An Introduction To

CNC Machining and Programming

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PREFACE

An Introduction to CNC Machining and Programming is intended to support the essentially practical activity of preparing and proving computer numerical control (CNC) part programs for turning, milling, and drilling. It will be of value to students in a wide range of courses dealing with CNC programming and calculations of all forms, tooling for CNC, and fixturing for CNC whether in a major or related course in a college, university, or industrial organization.

The preparation and proving of CNC part programs requires access to machinery and computer installations in order to obtain the necessary practical experience. Using such equipment, and understanding particular programming languages and techniques, requires instruction, examples, and exercises from a competent instructor. Students undertaking a course of study devoted to part programming will therefore find it necessary to attend an adequately resourced college or training center. The student must also have a good understanding of basic machining techniques, and should ideally have previous experience in turning, milling, and drilling operations. In preparing this text, these fundamental requirements have been borne in mind.

CNC part programming is an absorbing and time-consuming activity—it is one of the few areas of study where students complain that time has passed too quickly! Thus a primary objective of this book is to ensure that limited course time can be used to the best advantage by providing the opportunity to devote as much time as possible to preparing programs and using the associated equipment. Accordingly, an attempt has been made to include sufficient information to provide the student with much of the theoretical knowledge needed to support the more practical elements of study, thereby reducing the time spent on formal lectures and unnecessary note taking. The text also provides the student with the opportunity to study specific aspects of interest or needs.

This text is essentially practical in nature and is intended to provide adequate material for course work. It contains a series of assignments that provide the student with a practical understanding of CNC tooling, processing, and programming by various means. Throughout the book there are numerous fully detailed drawings of components in inch and metric units that, while primarily included to complement the text, may also be used as programming exercises in the early stages of a course. An additional series of projects, of varying degrees of complexity and intended for later use, should satisfy most levels of ability.

It is the author's experience that many mature people returning to college for retraining, also many younger students, are hampered in their programming work by never being taught how to apply their calculation skills in algebra, geometry, and trigonometry. It is generally outside the scope of a course of study devoted to part programming to spend much time rectifying this state of affairs, and yet it cannot be ignored. To assist both instructors and students there is a chapter devoted entirely to the type of calculations that will be encountered when preparing part programs manually; it is hoped that the completion of this material, supported by on-the-spot tutoring by faculty, will be of value.

This text will be of on going value to students, faculty, and industrial programmers alike.

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1

AN INTRODUCTION TO THE CONCEPT OF COMPUTER NUMERICAL CONTROL

DEFINITION OF NUMERICAL CONTROL

Numerical control (NC) is the term used to describe the control of machine movements and various other functions by instructions expressed as a series of numbers and initiated via an electronic control system.

Computerized numerical control (CNC) is the term used when the control system utilizes an internal computer. The internal computer allows for the following: storage of additional programs, program editing, running of programs from memory, machine and control diagnostics, special routines, and inch/metric–incremental/absolute switchability.

The two systems are shown diagrammatically in Figure 1.1. The control units may be free-standing or built into the main structure of the machine. The operating panel of an integrated control unit is shown in Figure 1.2.

THE APPLICATION OF COMPUTER NUMERICAL CONTROL

Computer numerical control is applied to a wide range of manufacturing processes such as metal cutting, woodworking, welding, flame cutting, sheet metal forming, sheet metal punching, water jet cutting, electrical discharge machining and laser cutting. The text that follows is restricted to its application to common machine-shop engineering processes, namely, turning, milling, and drilling, where it has been particularly successful.

THE ADVANTAGES OF COMPUTER NUMERICAL CONTROL

Computer numerical control is economical for mass, batch, and, in many cases, single-item production. Many factors contribute to this economic viability, the most important of these being as follows:

(a) high productivity rates
(b) uniformity of the product
(c) reduced component rejection

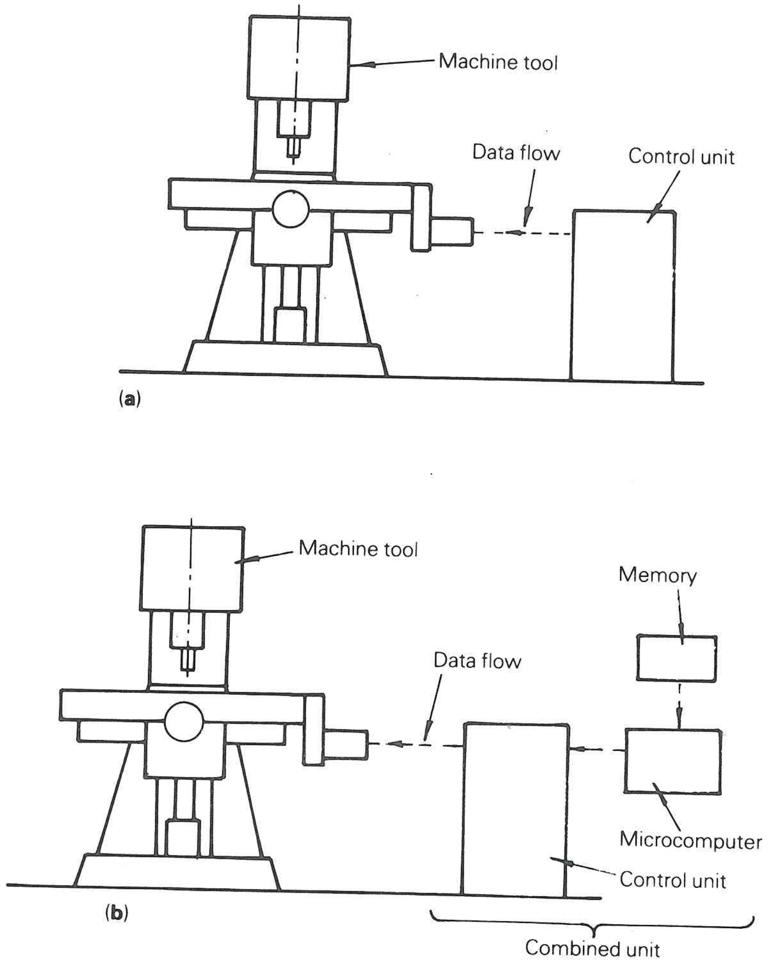


Figure 1.1 *Basic control systems: (a) numerical control and (b) computerized numerical control.*

(d) reduced tooling costs
(e) less operator involvement
(f) complex shapes machined easily

It is also the case that fewer employees will be required as conventional machines are replaced by modern technology, but those employees that remain will of necessity be high caliber technicians with considerable knowledge of metal-cutting methods, cutting speeds and feeds, work-holding, and tool-setting techniques and who are familiar with the control systems and programming for numerical control.

Figure 1.2 *Integrated control unit.*

THE CAPABILITY OF COMPUTER NUMERICAL CONTROL

The dramatic effect computer numerical control has already had on traditional engineering production techniques is now well appreciated. Machines controlled in this way are capable of working for many hours every day virtually unsupervised. They are readily adaptable to facilitate production of a wide range of components. Every function traditionally performed by the operator of a standard machine tool can be achieved via a computer numerical control machining program.

To appreciate just how versatile computer numerical control can be, it is only necessary to examine very briefly the human involvement in the production of a simple component such as the one shown in Figure 1.3. The hole only is to be produced by drilling on a conventional vertical milling machine. The activities of the operator in producing the component would be as follows:

1. Select a suitable cutting tool.
2. Locate the cutting tool in the machine spindle.
3. Secure the cutting tool.
4. Locate the component in the work-holding device.
5. Clamp the component.
6. Establish a datum in relation to face A.
7. Determine the amount of slide movement required.
8. Determine the direction of slide movement required.
9. Move the slide, monitoring the movement on the graduated dial allowing for leadscrew backlash, or digital readout if available.
10. Lock the slide in position.
11. Establish a second datum in relation to face B.

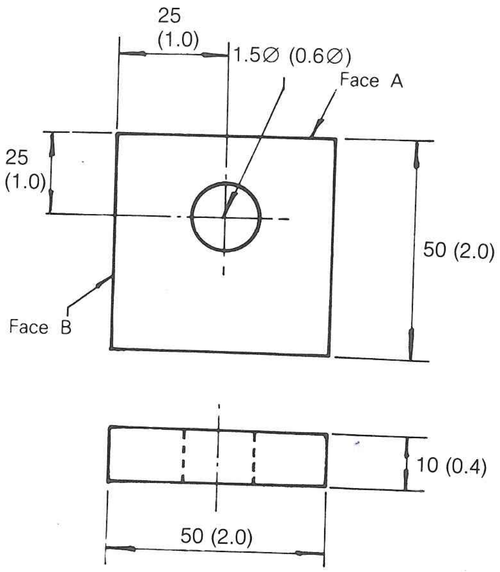


Figure 1.3 *Component detail. (Inch units are given in parentheses.)*

12. Determine the amount of slide movement required.
13. Determine the direction of slide movement required.
14. Move the slide, monitoring the movement on the graduated dial allowing for leadscrew backlash, or digital readout if available.
15. Lock the slide in position.
16. Select a suitable spindle speed.
17. Determine the direction of spindle rotation.
18. Select a suitable feed rate.
19. Switch on the spindle motor.
20. Switch on the coolant supply motor.
21. Engage the feed and machine the hole.
22. Disengage feed and withdraw tool.
23. Switch off the coolant supply motor.
24. Switch off the spindle motor.
25. Remove the component.
26. Verify the accuracy of the machine movement by measuring the component.

From this list it can be seen that even the simplest of machining operations involves making a considerable number of decisions that influence the resulting physical activity. A skilled machinist operating a conventional machine makes such decisions and takes the necessary action almost without thinking. Nevertheless, the decisions *are* made and the action *is* taken.

It is not possible to remove the human involvement totally from a machining process. No automatic control system is yet capable of making a decision in the true sense of the word. Its capability is restricted to responding to a manually or computer-prepared program, and it is during the preparation of the program that the decisions are made. Via that program the machine controller is fed with instructions that give effect to the decisions. In this way all the functions listed above, and many others not required in such a simple example of machining, may be automatically and repeatedly controlled. Figure 1.4 lists the elements of total machine control.

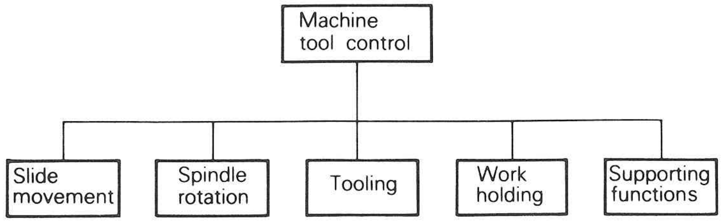


Figure 1.4 *Elements of machine control.*

SLIDE MOVEMENT

The success of any manual machining exercise is dependent on many factors, not least of which is the experienced worker's practical skills. These skills are most in evidence when they affect the accuracy of the finished product, such as when they are involved in positioning, via the machine slides, the cutting tool and workpiece in the correct relationship to each other. This aspect of machining skill is also the crucial factor when the machine is electronically controlled.

Slide movement on computer numerically controlled machines is achieved by:

(a) hydraulically operated pistons
(b) electric servo motors.

The use of electric motors is by far the most common technique. The motor is either directly coupled, or connected via a toothed belt drive, to the slide leadscrew. The servo motor, in effect, replaces the conventional handwheel and this is illustrated in Figure 1.5, which shows conventional machines, a center lathe and a vertical milling machine, fitted with servo motors. A few machine designs have retained handwheels as an aid to setup or to provide for both numerical and manual control.

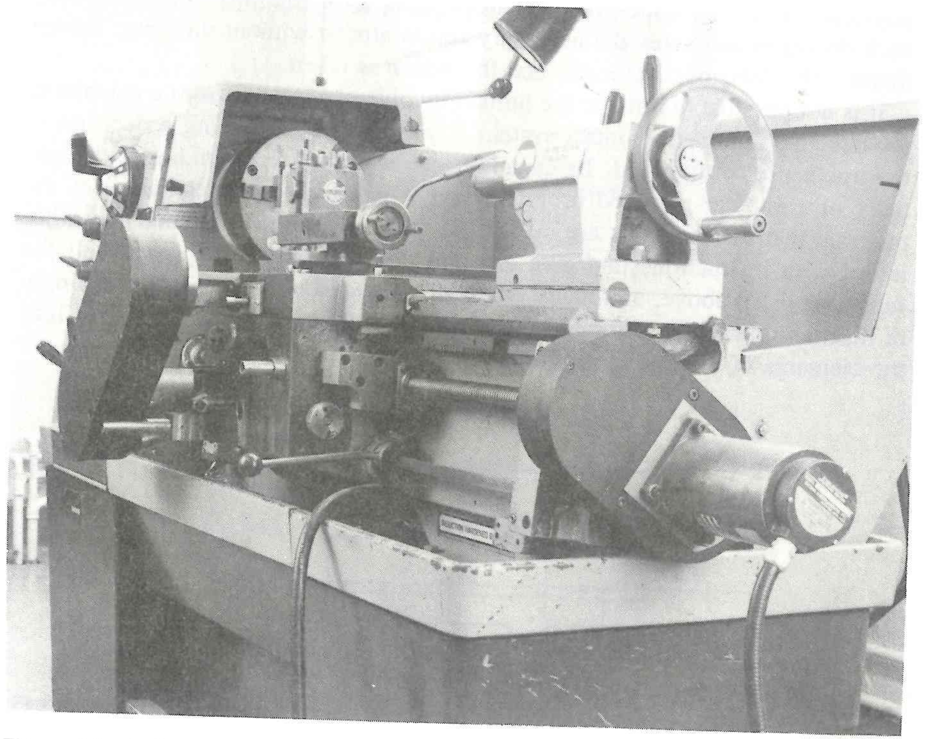


Figure 1.5 (a) *Conventional center lathe fitted with servo motors.*

Machine tools have more than one slide and so the slide required to move will have to be identified. The plane in which movement can take place may be longitudinal, transverse, or vertical. These planes are referred to as axes and are designated by the letters *X, Y, Z,* and sometimes *U, V, W*. Rotary axes *A, B,* and *C* can also be applied to a machine around a center axis mentioned previously. A rotary axis has as its centerline one of the three standard axes (*X* to *A*, *Y* to *B*, and *Z* to *C*). Their location on common machine tools is shown in Figure 1.6. Note that the *Z* axis always relates to a sliding motion parallel to the spindle axis.

The direction in which a slide moves is achieved by the direction of rotation of the motor, either clockwise or counterclockwise, and the movement would be designated as plus or minus in relation to a given datum. Figure 1.6 also shows how the direction of travel is designated on common machine tools. Slide movement and relative tool and work movement are discussed in more detail in Chapter 6.

The rate or speed at which slide movement takes place, expressed in feet/meters per minute or inches/millimeters per revolution of the machine spindle,

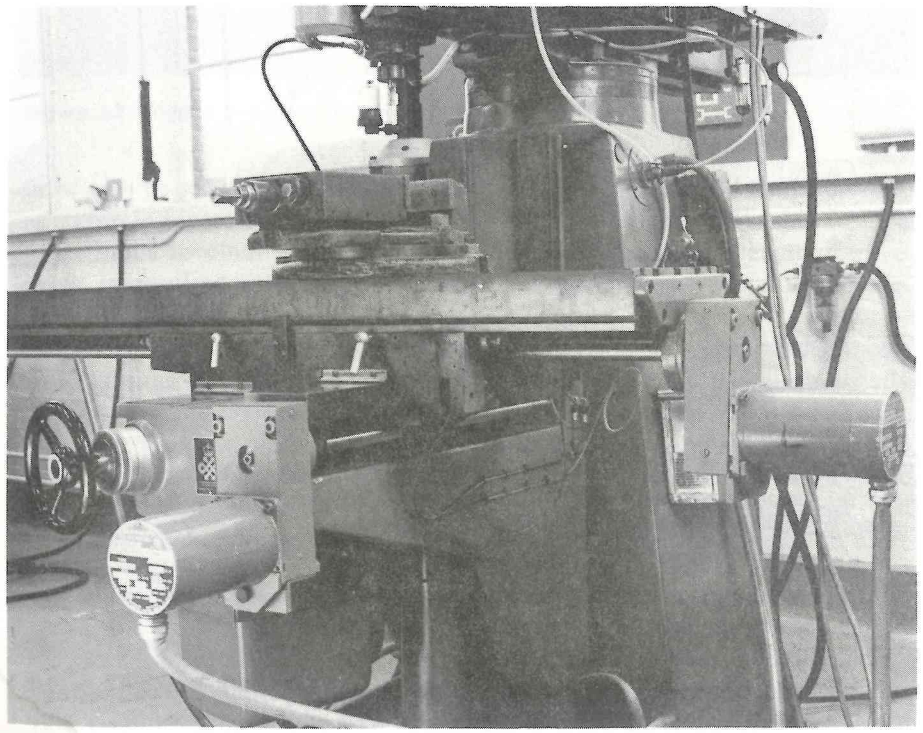


Figure 1.5 (b) *Conventional milling machine fitted with servo motors.*

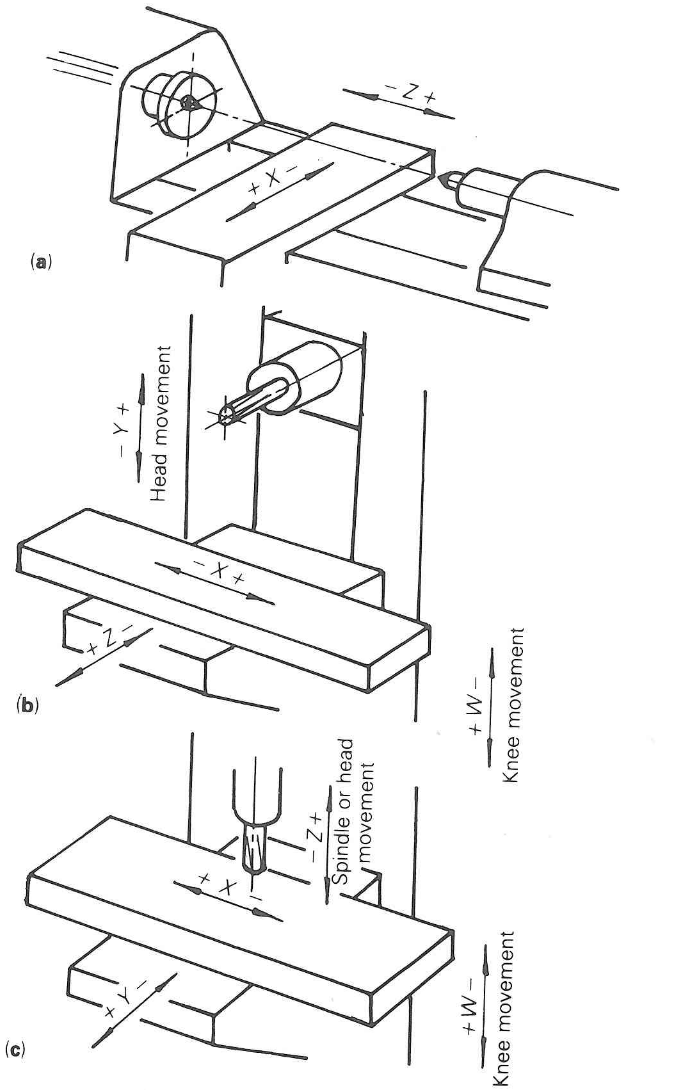


Figure 1.6 *Identification of slides and direction of the slide movement on common machine tools: (a) center lathe (turning center); (b) horizontal milling machine (horizontal machining center); (c) vertical milling machine (vertical machining center).*

will be proportional to the revolutions per minute of the servo motor; the higher the revolutions per minute, the faster the rate of slide travel.

The length of slide movement is controlled by either the number of revolutions or the number of part revolutions the motor is permitted to make, one complete revolution being equal to the lead of the leadscrew, in the same way as one turn of a handwheel is equal to the lead of a leadscrew. In some cases

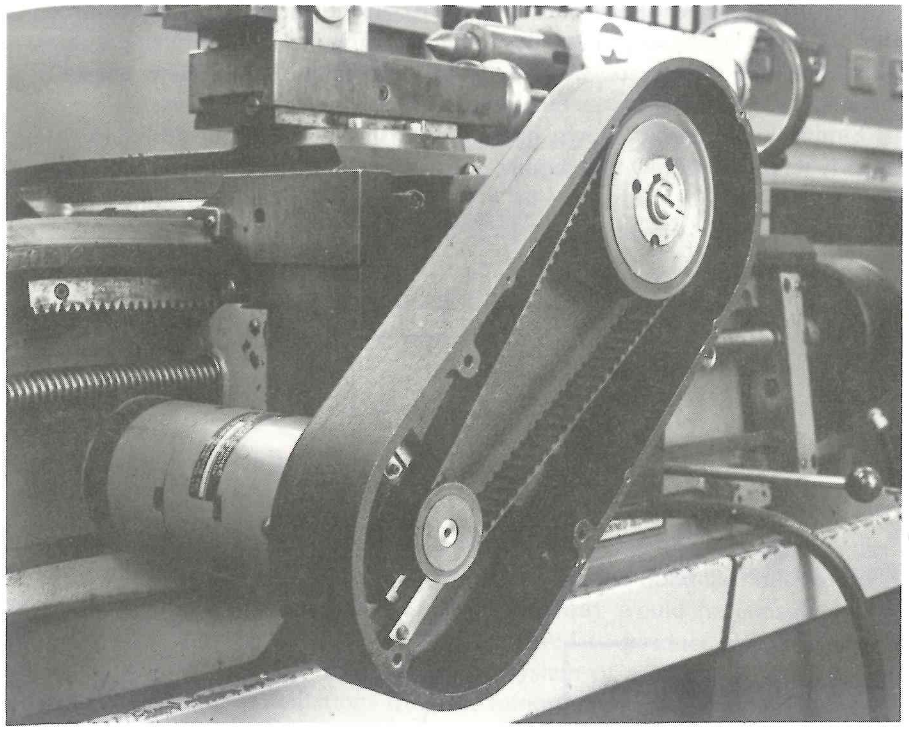


Figure 1.7 *Cogged belt drive from servo motor to leadscrew.*

there may be reduction pulleys or gears between the motor and the leadscrew, as shown in Figure 1.7, in which case the linear movement obtained in relation to the motor revolutions would be proportionally reduced. The length of travel made, or required to be made, by a slide is referred to as a coordinate dimension.

Since the slide movement is caused by the servo motor, control of that motor will in turn control the slide movement. The motor is controlled electronically via the machine control unit. All the relevant information, that is the axis, direction, feed rate, and length of movement, has to be supplied to the control unit in an acceptable numerical form. The input of information to the machine controller is achieved in a variety of ways: perforated tape, magnetic tape, via a computer link, computer disk, and manually. Data input is covered in more detail in Chapter 5.

Complex Slide Movement

So far, consideration has been given to simple linear movement involving one slide. There are, however, many instances when two or more slides have to be moving at the same time. It is possible to produce a 45° angle as shown in

Figure 1.8 by synchronizing the slide movements in two axes, but to produce the 30° angle in Figure 1.9 would require a different rate of movement in each axis, and this may be outside the scope of a simple NC system unless it is capable of accurately responding to two precalculated feed rates.

Similarly, the curve shown in Figure 1.10 would present problems, since ideally its production would require constantly changing feed rates in two axes. The curve could be designated by a series of coordinate dimensions as shown in Figure 1.11, and, providing the machine were capable of responding to the minute variations in size, a satisfactory result would be obtained, but the calculations necessary to approach the task in this way would be considerable. Complex slide movements such as those required to produce the curve can readily be achieved by the inclusion in the system of a computer capable of making the necessary calculations from the minimum of input data. Of course, the calculation of slide movements to produce complex profiles is not the only function of a computer. The other facilities it provides, in particular its ability to store data that can be used as and when required, will be considered later.

