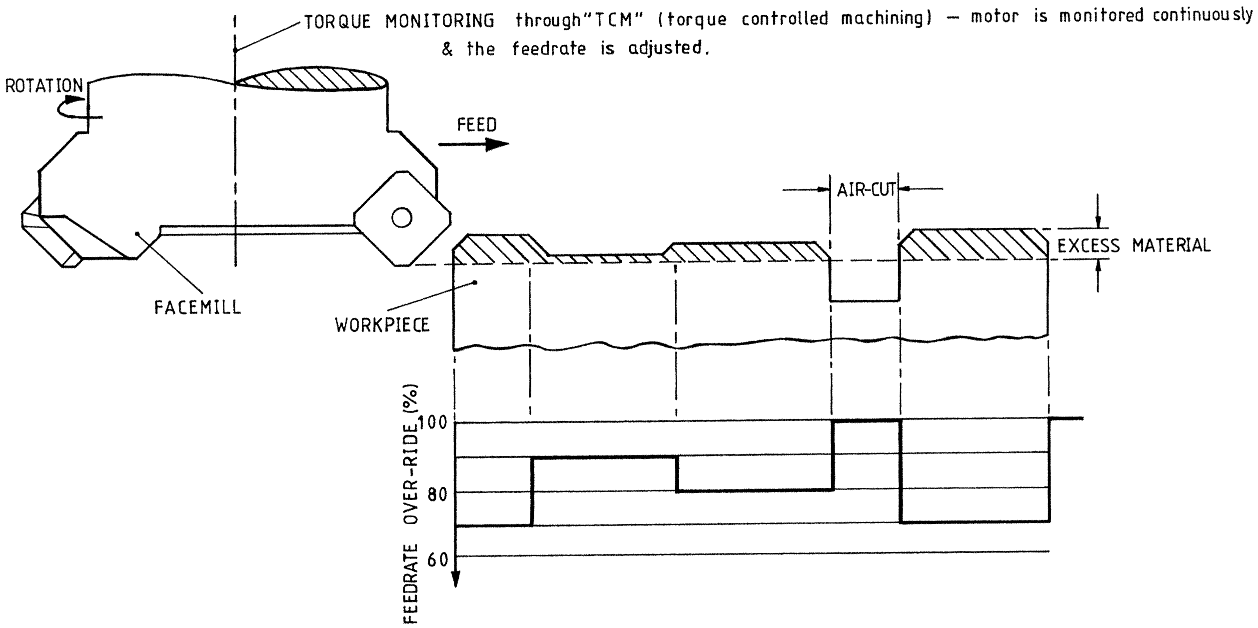


Fig. 1.25. Advantages of adaptive control when milling: optimised feedrates avoid tool damage; extended tool life; higher production rates; reduced intervention by operator; faster set-up times; reduced tool breakage.

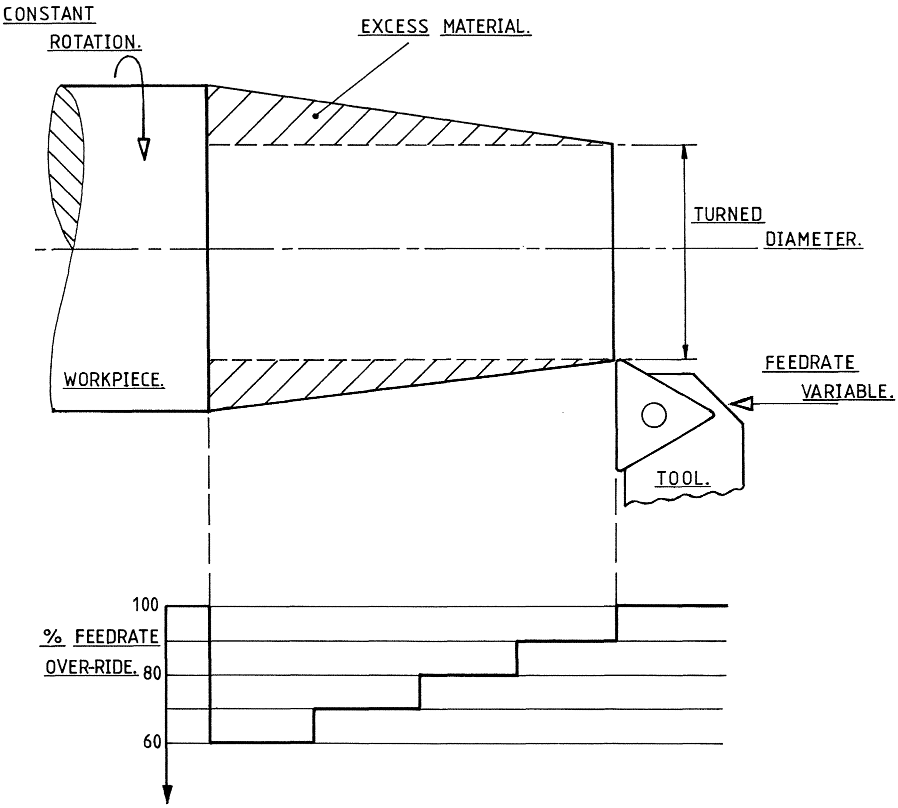


Fig. 1.26. Adaptive control in turning operations.

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

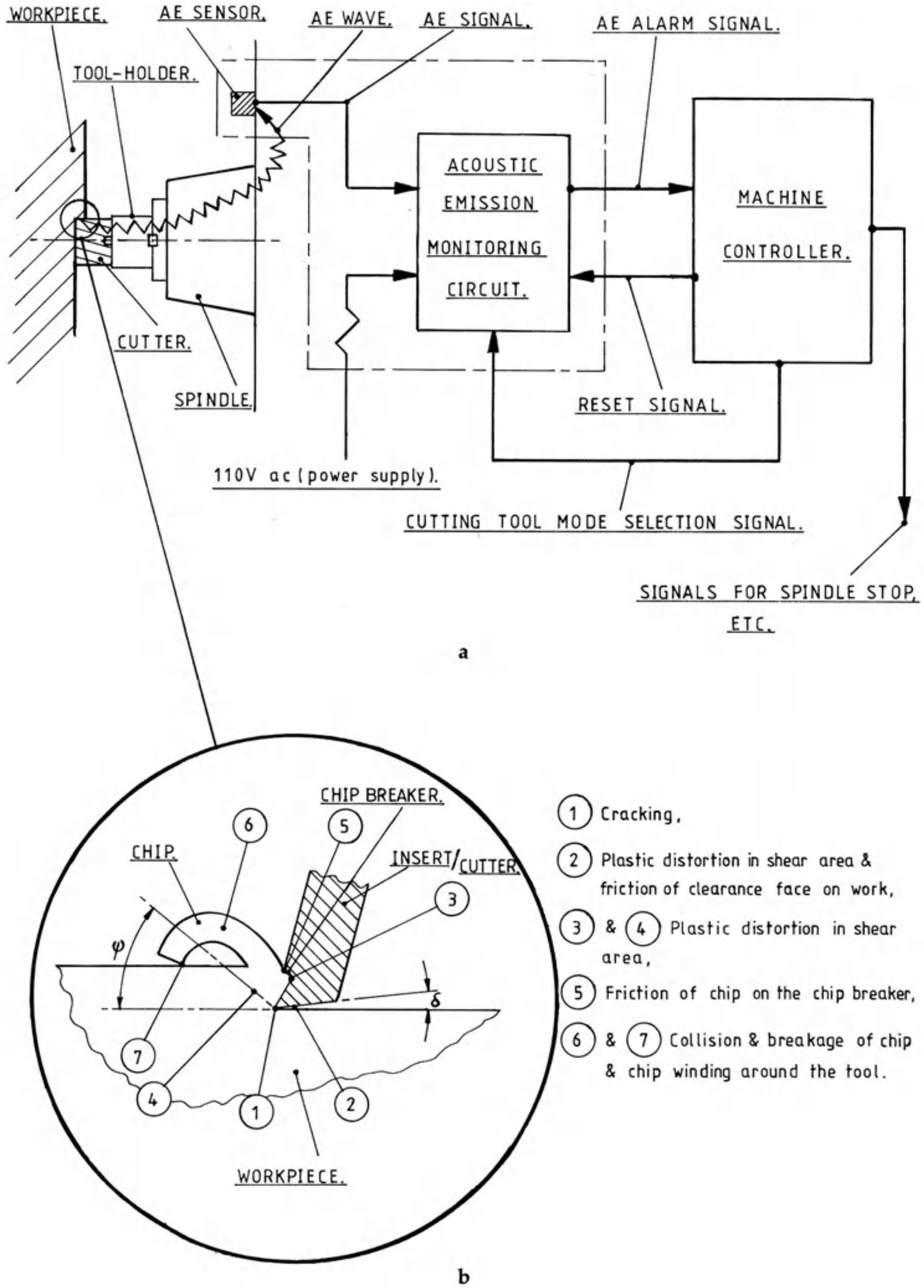


Fig. 1.27. **a** The application of acoustic emission to a horizontal machining centre. **b** Possible sources of acoustic emission during machining.

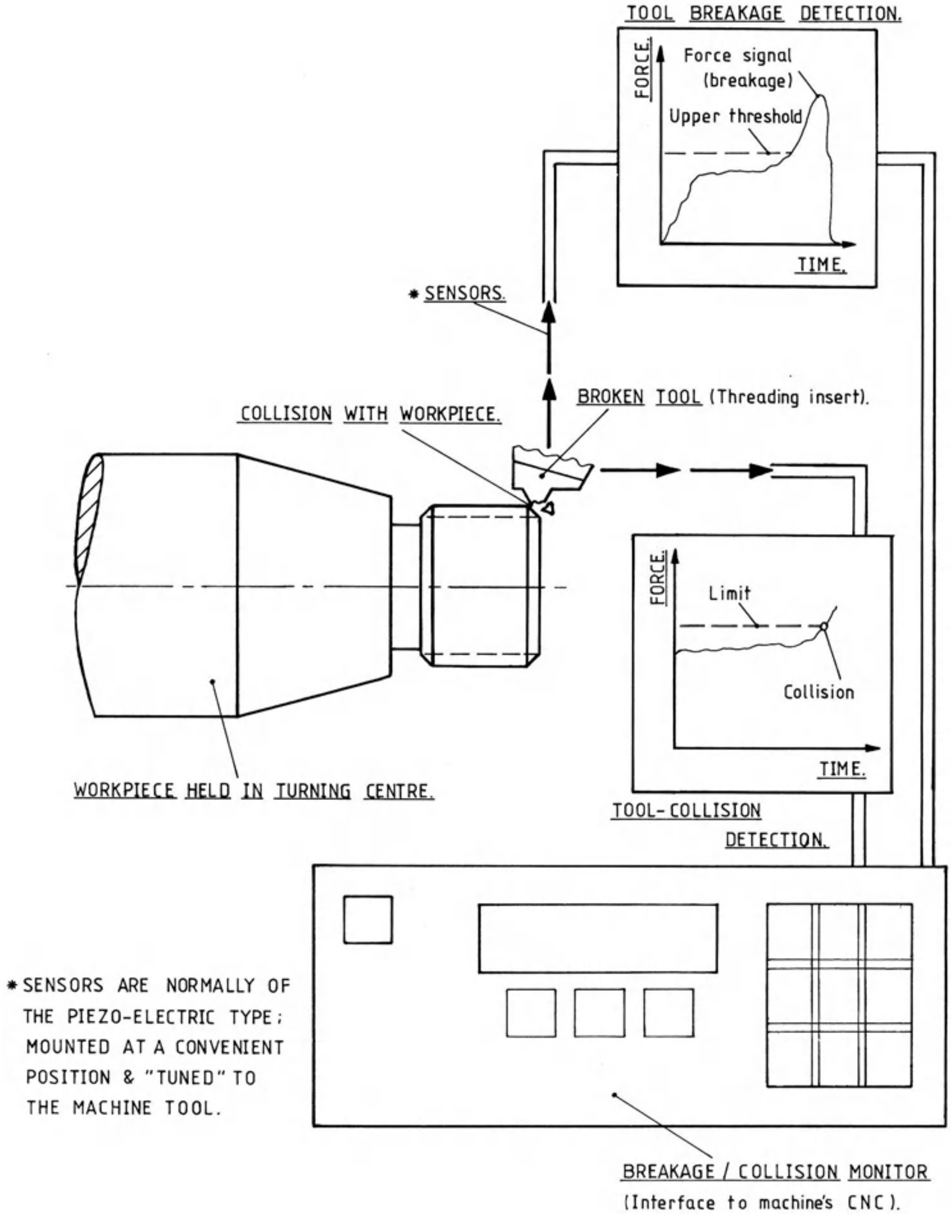


Fig. 1.28. A typical monitoring system used on a turning centre for unmanned machining in an FMS environment.

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. 1.28) 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.

1.8.2 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. 1.29, 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

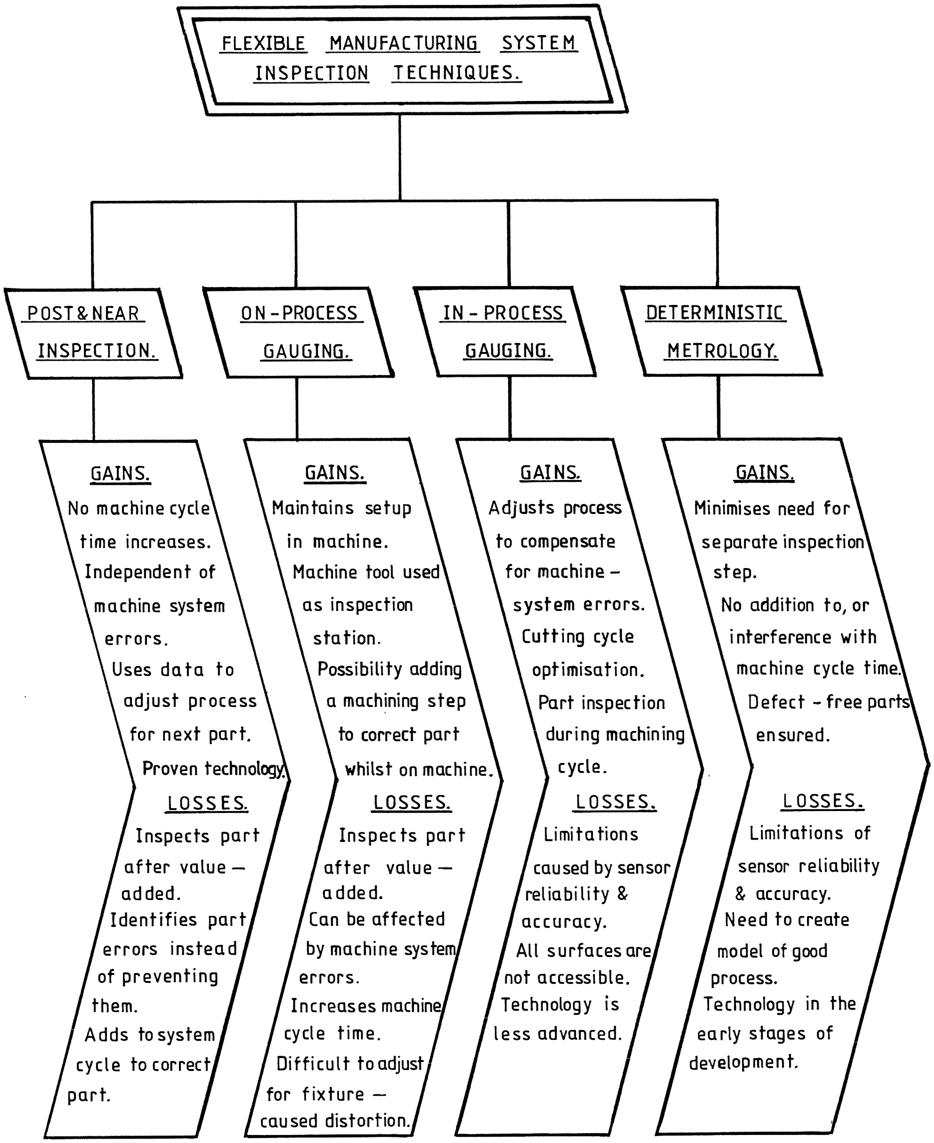


Fig. 1.29. Techniques applied to flexible manufacturing systems to maintain the quality of parts by different metrological methods and their advantages and limitations. [Courtesy of the FMS Magazine.]