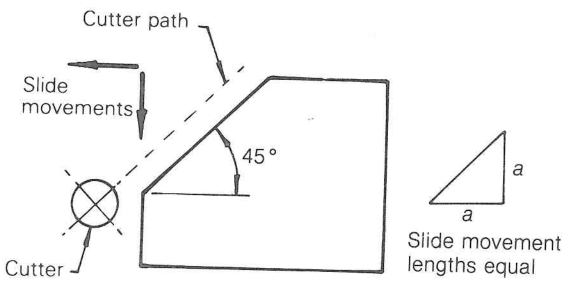


Figure 1.8 *Effect of equal rates of slide movement.*

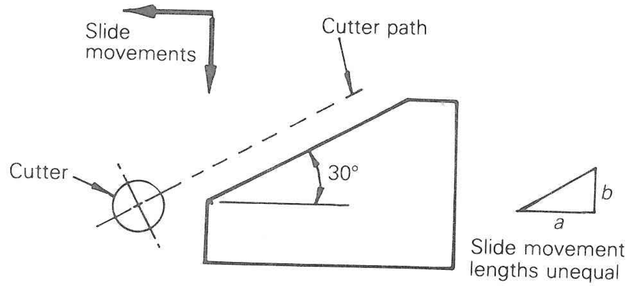


Figure 1.9 *Effect of unequal rates of slide movement.*

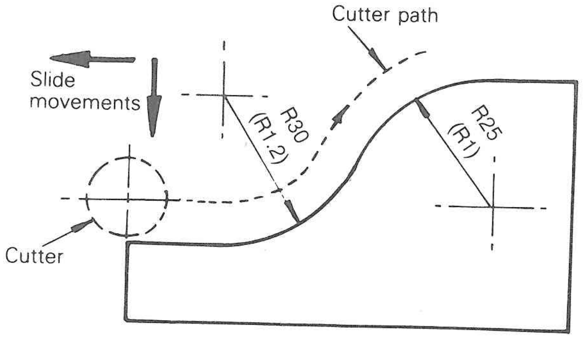


Figure 1.10 *Profile requiring constantly changing rates of slide movement. (Inch units are given in parentheses.)*

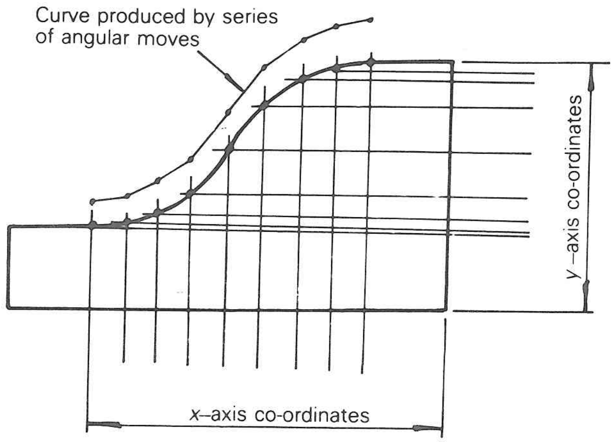


Figure 1.11 *Designation of a curved profile by a series of coordinate dimensions.*

Verification of Slide Movement

An important function of the skilled worker operating a conventional machine is to monitor the slide movement and verify its accuracy by measuring the component. A similar facility is desirable on computer numerically controlled machines.

Control systems without a facility to verify slide movements are referred to as "open-loop" systems, while those with this facility are called "closed-loop" systems. A closed-loop system is shown diagramatically in Figures 1.12 and 1.13.

The exact position of the slide is monitored by a transducer and the information is fed back to the control unit, which in turn will, via the feed motor, make any necessary corrections.

In addition to positional feedback some machines are equipped with "in-process measurement." This consists of probes that touch the machined surface and respond to any unacceptable size variation. The data thus gathered are fed back to the control system and corrections to the slide movement are made automatically.

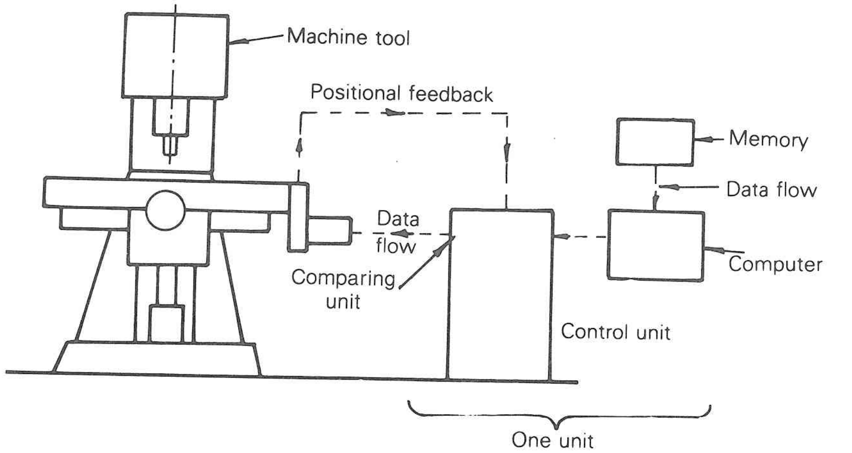


Figure 1.12 *Closed-loop control system.* *(Courtesy of AIMTECH.)*

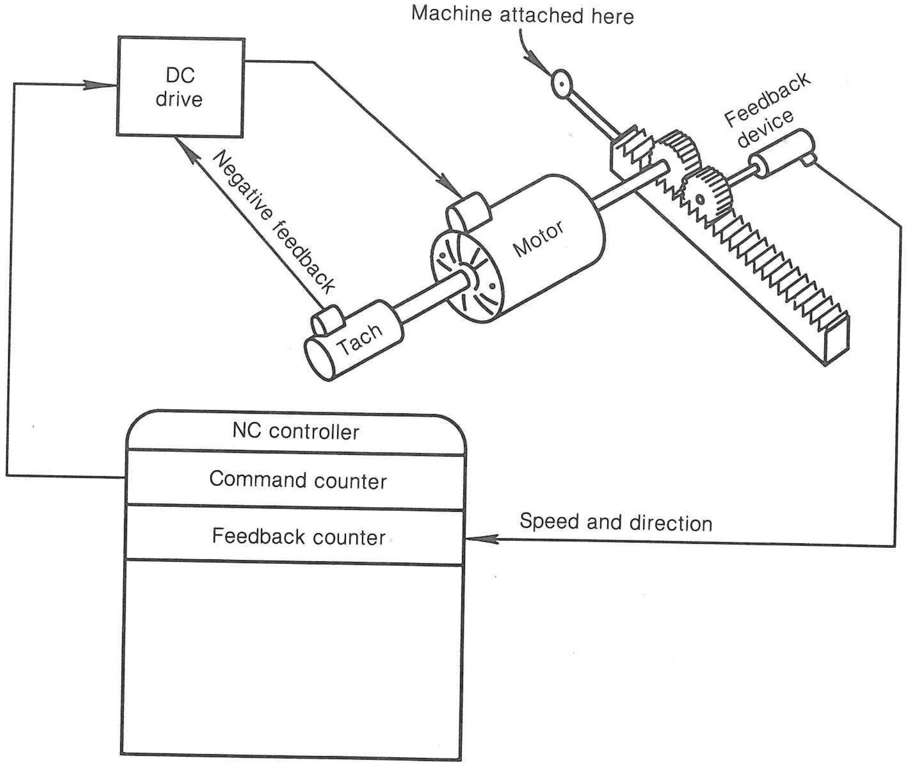


Figure 1.13 *Basic NC hardware concept.*

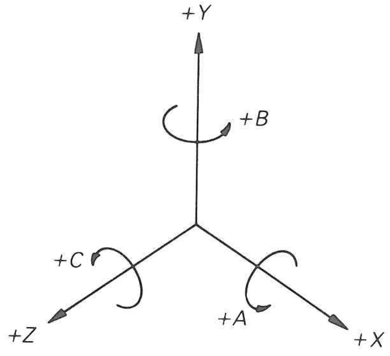


Figure 1.14 *Identification of rotary movements.*

ROTARY MOVEMENTS

Sometimes the production of a component requires rotary movement in addition to the linear movement of the machine-tool slides. This movement is provided by ancillary equipment such as rotary tables and indexers. These movements are controllable via the machining program. They are identified by the letters *A*, *B*, and *C* as indicated in Figure 1.14.

CONTROL OF MACHINE SPINDLES

Machine spindles are driven directly or indirectly by electric motors, and a few by hydraulic drive. The degree of automatic control over this motion usually includes stopping and starting, and the direction and speed of rotation. Some very early systems, and perhaps a few inexpensive modern systems, do not include control of the spindle motions at all, switching on and off and gear selection being a totally manual operation. On the other hand, on some very modern control systems the torque or horsepower necessary to carry out the machining operation can be monitored and compared with a predetermined value included in the machining program; when necessary, the spindle speed will be varied automatically to provide optimum cutting conditions. (See "Adaptive Control," Chapter 9.)

The speed of the spindle is often infinitely variable, and may automatically change as cutting is taking place to maintain a programmed surface speed. Thus, when facing the end of a bar on a lathe as the tool nears the work center, the spindle speed will increase. In this way material removal is achieved at the fastest possible rate with due regard to tool life and the surface finish required.

The direction of spindle rotation required can be determined as follows:

1. Clockwise (CW). When the spindle rotates a right-handed screw would

advance into the workpiece, or if the machine operator looked through the tool toward the workpiece, he would see it moving clockwise.

2. Counterclockwise (CCW). When the spindle rotates a right-handed screw would retract from the workpiece, or if the machine operator looked through the tool toward the workpiece, he would see it moving counterclockwise.

CONTROL OF TOOLING

Computer numerically controlled machines may incorporate in their design turrets or magazines that hold a number of cutting tools. The machine controller can be programmed to cause indexing of the turret or magazine to present a new cutting tool to the work or to facilitate tool removal and replacement where automatic tool-changing devices are involved.

Simpler machines rely on manual intervention to effect tool changes. In these cases the control unit is programmed to stop the automatic sequence at the appropriate time and the operator will make the change. There is sometimes a connection between the control unit and the tool-storage rack and the correct tool to be used is indicated by an illuminated lamp.

Tooling is dealt with in more detail in Chapter 3.

CONTROL OF WORK HOLDING

Work holding is another aspect of computer numerically controlled machining that can include manual intervention or be totally automatic. The work-holding devices themselves can be fairly conventional: vices, chucks, collets, and fixtures are all used. The computer numerical control can extend to loading the workpiece by the use of robots and securely clamping it by activating hydraulic or pneumatic clamping systems.

Again, as with tool changing, on simpler machines, a programmed break in a machining cycle can facilitate manual intervention as and when required.

Work holding is dealt with in detail in Chapter 4.

SUPPORTING FUNCTIONS

The various supplementary functions a skilled worker would perform during a manually controlled machining operation are, of course, vital to the success of the operation. For example, it may be necessary to clamp a slide, apply coolant, clear away swarf before locating a component, monitor the condition of tooling, and so on. Slide clamping is usually hydraulic, and hydraulic pressure provided by an electrically driven pump with the fluid flow controlled by solenoid valves has long been a feature of machine tool design. With the new technology the control of the electrical elements of such a system is included in the machining program. Similarly, it is a simple matter to control the on–off switching of a coolant pump and the opening or closing of an air valve to supply a blast of cleaning air. Tool monitoring, however, is more complex and is the subject of much research and innovation ranging from monitoring the loads exerted on spindle motors to recording variations in the sound the cutting tool makes. Some of these more advanced features of computer numerical control are discussed further in Chapter 9.

QUESTIONS

1 Explain with the aid of a simple block diagram the difference between an NC and a CNC machining system.

2 State two advantages of CNC over NC control systems.

3 The common axes of slide movement are X, Y, and Z. What is significant about the Z axis?

4 How are rotary movements about a given axis identified and when are they likely to be used?

5 What data are required to initiate a controlled slide movement?

6 On a vertical machining center the downward movement of the spindle is designated as a Z minus. From a safety aspect this is significant. Why is this so?

7 How is an angular tool path achieved?

8 With the aid of simple block diagrams to show data flow, explain the difference between an open-loop and a closed-loop control system.

9 How would a manual tool change be accommodated in a machine program?

10 Explain what is meant by "constant cutting speed" and how this is achieved on CNC machines.

2

MACHINE DESIGN

REPEATABILITY

The quality of conventional machine tools varies considerably. They are built to a price to meet a wide-ranging market. Generally speaking, the more expensive the machine is, the higher the quality of work that can be expected to be produced on it. However, an expensive conventional machine does not guarantee high-quality work. The key to success lies in the skills of the operator. The cheapest of machines is capable of producing very accurate work in the hands of the right person.

Skilled workers get to know their machines and make allowances for their failings. During the production of a component a skilled worker can, for example, compensate for leadscrew backlash, slide friction, lack of power, and so on. He or she can vary spindle speeds, feed rates, and tooling arrangements. The approach to a final cut can be gradual until it is correct and before a final commitment is made.

With a computer numerically controlled machine tool responding to a predetermined program, the capacity for readily varying the conditions when machining is under way is limited, and to make changes is inconvenient. As far as possible conditions have to be correctly determined at the time the program is produced and the machine is set up.

The slide movements are of prime importance. The movement must be precise, and this precision must continue throughout a machining program, which may involve thousands of components. The ability of the machine to produce continually accurate slide movement is called repeatability.

A precise definition of repeatability is as follows: the maximum difference that can occur between the shortest and longest positions achieved in a number of attempted moves to any programmed target position.

Repeatability is expressed as the mean of a number of attempted moves. A typical figure for repeatability would be ± 0.0003 in. or ± 0.008 mm. It follows that some moves must be well within those figures.

Repeatability is dependent on the following features being incorporated in the design of the machine:

(a) adequate strength
(b) rigidity
(c) minimum of vibration

(d) dimensional stability
(e) accurate control of the slide movements

Although many conventional machines have been, and continue to be, converted to computer numerical control, such conversions being referred to as "retrofits," their design in general does not meet the exacting requirements necessary to achieve a high standard of repeatability, while at the same time catering to the needs for high rates of metal removal that modern tooling and electronic control have made possible. Radical changes in design were inevitable and have resulted in the machines now generally known as vertical machining centers, horizontal machining centers, and turning centers. These are shown in Figure 2.1.

STATIC AND DYNAMIC LOADING

A simple analysis of the function of a machine tool reveals that it is subjected to certain loading which may be described as:

(a) static
(b) dynamic

Static loading is the term used to describe a situation where forces are acting on a structure when the machine, or that part of the machine, is not in motion.

Figure 2.1 (a) *Vertical machining center.*

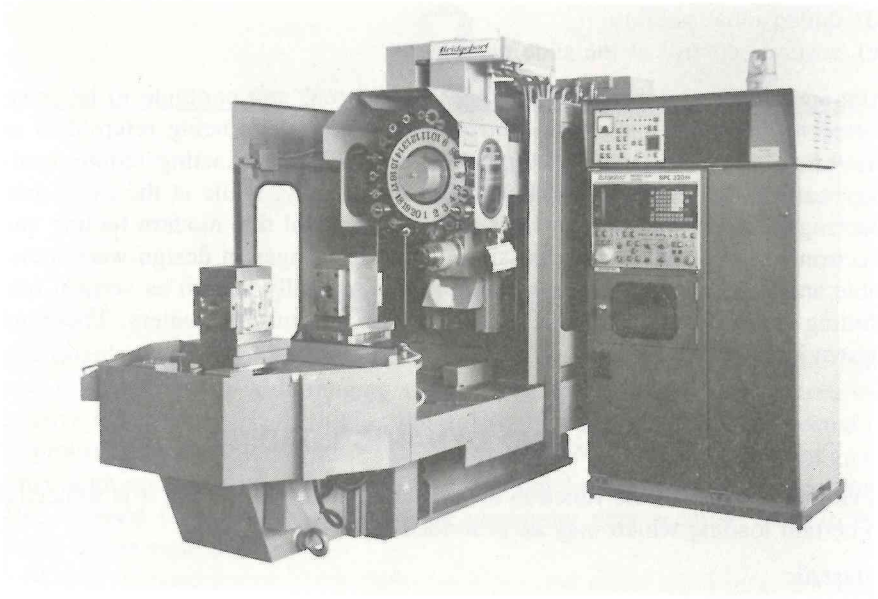


Figure 2.1 (b) *Horizontal machining center.*

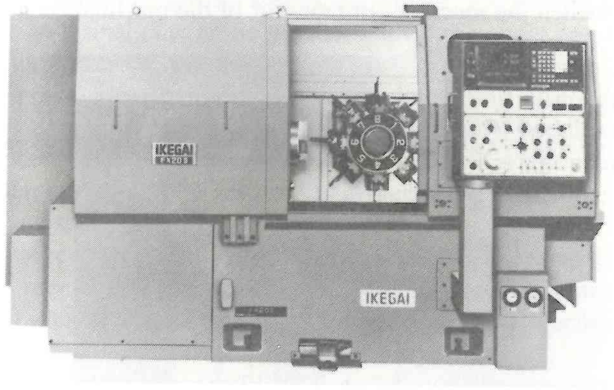


Figure 2.1 (c) *Turning center.*

For example, due to its mass, a milling machine table exerts a static load on the knee. If the table is offset on the knee, that static load could cause the table to drop slightly at the unsupported end. A heavy workload would exacerbate the problem, which is illustrated in Figure 2.2.

Dynamic loading is the term used to describe a situation where forces are acting on a structure when movement is taking place. An example of this, shown in Figure 2.3, is the radial force exerted on a milling machine spindle as the cutter is fed into the work. The spindle could deflect.

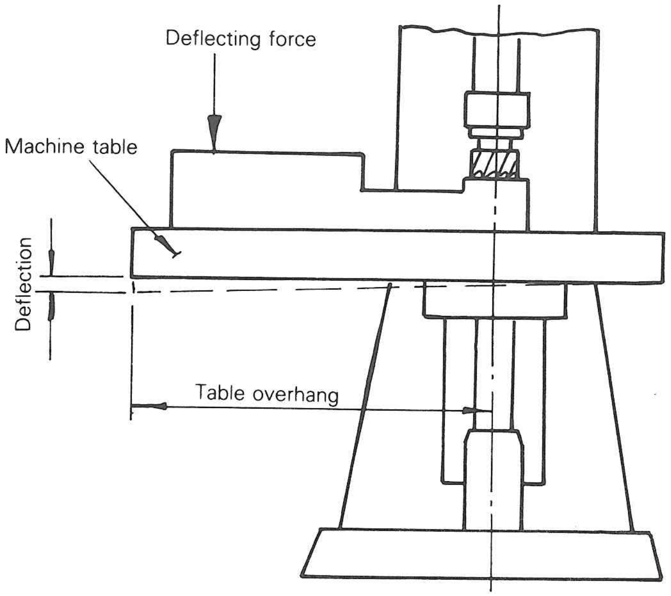


Figure 2.2 *Example of the possible effect of static loading.*

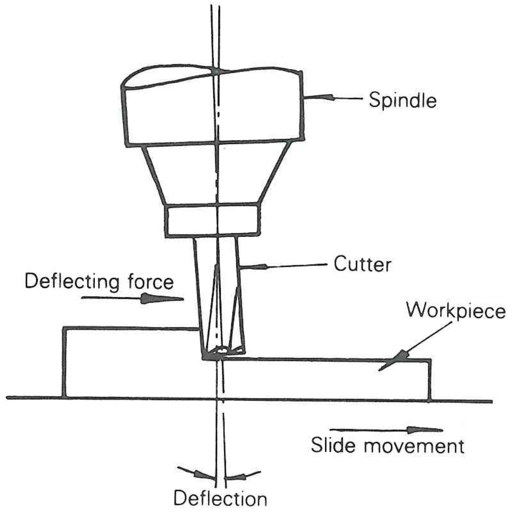


Figure 2.3 *Example of the possible effect of dynamic loading.*

Deflections such as those illustrated need only be quite small to affect the dimensional accuracy of the workpiece, so the machine structure and its subassemblies must be so designed to ensure that movement of this nature cannot occur.

BASIC STRUCTURE

For many years cast iron was considered to be the only material suitable for the basic structure of a machine tool. It possessed adequate strength and rigidity and tended to absorb vibration. In addition, the complex shapes required were easier to produce by casting than by any other method. Cast iron is still extensively used, but its traditional position as the most suitable material is now challenged by steel and, more recently, by concrete.

When castings are used, they are generally of one-piece box construction, heavily ribbed and stabilized by heat treatment.

Fabricated steel structures are increasingly being favored for very large machines. Steel plates of the same thickness as a cast iron structure have approximately twice the strength. By reducing the plate thickness, the weight of the structure can be considerably reduced, yet still provide the necessary strength. In use, the rigidity of such structures has proved to be more than adequate. However, the general use of steel is limited by the problems of making complex shapes and by its resonant quality, which is not conducive to effective damping of vibration.

The use of concrete or ceramics as a machine base is a comparatively new development. The advantages of concrete are its low cost and good damping characteristics. Very large structures can be cast on site, thus reducing the overall cost even further, since no transport is involved. Smaller structures can be provided with steel tubing cast into the concrete to permit easier handling. The cast iron bed of the machine is set on a cushion of air-setting resin and attached to the concrete by steel studs. The diagram in Figure 2.4 illustrates the concept.

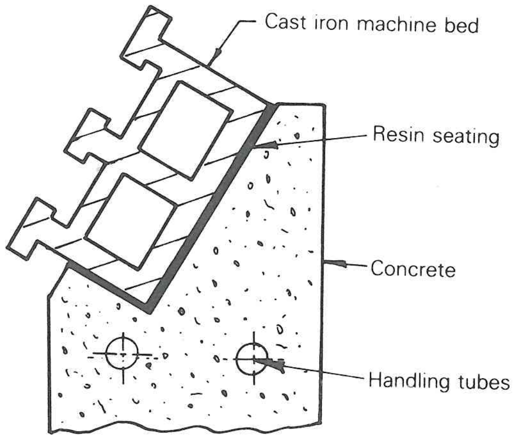


Figure 2.4 *Concrete base for a machine tool.*

MACHINE SPINDLES

The machine spindle is a very important design feature. The possibility of deflection has already been noted. In addition to the radial loads that cause deflection, a spindle assembly is also subjected to a thrust load acting along its axis. The design of the spindle assembly must be such that these loads are adequately contained. Inadequate support results not only in dimensional inaccuracies but also in poor surface finish and chatter. A well-supported spindle assembly is shown in Figure 2.5. Note that the spindle overhang has been kept to a minimum, a common feature of turning and horizontal machines.

The spindle of vertical machining centers presents additional problems, since it is a traditional feature of this type of machine for the spindle to move up and down. Obviously, the more the spindle is extended, the greater the risk of deflection. Some manufacturers have now moved away from the moving-spindle concept and instead the whole head assembly moves up and down.

Another design feature problem of vertical machining centers is that in order to provide an adequate work area, the spindle head must overhang. The length of overhang must be kept to a minimum, and Figure 2.6 shows how one manufacturer has improved on the traditional design without reducing the work area.

The forces that cause deflection of the spindle also result in a tendency for the complete spindle-housing assembly to twist. This has resulted in an increased use of bifurcated or two-pillar structures where the spindle housing is

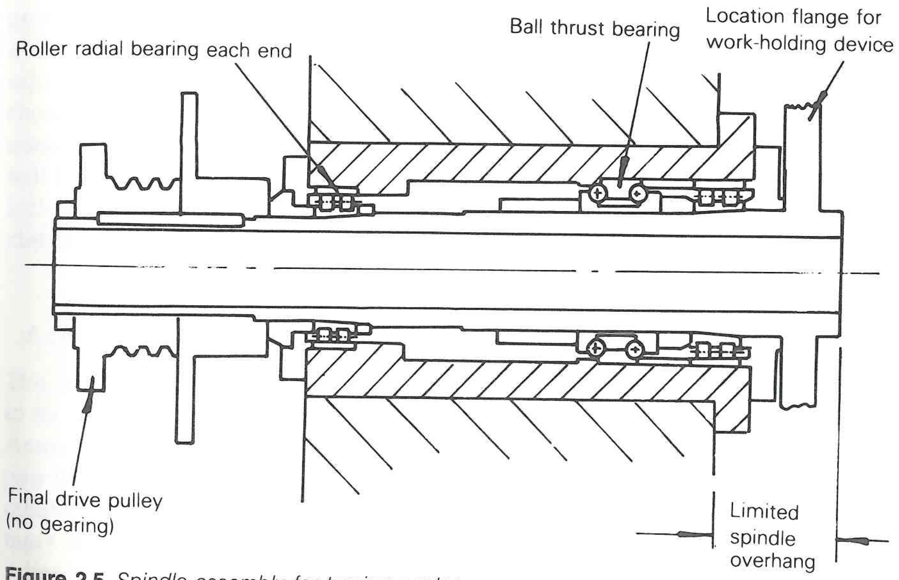


Figure 2.5 *Spindle assembly for turning center.*

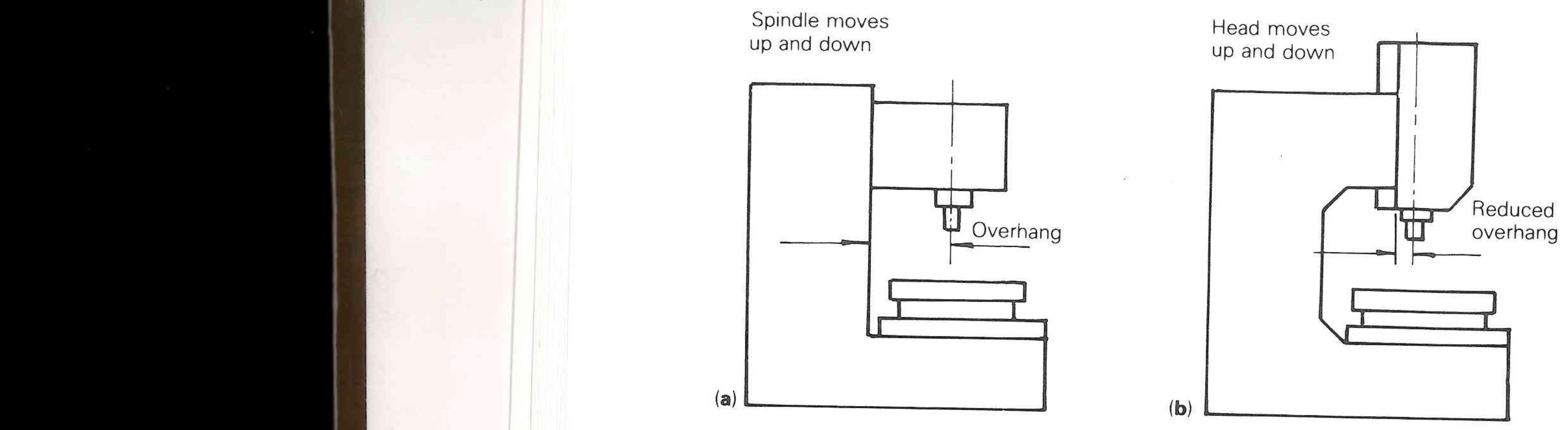


Figure 2.6 *Variations in the design of vertical machining centers: (a) conventional design; (b) improved design.*

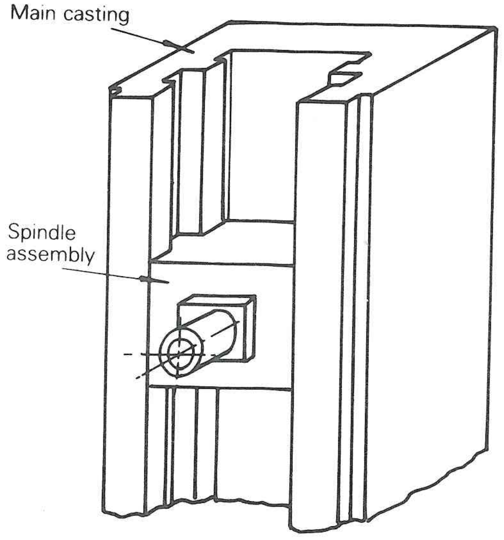


Figure 2.7 *Bifurcated structure.*

located between two substantial slideways that reduce the tendency to twist. A bifurcated structure is shown in Figure 2.7.

SPINDLE DRIVES

Two types of electric motors are used for spindle drives: direct current (DC) and alternating current (AC). They may be coupled direct to the spindle or via belts and/or gears. Many machines have a final belt drive which is quieter and produces less vibration than a geared drive.

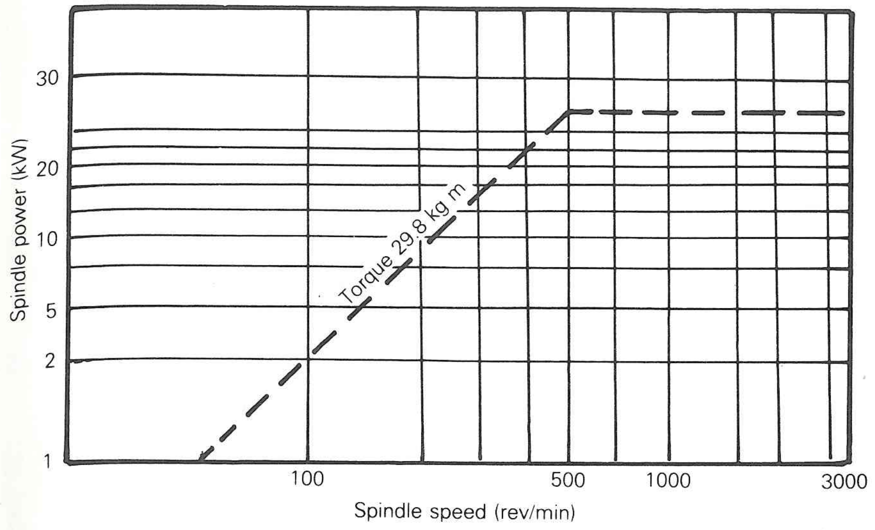


Figure 2.8 *An example of torque/spindle speed relationship when driven by a DC motor: constant torque after 500 rev/min.*

The majority of modern machines use DC motors. By varying the voltage input, their speeds are infinitely variable as they rotate and so a constant cutting speed can be maintained. The torque available from a DC motor is constant throughout most of the speed range, as illustrated in Figure 2.8.

There are some machines fitted with specially designed AC motors that also provide for variable spindle speeds, but the use of AC motors usually involves a stepped drive, that is, a series of spindle speeds will be available and the selection of a particular speed may involve switching from one speed range to another, high or low, for example, a feature that is common to many conventional machines. On computer numerically controlled machines the switching will be carried out as and when programmed via the control unit and may also include an automatic engagement or disengagement of an electrically operated clutch.

LEADSCREWS

The Acme form of leadscrew used on conventional machines has not proved to be satisfactory for numerically controlled machines. The movement of an Acme screw is dependent on there being clearance, i.e., backlash, between two flanks. At the same time friction between the mating flanks of the screw means that considerable resistance to motion is present. These two disadvantages are illustrated in Figure 2.9.

Computer numerically controlled machines, except perhaps for a few cheaper training machines, are fitted with recirculating ballscrews, which replace slid-

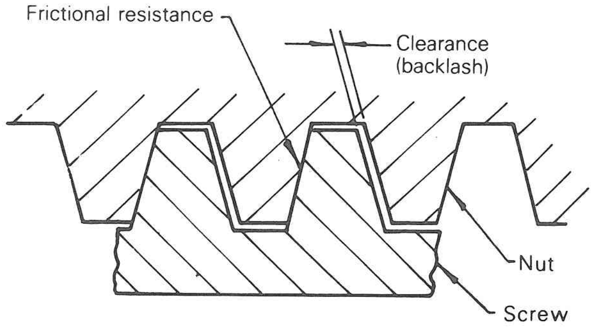


Figure 2.9 *Disadvantages of conventional Acme leadscrews.*

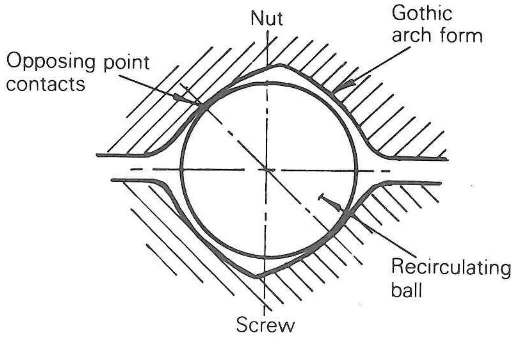


Figure 2.10 *Ball screw form.*

ing motion with rolling motion, resulting in reduced frictional resistance. The balls, which in effect form the nut, recirculate in and out of the thread. The thread form is referred to as a Gothic arch and is illustrated in Figure 2.10. The balls make opposing point contact which virtually eliminates backlash. Figure 2.11 shows an external ball return and Figure 2.12 an internal return. The internal ball return is more compact.

The advantages of recirculating ball screws over Acme screws are:

(a) longer life
(b) less wear
(c) low frictional resistance
(d) less drive power required due to reduced friction
(e) higher traversing speeds can be used
(f) no stick slip effect
(g) more precise positioning over the total life of the machine

Leadscrews are usually of substantial diameter and centrally positioned to avoid twisting the slide and thus reducing the efficiency of the movement.

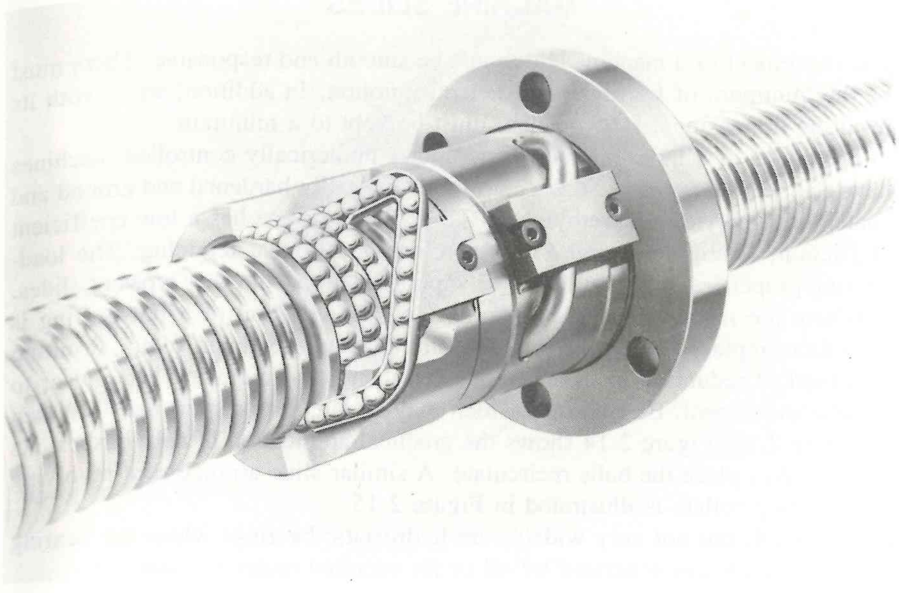


Figure 2.11 *Recirculating ball screw (external return).*

Figure 2.12 *Recirculating ball screw (internal return).*

MACHINE SLIDES

The movement of a machine slide must be smooth and responsive. There must be the minimum of frictional resistance to motion. In addition, wear, with its resulting dimensional inaccuracies, must be kept to a minimum.

The slides of a large number of computer numerically controlled machines have flat bearing surfaces. These surfaces are usually hardened and ground and coated with polytetrafluorethylene (PTFE). This surface has a low coefficient of friction, is slightly porous, and therefore is lubricant retaining. The load-bearing properties of flat surfaces are superior to those of other types of slides.

Where the machine loading permits, the sliding action of a flat bearing is sometimes replaced by a rolling action, in the form of balls or rollers, resulting in a marked reduction in the frictional resistance and requiring less power to achieve movement. Ball bushes, which may be circular or split, are illustrated in Figure 2.13. Figure 2.14 shows the practical application of split bushes. As motion takes place the balls recirculate. A similar slide arrangement involving recirculating rollers is illustrated in Figure 2.15.

Also used, but not very widely, are hydrostatic bearings where the bearing surfaces are always separated by oil or air supplied under pressure.

The automatic forced lubrication of slides is common, and protection is provided by telescopic or accordion covers.

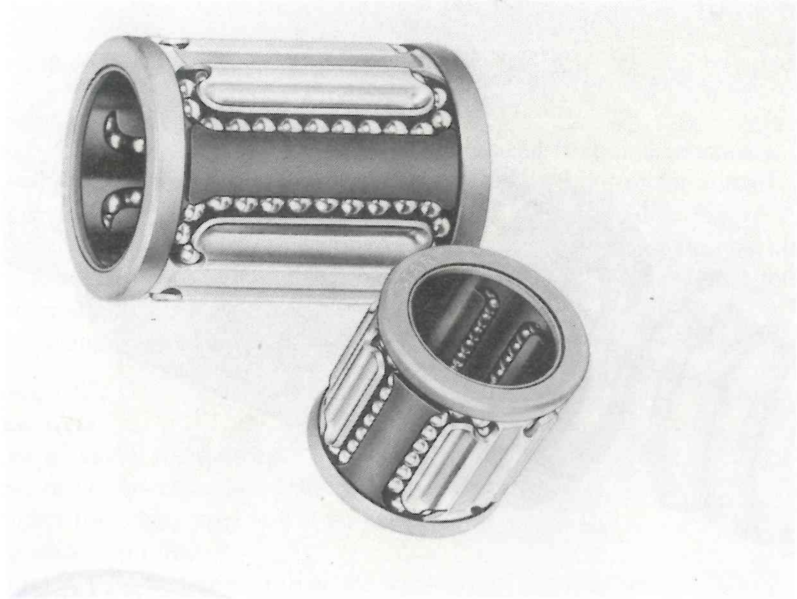


Figure 2.13 (a) *Ball bush.*

Figure 2.13 (b) *Split ball bush.*

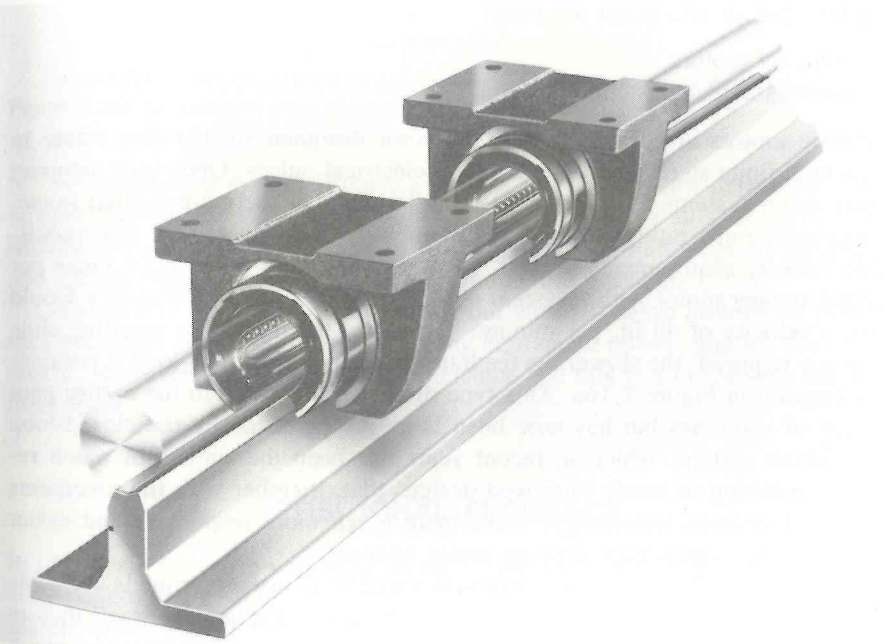


Figure 2.14 *Application of split ball bushes.*

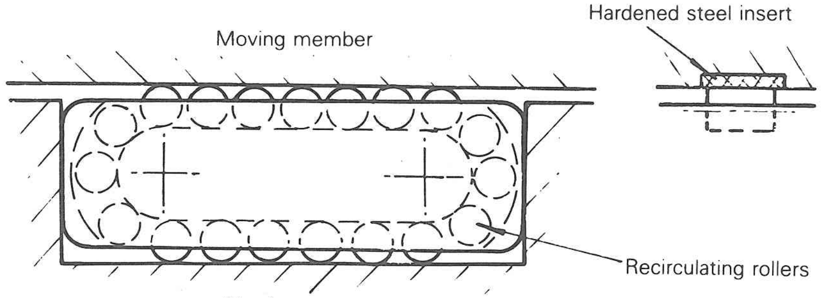


Figure 2.15 *Recirculating roller slide.*

SLIDE DRIVES

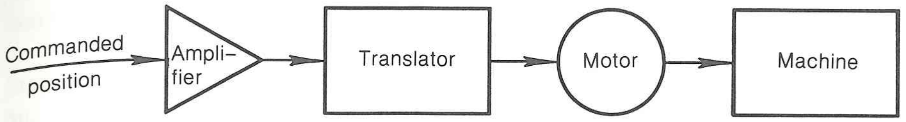
It was stated in Chapter 1 that both electric and hydraulic power are used to achieve slide motion. There are a number of very effective, responsive, and thoroughly proved hydraulic systems currently in use, but by far the most common power source is the electric motor, and so the text will be confined to dealing only with this method.

Two types of DC motor are used:

(a) stepping motors
(b) conventional, nonstepping motors

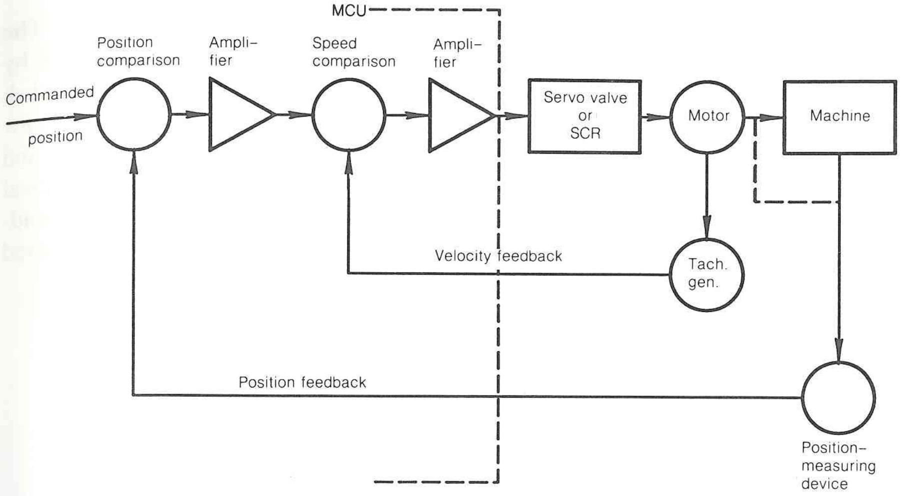
Stepping motors are a special type of motor designed so that they rotate in sequential finite steps when energized by electrical pulses. Open-loop stepping motor drive systems have two major limitations: (1) there are limited horsepower and torque ratings to meet requirements; (2) the increment size-versus-slide velocity requirements needed. An example would be an 8000 pulse per second stepper motor with a system requiring 0.0001 in. slide accuracy would have a velocity of 48 in. per minute. Therefore, the higher the machine slide accuracy required, the slower the feedrate obtainable. See open-loop servo control diagram in Figure 2.16a. This type of motor was fitted to the earlier generation of machines but has now been largely superseded by the closed-loop servo drive system, which in recent years has been the subject of much research, resulting in vastly improved designs that, together with improvements in control systems technology, make them much more responsive and easier to control than open-loop stepping motor systems.

The speeds of DC motors are infinitely variable. Constant torque is available throughout most of the speed range, which means that relatively small motors can be used, and when they are directly coupled to the machine leadscrew a torsionally stiff drive is provided. The motors provide regenerative braking, resulting in a virtually nonexistent slide overrun.



(From Fundamentals of Numerical Control, Publication SD-100, Allen Bradley Corp., Milwaukee, WI.)

Figure 2.16a *Open-loop servo control (block diagram).*



(From Fundamentals of Numerical Control, Publication SD-100, Allen Bradley Corp., Milwaukee, WI.)

Figure 2.16b *Closed-loop servo system, servo block diagram.*

The closed-loop system (Figure 2.16b) is not drive-motor-dependent using stepper motors, AC motors, DC motors, SCR drives, hydraulic motors, or hydraulic cylinders. With this type of drive system, resolutions of 50 millionths and speeds higher then 400 inches per minute are possible.

Considerable research is being carried out with AC servo motors. At present they are larger than DC motors providing equivalent power, and are also more costly. However, they need less maintenance and this is a factor very much in their favor.

POSITIONAL FEEDBACK

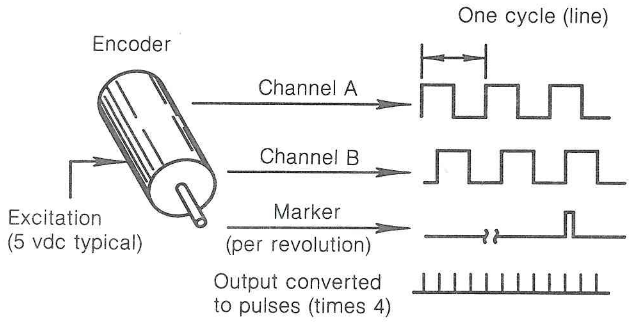
In Chapter 1 reference was made to the concept of open-loop and closed-loop slide positioning systems. The closed-loop positioning system is an important feature of any good computer numerically controlled machine. The concept can be summarized as instruction–movement–information–confirmation. The crucial feedback information is provided by a transducer.

A transducer can be described as a device that receives and transmits information. This information is received in one form, converted, and then transmitted in another form acceptable to the receiver.

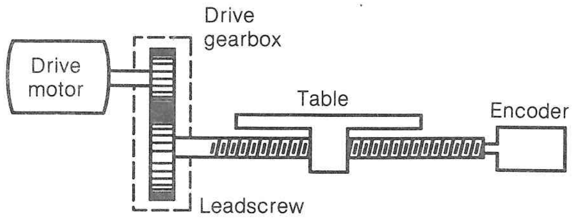
A variety of transducers have been applied, with varying success, to computer numerically controlled machines. Two of the more common types are described below.

Rotary-Type Transducers

A rotary-type transducer transmits angular displacement as a voltage. The transducer creates electrical pulses and transmits them back to the control by use of electrical windage in resolvers/synchro resolvers or photoelectric disk encoders. Physically, this transducer is attached to one end of the leadscrew either by direct means or through the use of precision gears (Figures 2.17a and 2.17b). Within this relatively small package there are a series of electrical windings. One of these windings, referred to as a rotor, rotates with the leadscrew. Around the periphery of the leadscrew are a series of interconnected windings that do not rotate and that are referred to as the stator.

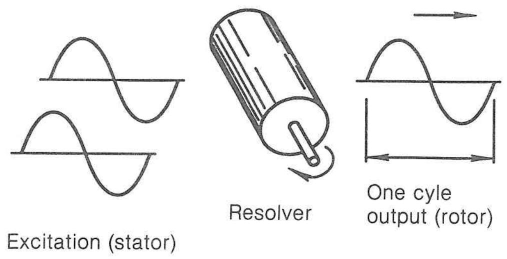


Using channels A or B or both permits encoder signals to be 1, 2, or 4 times the number of lines; marker signal occurs once per revolution and is used for reference

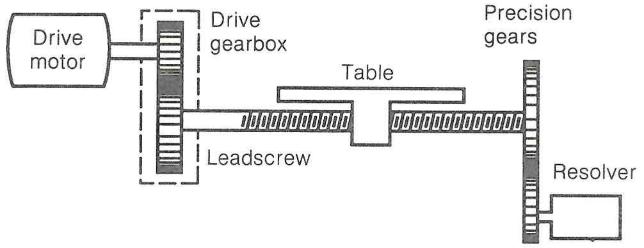


Encoder feedback coupled directly to leadscrew

(From *Fundamentals of Numerical Control*, Publication SD-100, Allen Bradley Corp., Milwaukee, WI.)
Figure 2.17a *Encoder.*



Output phase angle indicates shaft-angle position of the rotor



Precision gearing in the proper ratio must be used when
the feedback device is not compatible with leadscrew pitch

(From *Fundamentals of Numerical Control*, Publication SD-100 Allen Bradley Corp., Milwaukee, WI.)
Figure 2.17b. *Resolver.*

The stator windings or photocells are fed with electrical power at a voltage rate that has been determined by the machine control unit in response to digital information relating to the required slide movements it has received via the part program. As the servo motor rotates the leadscrew, a voltage is induced in the rotor photocells, and this voltage will vary according to the angular position of the leadscrew in relation to the stator windings or photo encoder disk. Information relating to the induced voltage is fed back to the control unit, which, in effect, counts the number of complete revolutions and part revolutions the leadscrew has made, thus confirming that the movement achieved corresponds to the original instruction.

Optical Gratings

An optical grating transducer transmits linear movement as a voltage signal in the form of a series of pulses.