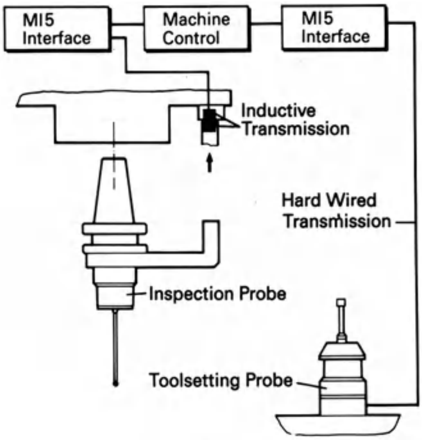
can be used for 100% inspection or be based on a statistical sampling scheme which is found to be satisfactory and might be determined by batch size, complexity of part, predicted tool wear and processing time, or indeed, on other more urgent assessment criteria. As its name implies, these near-gauging 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. 1.30, 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. 1.31). By using "probing" for both tool and workpiece setup, real savings in terms of



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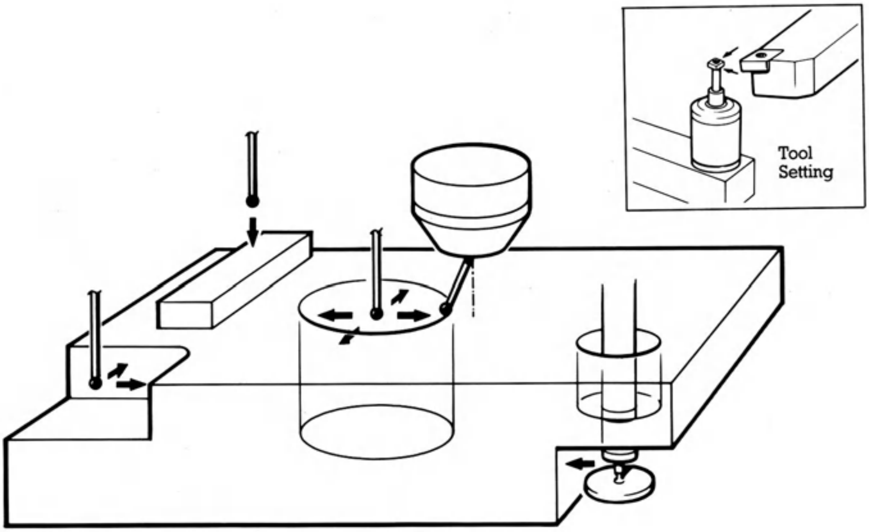

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production occur, as the resulting time is drastically reduced for individual parts or batches. It is not necessary to probe every dimension on every part machined, as a reasonable statistical sampling plan can be incorporated and, in any case, only 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

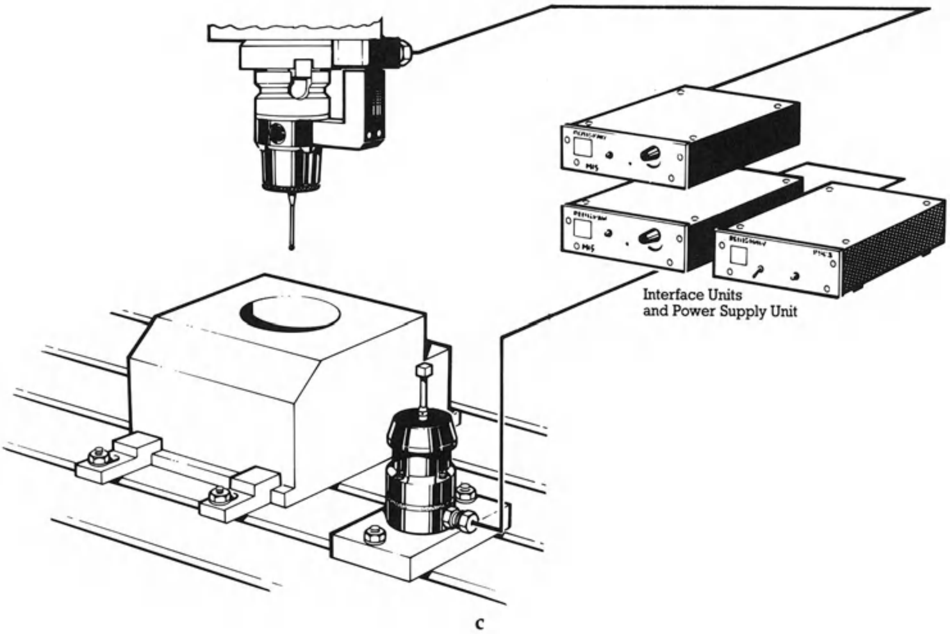
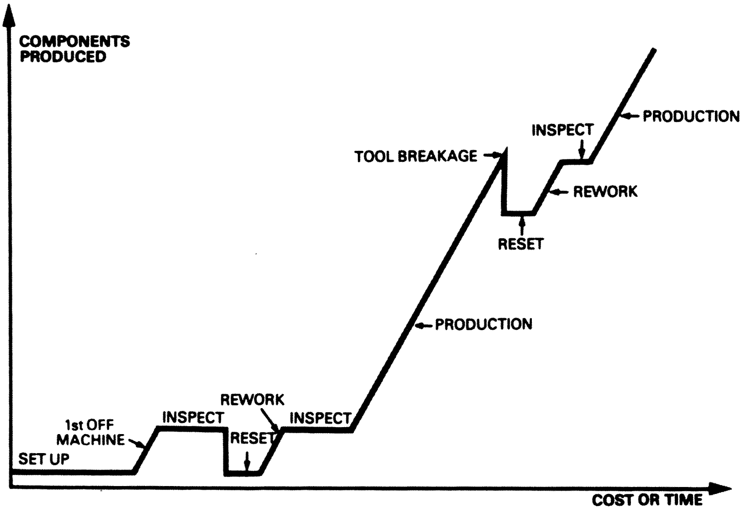


Fig. 1.30. In-machine gauging using touch-trigger probes in milling/machining centres. It has applications for: fixture alignment; workpiece interrogation of critical dimensions; tool presetting and tool offset updating; tool breakage detection. **a** Typical machining centre arrangement. **b** In-cycle 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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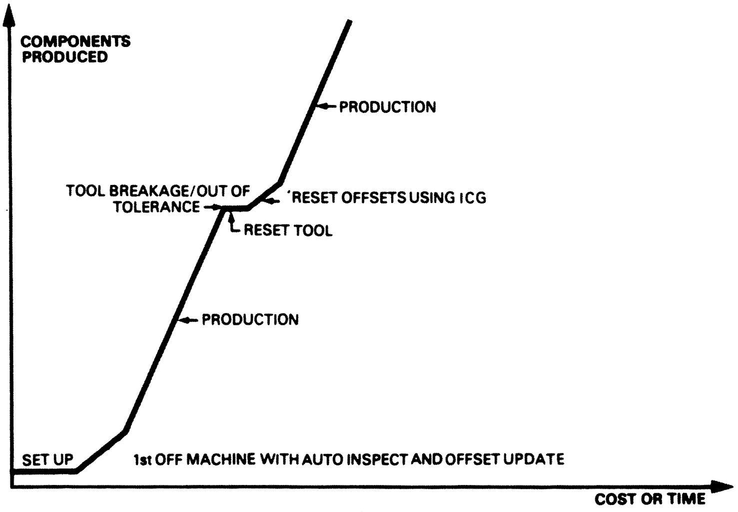

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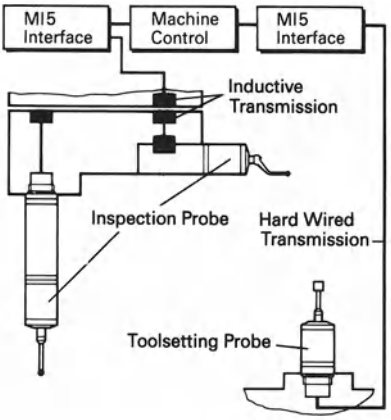
machining process and the corrective actions necessary to anticipate these errors in a real-time sense, and in so doing, correct them. In any machining process the objective is to cut a good workpiece and in this way eliminate the need for further inspection. In order to achieve this aim, the deterministic 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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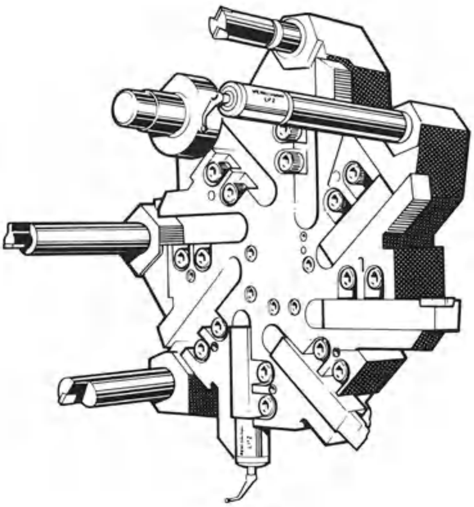

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Fig. 1.31. **a** Conventional use of NC. **b** NC machining with in-cycle gauging. **c** Typical lathe arrangement. **d** Turning centre tool turret with touch-trigger probing.

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".

1.9 Tool Management

1.9.1 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, Volume I, 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 3. 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.

1.9.2 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 3):

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. 1.32). 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 pre-set value.

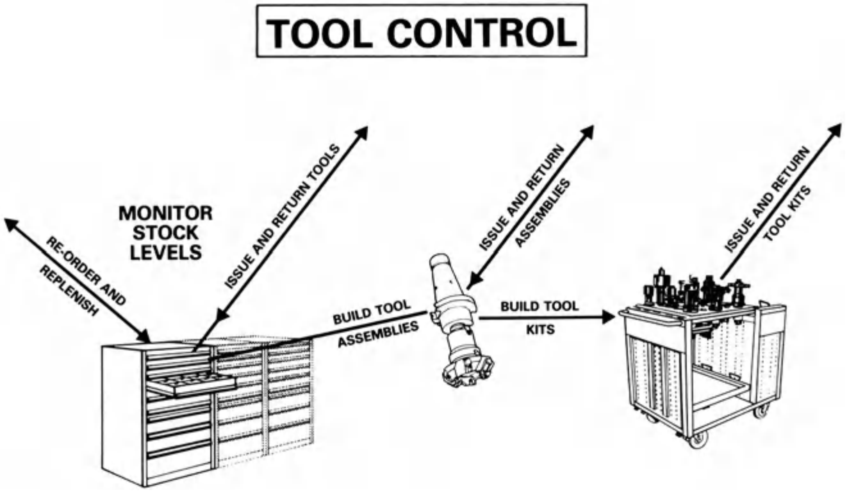


Fig. 1.32. Tools must be precisely controlled at the "focal point" of kit build-up/replenishment, namely in the tool preparation area. [Courtesy of Sandvik (UK) Ltd.]

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. 1.33. 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

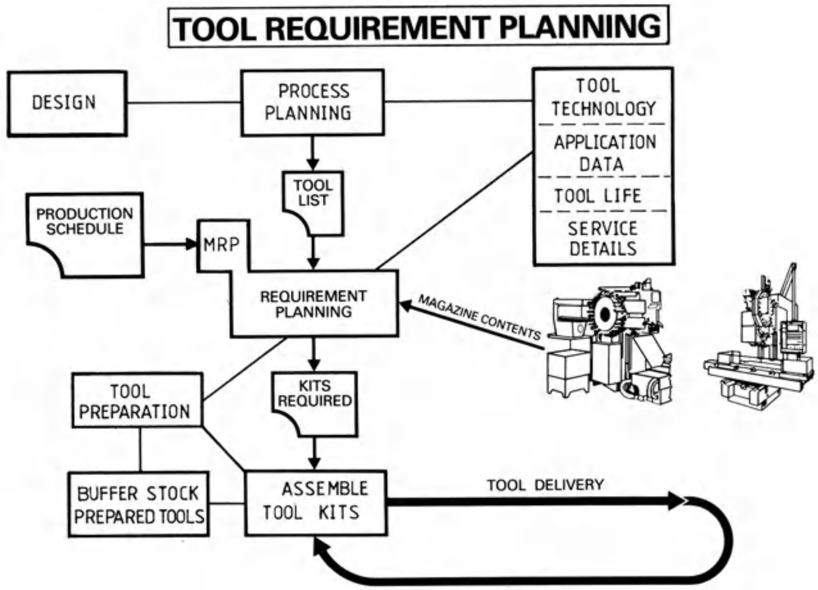


Fig. 1.33. Any tool requirement planning system is based upon extraneous manufacturing factors such as product design and the master schedule. [Courtesy of Sandvik (UK) Ltd.]

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.

1.9.3 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. 1.34, 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. 1.34. 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 downtime 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.

1.9.4 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 2
Cutting Fluids

2.1 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 1. 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.

2.2 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. 2.1.

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

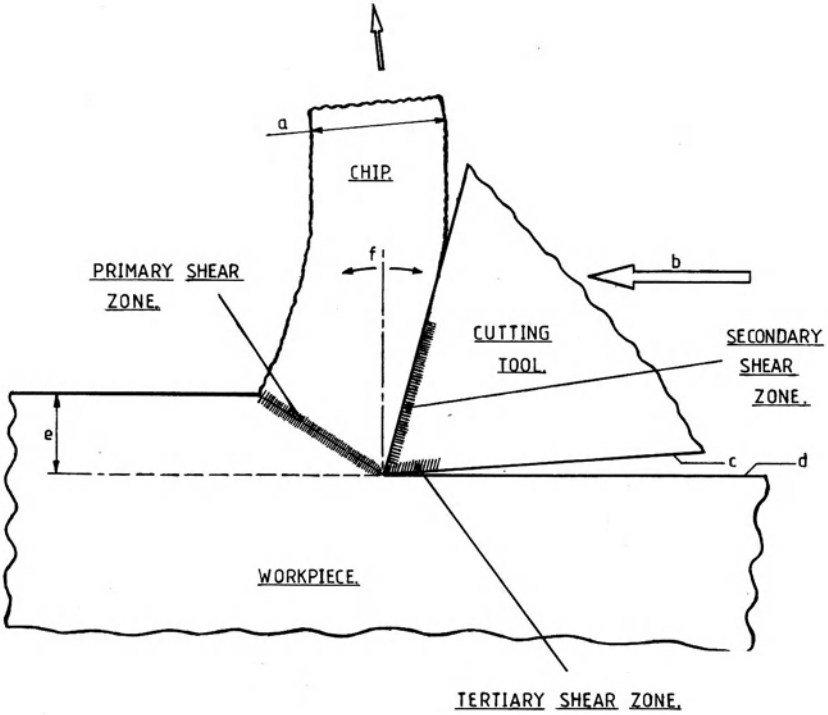


Fig. 2.1. Schematic diagram of stock removal process. a chip thickness; b cutting speed; c tool flank; d machined surface; e depth of cut; f rake angle.

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. 2.1, 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. 2.2a, 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. 2.2b, and the isotherms show the temperature distribution across the workpiece, tool and chip. A typical temperature distribution, as illustrated in Fig. 2.2b, 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

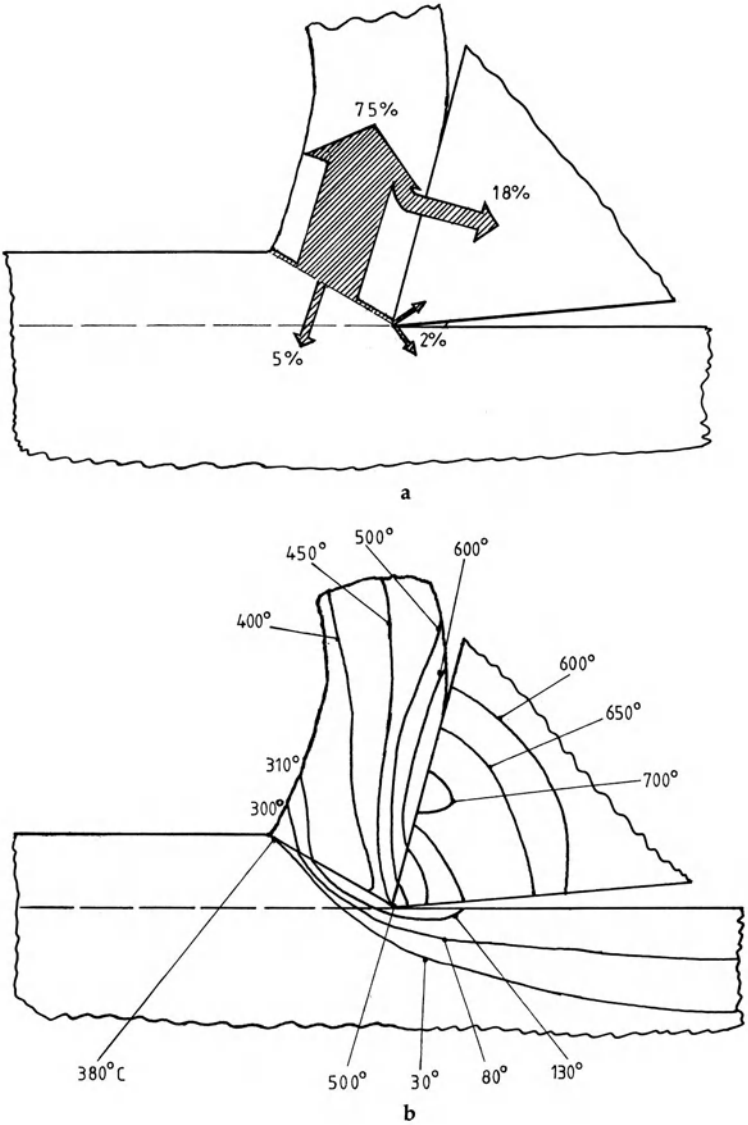


Fig. 2.2. The temperature distribution in the workpiece, tool and chip. **a** The heat dissipation during cutting. **b** Isotherm distribution. [After Kronenberg & Vieregge.]