The principle of the optical grating can be shown in a practical way as follows. Figure 2.18 represents a pair of optical gratings, each consisting of a

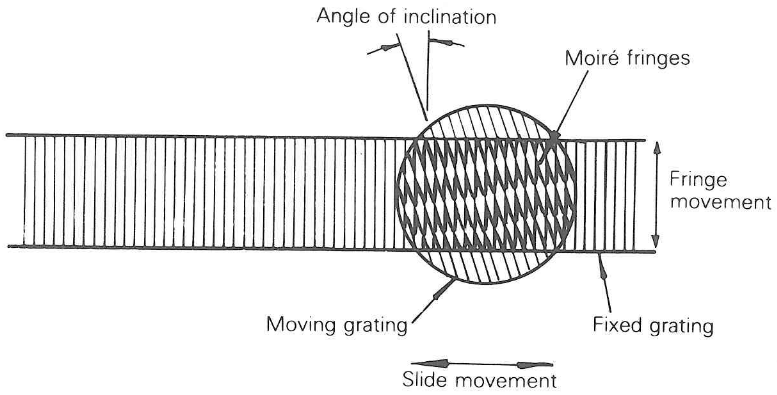


Figure 2.18 *Principle of optical grating.*

number of evenly spaced parallel lines. One grating is fixed and the other is caused to move along. The reader is invited to reproduce the moving grating on either a piece of tracing paper or clear plastic film. Place the second grating over the first and, with the lines inclined at a slight angle, move the second grating across the first. A fringe pattern similar to the one shown will be observed moving across the fixed grating. This pattern is referred to as Moiré fringe.

There is a mathematical connection between the spacing of the gratings, the angle of inclination and the apparent fringe movement. This principle is applied to measuring the movement of machine slides.

For practical purposes the gratings are etched either on gelatine-coated glass or on stainless steel. The fixed grating is attached to the main casting of the machine and the moving grating is positioned immediately above the fixed grating, but is attached to the moving slide. Gratings for applications of this nature have 100 to 200 spacings per inch or 25 mm.

If glass is used, a light source is directed through the grating; if stainless steel is used, the light is reflected off the surface. This light is focused onto a phototransistor, which responds according to whether the projected light is uninterrupted or interrupted, that is, a fringe is present or not present. The electrical pulses produced in this way each represent a known linear value. The number of pulses is counted and this information is fed back to the control unit as confirmation that the correct movement has been made.

Both the transducers described have a weakness. One monitors revolutions of the leadscrew, the other movements made by a slide. Neither of these factors may be a precise indication of the position of the tool in relation to the work, which would be the function of a perfect transducer. Such a transducer poses many design problems and has yet to be developed.

The locations of a linear and a rotary transducer on machine tools are illustrated in Figure 2.19.

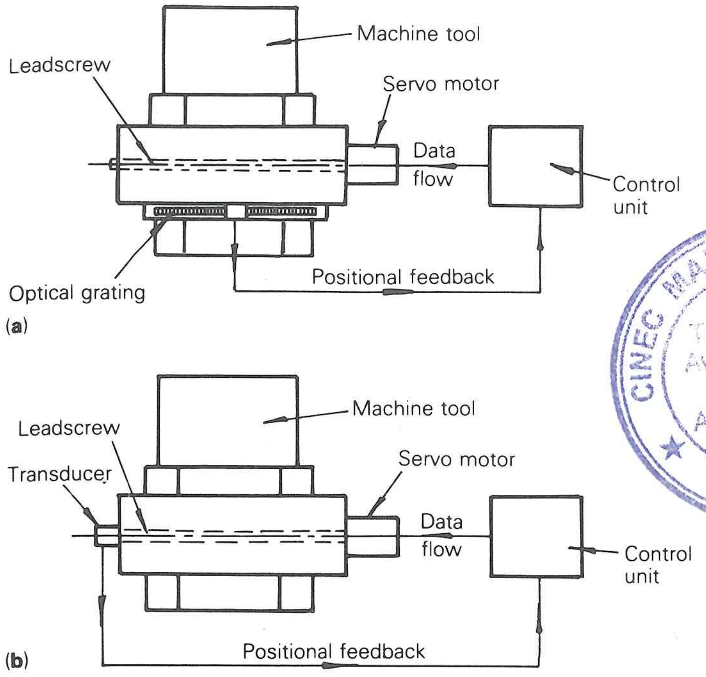


Figure 2.19 *Location of positional transducers on machining centers: (a) linear transducer; (b) rotary transducer.*

TEMPERATURE VARIATIONS THAT AFFECT DIMENSIONAL STABILITY

Manufacturers design their machines so that the correct alignments are achieved at a stated temperature. "Warm up" times are often quoted and sometimes warning lights are built into the control system. Deviation from the stated temperature can cause twisting or distortion of the machine castings and can have a considerable effect on the accuracy of the work produced.

Heat sources that have to be accommodated in the design of the machine, or otherwise eliminated, are as follows:

(a) heat due to friction in motors, bearings and slides
(b) heat due to the metal-cutting action
(c) heat due to accumulated chips or swarf
(d) heat in the environment

Heat due to friction is eliminated or its effect reduced in a variety of ways. For example, main drive motors are sometimes placed outside the main structure (which also helps to reduce vibration) and the final drive to the spindle is via belts. Motors that are attached to the machine body have heat radiation facilities in the form of vanes built into their structure. Some are cooled by a ducted air flow. Spindles may be air or oil cooled; sometimes when oil is used there are cooling facilities for the recirculating oil. Heat produced by slide movement is virtually eliminated by the efforts made to produce frictionless slides, as mentioned earlier.

Heat produced by the cutting action is kept to a minimum by ensuring that the correct cutting conditions prevail, that is, by using tools with the correct geometry for the material being cut and the operation being carried out, and by ensuring that the correct cutting speed and feed rates are employed. In addition, coolant, as a flood or as spray mist, can be applied to the cutting area. Some machines provide each cutting tool with an individual coolant supply, as illustrated in Figure 2.20.

Heat due to chip accumulation can be a major problem, especially when the machines are totally enclosed for safety. The ideal situation is to have the chips falling away from the machine. Figure 2.21a illustrates how the sloping bed of a turning center permits the chips to fall away, while Figure 2.21b shows a horizontal machining center with the same facility. An added refinement is to have the chips continuously removed by conveyor.

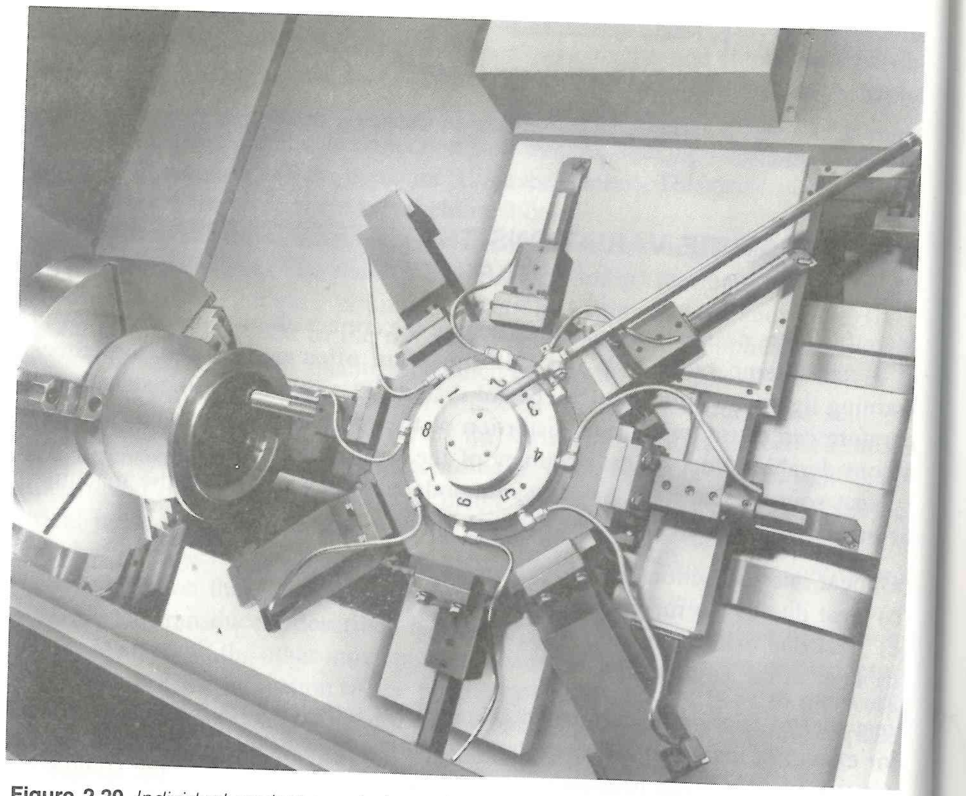


Figure 2.20 *Individual coolant supply to cutting tools.*

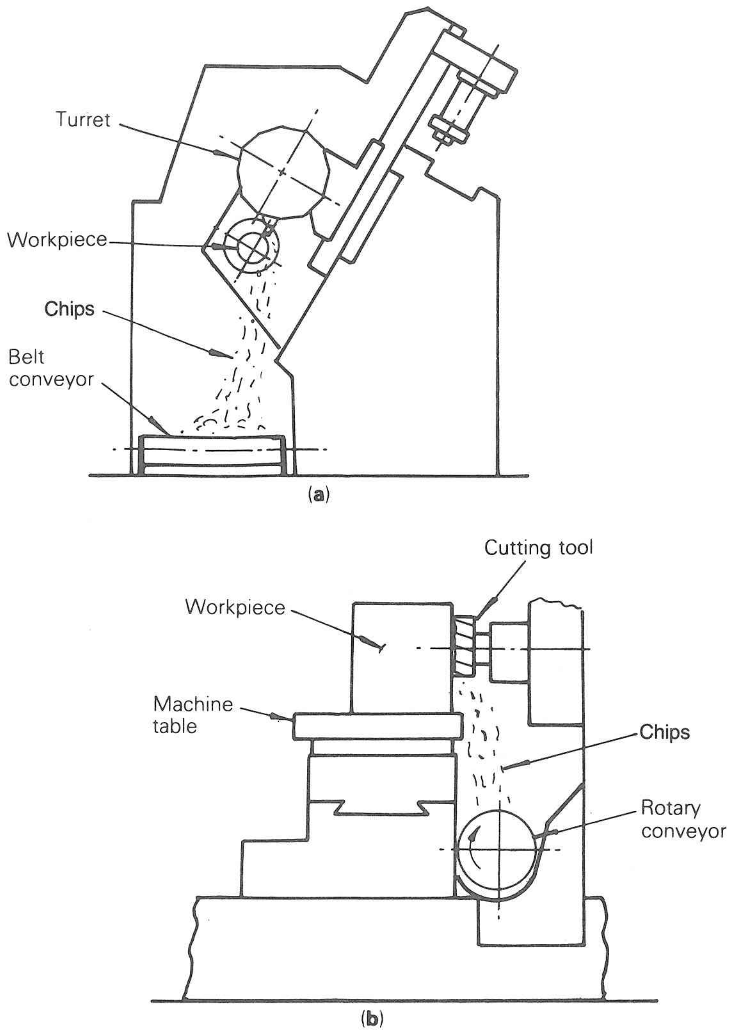


Figure 2.21 *Chip removal arrangements: (a) turning center; (b) horizontal machining center.*

It is best if the room temperatures for workshops containing computer numerically controlled machines are maintained at a constant 20°C or 72° F, but with recent control upgrades this is no longer mandatory. The presence of a radiator or a constantly opening and closing door close to a machine can have a detrimental effect, and very warm summer days have been known to halt production in factories where the air conditioning was inadequate.

It is also worth noting that excesses in temperature not only affect the dimensional stability of a machine but can also cause malfunctioning of the electronic control systems.

Figure 2.22 *Additional machining facilities provided by second turret.*

ADDITIONAL MACHINING FACILITIES

A number of machines currently available have special design features that extend their capabilities by providing machining facilities not generally available. They include the following.

1. Turning centers with two turrets positioned in such a way that two tools can cut simultaneously. An example is shown in Figure 2.22.
2. Turning centers which use special tool holders that are power driven and can be programmed to rotate when the machine spindle is stationary, thus permitting the milling of flats, keyways, and slots and the drilling of holes offset from the machine axis as illustrated in Figure 2.23.
3. A turning center with a similar facility to that described above, but where the rotating holders are located in a separate turret. In addition the spindle, when clamped to prevent rotation, can be caused to slide in the *Y* axis, thus giving four-axis control: *X*, *Y*, *Z*, and *C* (rotary).
4. A milling machine with two spindles providing for machining operations in the vertical and horizontal planes, a facility that is particularly useful and time saving when machining large components that cannot be readily reset. This feature is illustrated in Figure 2.24.
5. A turning center using a tooling magazine, as opposed to a turret, to provide for a greatly extended tooling range.

SAFETY

The safety aspects of computer numerically controlled machines have to be related not only to the machine operator but also to the very costly equipment. There are two problem areas: the high voltage involved and the extreme me-

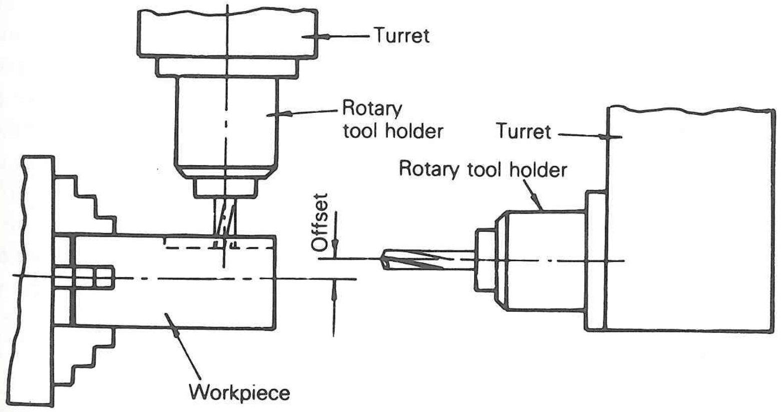


Figure 2.23 *Example of additional machining facilities on a turning center.*

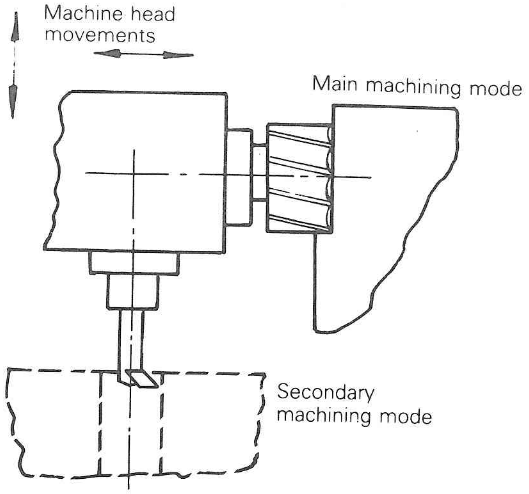


Figure 2.24 *Example of additional machining facilities on a horizontal machining center.*

chanical forces resulting from high spindle speeds and rapid slide movements.

The electrical services are protected by lockable covers, and access should be limited to authorized persons.

The mechanical dangers are greatly reduced by total enclosure, a common feature of computer numerically controlled machines. This affords protection from flying chips and broken tooling, reduces noise level and prevents contamination of the atmosphere by coolant, the latter being a considerable problem when spray cooling is employed.

When machines are not totally enclosed guards are used, these being fitted with interlocking switches so that there is no machine movement until the guard is correctly positioned.

The electrical control of mechanical features is also extended to work-holding devices. If the work is not correctly held, there is no machine movement.

Excessive slide movement, which could damage the machine or workpiece, is prevented by limit switches, and this can also be extended further by programmable safety zones that fall into three categories: safe, warning, and fault. Tool movement in the safe zone is unrestricted; in the warning zone it is only possible by the operator making a conscious response to a power cut-off; in the fault zone no movement at all is possible. The whole machine can, of course, be instantly immobilized by activating the obligatory emergency switch.

Reference was made earlier to conventional machines being retrofitted with computer numerical control systems. These machines often do not have the built in safety features referred to above and because of this the utmost care must be taken in their use.

The reader should appreciate that, on all computer numerically controlled machines, whether purpose built or retrofitted, slide movements can be very rapid, and movements made at the wrong time or in the wrong direction can have disastrous results both for the operator and for the equipment. Accidents of this nature are more likely to happen during machine setting and program proving, and when restarting after a program stop.

A clearly defined code of operation, with the accent on safety, is desirable for all remote controlled machine tools, particularly those used in educational and training establishments, and the student should be made fully aware of the inherent dangers.

QUESTIONS

1 Define repeatability as applied to CNC machine tools.

2 List five qualities which need to be incorporated in a machine design if repeatability is to be maintained.

3 What are bifurcated structures and why are they used?

4 Why is it desirable that slide leadscrews should be centrally positioned?

5 What do you understand by the term dimensional stability as applied to CNC machine tools?

6 List four factors that can affect the dimensional stability of a CNC machine tool.

7 Explain the difference between static and dynamic loading by quoting examples of where they occur in a CNC machine tool.

8 Why do some manufacturers recommend a warm up period before a CNC machine tool is used?

9 How do some machine designs eliminate the problems caused by the heat present in chips?

10 List the various techniques that are used on machine-tool slides to reduce the frictional resistance to motion.

11 List the advantages of using DC servo motors for slide movement on CNC machines.

12 Why is it that gearboxes are not necessary when machine spindles are driven by DC motors?

13 Why is the traditional Acme form of leadscrew unsuitable for CNC machines?

14 List the advantages of using recirculating ball screws to facilitate slide movement.

15 What is the name given to the thread form of ball screw?

16 What is a positional transducer and where and why it is used on a CNC machine?

17 What are the two problem areas that make safety an important consideration in the design of CNC machine tools?

18 Many CNC machines are totally enclosed. List three advantages of such an arrangement.

19 How can the danger of inadequate work holding be eliminated?

20 Explain the differences among safe, warning, and fault safety zones and their purpose in CNC machine tool control systems.

3

TOOLING FOR COMPUTER NUMERICALLY CONTROLLED MACHINING

To the onlooker one of the most startling aspects of computer numerically controlled machining is the rapid metal-removal rates used. That there are cutting tools capable of withstanding such treatment can seem quite incredible. Add to this indexing times of less than one second and automatic tool changing providing a "chip-to-chip" time of around five seconds and it is easy to understand why many production engineers consider tooling to be the most fascinating aspect of computer numerically controlled machining.

MATERIALS FOR CUTTING TOOLS

Although high-speed steel (HSS) is used for small-diameter drills, taps, reamers, end mills, and spot drills, the bulk of tooling for computer numerically controlled machining involves the use of cemented carbide.

The physical properties necessary in a cutting tool are hardness at the metal-cutting temperature, which can be as high as 600° C, and toughness. High-speed steel is tougher than cemented carbide but not as hard and, therefore, cannot be used at such high rates of metal removal. On the other hand, the lack of toughness of cemented carbide presents problems, and this has meant that a tremendous amount of research has gone into developing carbide grades that, when adequately supported, are able to meet the requirements of modern machining techniques. It is only necessary to observe a computer numerically controlled machine in action to see how successful this research has been.

The hardness of cemented carbide is almost equal to that of diamond. It derives this hardness from its main constituent, tungsten carbide. In its pure form tungsten carbide is too brittle to be used as a cutting tool, so it is pulverised and mixed with cobalt.

The mixture of tungsten carbide and cobalt powder is pressed into the required shape and then sintered. The cobalt melts and binds the tungsten carbide grains into a dense, nonporous structure.

In addition to tungsten carbide, other hard materials such as titanium and tantalum carbides are used, and by providing tungsten carbide tools with a thin layer of titanium carbide, resistance to wear and useful life are increased by up to five times.

THE PRACTICAL APPLICATION OF CEMENTED CARBIDES

Solid Tools

Solid carbide tools are somewhat restricted in their use owing to their lack of toughness. However, they are particularly useful when the work material is difficult to machine with high-speed steel, thus precluding the use of this material even for the small sizes referred to earlier. Solid carbide milling cutters as small as 1/32 in. diameter, drills as small as 1/64 in. or No. 80 (0.0135 in.) diameter and reamers as small as 1/16 in. diameter are available. The successful application of solid carbide tooling depends greatly on the tool being short and mounted with the minimum of overhang, and the machines on which they are used being vibration free and having no play or misalignment. The correct speeds and feeds have to be determined with great care, often by experiment on the particular work in hand.

Brazed Tips

When the shank size of a cutting tool is large enough, a more viable technique is to braze the carbide tip to a medium carbon steel shank. Drills, reamers, milling cutters, and turning tools produced in this way are available.

Indexable Inserts

While both types of tooling previously referred to have their particular uses, by far the most widely used application of cemented carbides is as inserts located in special holders or cartridges.

The advantages of inserts are as follows:

1. correct cutting geometry
2. precise dimensions
3. no resharpening
4. rapid replacement

The first two factors are particularly relevant where preset tooling is concerned. (Preset tooling is discussed subsequently in the text.)

The inserts are indexable, that is, as a cutting edge becomes dull the insert is moved to a new position to present a new edge to the work. The number of cutting edges available depends on the design of the insert.

The control of chips is an essential requirement when high metal-removal rates are involved, and this can be a built-in feature of the insert itself, in the form of a groove, or of the holder, in the form of a chip-breaking pad clamped on the top of the insert.

AMERICAN NATIONAL STANDARDS INSTITUTE AND INTERNATIONAL STANDARDS ORGANIZATION CODES

Although there is still a wide range of cemented carbide grades, insert shapes, and tool-holder designs currently available, the initially somewhat confusing situation was greatly helped by the introduction of the American National Standards Institute (ANSI) and International Standards Organization (ISO) codes. Manufacturers' literature usually states where their particular products correspond with the ANSI/ISO recommendations.

Carbide Grades

Carbide grades vary according to their wear resistance and toughness. As the wear resistance increases, the toughness decreases. The ANSI/ISO systems differ in how they handle grade classification, but suppliers of carbide can provide either set of information. The ANSI system allows carbide manufacturers to create their own grade coding system, which they in turn explain in their catalog. (See example in Figure 3.1a.) The ISO code groups carbides according to their application, and they are designated by the letters P, M, and K and a number. A corresponding color code of blue (P), yellow (M), and red (K) is also used. An interpretation of the code is given in Figure 3.1b.

Inserts

Inserts are designated according to shape, size, geometry, cutting direction, etc. An interpretation of the ANSI/ISO codes is given in Figures 3.2a and 3.2b. Note that only slight differences in the two systems exist, one being the use of English or metric dimensions.

Holders and Cartridges

Holders and cartridges are designated according to a number of factors, which include tool style, method of holding the insert, tool height, and width.

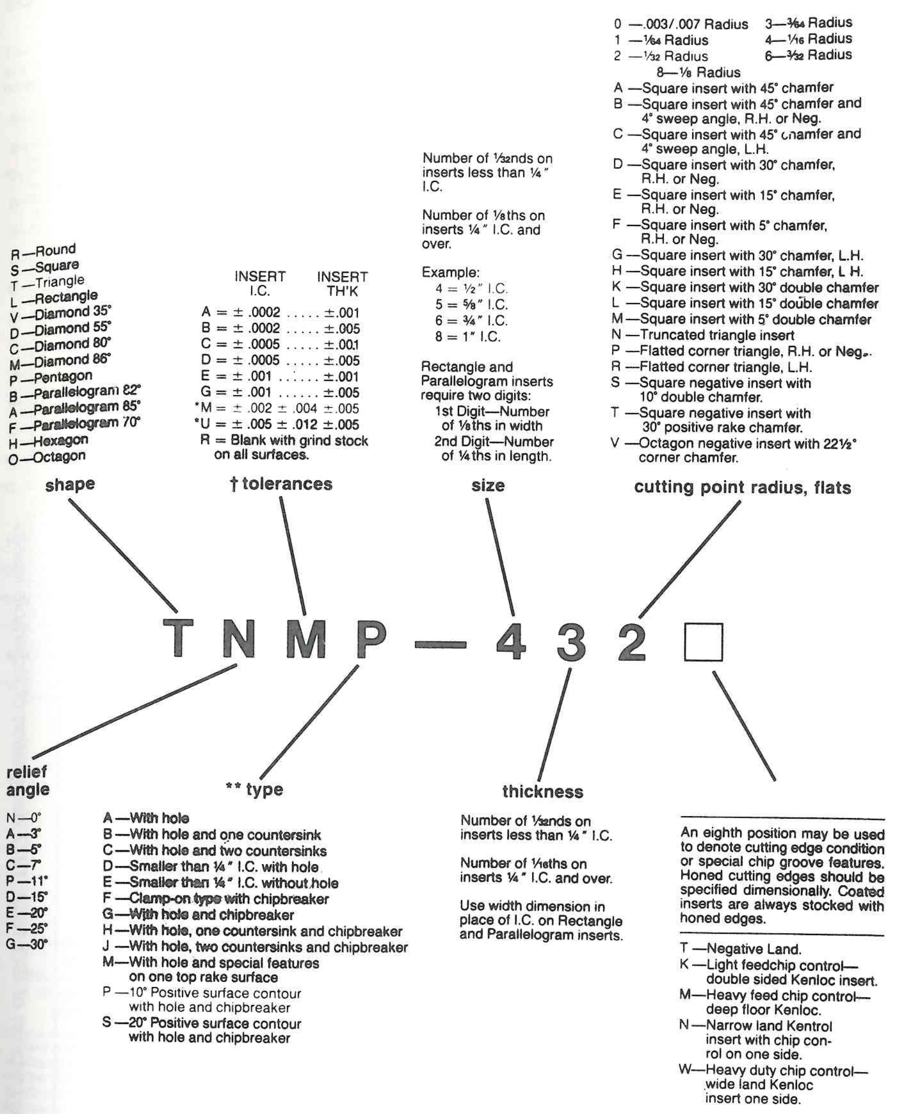
The shanks of the holders and cartridges can be "qualified," that is, when the insert is located, the distance from the tool tip to a stated location face is guaranteed within a tolerance of ±0.003 to ±0.005 in. depending on shank size. Qualified tooling and its application are dealt with in more detail later in this chapter.