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.

2.2.1 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. 2.3. 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.

2.2.2 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. 2.4, 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. 2.5 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

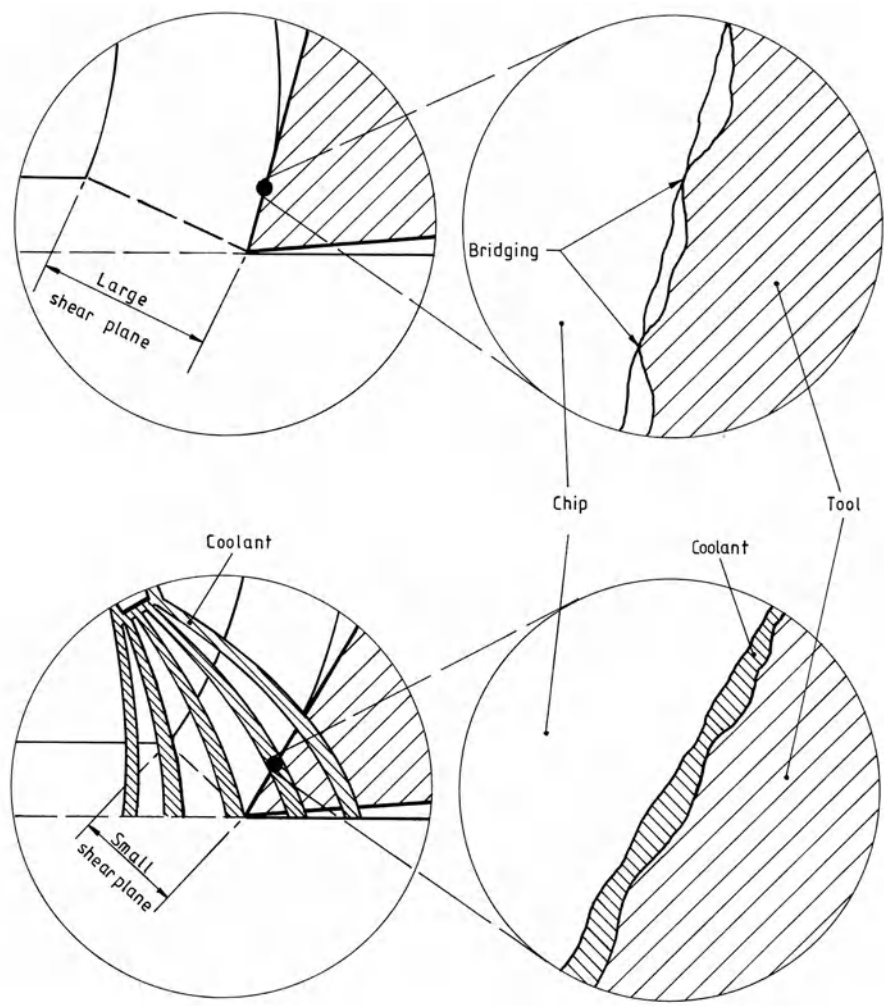


Fig. 2.3. The effect of rake angle on the thickness of the chip. [Courtesy of Cimcool.]

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. 2.6). 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

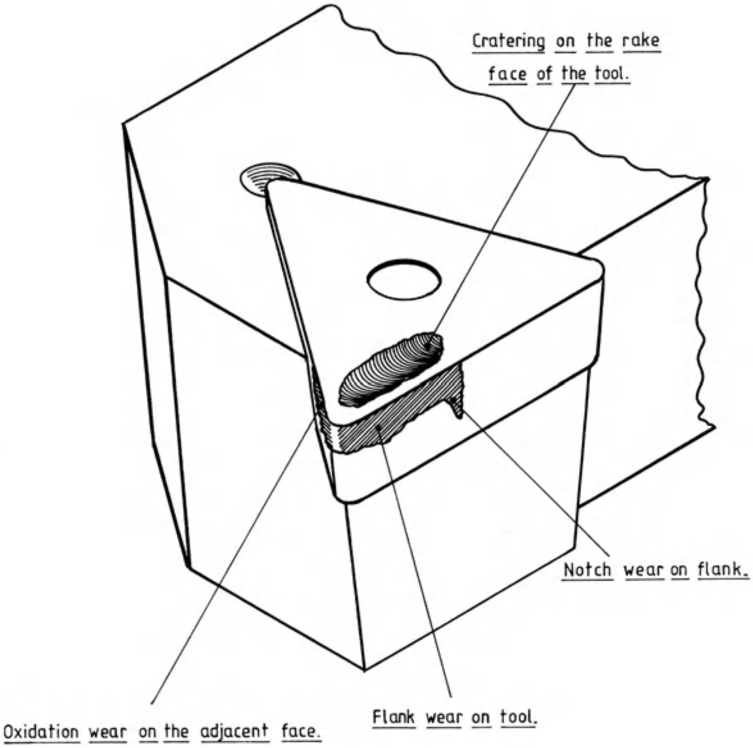


Fig. 2.4. Types of wear at the cutting edge.

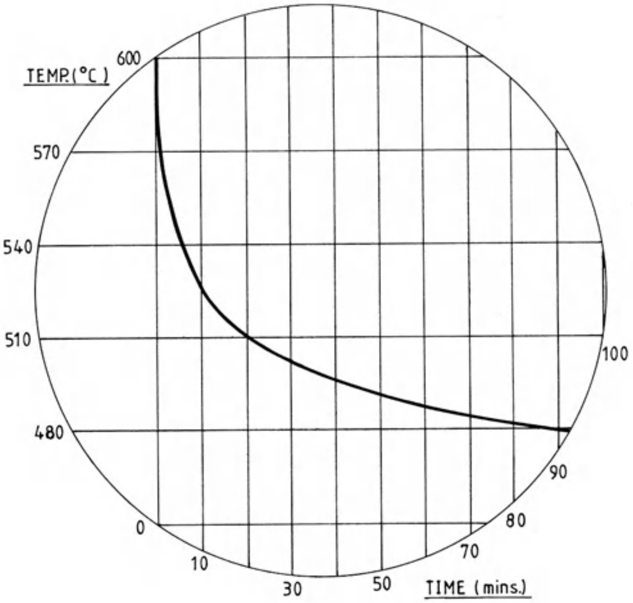


Fig. 2.5. The effect of temperature on the tool life. [Courtesy of Cimcool.]

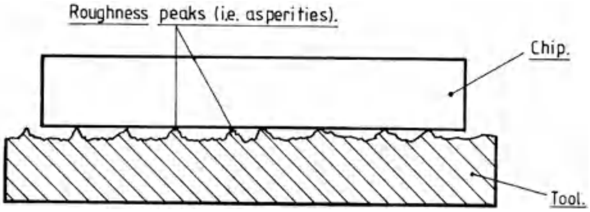


Fig. 2.6. The friction between the chip and the tool. [Courtesy of Cimcool.]

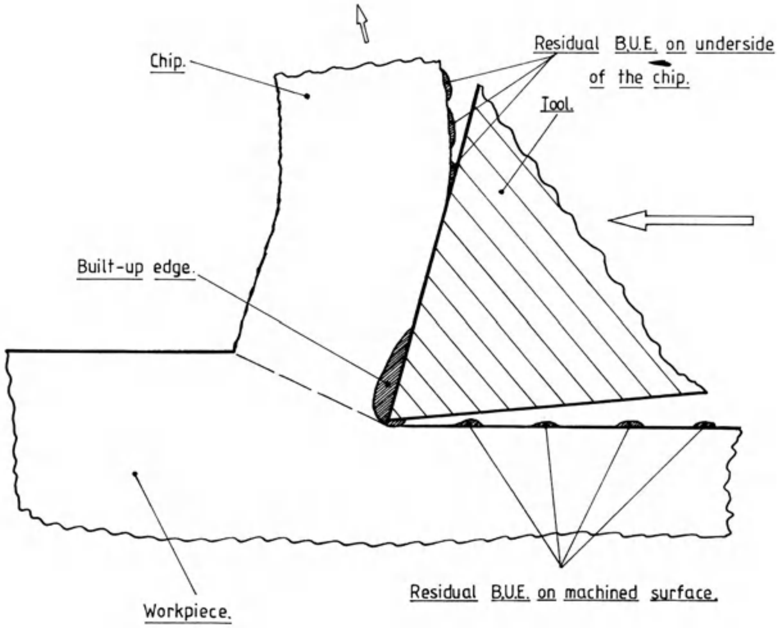


Fig. 2.7. Build-up on the tool and residual effects on the workpiece and chip.

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. 2.7). 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).

2.2.3 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. 2.8) – 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

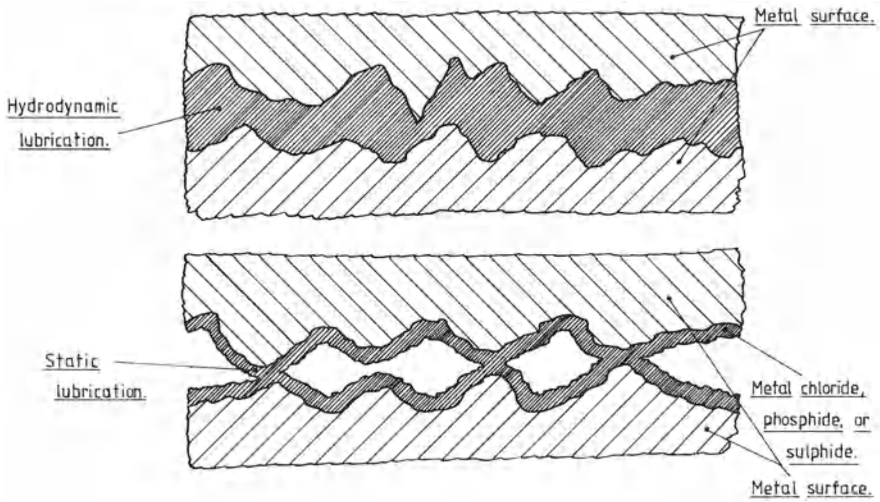


Fig. 2.8. Boundary lubrication. The effectiveness between rotating surfaces.

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. 2.8). 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. 2.8). 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. 2.8). 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

2.3 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".

2.3.1 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. 2.9.

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.

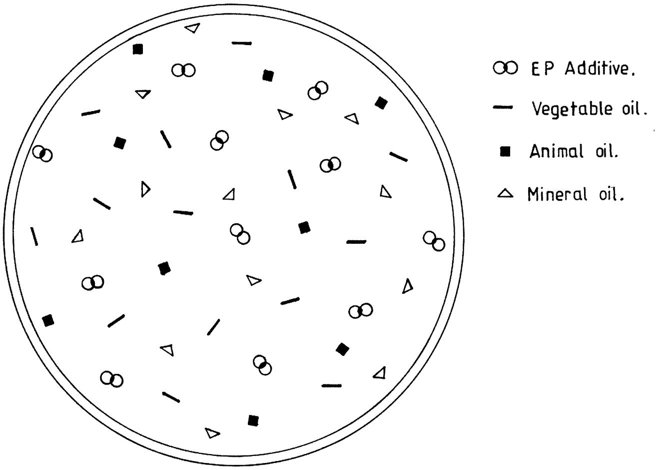


Fig. 2.9. The schematic structure of a oil-based cutting fluid. [Courtesy of Cimcool.]

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.

2.3.2 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

2.3.3 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. 2.10. 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. 2.11). The polarised film subsequently formed is no thicker than the molecules themselves and so is invisible.

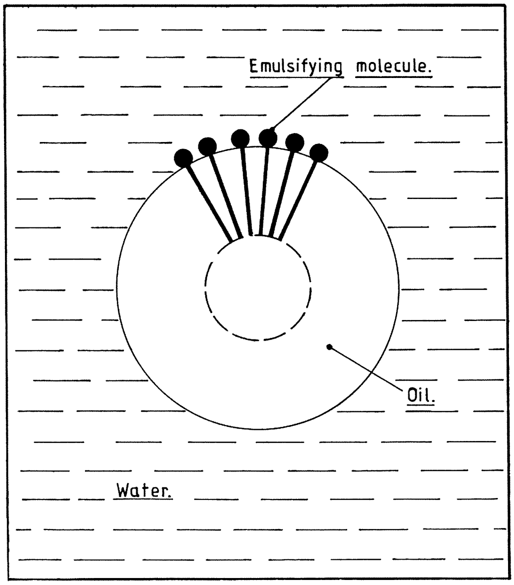


Fig. 2.10. An emulsifying molecule at the boundary surface in an oil-in-water emulsion. [Courtesy of Cimcool.]

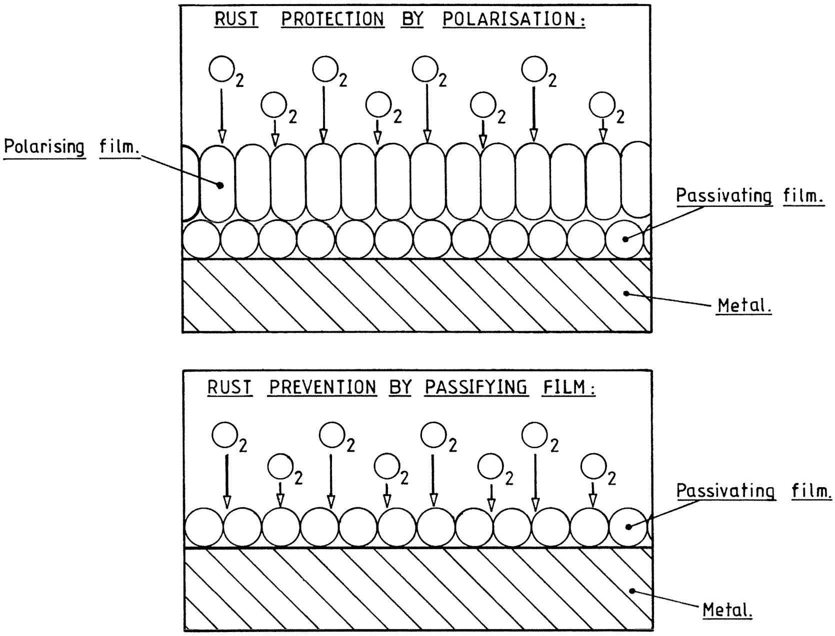


Fig. 2.11. The principle of polar and passivating corrosion protection. [Courtesy of Cimcool.]

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 2.1. 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 2.1.