An interpretation of the ANSI/ISO codes for tool holders and cartridges is given in Figures 3.3a, 3.3b, and 3.3c. Note again that only minor differences appear between ANSI and ISO systems.

		ISO Code	Application
Increasing wear resistance Increasing cutting speed	Color code: Blue	P01	For finishing steel, high cutting speeds, light feeds, favorable conditions.
		P10	Slightly tougher grade for finishing and light roughing steel and castings. No coolant.
		P20	For medium roughing of steel, less favorable conditions. Moderate cutting speeds and feeds.
		P30	For general-purpose turning of steel and castings, medium roughing.
		P40	For heavy roughing of steel and castings. Intermittent cutting, low speeds and feeds.
		P50	For difficult conditions. Heavy roughing intermittent cutting. Low cutting speed and feed.
	Color code: Yellow	M10	For finishing stainless steel using high cutting speeds.
		M20	For finishing and medium roughing of alloy steels.
		M30	For light to heavy roughing of stainless steel and materials difficult to cut.
Increasing shock resistance Increasing feed		M40	For roughing tough-skinned materials using low cutting speeds.
	Color code: Red	K01	For finishing plastics and cast iron.
		K10	For finishing brass and bronze using high cutting speeds and feeds.
		K20	For roughing cast iron. Intermittent cutting, low speeds, high feeds.
		K30	For roughing and finishing cast iron and non-ferrous materials. Favourable conditions.

Figure 3.1b *Selection of ISO carbide grades for metal-cutting applications.*

indexable inserts identification system



shape

R—Round
S—Square
T—Triangle
L—Rectangle
V—Diamond 35°
D—Diamond 55°
C—Diamond 80°
M—Diamond 86°
P—Pentagon
B—Parallelogram 82°
A—Parallelogram 85°
F—Parallelogram 70°
H—Hexagon
O—Octagon

† tolerances

	INSERT I.C.	INSERT TH'K
A =	± .0002	±.001
B =	± .0002	±.005
C =	± .0005	±.001
D =	± .0005	±.005
E =	± .001	±.001
G =	± .001	±.005
*M =	± .002 ± .004	±.005
*U =	± .005 ± .012	±.005

R = Blank with grind stock on all surfaces.

size

Number of 1/32nds on inserts less than 1/4" I.C.

Number of 1/8ths on inserts 1/4" I.C. and over.

Example:
4 = 1/2" I.C.
5 = 5/8" I.C.
6 = 3/4" I.C.
8 = 1" I.C.

Rectangle and Parallelogram inserts require two digits:
1st Digit—Number of 1/8ths in width
2nd Digit—Number of 1/4ths in length.

cutting point radius, flats

0 —.003/.007 Radius
1 —1/64 Radius
2 —1/32 Radius
3—3/64 Radius
4—1/16 Radius
6—3/32 Radius
8—1/8 Radius
A —Square insert with 45° chamfer
B —Square insert with 45° chamfer and 4° sweep angle, R.H. or Neg.
C —Square insert with 45° chamfer and 4° sweep angle, L.H.
D —Square insert with 30° chamfer, R.H. or Neg.
E —Square insert with 15° chamfer, R.H. or Neg.
F —Square insert with 5° chamfer, R.H. or Neg.
G —Square insert with 30° chamfer, L.H.
H —Square insert with 15° chamfer, L H.
K —Square insert with 30° double chamfer
L —Square insert with 15° double chamfer
M —Square insert with 5° double chamfer
N —Truncated triangle insert
P —Flatted corner triangle, R.H. or Neg.
R —Flatted corner triangle, L.H.
S —Square negative insert with 10° double chamfer.
T —Square negative insert with 30° positive rake chamfer.
V —Octagon negative insert with 22½° corner chamfer.

relief angle

N—0°
A—3°
B—5°
C—7°
P—11°
D—15°
E—20°
F—25°
G—30°

**** type**

A—With hole
B—With hole and one countersink
C—With hole and two countersinks
D—Smaller than 1/4" I.C. with hole
E—Smaller than 1/4" I.C. without hole
F—Clamp-on type with chipbreaker
G—With hole and chipbreaker
H—With hole, one countersink and chipbreaker
J—With hole, two countersinks and chipbreaker
M—With hole and special features on one top rake surface
P—10° Positive surface contour with hole and chipbreaker
S—20° Positive surface contour with hole and chipbreaker

thickness

Number of 1/32nds on inserts less than 1/4" I.C.

Number of 1/16ths on inserts 1/4" I.C. and over.

Use width dimension in place of I.C. on Rectangle and Parallelogram inserts.

An eighth position may be used to denote cutting edge condition or special chip groove features. Honed cutting edges should be specified dimensionally. Coated inserts are always stocked with honed edges.

T —Negative Land.
K —Light feedchip control—double sided Kenloc insert.
M—Heavy feed chip control—deep floor Kenloc.
N —Narrow land Kentrol insert with chip control on one side.
W—Heavy duty chip control—wide land Kenloc insert one side.

*Exact tolerance is determined by size of insert.
**Shall be used only when required.
†A & B I. C. Tolerances only in uncoated grades.

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Figure 3.2a *ANSI indexable inserts identification system.*

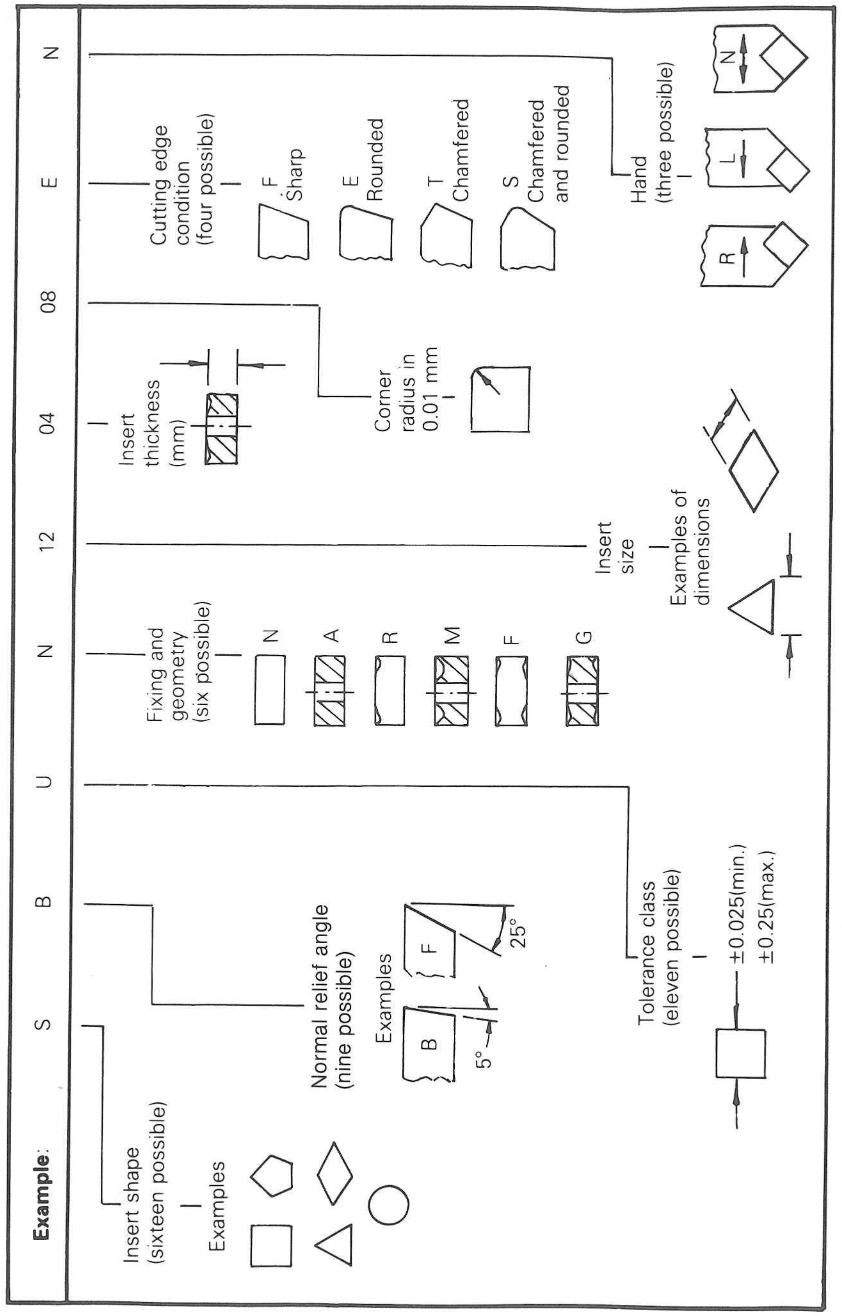
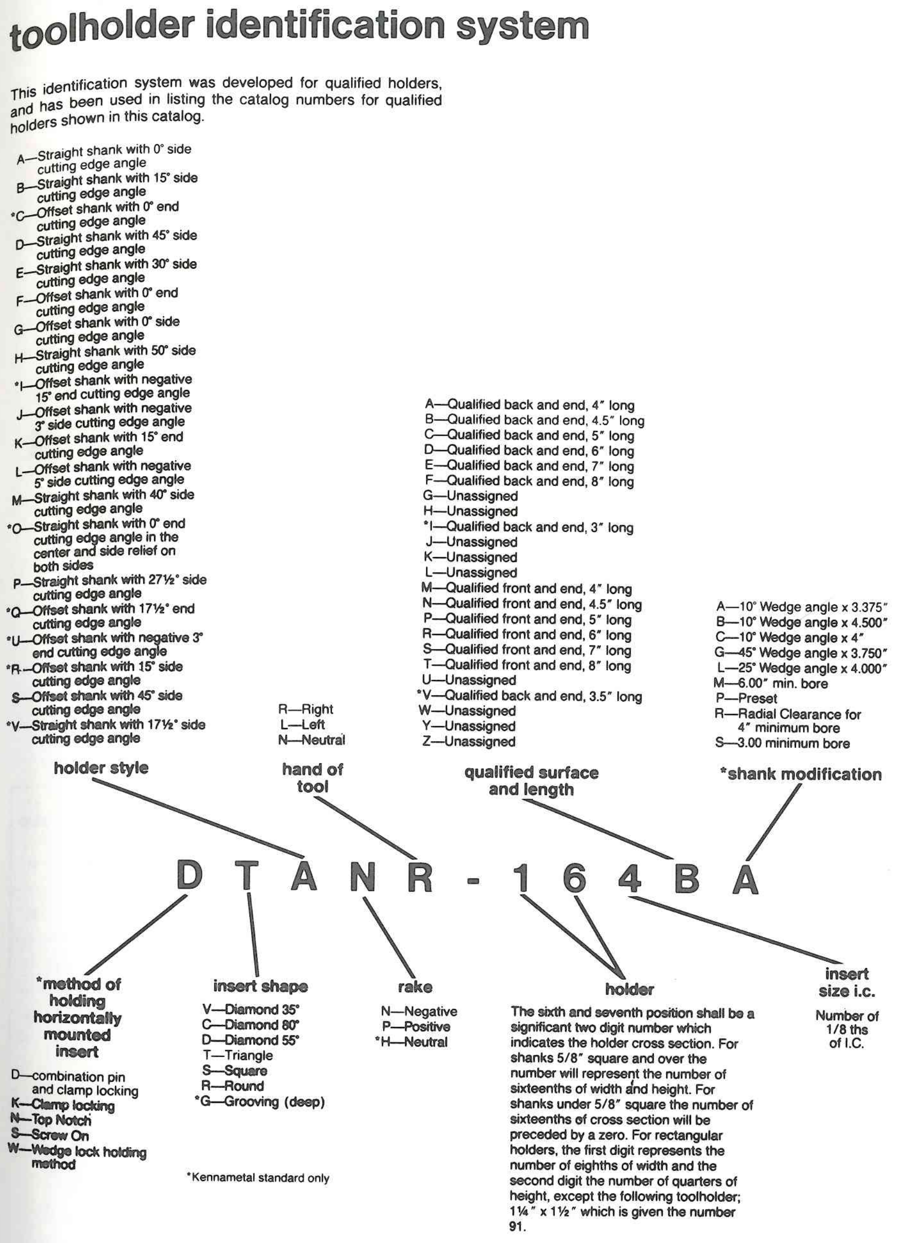


Figure 3.2b *Interpretation of ISO 1832: 1977 designation of indexable inserts.*



toolholder identification system

This identification system was developed for qualified holders, and has been used in listing the catalog numbers for qualified holders shown in this catalog.

A—Straight shank with 0° side cutting edge angle
B—Straight shank with 15° side cutting edge angle
*C—Offset shank with 0° end cutting edge angle
D—Straight shank with 45° side cutting edge angle
E—Straight shank with 30° side cutting edge angle
F—Offset shank with 0° end cutting edge angle
G—Offset shank with 0° side cutting edge angle
H—Straight shank with 50° side cutting edge angle
*I—Offset shank with negative 15° end cutting edge angle
J—Offset shank with negative 3° side cutting edge angle
K—Offset shank with 15° end cutting edge angle
L—Offset shank with negative 5° side cutting edge angle
M—Straight shank with 40° side cutting edge angle
*O—Straight shank with 0° end cutting edge angle in the center and side relief on both sides
P—Straight shank with 27½° side cutting edge angle
*Q—Offset shank with 17½° end cutting edge angle
*U—Offset shank with negative 3° end cutting edge angle
*R—Offset shank with 15° side cutting edge angle
S—Offset shank with 45° side cutting edge angle
*V—Straight shank with 17½° side cutting edge angle

holder style

R—Right
L—Left
N—Neutral

hand of tool

A—Qualified back and end, 4″ long
B—Qualified back and end, 4.5″ long
C—Qualified back and end, 5″ long
D—Qualified back and end, 6″ long
E—Qualified back and end, 7″ long
F—Qualified back and end, 8″ long
G—Unassigned
H—Unassigned
*I—Qualified back and end, 3″ long
J—Unassigned
K—Unassigned
L—Unassigned
M—Qualified front and end, 4″ long
N—Qualified front and end, 4.5″ long
P—Qualified front and end, 5″ long
R—Qualified front and end, 6″ long
S—Qualified front and end, 7″ long
T—Qualified front and end, 8″ long
U—Unassigned
*V—Qualified back and end, 3.5″ long
W—Unassigned
Y—Unassigned
Z—Unassigned

qualified surface and length

A—10° Wedge angle x 3.375″
B—10° Wedge angle x 4.500″
C—10° Wedge angle x 4″
G—45° Wedge angle x 3.750″
L—25° Wedge angle x 4.000″
M—6.00″ min. bore
P—Preset
R—Radial Clearance for 4″ minimum bore
S—3.00 minimum bore

***shank modification**

D T A N R - 1 6 4 B A

***method of holding horizontally mounted insert**

D—combination pin and clamp locking
K—Clamp locking
N—Top Notch
S—Screw On
W—Wedge lock holding method

insert shape

V—Diamond 35°
C—Diamond 80°
D—Diamond 55°
T—Triangle
S—Square
R—Round
*G—Grooving (deep)

*Kennametal standard only

rake

N—Negative
P—Positive
*H—Neutral

holder

The sixth and seventh position shall be a significant two digit number which indicates the holder cross section. For shanks 5/8″ square and over the number will represent the number of sixteenths of width and height. For shanks under 5/8″ square the number of sixteenths of cross section will be preceded by a zero. For rectangular holders, the first digit represents the number of eighths of width and the second digit the number of quarters of height, except the following toolholder; 1¼″ x 1½″ which is given the number 91.

insert size i.c.

Number of 1/8 ths of I.C.

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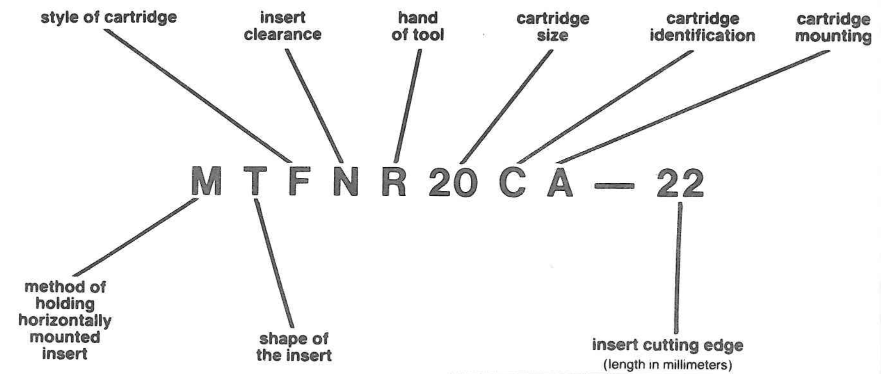
Figure 3.3a *ANSI toolholder identification system.*

ANSI/ISO cartridge identification system



style of cartridge:
- F—offset shank with 0° end cutting edge angle
- G—offset shank with 0° side cutting edge angle
- K—offset shank with 15° end cutting edge angle
- L—offset shank with 5° side cutting edge angle
- R—offset shank with 15° side cutting edge angle
- S—offset shank with 45° side cutting edge angle
- T—offset shank with 30° side cutting edge angle
- Y—offset shank with 5° end cutting edge angle
- Q—offset shank with 17½° end cutting edge angle

insert clearance:
- N—0° (neg. rake)
- P—11° (pos. rake)
- O—neutral

hand of tool:
- R—right hand
- L—left hand

cartridge size: height of cutting edge of cartridge in millimeters

cartridge identification: C—cartridge

cartridge mounting: A—angular

method of holding horizontally mounted insert
- C—top clamping
- M—combination pin and top clamp locking
- *N—Top Notch clamping

*Kennametal standard

shape of the insert
- S—square
- T—triangular
- C—rhombic with 80° corner angle
- D—rhombic with 55° corner angle
- K—parallelogram-shaped with 55° corner angle

insert cutting edge
(length in millimeters)

IC	¼″ 6,35	⅜″ 9,52	½″ 12,70	⅝″ 15,88	¾″ 19,05	1″ 25,40
triangle	11	16	22	27	33	44
square round		09	12	15	19	25
diamond 55°			15	19		
diamond 80°			12	15	19	25
diamond 35°		16				

D—insert I.C.
L—length of insert cutting edge

Top Notch is T.M.

NOTE: Threading and grooving cartridges are identified as NER or NEL with the last position in the identification system being the designated Insert Size 2, 3 or 4.
Ref. NER 20CA-2.

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Figure 3.3b *ANSI/ISO cartridge identification system.*

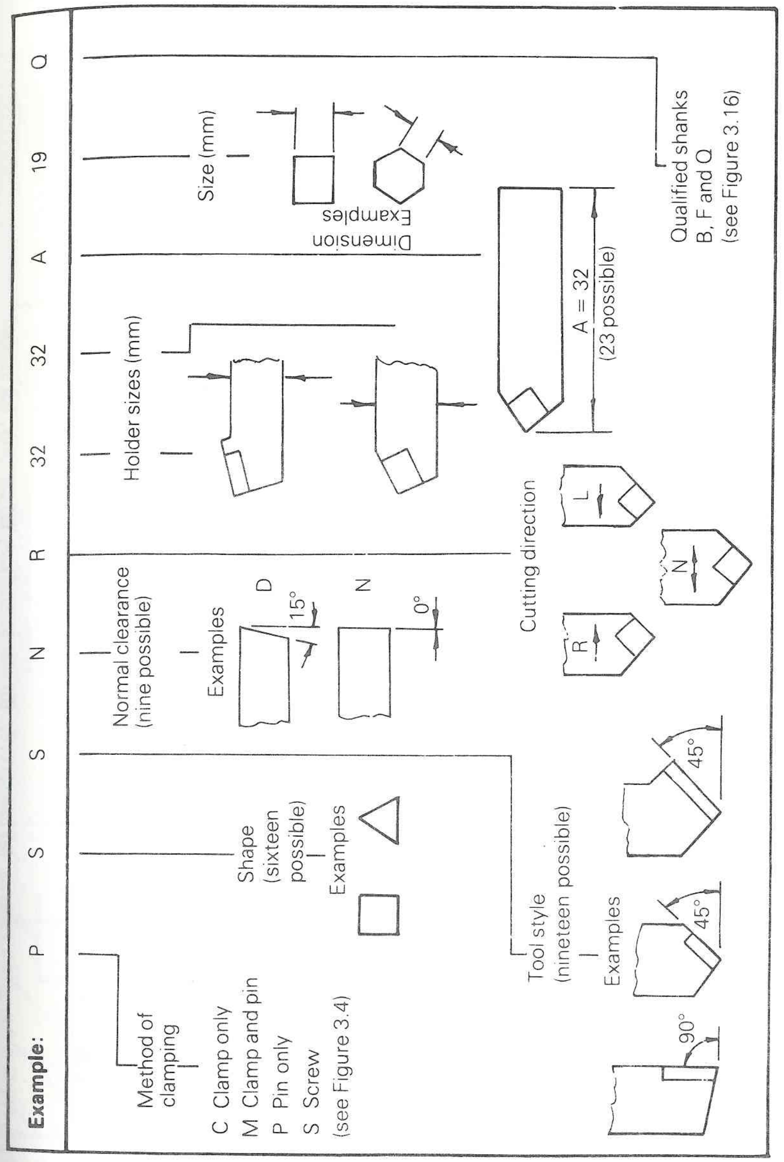

Figure 3.3c *Interpretation of ISO 1832: 1977 designation of tool holders and cartridges.*