2.3.4 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. 2.12). 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. 2.13). The properties of synthetic cutting fluids can be summarised as follows:

very clean
excellent corrosion protection
ong life of cutting fluid
xcellent cooling
ansparent
sy to mix

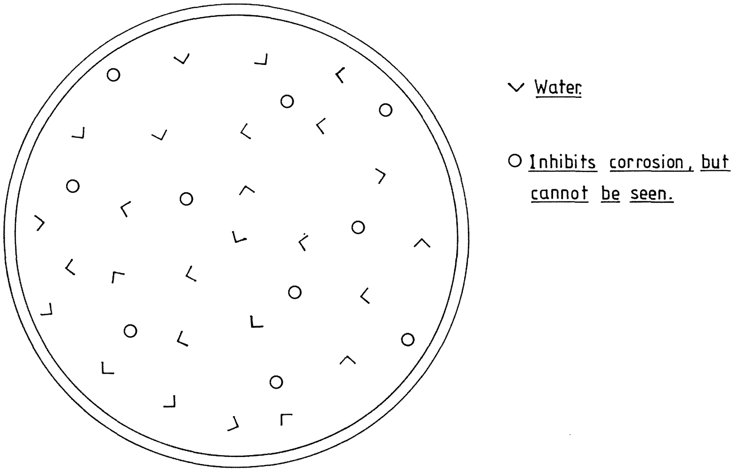


Fig. 2.12. The schematic composition of a synthetic cutting fluid. [Courtesy of Cimcool.]

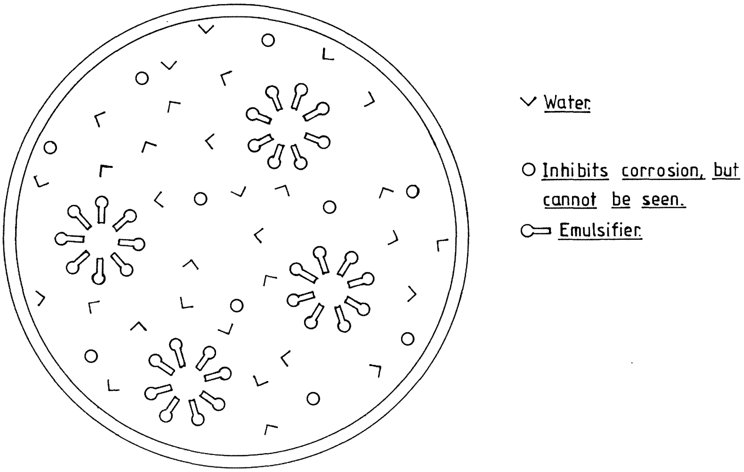


Fig. 2.13. The schematic composition of a synthetic cutting fluid for heavy cutting. [Courtesy of Cimcool.]

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. 2.14). 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

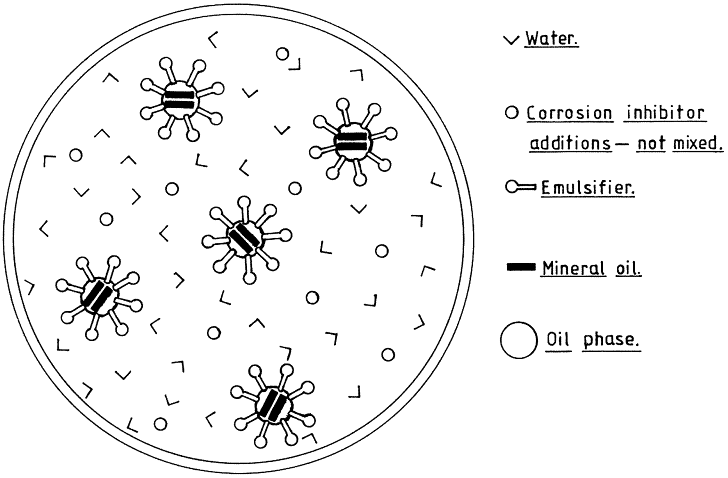


Fig. 2.14. The schematic composition of a semi-synthetic cutting fluid. [Courtesy of Cimcool.]

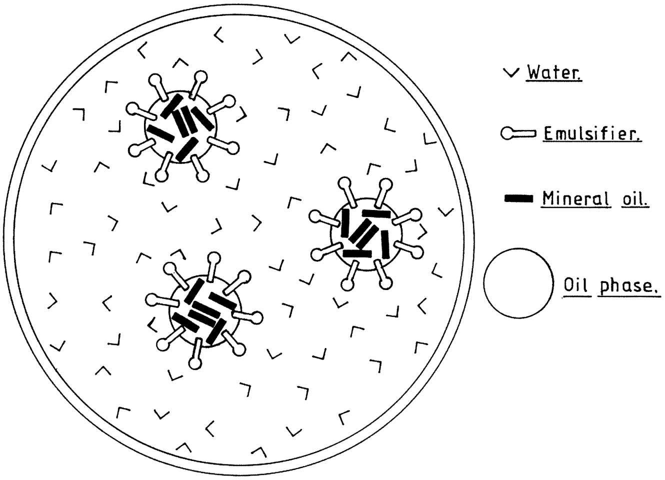


Fig. 2.15. The schematic composition of an emulsion cutting fluid. [Courtesy of Cimcool.]

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. 2.15). Products intended for very heavy cutting operations also contain EP additives (Fig. 2.16). The properties of an emulsion cutting fluid are as follows:

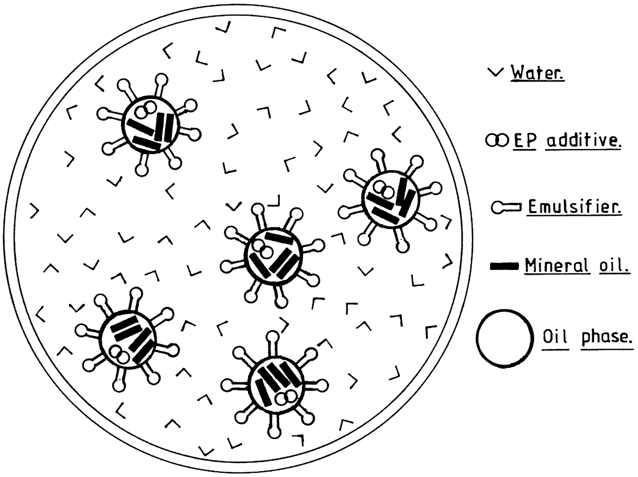


Fig. 2.16. The schematic composition of an emulsion cutting fluid for heavy cutting. [Courtesy of Cimcool.]

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.

2.3.5 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. 2.17, 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. 2.17 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.

2.3.6 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. 2.18), 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

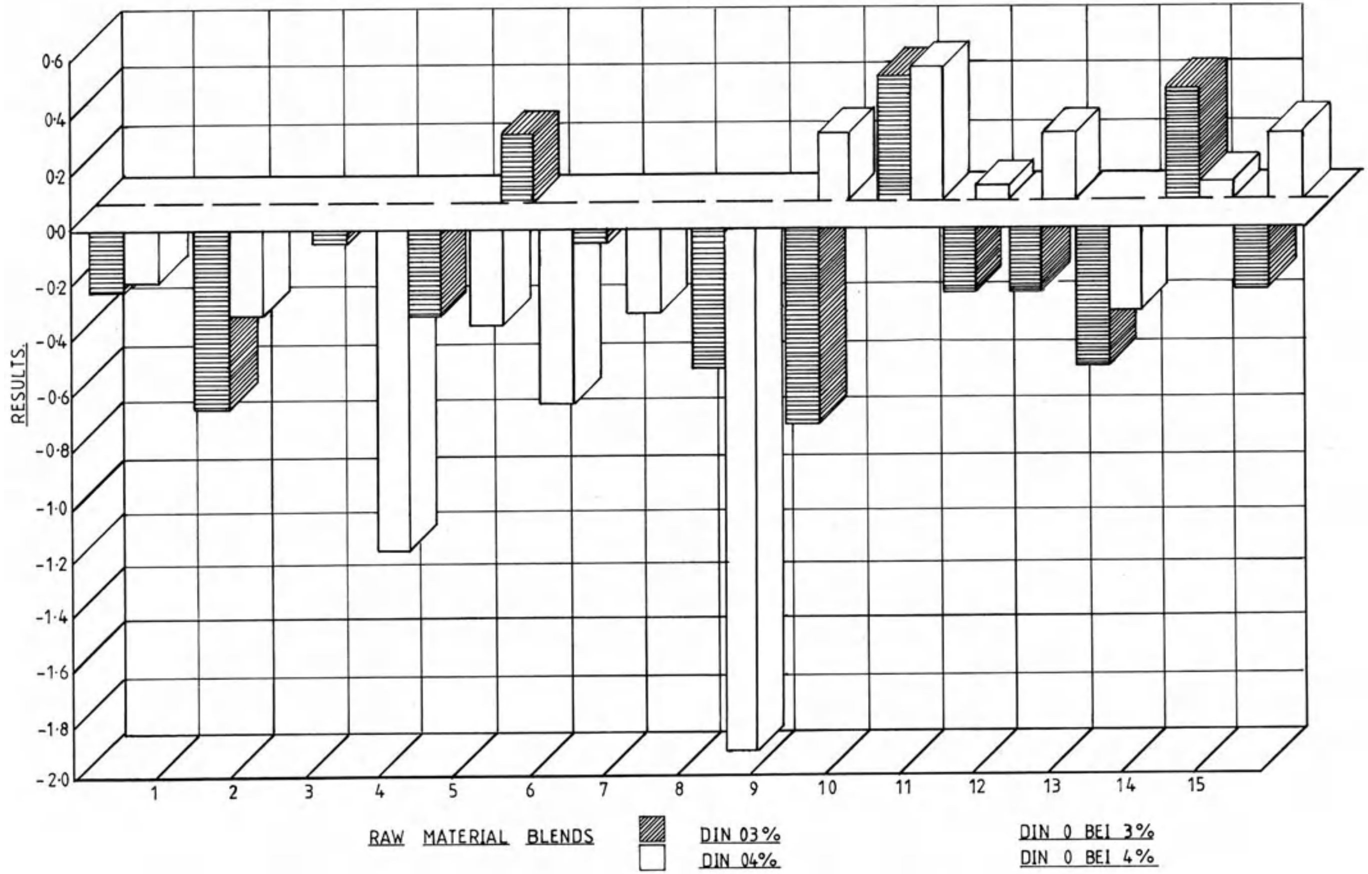


Fig. 2.17. Computer-aided design (CAD) used to select a corrosion inhibitor. [Courtesy of Cimcool.]

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.

2.4 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. 2.18. 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.

2.4.1 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.

2.5 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.

2.5.1 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.

2.5.2 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. 2.19. 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.

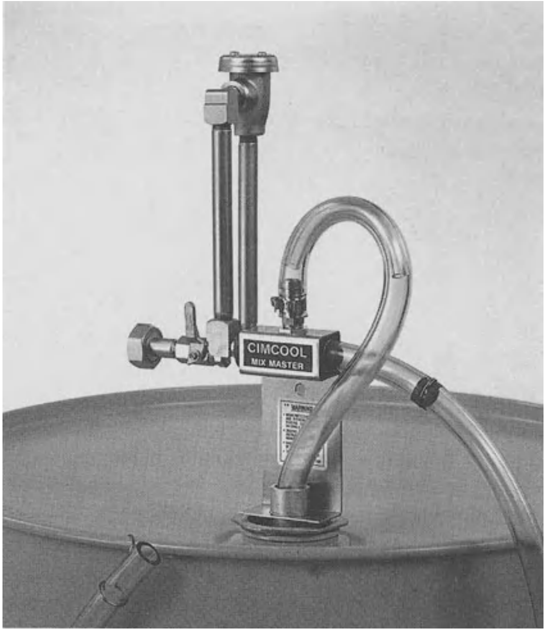


Fig. 2.19. A "Mix Master" automatic mixing unit for making up aqueous cutting fluid. [Courtesy of Cimcool.]

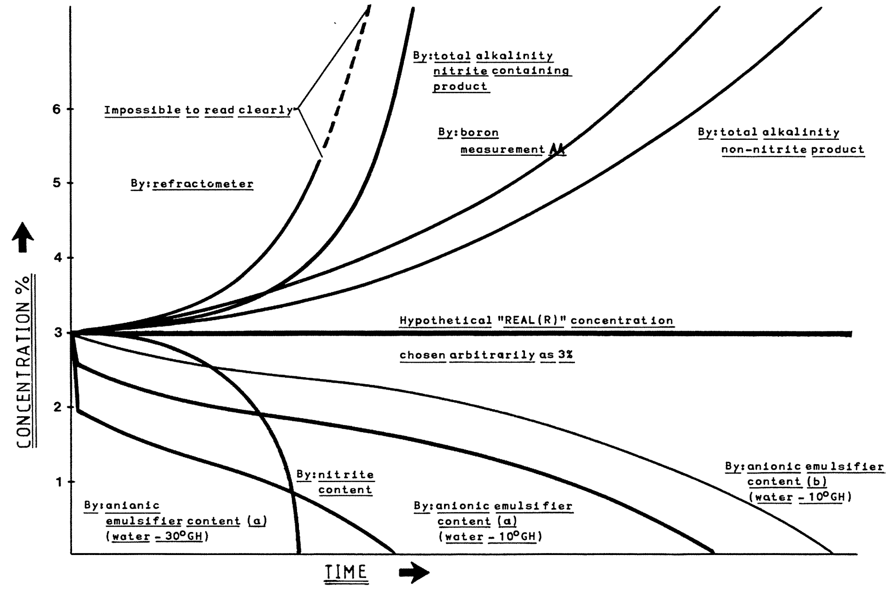


Fig. 2.20. Illustrates the results of the concentration measurements using different methods. [Courtesy of Cimcool.]

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 2.20 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 2.5.4. 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.

2.5.3 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.

2.5.4 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. 2.20 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.

2.5.5 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.

2.5.6 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. 2.21 is used for periodic cleaning of the cutting fluids used in machines with their own self-contained circuit.

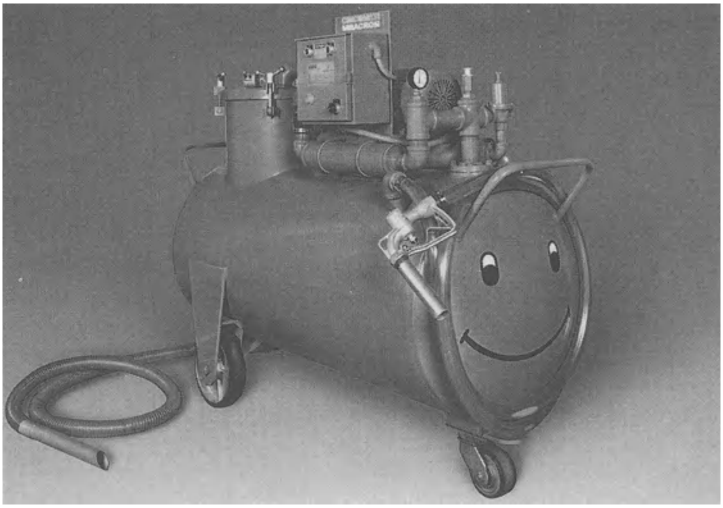


Fig. 2.21. A cutting fluid recovery unit. [Courtesy of Cimcool.]

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.

2.5.7 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.

2.5.8 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 3 we will consider the effects of utilising work-holding devices and review just some of the methods of workpiece constraint.

Chapter 3
Workholding Technology

3.1 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. 3.1) and if, after clamping, it has freedom to move in

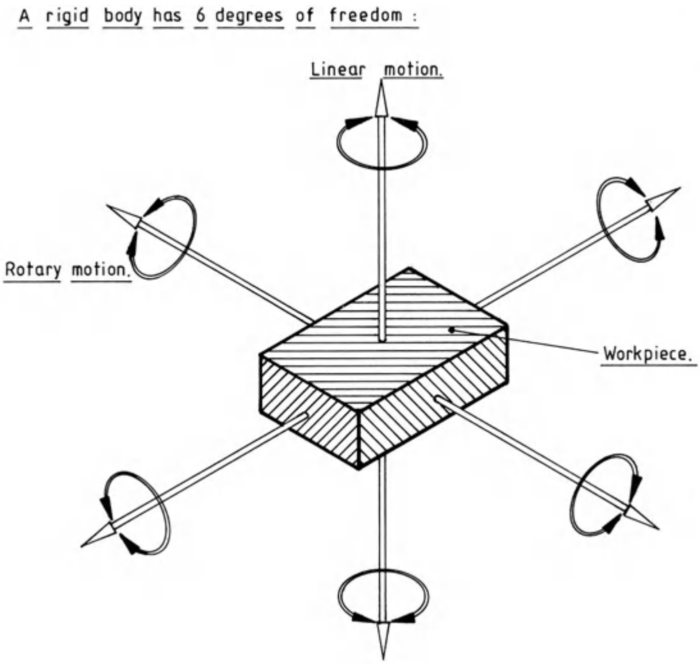


Fig. 3.1. The restraint and location of the workpiece during machining operations. Restraint: a workpiece requires an applied force to overcome the cutting forces exerted during machining. Location: the workpiece must be positively located in a known relationship to the machine tool axes.

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.

3.2 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. 3.2 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. 3.2. 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.

3.2.1 Collets and Collet Chucks

The simple construction of collets means that they are trouble-free in operation and maintenance, with Fig. 3.3 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.

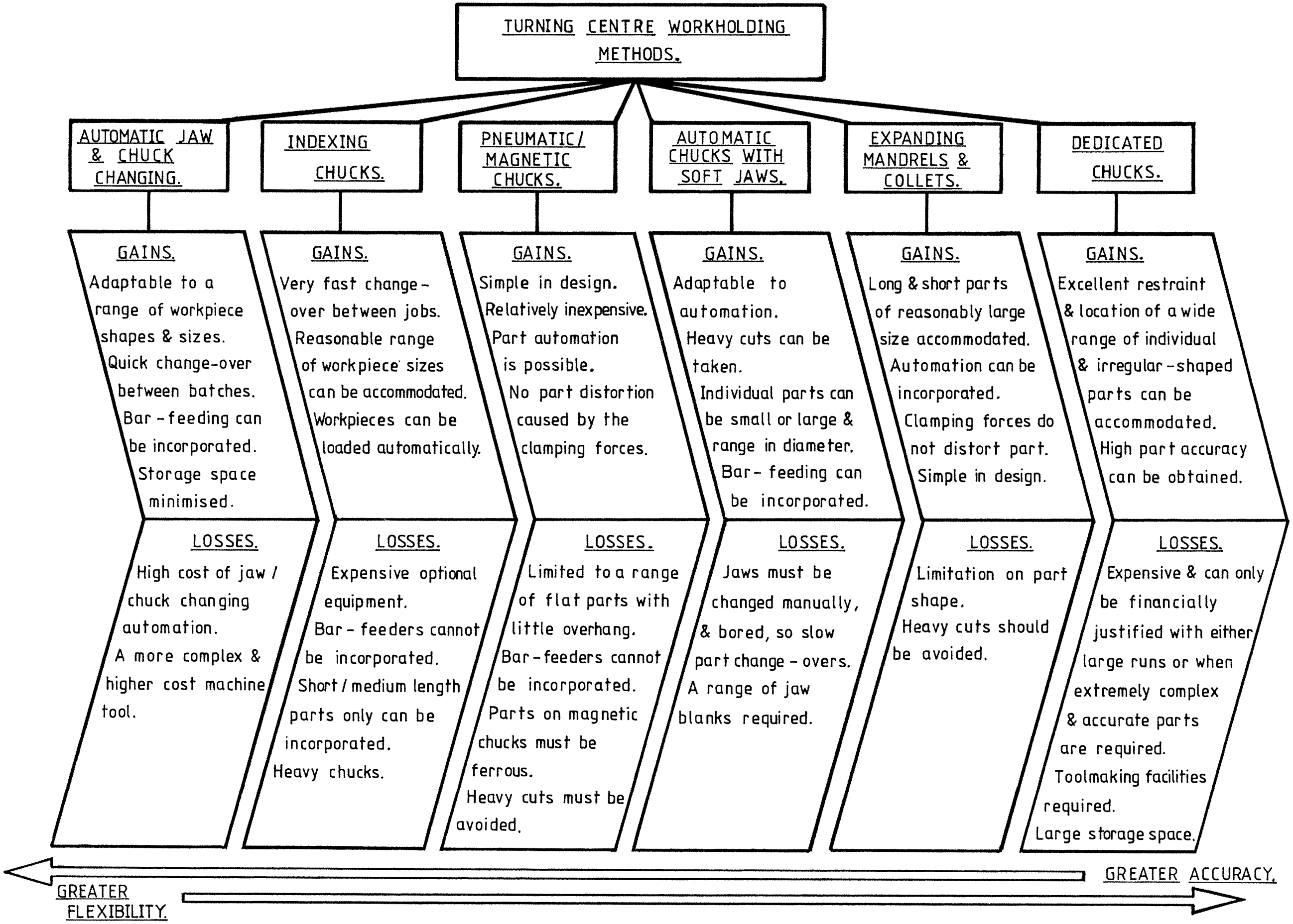


Fig. 3.2. Workholding methods for turning centres and their advantages and limitations.

Fig. 3.3. 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.

3.2.2 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. 3.4) provides the means by which rotation is transmitted, whereas the live centre (Fig. 3.5) 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. 3.4c, Fig. 3.4b will also achieve the same objective.

The operating principle is best discussed in conjunction with the general arrangement of the setup given in Fig. 3.4. 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

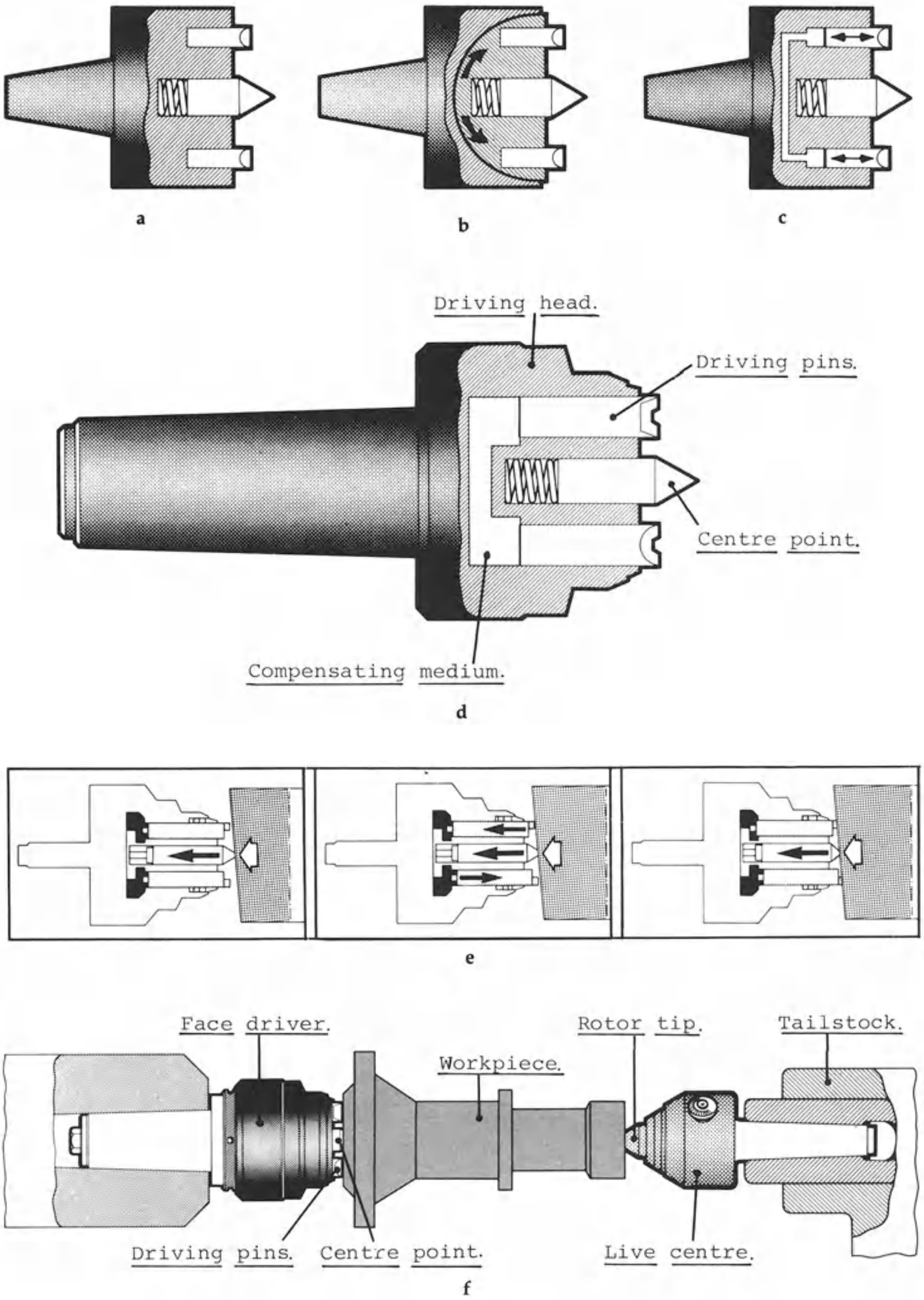


Fig. 3.4. Typical face drivers in turning operations. **a** Face driver with fixed driving pins. **b** Face driver with fixed driving pins on a floating cup-shaped plate. **c** Face driver with axially (i.e. "floating") moveable driving pins. **d** Detail of type **c**. **e** Typical applications. **f** General arrangement of setup. [Courtesy of Sandvik (UK) Ltd.]

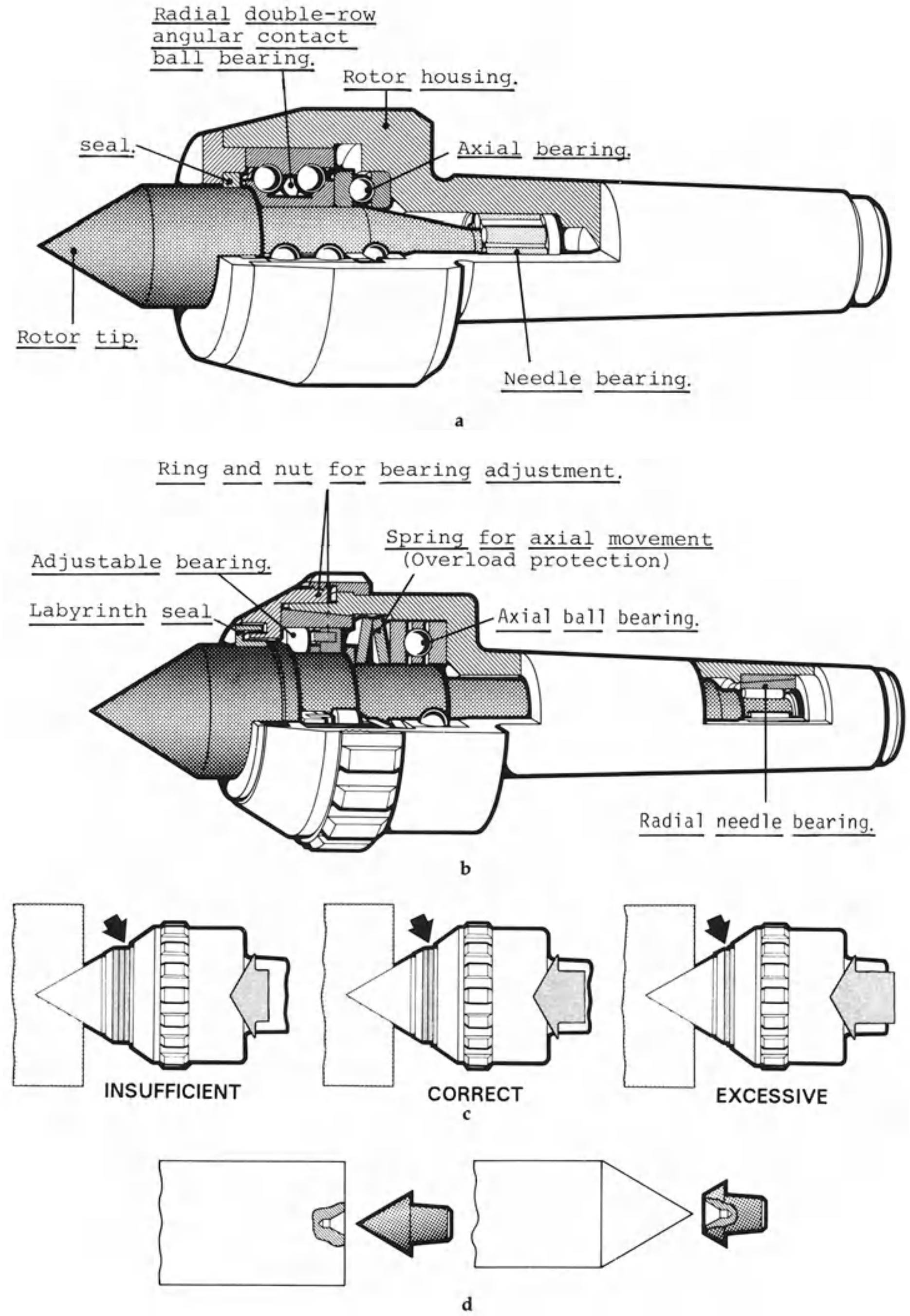


Fig. 3.5. Typical "live" centres used for support in turning operations. **a** Designed for normal operation. **b** Designed for high-precision operation. **c** Axial force indicators. **d** Interchangeable centre tips (centring plugs). [Courtesy of Sandvik (UK) Ltd.]

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 $5 \times 11\,\text{mm} = 55\,\text{mm}$ and the force per edge is then $\frac{1650}{55} = 30\,\text{daN/mm}$, 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. 3.5). 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.

3.2.3 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. 3.6a). 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,

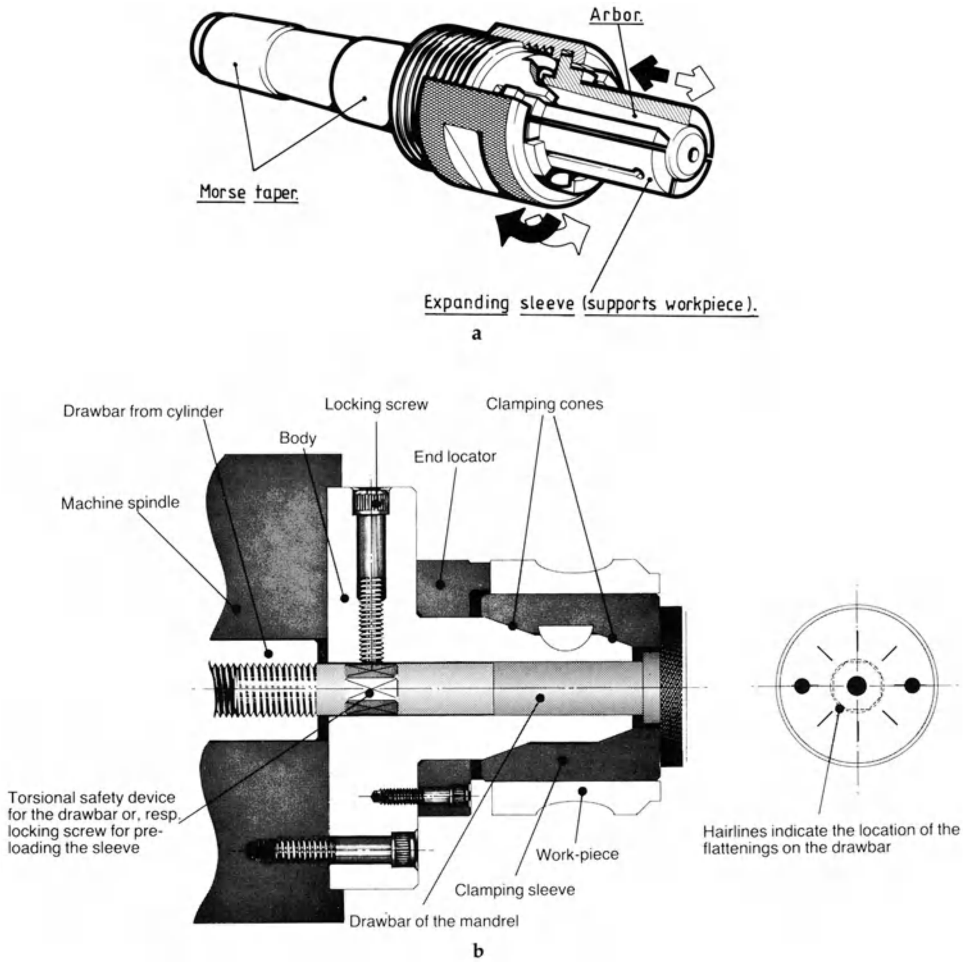


Fig. 3.6. Two examples of expanding mandrels used on turning centres. **a** Conventional expanding mandrel with manual adjustment. **b** Power operated expanding mandrel. [**a** Courtesy of Sandvik (UK) Ltd. **b** Courtesy of Forkardt GmbH & Co.]

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. 3.6b) 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. 3.6a) 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. 3.6b). 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.