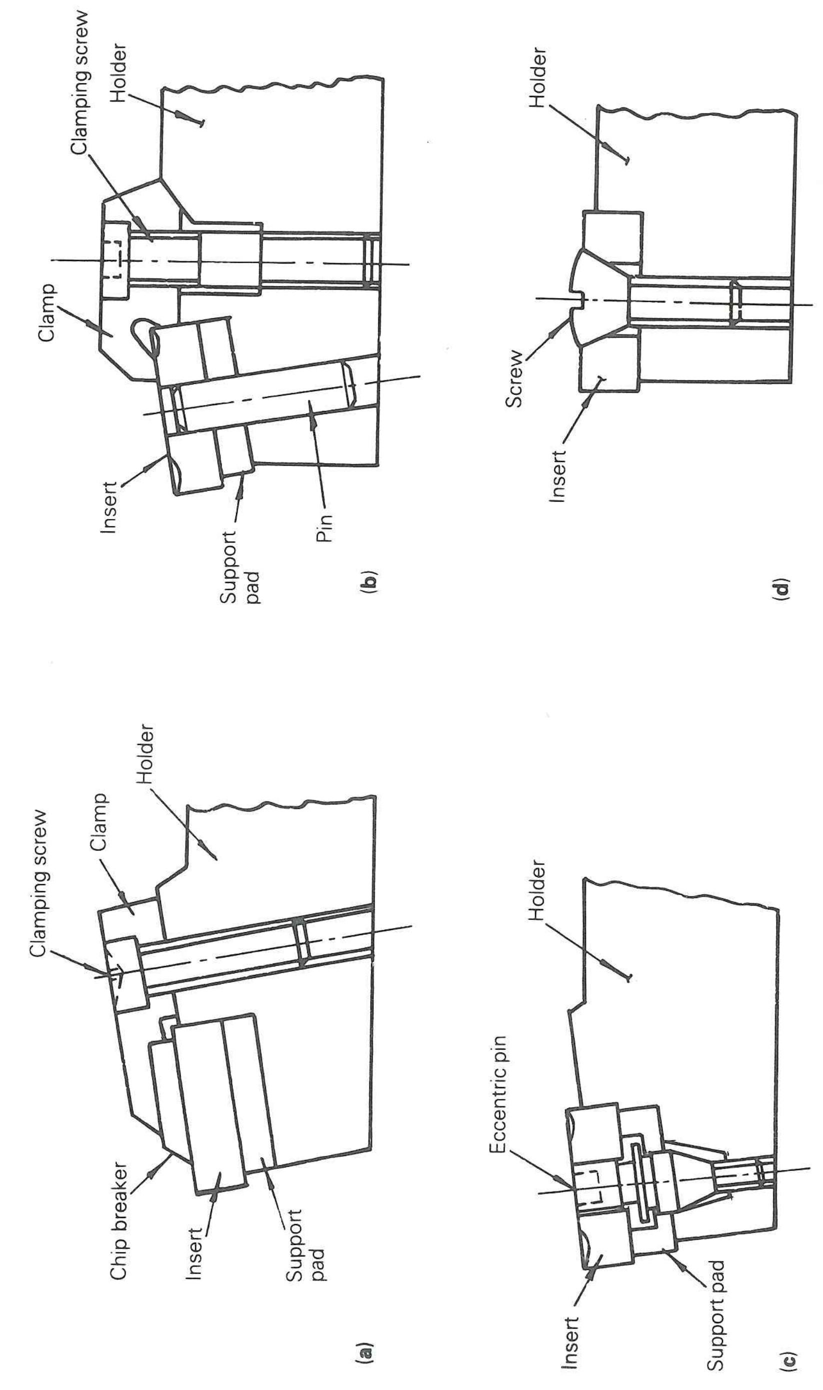

Figure 3.4 *Insert clamping arrangements:* (a) *clamp only,* (b) *clamp and pin,* (c) *pin only,* (d) *screw.*

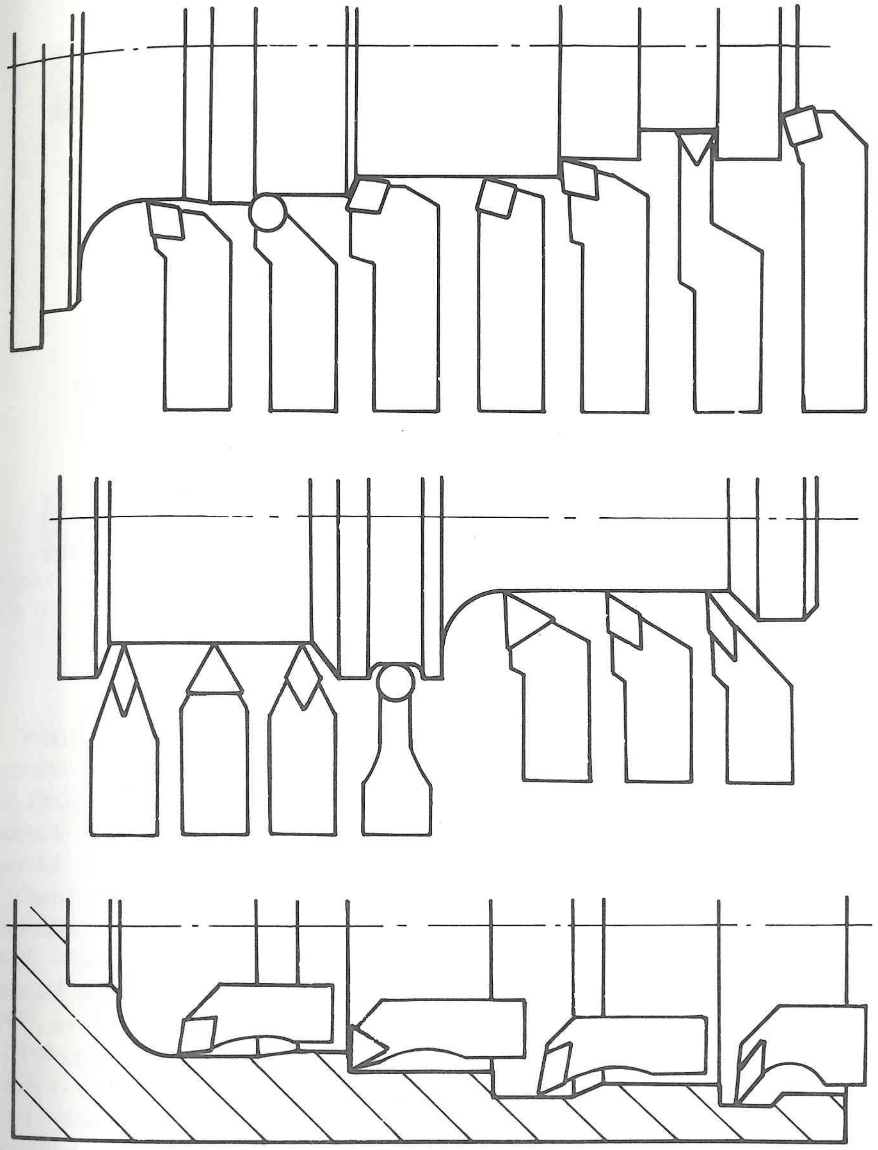

Figure 3.5 *Use of insert shapes for various turning operations.*

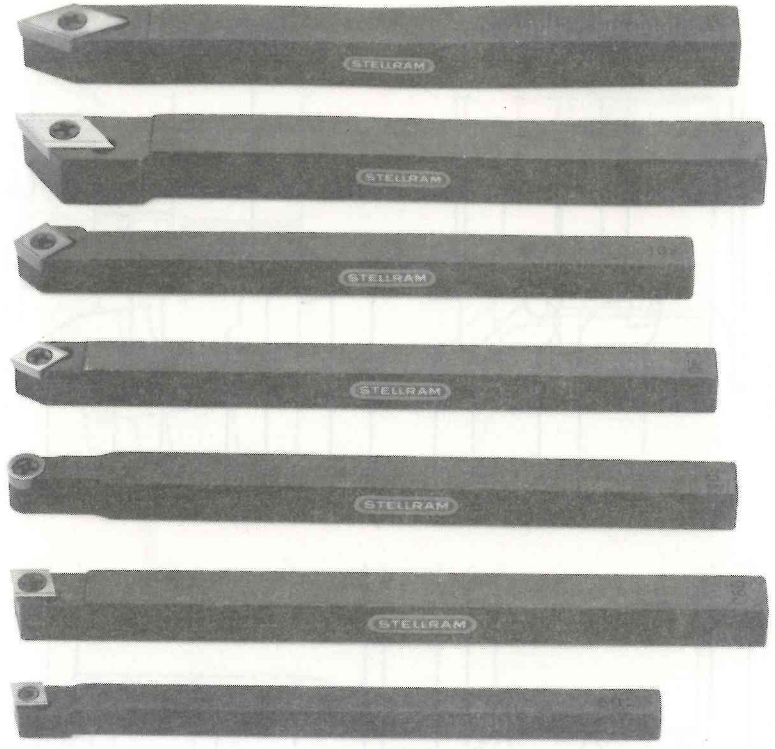

Figure 3.6 *Range of indexable insert turning tools.*

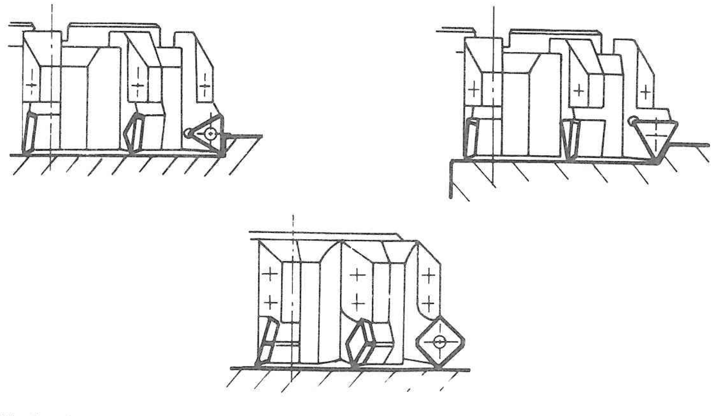

Figure 3.7 *Application of various insert shapes to face milling cutters.*

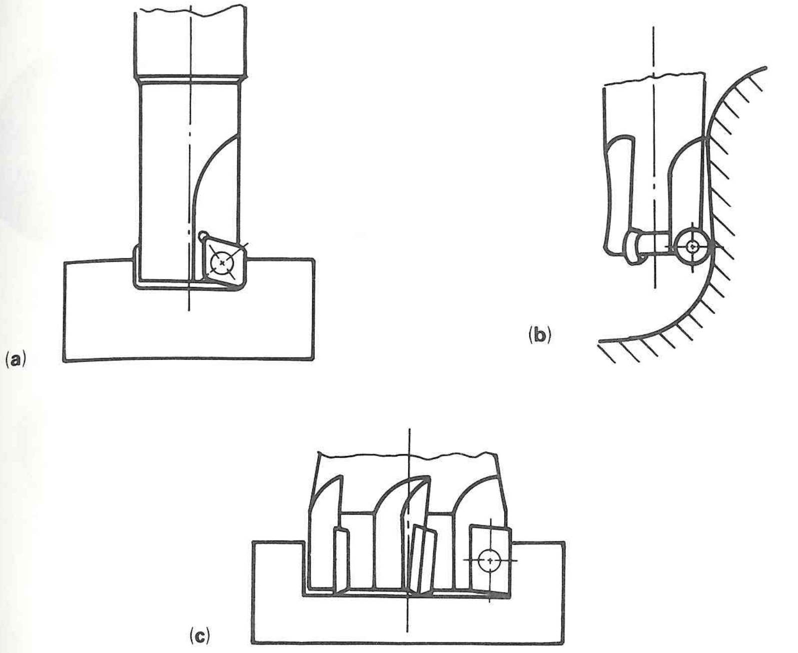

Figure 3.8 *Application of insert cutters to various milling operations:* (a) *boring,* (b) *contouring, and* (c) *slot milling.*

When grinding carbide and ceramic cutting tools, or otherwise fabricating cemented carbide, a suitable means for collection and disposal of dust, mist, or sludge should be provided. Inhalation of dust or mist containing metallic particles can be hazardous, particularly if exposure continues over an extended period of time. Therefore, adequate ventilation should be provided. General Industry Safety and Health Regulations, Part 1910, U.S. Department of Labor, published in Title 29 of Federal Regulations, particularly those sections dealing with ventilation, local exhaust systems, and occupational health and environmental control as it relates to cobalt (Co), metal fume and dust, and tungsten (W), as well as other government regulations, should be consulted.

Tungsten carbide and ceramic cutting edges, and related supporting holders such as milling cutters and boring bars, are only one part of the man–machine–tool system. Many variables exist in machining operations, including the metal removal rate; the workpiece size, shape, strength, and rigidity; the chucking or fixturing; the load carrying capability of centers; the cutter and spindle speed and torque limitations; the holder and boring bar overhang; the available power; and the condition of the tooling and the machine. A safe metalcutting operation must take all of these variables, and others, into consideration.

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Figure 3.9a *ANSI/ISO cartridges in boring bar applications.*

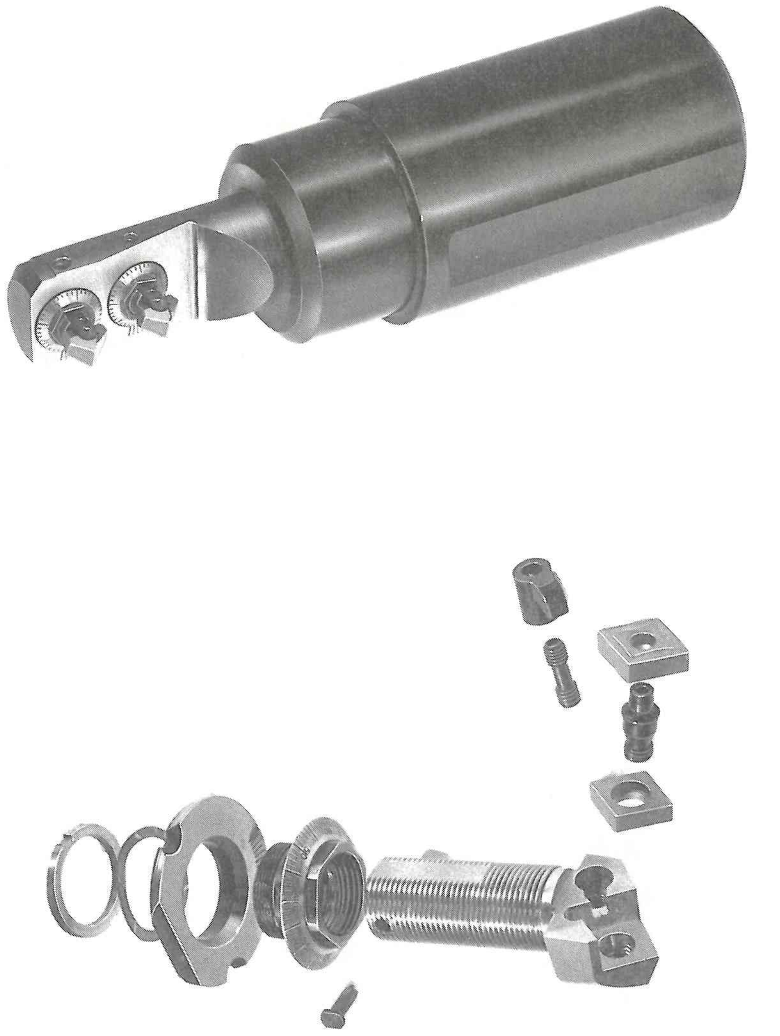

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Figure 3.9b *Tenthset precision boring cartridge with front adjustment of 0.0001 in.*

Figure 3.9c *Applications of cartridges to a face milling cutter.*

TOOLING SYSTEMS

The production of a machined component invariably involves the use of a variety of cutting tools, and the machine has to cater for their use. The way in which a range of cutting tools can be located and securely held in position is referred to as a tooling system and is usually an important feature of the machine tool manufacturers' advertising literature.

The tooling system for a machining center is illustrated in Figure 3.10. Note the use of tool holders with standard tapers, a feature that can be very helpful in keeping tooling costs to a minimum.

The types of tool holders shown in Figure 3.10 are retained in and released from the machine spindle by a hydraulic device, an arrangement that lends itself to automation, since it is relatively simple to control hydraulic systems using electrically activated solenoid valves which themselves can be controlled via the machine control system. The hydraulic force retaining the holder is supplemented by a mechanical force exerted by powerful disk springs, as illustrated in Figure 3.11, for added safety. It should be noted that less expensive machines may use a mechanical device in conjunction with pneumatics or hydraulics for tool changes.

Not all machines have automatic tool-changing arrangements and when manual tool changing is involved, mechanical retaining devices are used. Conventional tool holders for milling situations use the tried and tested screwed drawbar arrangement, but unfortunately their use is not in keeping with modern machining techniques, where the accent is on speed. Because of this, several machine tool manufacturers have introduced tool holders of their own design that have dispensed with the need to undo a drawbar each time a tool holder is changed and as a result they have greatly speeded up the replacement process.

As with milling, a tooling system for a turning center will indicate the range of tooling which can be accommodated on the machine. One such system is illustrated in Figure 3.12.

TOOL IDENTITY

The automatic selection and presentation of a cutting tool to the workpiece is a prime function of computer numerically controlled machining. To achieve this there must be a link between programming and machine setup. Tool stations are numbered according to the tooling stations available (see Figures 2.1 and 3.13), and when writing a program, the programmer will provide each tool with a corresponding numerical identity, usually in the form of the letter T followed by two digits: T01, T02, T03 and so on. The machine setter will need to know the type of tool required and will set it in its allocated position. The transfer of information between the programmer and the machine setter is discussed in more detail in Chapter 8.

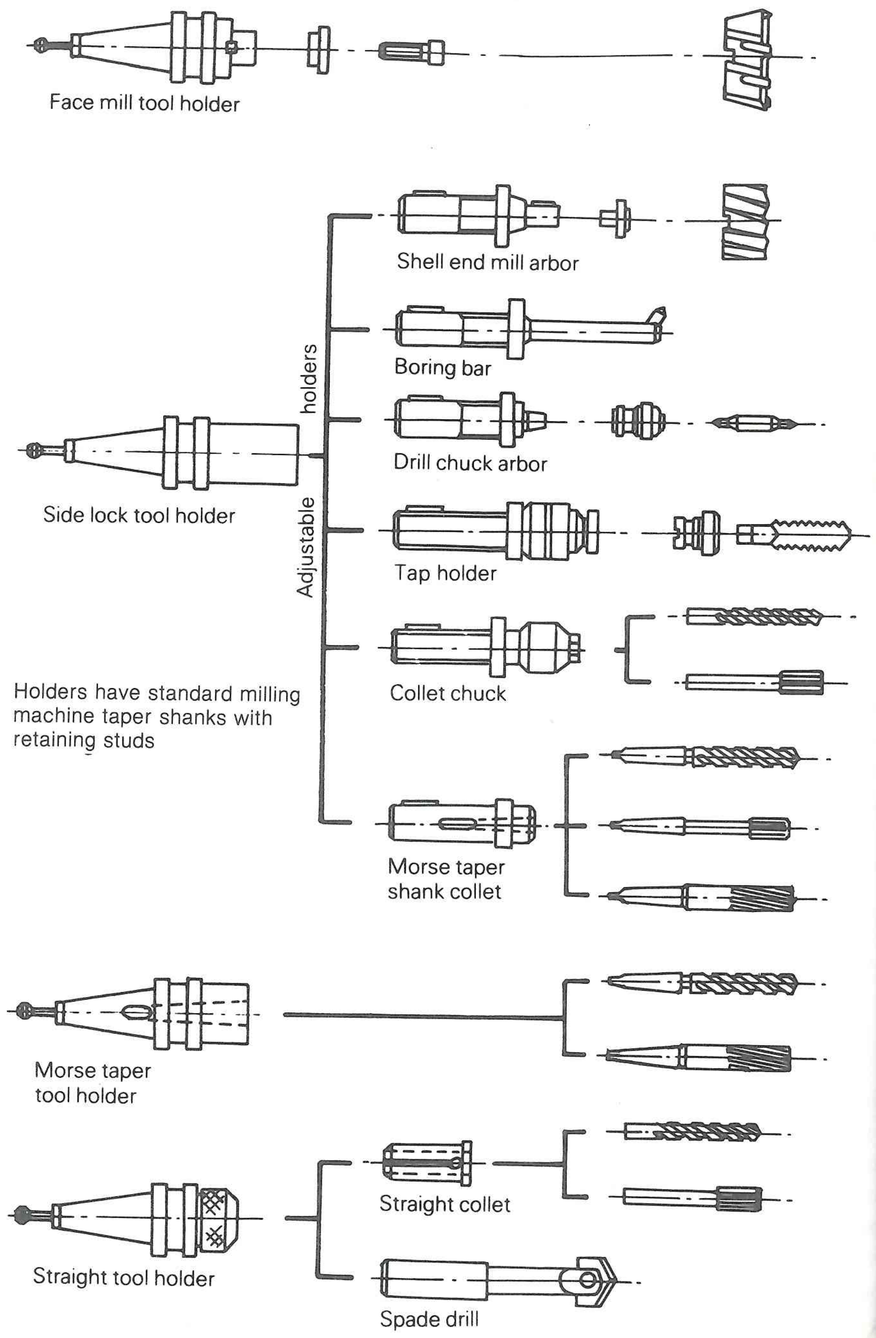

Figure 3.10 *Tooling system for a machining center.*

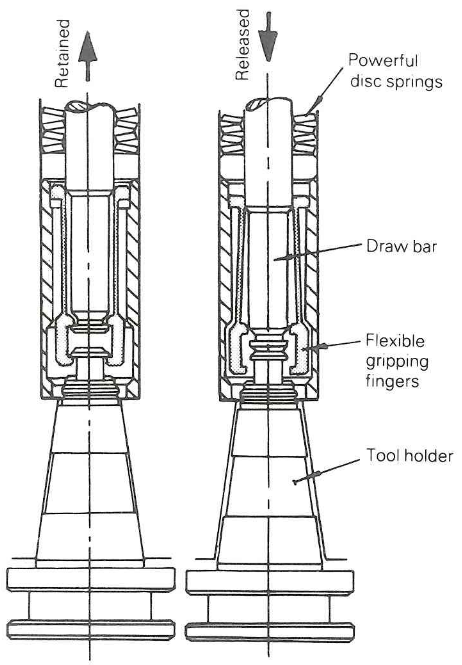

Figure 3.11 *Hydraulic–mechanical draw bar assembly used on machining centers.*

INDEXABLE TURRETS

The turret is the part of some machines in which the cutting tools are located. They are automatically indexable, that is, they can be programmed to rotate to a new position so that a different tool can be presented to the work. Indexable turrets are used on the majority of turning centers and on some milling/drilling machines.

There are a number of turret configurations currently available on turning centers. Several different types appear in the illustrations used throughout this book. The number of tools that can be accommodated varies with machine type, but eight or ten tool positions are usually sufficient to satisfy most machining requirements, and in many cases a standard setup consisting of a range of external and internal turning tools is advised.

There are some machines in which the turret is removable and, if two turrets are available, the spare one can be loaded with tools for a particular job before they are needed and then the turret is attached to the machine when required, a technique that reduces the machine down time considerably.

A variation of the rotating turret is the indexable slide on which the tools are mounted. The manufacturers of this particular arrangement claim that linear

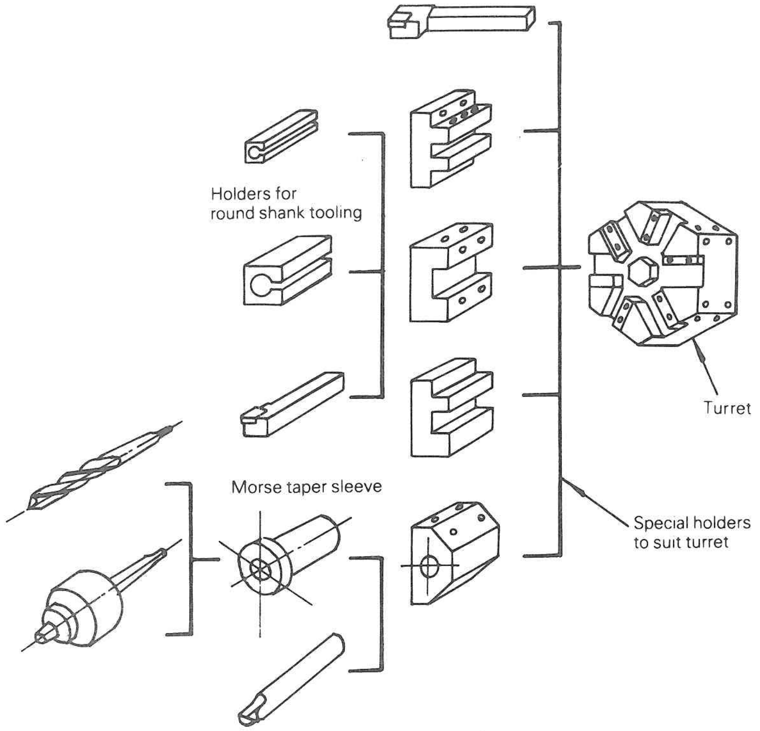

Figure 3.12 *Tooling system for turning center.*

tool indexing is much more rapid than rotary indexing. An optional extra available is a subbase plate to which the tools may be attached away from the machine. As with the removable turret referred to, this base plate is interchangeable and so a spare one can be loaded with tools in advance and then quickly attached to the machine when required.

Turrets generally fitted to milling/drilling machines are somewhat different from those fitted to turning centers, because each tooling position is in fact a spindle that has to rotate at a predetermined speed. Only the tool in the machining position will rotate, the others remaining stationary. A turret of this type, with ten tooling positions, is shown in Figure 3.13. (The concept of individually rotating tool holders has been extended more recently to turning centers. See Chapter 2.)

TOOL MAGAZINES

A tool magazine is an indexable storage facility used on machining centers to store tools not in use. The most common types of magazines are the rotary drum type illustrated in Figures 2.1a and 2.1b, the turret type in Figure 3.13, and the chain type illustrated in Figure 3.14. When a tool is called into use, the magazine will index, on most machines by the shortest route, to bring the tool to a position where it is accessible to a mechanical handling device. When the tool is no longer required, it is returned to its allotted position in the magazine prior to the magazine indexing to the next tool called.