3.2.4 Specially Engineered Chucks

Often there is a need to either manufacture or purchase specially engineered workholding equipment (Fig. 3.7) 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

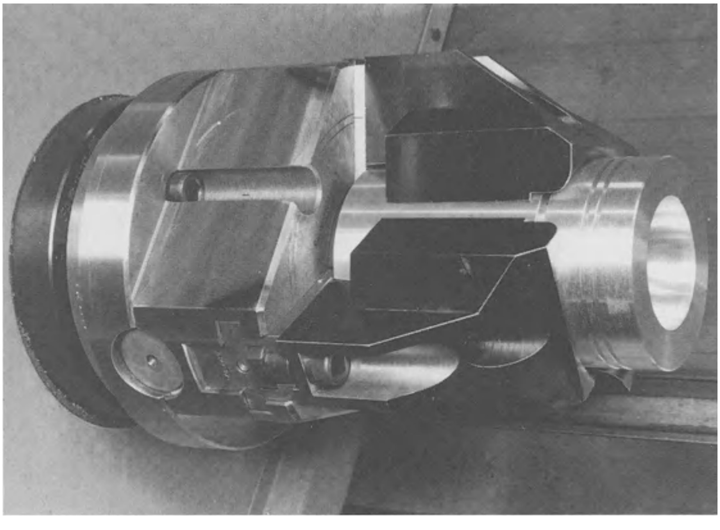


Fig. 3.7. A specially engineered chuck for the machining of piston crowns. [Courtesy of Gildemeister (UK) Ltd.]

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.

3.2.5 Conical Clamping Rings for Workholding Applications

The principle of operation of the conical clamping ring for workholding can be gauged by Fig. 3.8 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 3.2.1, the clamping ring grips the entire outer or inner circumference, as shown in Figs. 3.8a and 3.8b, 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.

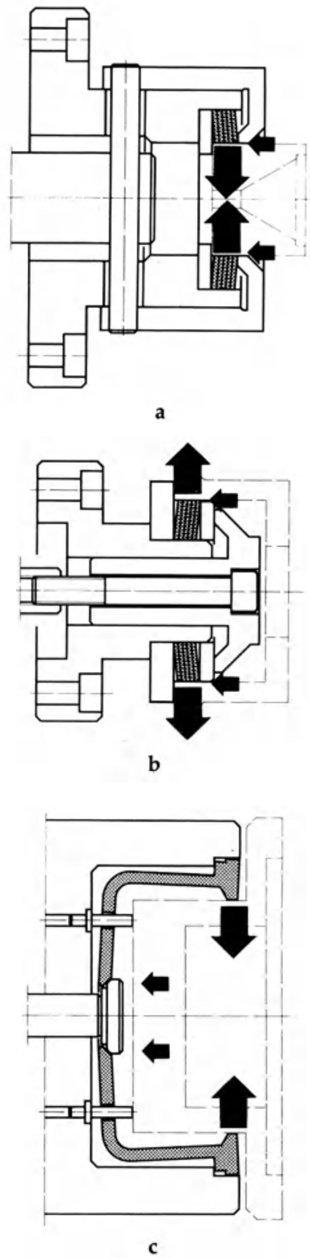


Fig. 3.8. Utilising the principle of a hardened spring steel conical clamping ring for workholding applications. **a** Disc pack chuck for outer clamping. **b** Disc pack mandrel for inner clamping. **c** Basket chuck for outer clamping. [Courtesy of Ringspann (UK) Ltd.]

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. 3.8a,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. 3.8c.

3.2.6 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. 3.9 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

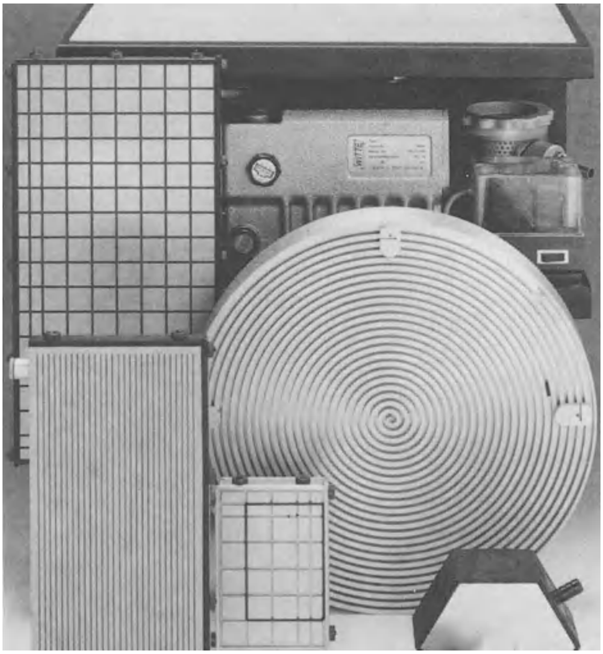


Fig. 3.9. A range of vacuum chucks, fixtures and clamps for turning and machining centres. [Courtesy of Thame Engineering.]

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. 3.10, which is true for chucks, tables, cubes and tombstones. Fig. 3.10a 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. 3.10b). 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 3.7.6 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.

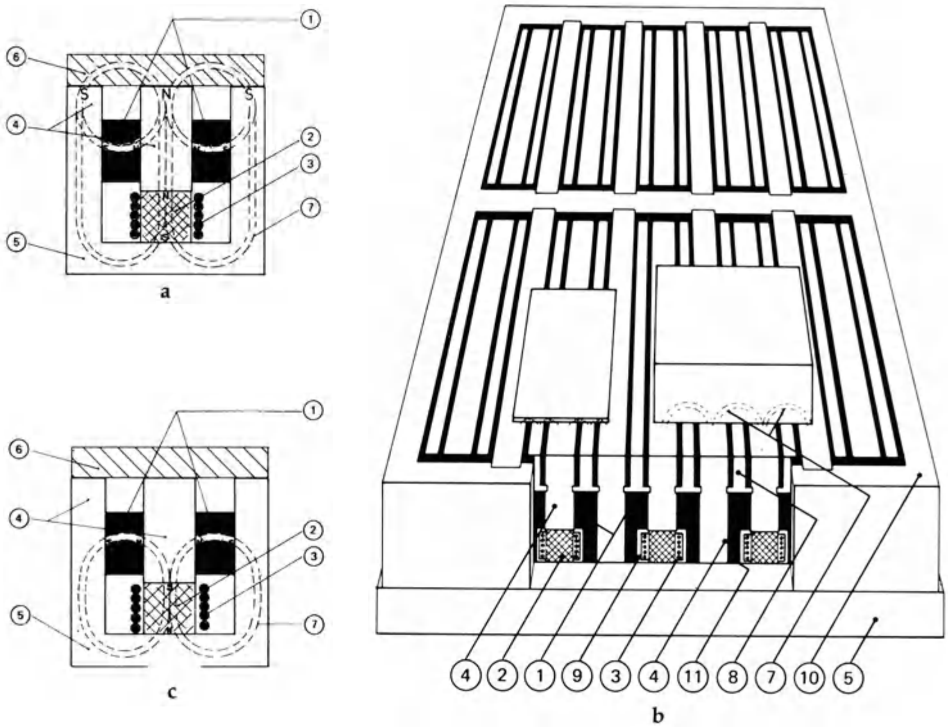


Fig. 3.10. The workholding principle for ferrous materials using magnetic chucks, tables, cubes, etc. 1, static permanent magnet; 2, reversible permanent magnet; 3, coil; 4, direct polepieces; 5, armature; 6, workpiece; 7, magnetic flux; 8, induced polepieces; 9, dielectric; 10, ferro-magnetic frame; 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.

3.2.7 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.

3.3 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. 3.11 and 3.12. If we consider the general arrangement, as depicted in Fig. 3.11, 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

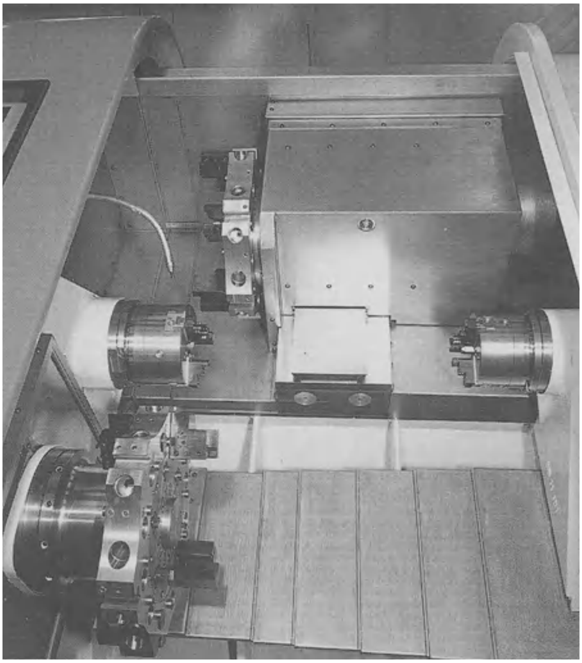


Fig. 3.11. A twin-turret 2-spindled turning centre having the ability to synchronise rotations of chucks. This allows the rear spindle to advance and grip the part and retreat, allowing "backturning" to commence. [Courtesy of Gildemeister (UK) Ltd.]

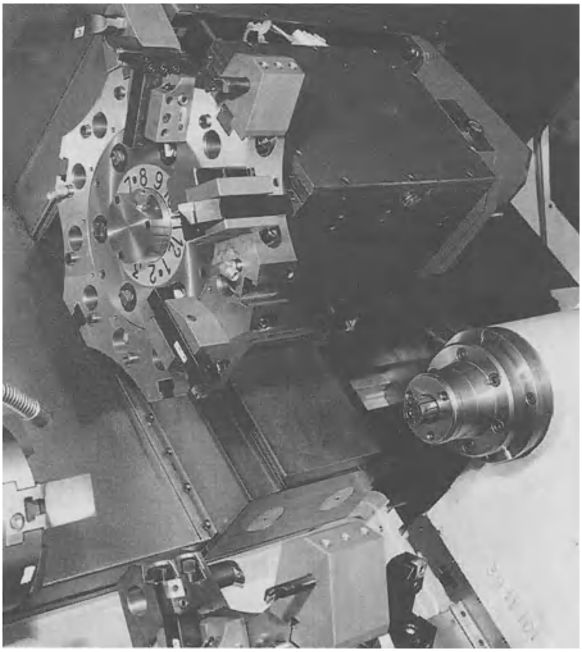


Fig. 3.12. An expanding mandrel in the rear spindle allowing "backturning" by the lower turret. [Courtesy of Gildemeister (UK) Ltd.]

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. 3.12 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.

3.4 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 3.2.2), 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. 3.13). 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.

3.5 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

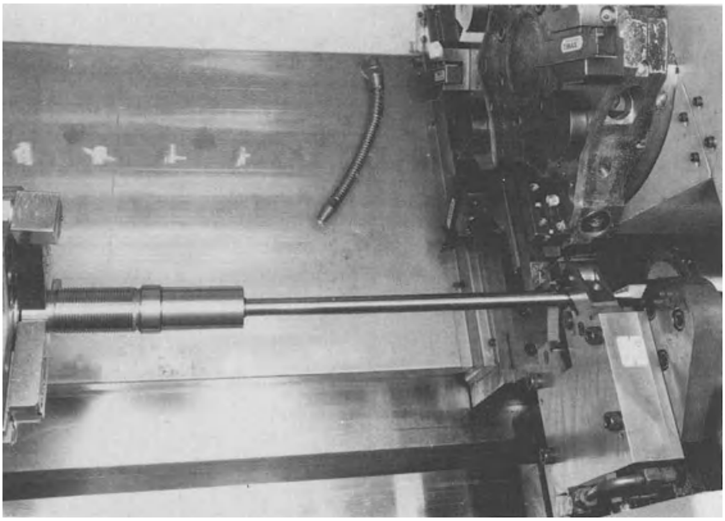


Fig. 3.13. Supporting a long slender workpiece using a programmanle steady whilst the top turret turns the diameter. [Courtesy of Gildemeister (UK) Ltd.]

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. 3.14, 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

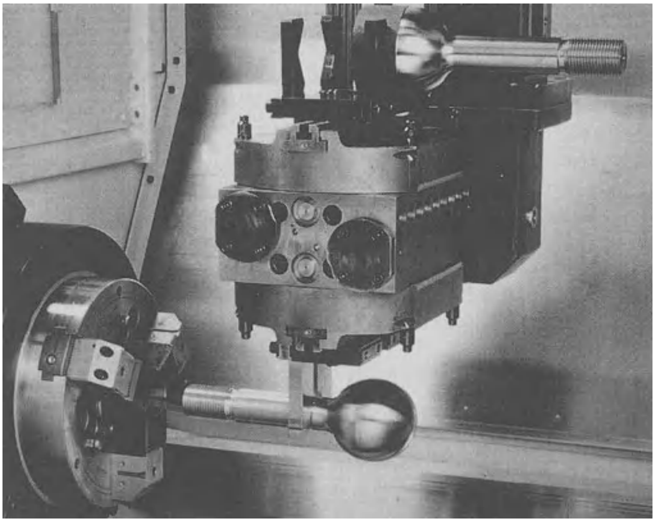


Fig. 3.14. Using a gantry robot to simultaneously load and unload workpieces to a turning centre. [Courtesy of Gildemeister (UK) Ltd.]

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.

3.6 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. 3.15, 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. 3.15, 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

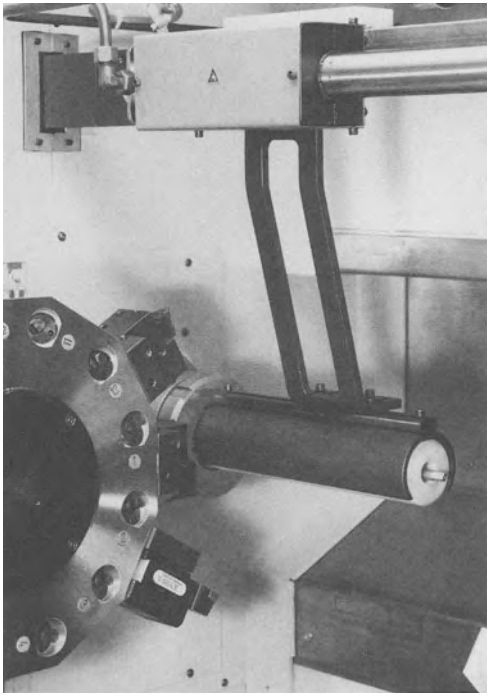


Fig. 3.15. A part-catcher partially supporting the workpiece and minimising damage whilst the parting-off operation is undertaken. [Courtesy of Gildemeister (UK) Ltd.]

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.

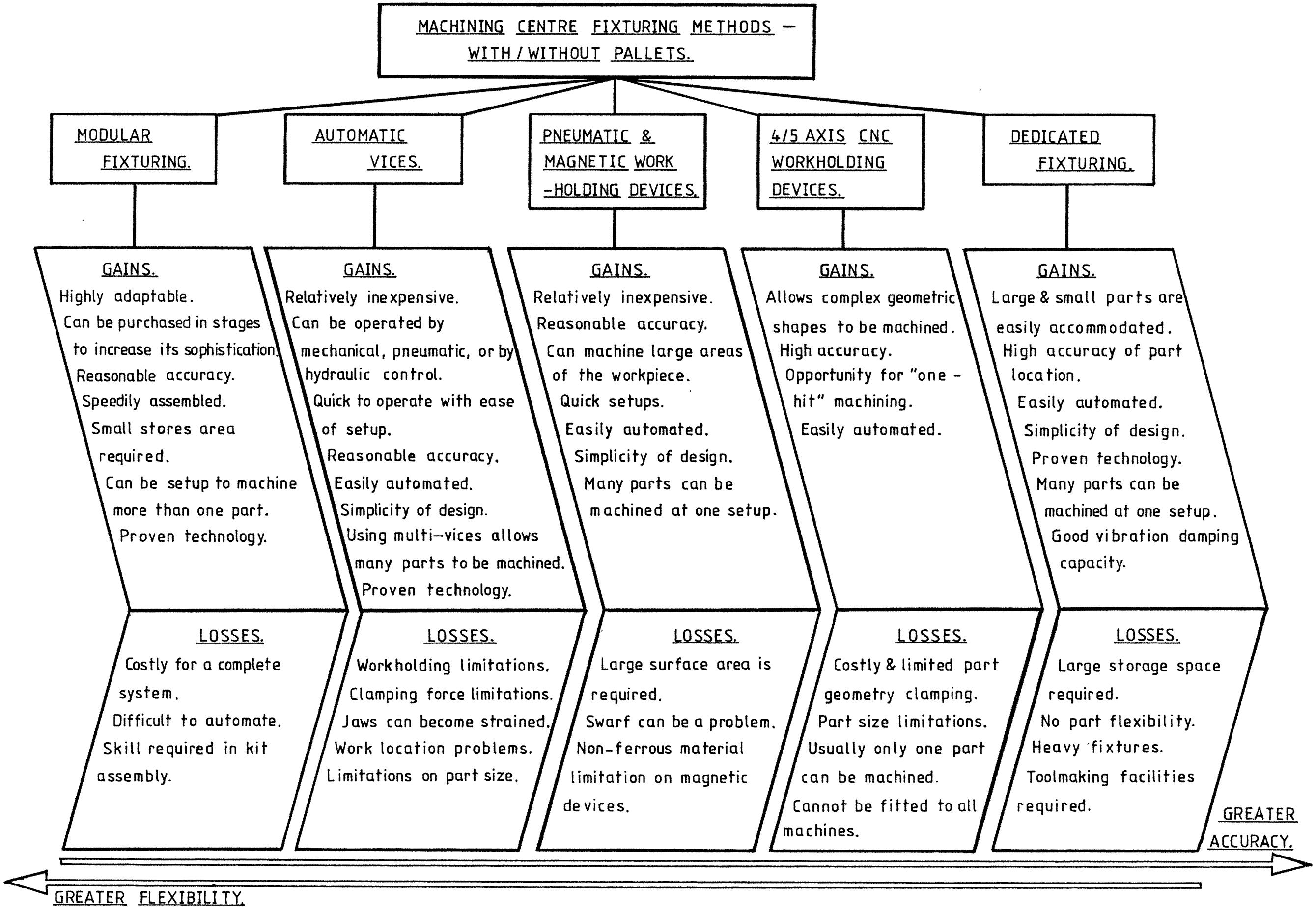
3.7 Machining Centre Workholding Techniques

The general comments made about workholding techniques for turning centres (section 3.2) 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. 3.16 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.

3.7.1 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



MACHINING CENTRE FIXTURING METHODS – WITH / WITHOUT PALLETS.

MODULAR FIXTURING.

GAINS.
Highly adaptable.
Can be purchased in stages to increase its sophistication.
Reasonable accuracy.
Speedily assembled.
Small stores area required.
Can be setup to machine more than one part.
Proven technology.

LOSSES.
Costly for a complete system.
Difficult to automate.
Skill required in kit assembly.

AUTOMATIC VICES.

GAINS.
Relatively inexpensive.
Can be operated by mechanical, pneumatic, or by hydraulic control.
Quick to operate with ease of setup.
Reasonable accuracy.
Easily automated.
Simplicity of design.
Using multi–vices allows many parts to be machined.
Proven technology.

LOSSES.
Workholding limitations.
Clamping force limitations.
Jaws can become strained.
Work location problems.
Limitations on part size.

PNEUMATIC & MAGNETIC WORK -HOLDING DEVICES.

GAINS.
Relatively inexpensive.
Reasonable accuracy.
Can machine large areas of the workpiece.
Quick setups.
Easily automated.
Simplicity of design.
Many parts can be machined at one setup.

LOSSES.
Large surface area is required.
Swarf can be a problem.
Non-ferrous material limitation on magnetic devices.

4/5 AXIS CNC WORKHOLDING DEVICES.

GAINS.
Allows complex geometric shapes to be machined.
High accuracy.
Opportunity for "one - hit" machining.
Easily automated.

LOSSES.
Costly & limited part geometry clamping.
Part size limitations.
Usually only one part can be machined.
Cannot be fitted to all machines.

DEDICATED FIXTURING.

GAINS.
Large & small parts are easily accommodated.
High accuracy of part location.
Easily automated.
Simplicity of design.
Proven technology.
Many parts can be machined at one setup.
Good vibration damping capacity.

LOSSES.
Large storage space required.
No part flexibility.
Heavy fixtures.
Toolmaking facilities required.

Fig. 3.16. 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. 3.30). 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. 3.17) 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.

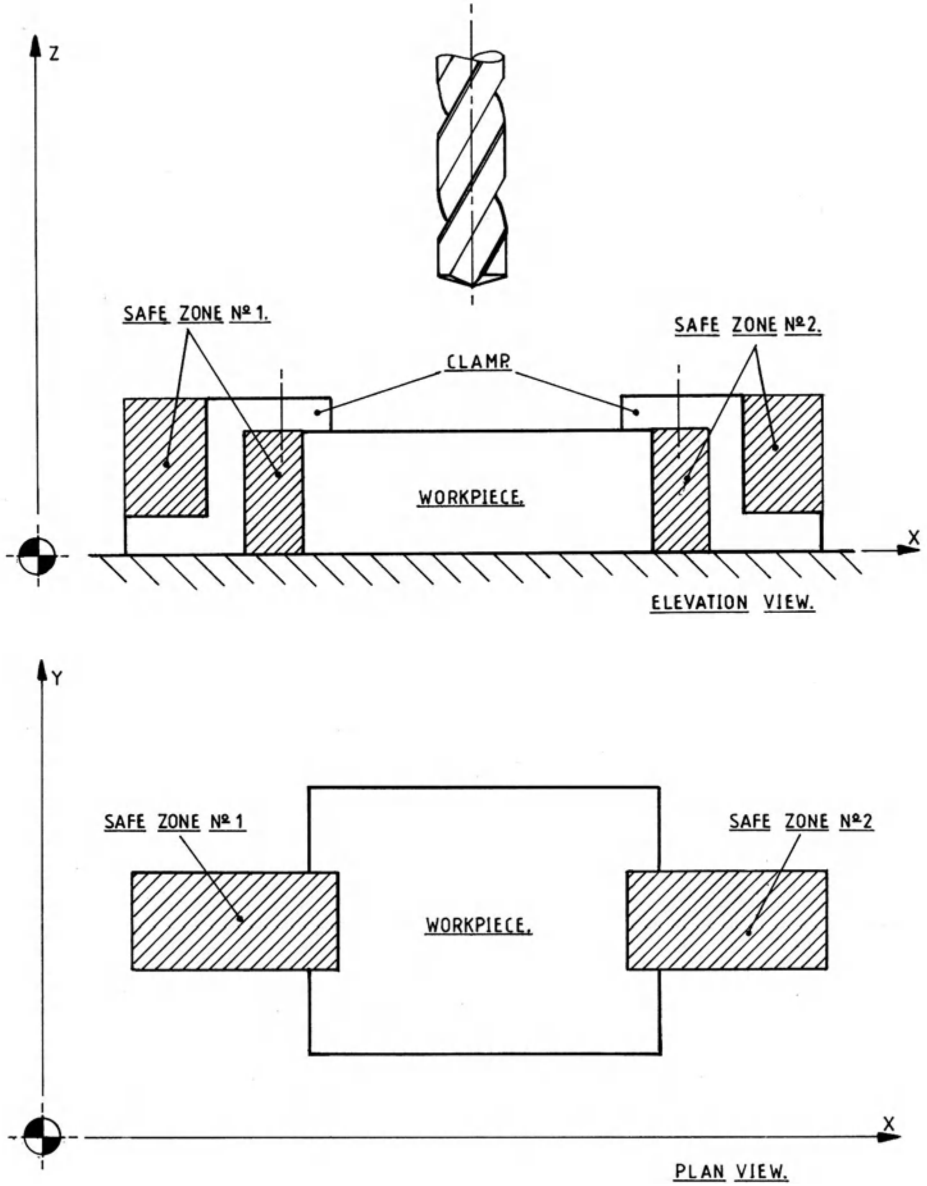


Fig. 3.17. The programmed safe zones for the clamping positions which are related to the machine zero and avoid crashes.

3.7.2 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. 3.18) are easy to handle with the operator needing

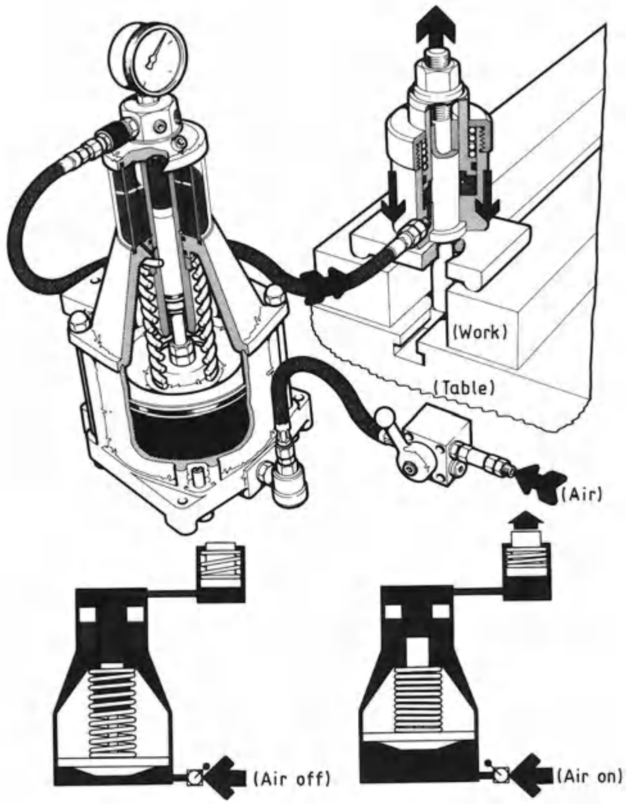


Fig. 3.18. The clamping of workpieces using pneumatic input to intensify the hydraulic pressure on the part. Principle of operation: compressed air is fed via a pneumatic connection into the pressure converter. The raised pressure in the hydraulic oil in the pressure converter is transmitted via the 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:

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

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

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

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 $0.2\,\mathrm{m^2}$ and is connected by piping to another piston which has an area of $0.05\,\mathrm{m^2}$; in order for a smaller piston to maintain an equalising pressure its force must be considerably greater, as follows:

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

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:

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

therefore

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

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. 3.18 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.

3.7.3 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. 3.19 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

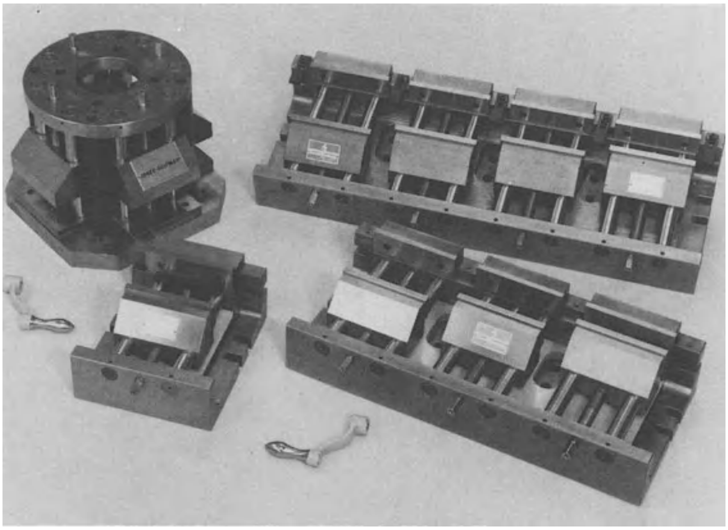


Fig. 3.19. A range of multi-vices offering many configurations for multi-part setups on vertical or horizontal machining centres. [Courtesy of Jones & Shipman.]

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.

3.7.4 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. 3.20, 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

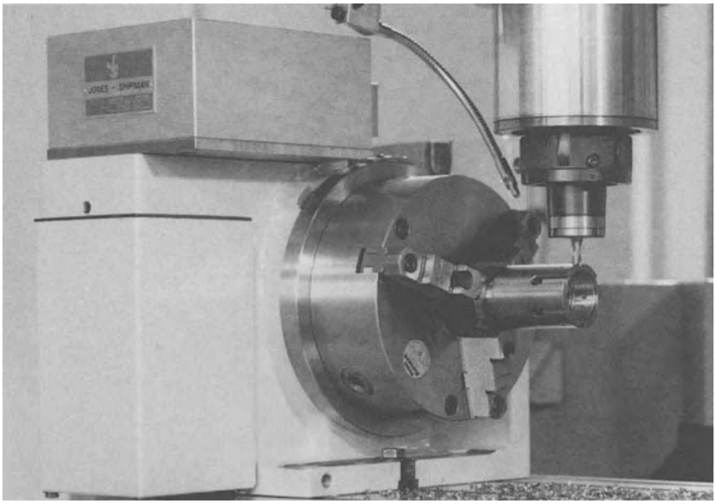


Fig. 3.20. A "full" 4-axis rotary table on a vertical machining centre. This extra CNC axis offers greater machining versatility. [Courtesy of Jones & Shipman.]

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.

3.7.5 "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. 3.21. 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

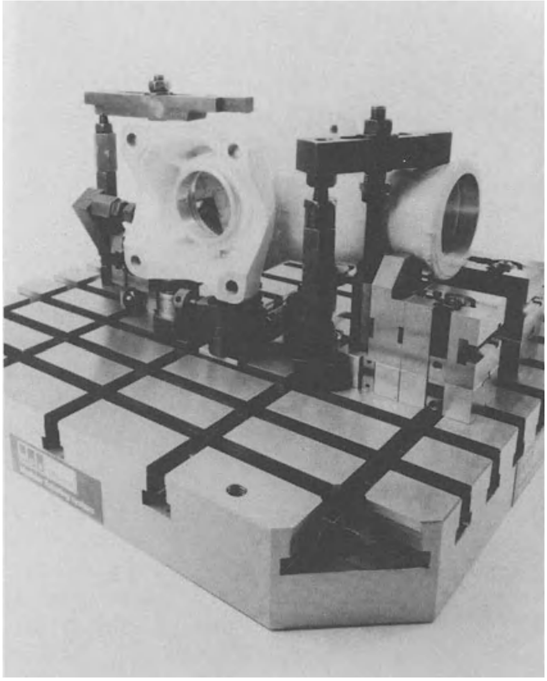


Fig. 3.21. A pallet featuring the "modular fixturing system" which offers the benefits of reusable elements, flexibility of setup, speed in assembly and, as a result, an overall reduction in fixture costs. [Courtesy of WDS Wharton.]

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. 3.21) 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. 3.22).