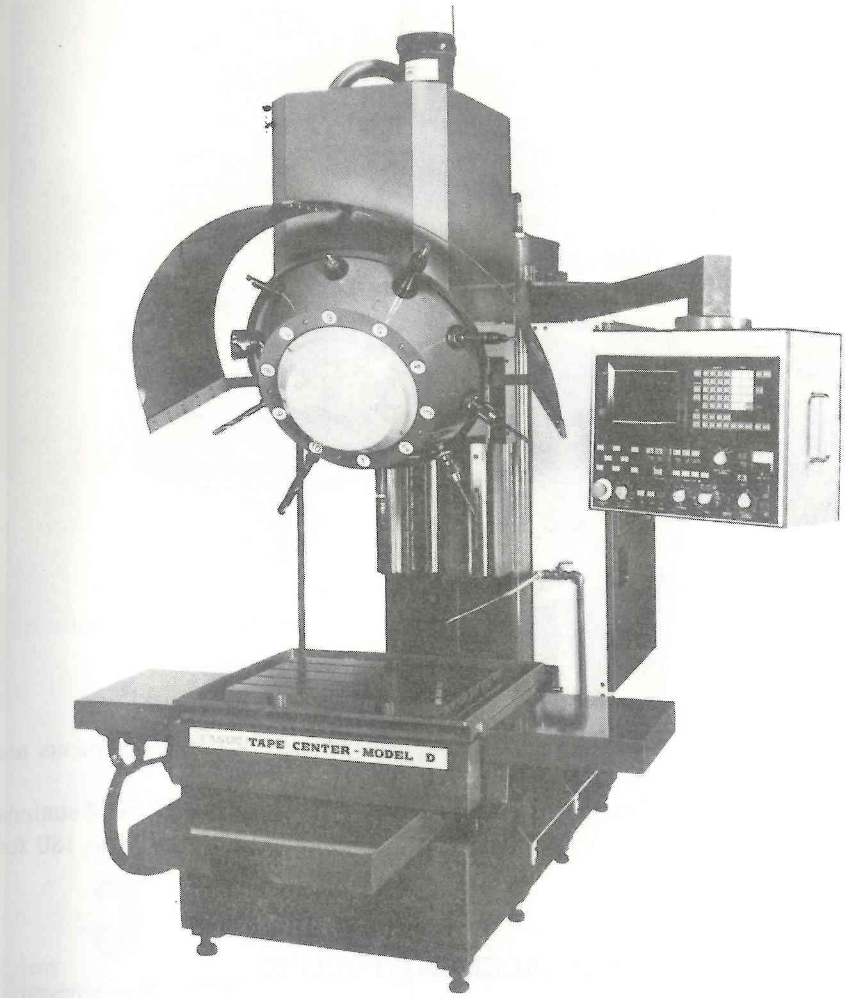

Figure 3.13 *Milling/drilling center with indexable turret.*

The position of the tool magazine in relation to the spindle varies from one machine to another. There are also variations in the design of the tool-handling

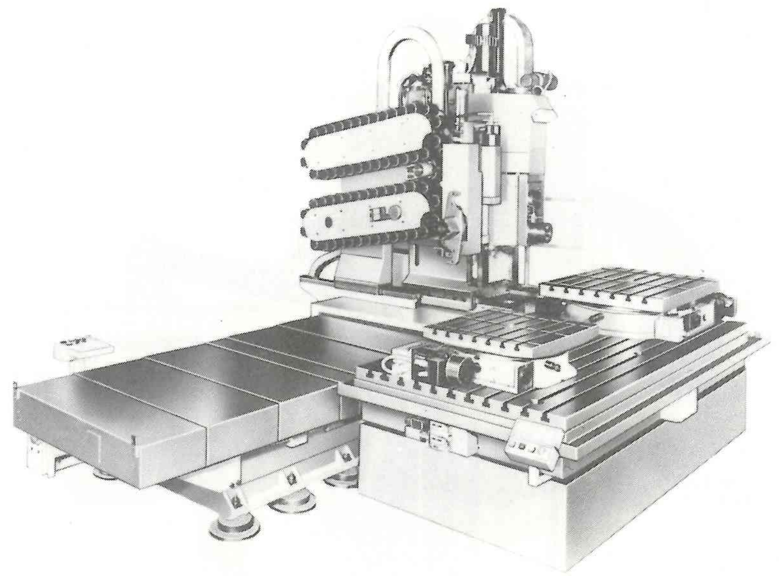

Figure 3.14 *Horizontal machining center with chain-type tooling magazines.*

devices. The two features are, of course, interrelated. Two arrangements are shown in Figure 3.15.

The capacity of magazines is another variable feature, with 12 to 24 stations being typical numbers for the rotary drum magazines and from 24 to 180 for the chain type.

REPLACEMENT TOOLING

From time to time, owing to wear or breakage, cutting tools have to be replaced. Such changes need to be rapid, with the minimum loss of machining time.

If the machining program is to remain valid, one of two requirements must be met:

1. The replacement tool must be dimensionally identical to the original.
2. The program must be capable of temporary modification to accommodate the tool variations.

Identical replacement tooling can be achieved by using qualified or preset tooling. Temporary program modifications are achieved by offsetting the tool from its original datum.

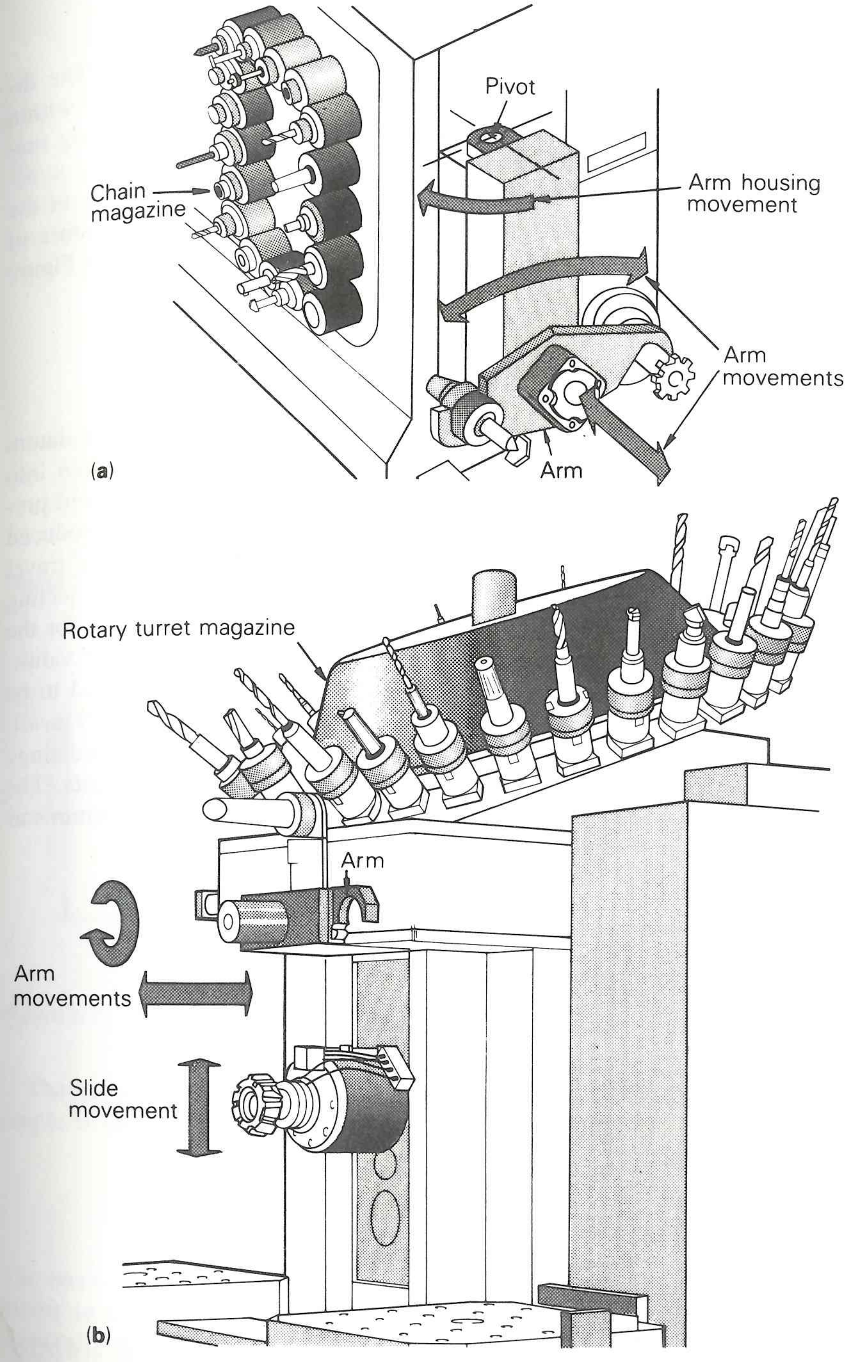

Figure 3.15 *Auto tool changers.*

QUALIFIED TOOLING

The ISO code illustrated in Figure 3.3c refers to qualified tooling. The dimensions from up to three datum faces to the tool tip can be guaranteed within ±0.08 mm (±0.003 in.). Thus if the tolerance on the dimension being machined is such that a variation in size within ±0.08 mm (±0.003 in.) is acceptable, one tool can readily be replaced by another. Precise location of the holder or cartridge in the machine turret or spindle is an essential feature of replacing tooling of this type. The qualified dimensions are illustrated in Figure 3.16.

PRESET TOOLING

Preset tooling involves setting the cutting edge of the tool in relation to a datum face to predetermined dimensions, these dimensions having been taken into consideration when the part program was written. A simple explanation of presetting is given in Figure 3.17. The through hole in the component is produced by drilling, and drill A is to be replaced by drill B. Since the depth of travel on a through hole is not precise, it would be sufficient to set the projecting length of the drill with a rule and, providing dimension *X* is the same for the replacement drill as it was for the original, the program would still be valid.

When closer tolerances are involved, the setting technique will need to be more precise. A wide range of specialized equipment is commercially available, the basic requirements of such equipment being a dummy tool locating/holding device with datum faces and appropriate measuring instruments. The tip of the tool is then set to predetermined dimensions in relation to datums as illustrated in Figure 3.18.

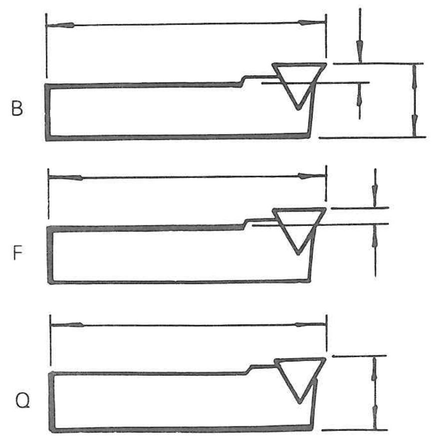

Figure 3.16 *Qualified tooling. Dimensions indicated guaranteed to within ±0.08 mm (0.003 in.).*

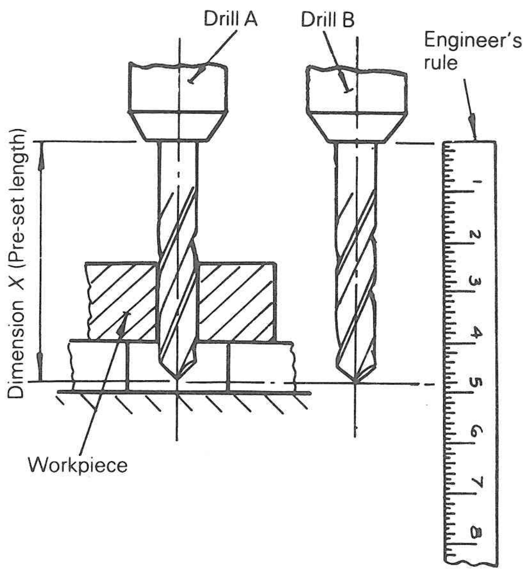

Figure 3.17 *Simple presetting of tool length.*

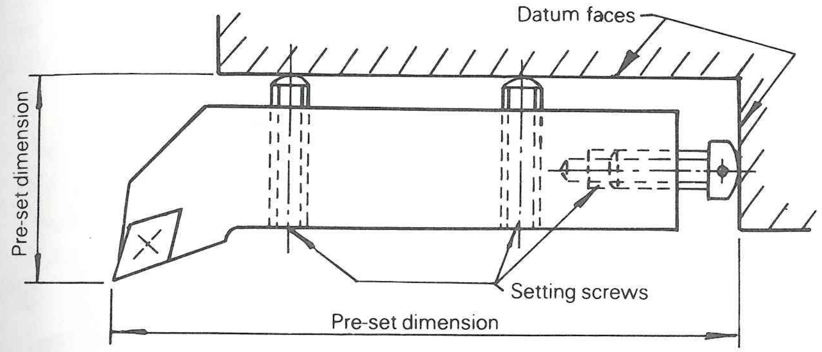

Figure 3.18 *Principle of presetting a tool holder.*

The more elaborate tool-setting equipment uses optical projection. An example is shown in Figure 3.19.

CUTTER COMPENSATION

The basis of computer numerical control is programming machine slide movements to occur over a stated distance in relation to a predetermined datum. Generally there is one datum for each axis of movement. However, most machining operations involve the use of more than one tool, varying in length or

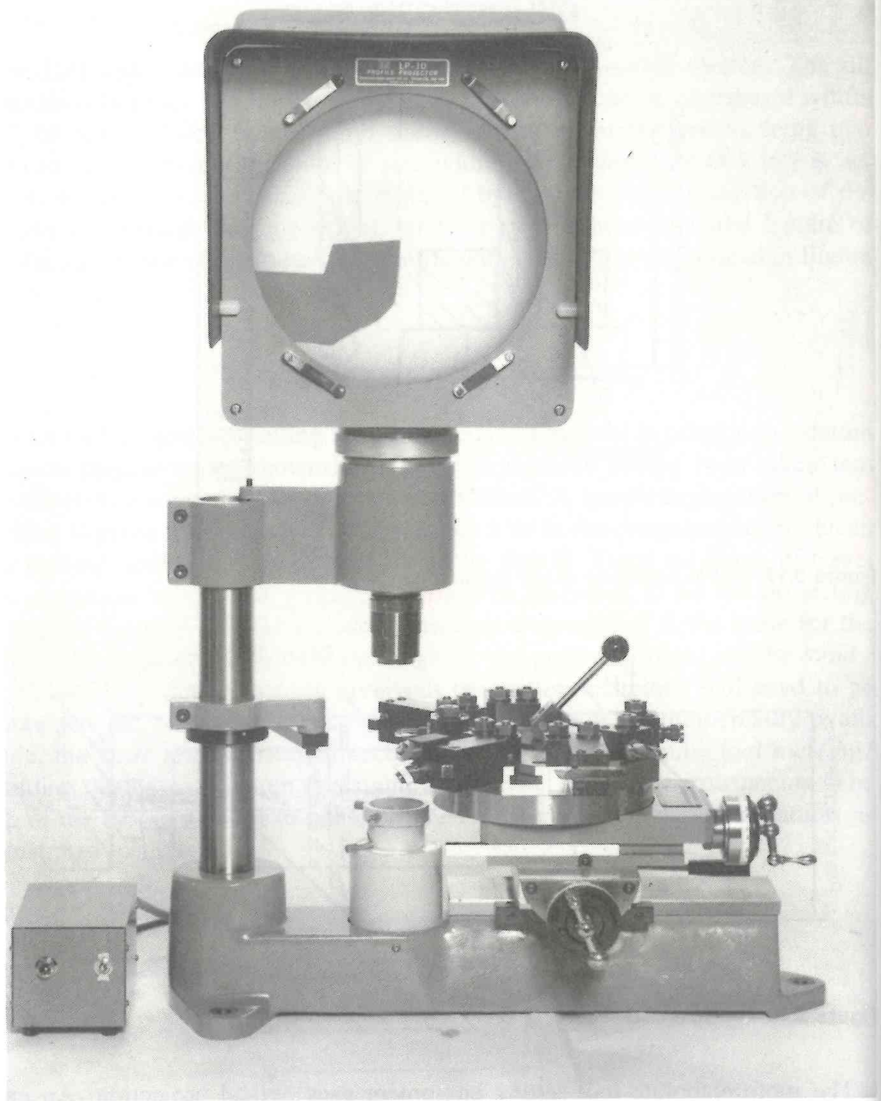

Figure 3.19 *Presetting tooling on a replacement turret using optical projection.*

diameter, which means that if the cutting edge of one tool is set to the datum to which slide movements are to be related, tools that have dimensional variations from the set tool will not start their movements from the same datum. Some compensation in slide movement is necessary to accommodate the dimensional variations of the tools. This compensation is referred to as tool offset and the offset facility is available only on computerized numerically controlled machines. Once the offset has been established, the slide movement is automatically adjusted as required during the program run.

An offset is therefore a dimensional value defining the position of the cutting edge, or edges, of a tool in relation to a given datum.

Tool Length Offsets

Consider the component shown in Figure 3.20a. The programmer has decided that the *Z* datum clearance plane will be 0.1 in. (2 mm in Figure 3.20b) above the top face of the work. All tool movement in the *Z* axis will be in relation to that datum. The machine setter or operator will establish the datum either by "touching on" to the work surface and moving away 0.1 in. (2 mm in Figure 3.20b) or by touching on to a suitable 0.1 in. (2 mm in Figure 3.20b) thick setting block, and then setting the *Z* axis readout to zero.

Now consider the tooling shown in Figure 3.20b and assume the tool T01 has been set as described above. This is now the master tool. However, the machining that is required also involves using tools T02 and T03 and the position of their cutting edges in the *Z* axis does not correspond to that of tool T01. Tool T02 is too short and tool T03 is too long. Any movements in relation to the *Z* zero axis involving these tools must take into account their starting position.

The tool setter or machine operator must therefore establish the length and direction of movement which is necessary to bring the end of each tool to the

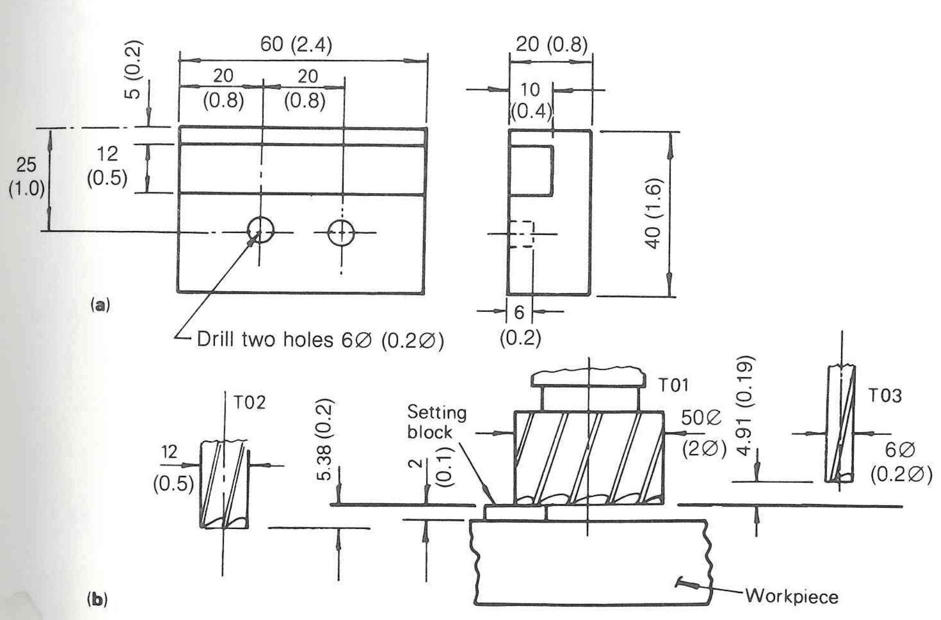

Figure 3.20 (a) *Component detail and* (b) *tool length offsets for the milling/drilling operation. (Inch units are given in parentheses.)*

zero position. This can be done by touching each tool on to the setting block and noting on the digital readout its variation from zero. Tool T02 will require a movement in the Z axis of 0.2 in. (5.38 mm) and tool T03 a movement of −0.19 in. (−4.91 mm). These dimensions are the tool length offsets.

Having established the offsets, the operator records them either by setting a series of numbered thumb-wheel switches or, as is the case with most modern control units, by entering them via the control panel key pad into an offset file or page, which can be displayed on the controller visual display screen. The method of entering offsets and the display format vary according to the control unit. The entry for the offsets relating to the tooling in Figure 3.20 could appear as shown in Figure 3.21.

With the tool length offsets being established at the machine, the part programmer is now able to ignore the variations in tool length and write the program on the assumption that all tools are starting their movements from the Z axis zero datum.

(a)

T	**Length**	**Diameter**
1	0.0000	2.0000
2	−0.2000	0.5000
3	0.1900	0.2000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	0.0000	0.0000
10	0.0000	0.0000
11	0.0000	0.0000
12	0.0000	0.0000
13	0.0000	0.0000
14	0.0000	0.0000

(b)

T	**Length**	**Diameter**
1	0.0000	50.0000
2	−5.3800	12.0000
3	4.9100	6.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	0.0000	0.0000
10	0.0000	0.0000
11	0.0000	0.0000
12	0.0000	0.0000
13	0.0000	0.0000
14	0.0000	0.0000

Figure 3.21 (a) *Inch and* (b) *metric tool offset file for milling.*

Tool length offsets are not confined to milling. They are also applicable to turning, but in this case two offset lengths are involved, one in the *X* axis and the other in the *Z* axis. The set of tools with varying lengths shown in Figure 3.22 illustrates the situation, while Figure 3.23 shows how the necessary offsets would be entered in an offset file.

Tool Radius Offsets

Just as cutting tools vary in length, they may also vary in diameter or, in the case of turning tools, in the radius of the tool tip.

Consider the profile shown in Figure 3.24. This profile could be machined by a cutter of, say, 15 mm (0.6 in.) diameter or 30 mm (1.2 in.) diameter and the path of each cutter will vary as indicated. Similarly, the profile of the component shown in Figure 3.25 could be turned using a tool with a tip radius of 1 or 2 mm (0.04 or 0.08 in.) and again the cutter paths will vary.

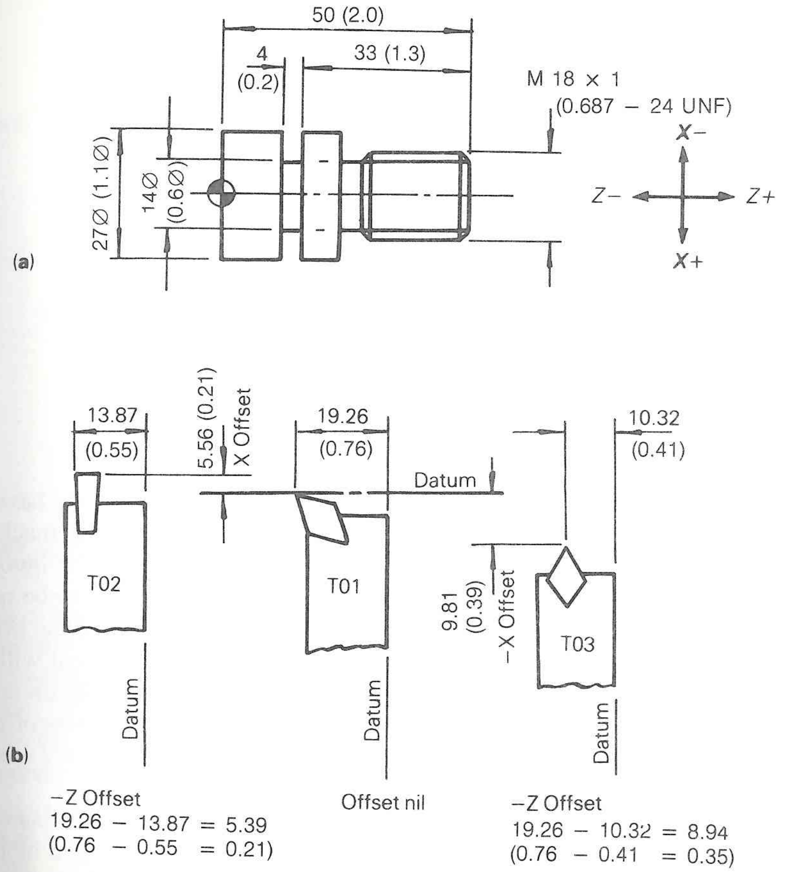

Figure 3.22 (a) *Component detail and* (b) *tool length offsets for a turning operation. (Inch units are given in parentheses.)*

(a)

T	*X*	*Z*	**Radius**
1	0.0000	0.0000	0.0800
2	0.2100	−0.2100	0.0000
3	0.3900	−0.3500	0.0600
4	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000
9	0.0000	0.0000	0.0000
10	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000
14	0.0000	0.0000	0.0000

(b)

T	*X*	*Z*	**Radius**
1	0.0000	0.0000	2.0000
2	5.5600	−5.3900	0.0000
3	−9.8100	−8.9400	1.5000
4	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000
9	0.0000	0.0000	0.0000
10	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000
14	0.0000	0.0000	0.0000

Figure 3.23 (a) *Inch and* (b) *metric tool offset file for turning.*

Without a cutter radius compensation facility the programmer would have to state the precise size of the cutting tools to be used and program the machine slide movements accordingly. With the facility the cutter size can be ignored and the work profile programmed. The exact size of the cutting tool to be used for machining is entered by the operator into the offset file and when the offset is called into the program, automatic compensation in slide movement will be made. Radius compensation also would allow the programmer to program nominal sized cutters and compensate for tool diameter variations or effects of machining cutter deflections. This type of programming may be necessary owing to limits on the amount of compensation available.