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. 3.21) 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

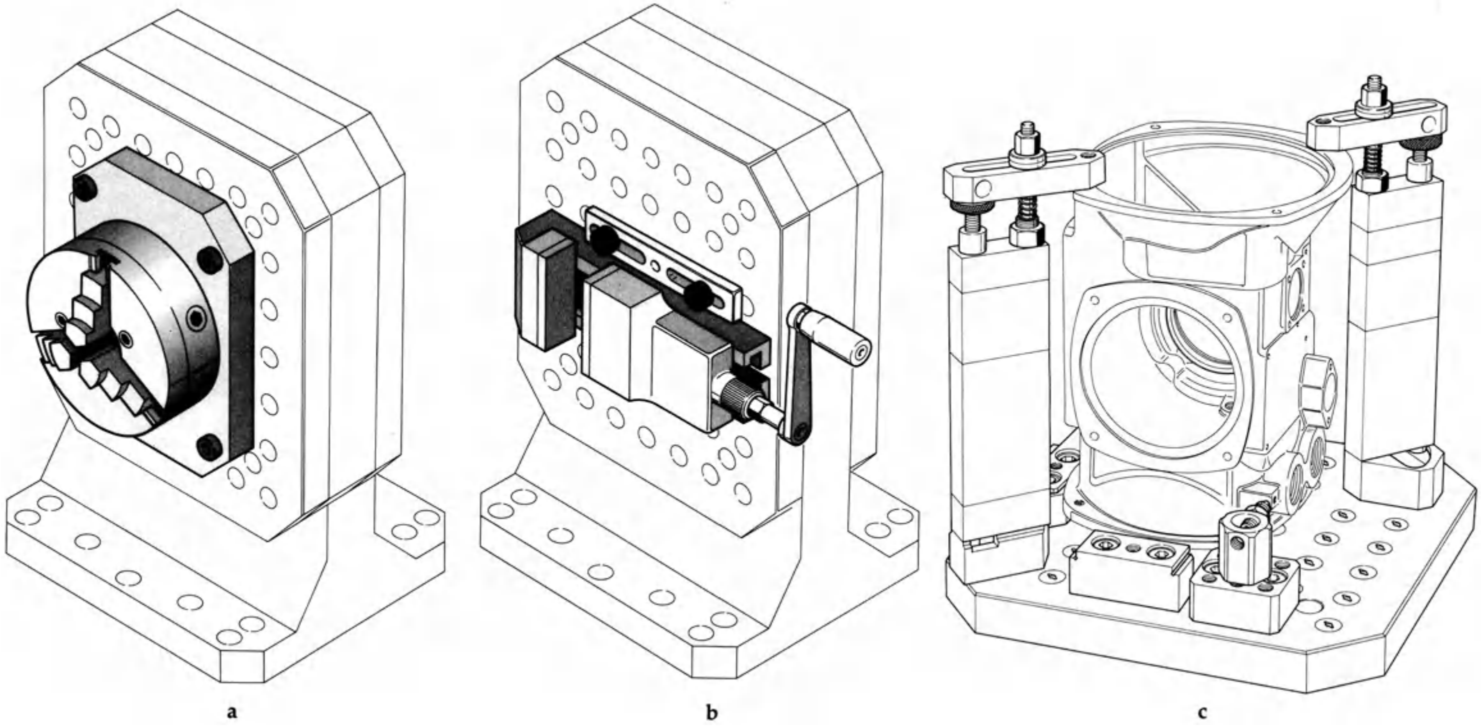


Fig. 3.22. The adaptability of "modular fixturing" for machining centres. **a** A chuck fitted to a grid plate on a "tombstone". **b** A vice positioned on a grid plate on a "tombstone". **c** Workpiece setup using elements from the "modular fixing kit" for a machining centre. [Courtesy of Wix & Royd 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. 3.22) – 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:

$$\mathrm{MF_{tot}} = \mathrm{N}(1 + \mathrm{Y})\left[\mathrm{C_{ass}} + \mathrm{C_{MF_c}} \cdot \mathrm{T_u}\left(\frac{1}{\mathrm{T_w}} + \frac{\mathrm{IR}}{2} + 0.05\right)\right] + \mathrm{C_{MF_s}} \times \mathrm{T_N} + \Delta \mathrm{C_{c_{man}}} \quad (£)$$

Nomenclature:

$\mathrm{MF_{tot}}$ = total cost of modular fixture (£)
N = number of different fixtures necessary (number)
Y = relative number of repetitive assemblies (number)
$\mathrm{C_{ass}}$ = assembly costs for one modular fixture (£)
$\mathrm{C_{MF_c}}$ = cost contribution of modules (£)
$\mathrm{T_u}$ = average utilisation of fixture (days)
$\mathrm{T_w}$ = write-off period (10 years)
$\mathrm{C_{MF_s}}$ = storage cost for modular system (£)
$\mathrm{T_N}$ = period for cost consideration (years)
$\Delta \mathrm{C_{c_{man}}}$ = 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

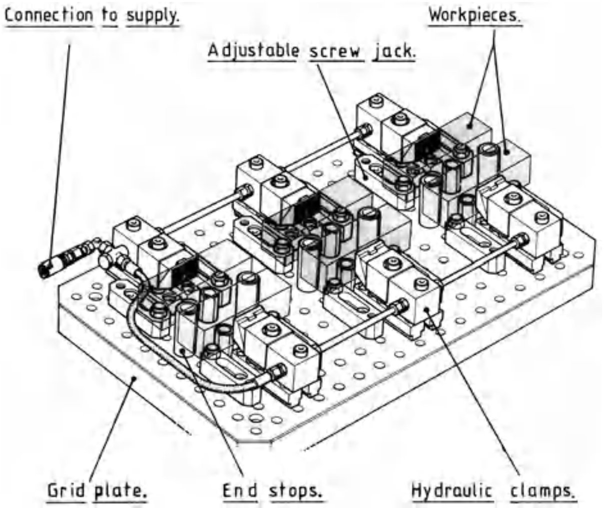


Fig. 3.23. Hydraulic clamping of multiple parts based upon the "modular fixturing concept" on a hole pattern in a grid plate. [Courtesy of Wix & Royd Ltd.]

effected as shown in Fig. 3.23. 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 3.2.6, but we will now consider the applications and indeed some of the problems associated with milling components by such methods.

3.7.6 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. 3.24, 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. 3.24. 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. 3.25a), 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. 3.25a 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. 3.25b) 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, Volume I).

Face milling operations (Fig. 3.25c,d) offer more variable machining conditions than those for both up- and down-cut milling operations. For example, in Fig. 3.25c, 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. 3.25d), 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.

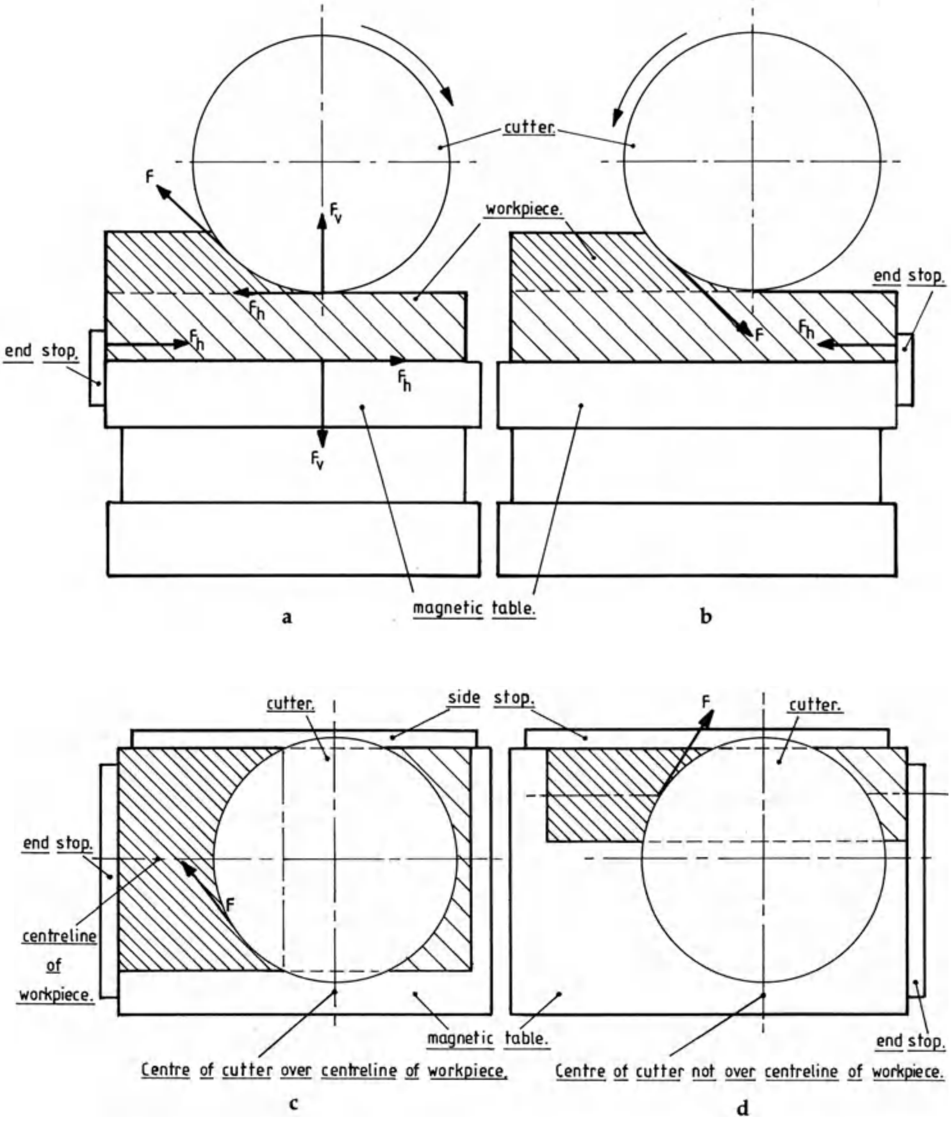


Fig. 3.25. The force vectors with different milling techniques on magnetic tables. **a** Up-cut milling. **b** Down-cut milling. **c** On-centre milling. **d** Off-centre milling. [Courtesy of Eclipse Magnetics Ltd.]

3.8 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.

3.8.1 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. 3.26.

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.

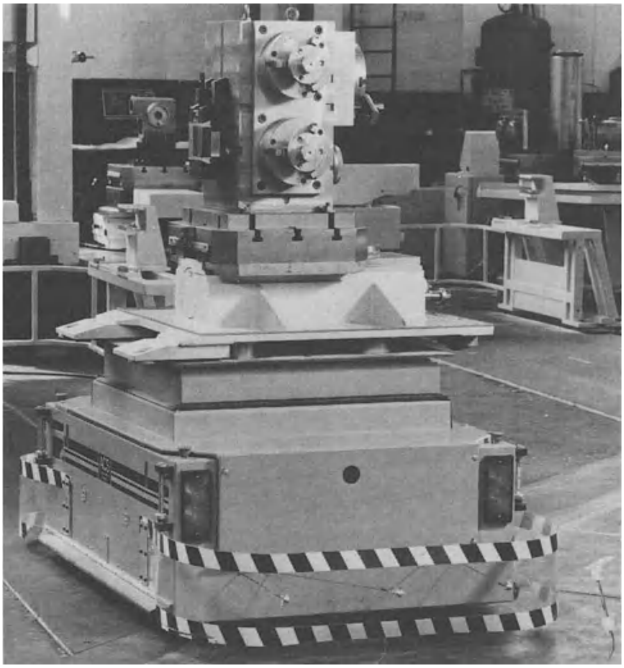


Fig. 3.26. An automated guided vehicle in the process of delivering a range of palletised workpieces held on a "cube" to a horizontal machining centre. [Courtesy of Cincinnati Milacron.]

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. 3.26) 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. 3.26) 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.

3.8.2 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. 3.27) 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. 3.27 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

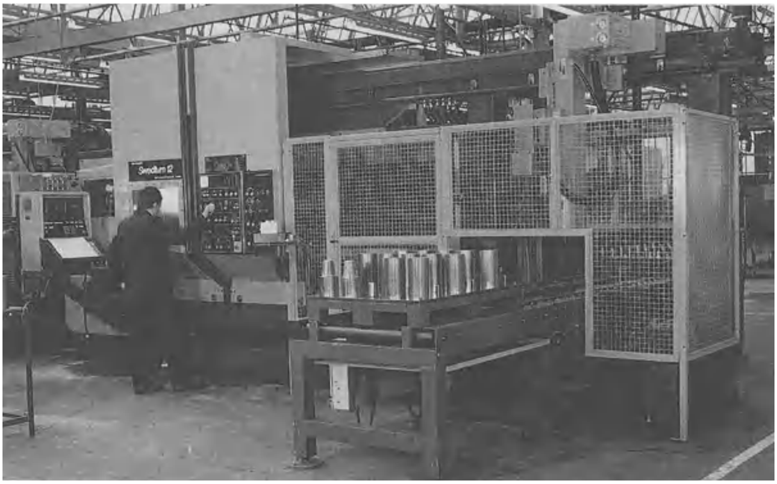


Fig. 3.27. Handling raw material billets by means of a computerised part changer (CPC) for automatic loading into a 4-axis turning centre. [Courtesy of SMG (UK) Ltd.]

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. 3.27) 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.

3.8.3 Rail-Guided Vehicles (RGVs) for Prismatic Manufacture on Machining Centres

The statements made about AGVs in section 3.8.1 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. 3.28), which is yet another cost saving.

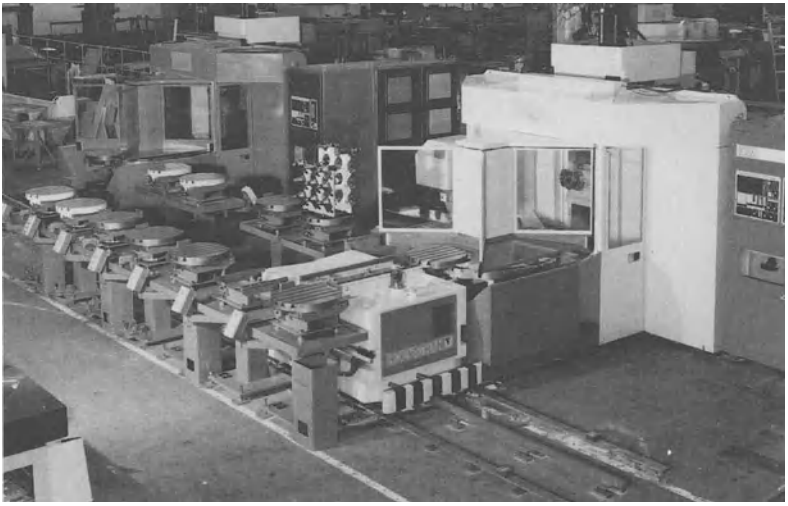


Fig. 3.28. A rail-guided vehicle (RGV) automatically delivering palletised workpieces and cutting tools to two horizontal machining centres in an FMC under test. [Courtesy of FMT.]

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. 3.28). 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.

3.9 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. 3.29 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. 3.30. 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

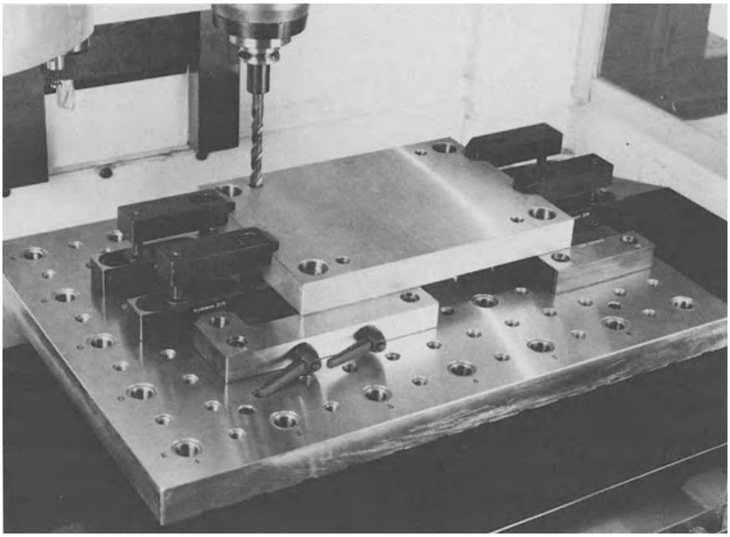


Fig. 3.29. A part setup on the precision fixture which is left permanently in situ on the table and accessories are quickly added when the workpiece geometry changes. [Courtesy of System 3R International.]

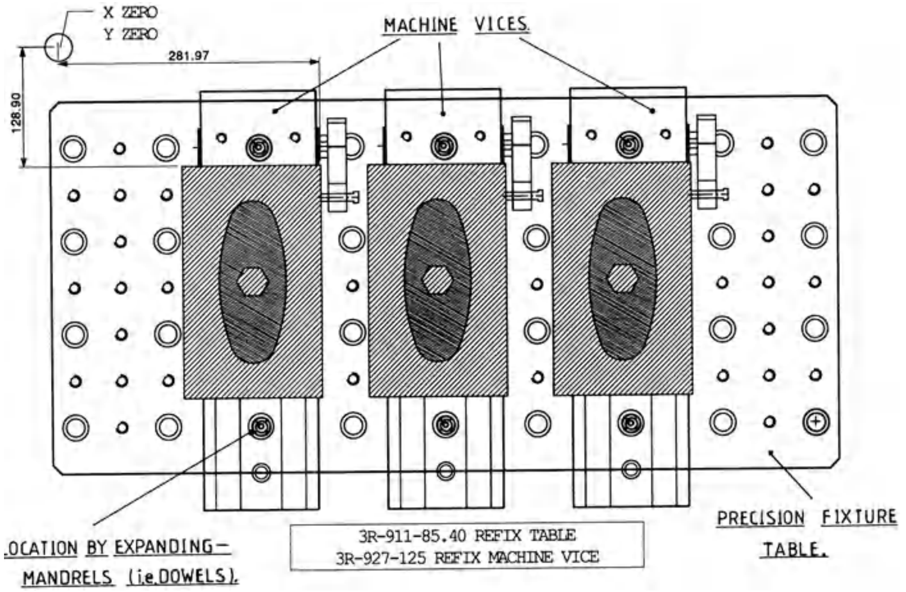


Fig. 3.30. A computer "hardcopy" off the CADCAM system showing the multi-vice setup where the precise location of each part is known. [Courtesy of System 3R International.]

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 Volume III 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.

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 interconnected 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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