For milling machines the cutter size is entered as a diameter, in the example shown in Figure 3.21, and the machine slide movement is compensated by half of the dimensional entry. Note, depending on the control, the information could be entered as a radius with full amount of compensation occurring. For turning

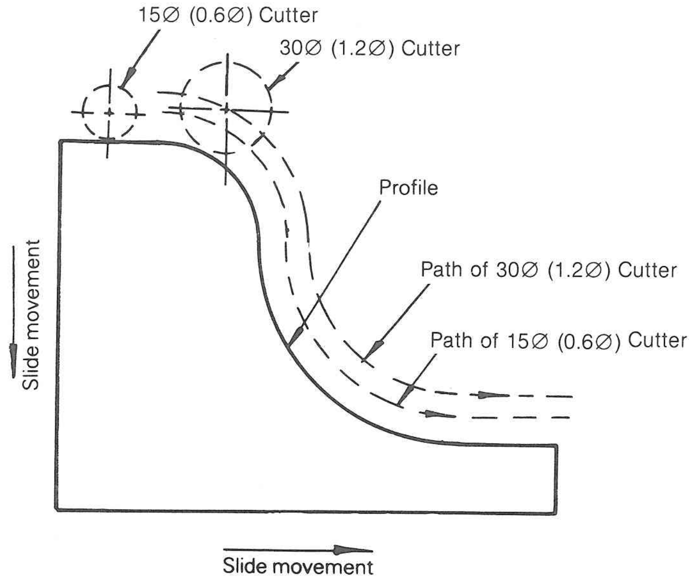

Figure 3.24 *Cutter radius offset for milling operation. (Inch units are given in parentheses.)*

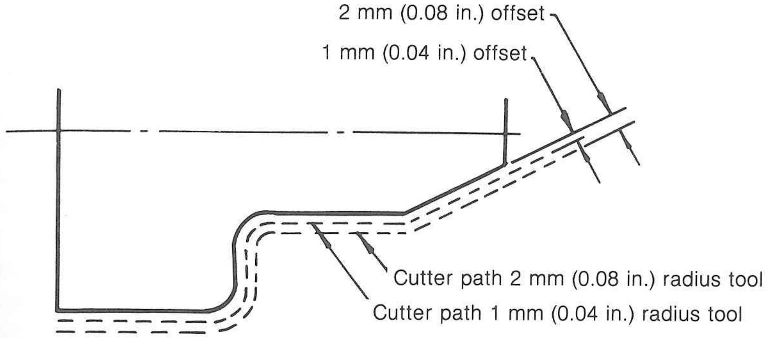

Figure 3.25 *Cutter radius offset for turning operation. (Inch units are given in parentheses.)*

centers the offset will be entered as a radius alongside the tool length offsets, as shown in Figure 3.23.

Cutter radius compensation can be to the right or left of a profile. To determine which is applicable the programmer should imagine a position above the tool facing the direction in which cutting is taking place. Thus cutter radius compensation to machine the profile shown in Figure 3.24 would be to the left. Compensation direction will be determined by a special program code discussed in the programming area.

Tool offsets can be entered, modified or erased by the machine operator at will and so it is possible to use the facility to:

(a) accommodate replacement tooling which varies dimensionally from the original;
(b) make variations to the component size;
(c) initiate a series of cuts, say roughing and finishing, using the same dimensional program data.

While offsets have a direct effect on the machining currently being carried out, they do not affect the basic part program.

Identification of Cutter Offsets

Reference again to Figures 3.21 and 3.23 will show that the offsets are numbered. In a similar way tooling used in any part program is given a numerical identity. The two, tools and offsets, have to be related to each other when the part program is being made. The number of tool stations on any one machine is limited, perhaps 12 to 16 on a turning center to rather more on machining centers equipped with magazines. The number of offsets available will be greater than the number of tools available so that any tool can be used with any offset. Thus if the tools are numbered T01, T02, T03, T04, and so on, and the offsets are numbered 01 to 32, the programmer may call for tool number one to be used with offset number one. The data entry in the part program could read T0101, sometimes special codes like H01 may call the offset active. It follows that, since there are more offsets available than tools, the program could well call for the same tool to be used elsewhere with yet another offset, say T0106. It is imperative that the programmer's intentions are clearly relayed to the shop floor. (See Chapter 8.)

TOOL CONTROL

The efficient use of expensive computer numerically controlled machining facilities requires a very methodical approach to the provision of tooling. It is essential that the tooling, both original and replacement, available at the machine correspond to the tooling required by the part program. Close cooperation between personnel concerned with programming, tool preparation, and machining must be maintained.

Efficient tool control should provide for the following functions:

(a) reconditioning, including regrinding when appropriate, replacing damaged or worn inserts, etc.;
(b) preparation, including sizing, presetting, identifying, etc.;
(c) storage until required for use;
(d) transportation;
(e) storage alongside the machine.

The concept is illustrated diagrammatically in Figure 3.26.

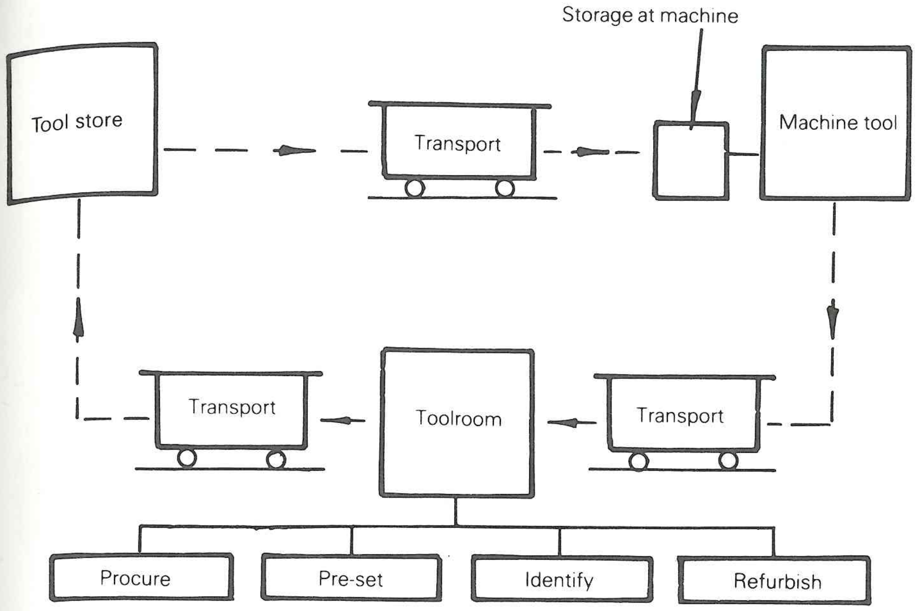

Figure 3.26 *Tool control system.*

Tools that can be reconditioned by grinding require skilled attention. Cutting efficiency over long periods of machining at very high rates of metal removal demands exact tool geometry. The less than precise methods often applied to tooling used on conventional machines are not acceptable for computer numerically controlled machining.

The accuracy demanded and the nature of the equipment used when presetting or establishing the precise size of tools call for skilled personnel working in clean conditions.

As tooling is prepared it must immediately be marked to facilitate identification, which can be done in a number of ways. Identification will of course correspond to the tool identity allocated by the part programmer and the tool preparation will be based on instructions he or she has prepared.

The storage of tooling not immediately needed requires the use of heavy-duty steel racks in which the tools are identified as to future machine magazine location.

Stored tooling may be for a specific job or it may be for general use. Either way, the tooling available should be fully documented regarding its dimensional features, application, etc. It is also helpful if the available tooling is listed in a manner that provides a ready reference facility for part programmers, machine setters, and others associated with the practicalities of the production process. The tooling list itself is often referred to as the "tool library."

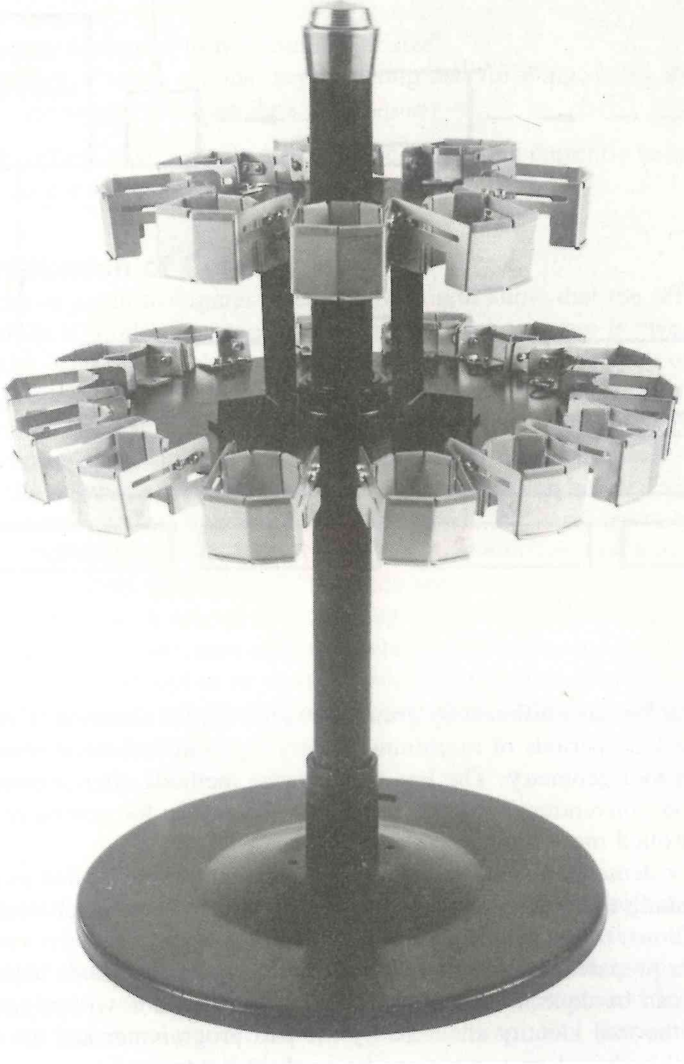

Figure 3.27 *Tool storage wheel.*

Transport of sets of tooling about the plant will require suitable carts. In some cases, to reduce handling, such carts are used for storage at the machine. If space on the shop floor is restricted, transfer to a stand may be more appropriate. One example of such a stand is referred to as a "tool wheel," since it rotates to facilitate access to each tool; this is shown in Figure 3.27.

QUESTIONS

1 When are high-speed steel-cutting tools likely to be used in CNC machining?

2 When are solid carbide tools, as opposed to tips, likely to be used in CNC machining?

3 Why are solid carbide tools not widely used?

4 State three advantages of using indexable inserts.

5 State two methods used to control chips when using indexable inserts.

6 What is the significance of the letters P, M, and K in relation to the classification of carbide grades?

7 How are carbide inserts classified?

8 What is the difference between a holder and a cartridge?

9 Make an outline sketch of a tool suitable for use on a turning center and explain the meaning of the term "qualified."

10 How many methods of locating and clamping inserts in holders and cartridges are included in the ISO code?

11 The following is the specification for a tool holder: M P D F L 40 40 D 24 F. What is the meaning of each letter and number?

12 Explain the difference between a tool turret and a tool magazine.

13 If a machining program is to remain valid when tool replacement is carried out, one of two conditions must be met. What are those conditions?

14 Explain with the aid of a simple diagram what is meant by preset tooling.

15 What is a tool length offset and when is it likely to be necessary?

16 What is cutter radius compensation, and how does it simplify programming?

17 How is it possible to determine whether cutter compensation is to the right or left of a machined profile?

18 List the functions of an efficient tool control system.

19 What is the function of a tool library?

20 What is a tool wheel and when is it used?

4

WORK HOLDING AND LOADING FOR COMPUTER NUMERICALLY CONTROLLED MACHINING

THE APPLICATION OF COMMON WORK-HOLDING DEVICES

The basic requirements of any work-holding device are that it must

(a) securely hold the work;
(b) provide positive location;
(c) be quick and easy to operate.

There are a variety of devices in general use that have been tried and tested in conventional machining situations. Chucks, collets, and vices are obvious examples, and these are also used on computer numerically controlled machines. Work-holding devices such as these may be mechanical, pneumatic, or hydraulic in operation. Mechanically operated devices usually involve manual intervention and, although it is not uncommon to see workpieces being loaded and clamped in this way, it is not a practice that is in keeping with automatic machining processes. Because of this, hydraulically or pneumatically operated devices, especially the latter, are favored. The operation of hydraulic or pneumatic clamping is easily controlled electronically via the machine control unit and also provides for rapid operation and uniform clamping pressure. The application of a power-operated collet is shown in Figure 4.1 and a power-operated chuck is shown in Figure 4.2.

Conventional devices such as these are more suited to machining where the component or the stock material is uniform in shape, that is, rectangular, round, hexagonal, etc. Components of irregular shape, such as castings, can be accommodated, as with conventional machining, on specially built fixtures sometimes incorporating pneumatic or hydraulic clamping arrangements.

THE IMPORTANCE OF ACCURATE LOCATION

It is established working practice that, wherever possible, work should be positively located, that is, it should be positioned in such a way that, when the cutting forces are applied, no movement can take place.

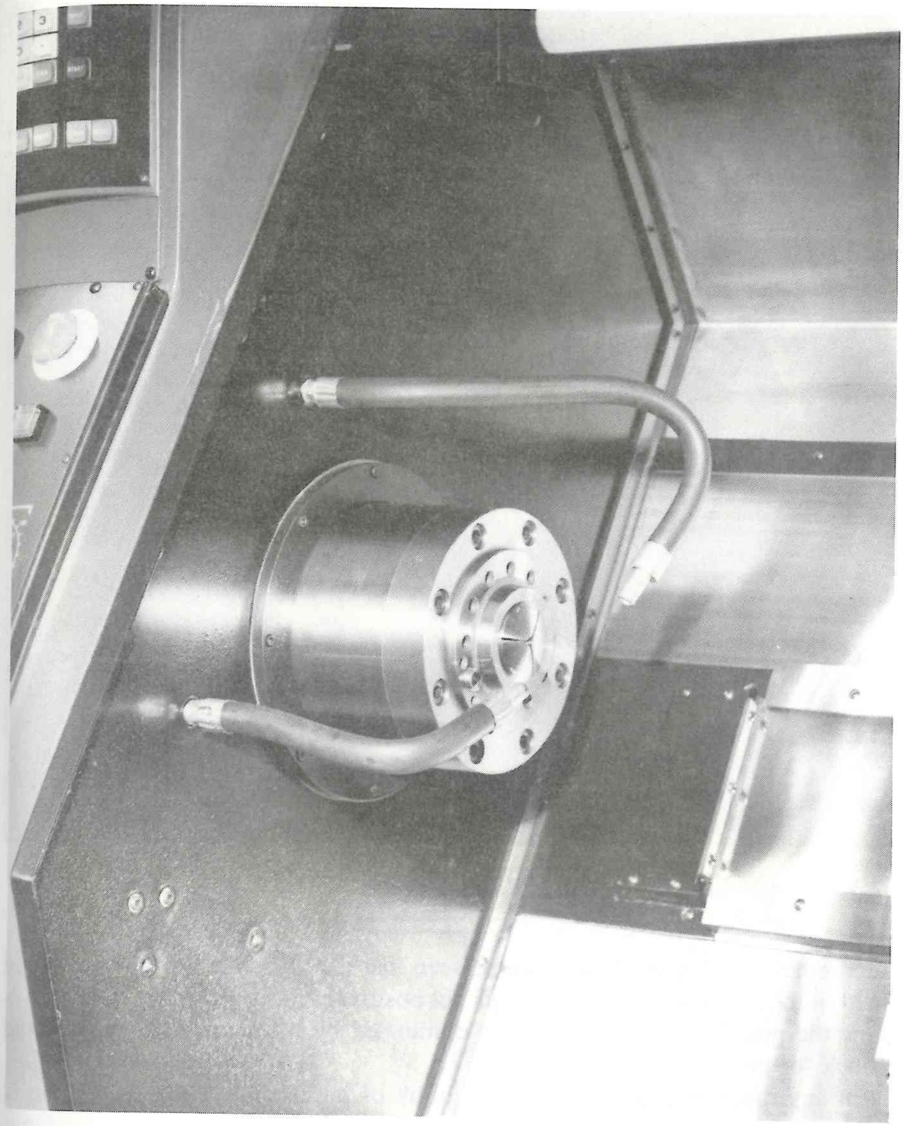

Figure 4.1 *Use of collet for work holding on a turning center.*

Figure 4.3 shows two applications of a conventional machine vice. In both cases the work is located against the fixed jaw but in Figure 4.3a the security of the workpiece depends on a frictional hold and the cutting force could result in movement of the workpiece. In Figure 4.3b no movement is possible since the fixed jaw of the vice not only locates the workpiece but also absorbs the forces resulting from the cutting action.

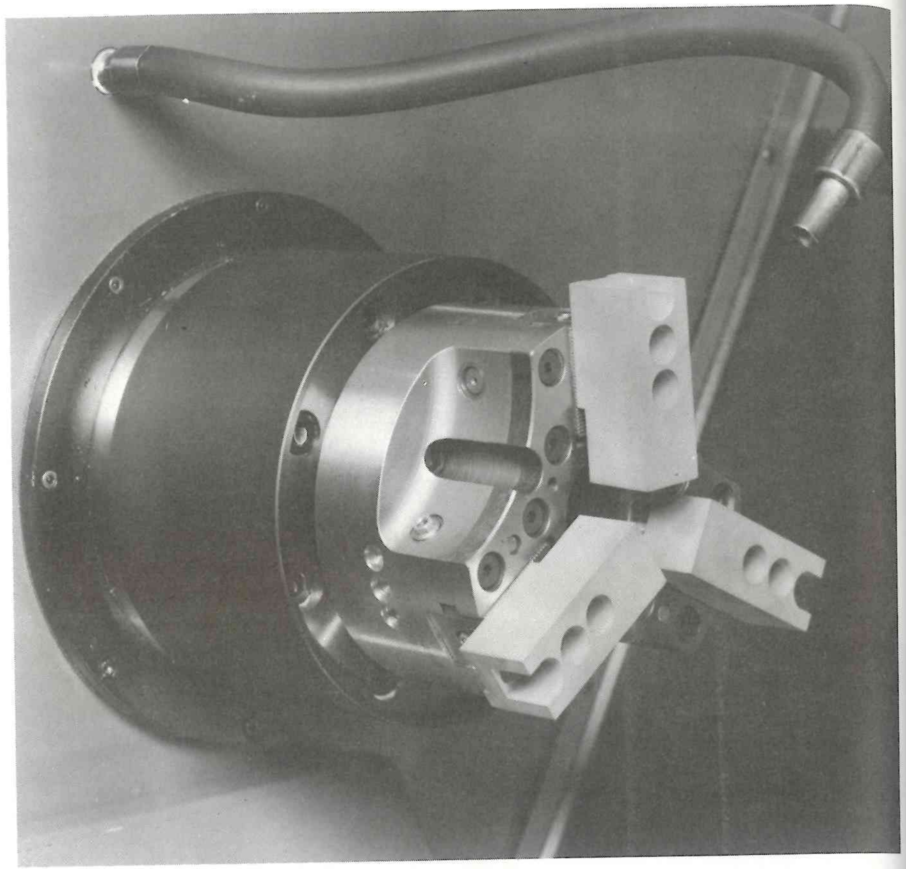

Figure 4.2 *Use of power-operated chuck on a turning center.*

Similarly, in Figure 4.4a it can be seen that it is possible for the workpiece held in the chuck to move, since it is not positively located. Figure 4.4b shows how the possibility of movement is eliminated by using the back face of the chuck for positive location.

In any machining process the possibility of movement of the workpiece is unacceptable for safety reasons. In computer numerically controlled machining processes there is also the problem that movement, however slight, means a loss of dimensional accuracy, since there is generally no constant monitoring of the workpiece size as machining proceeds. Additionally, the location of the component is often directly related to the part program, since the programmer, when writing the program, will establish datums on which all numerical data controlling the machine slide movements will be based. If the component is not precisely positioned in relation to those datums, then the machining features required will not be achieved.

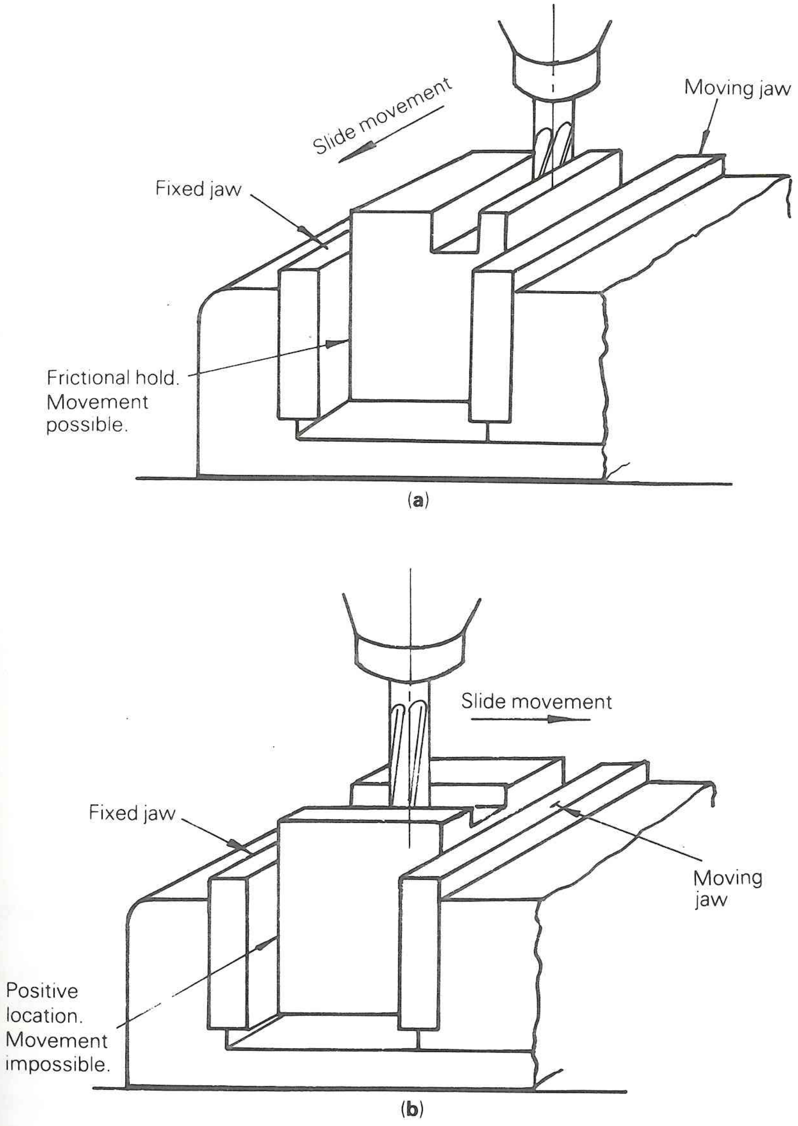

Figure 4.3 *Positive location of a milled component:* (a) *unsatisfactory and* (b) *satisfactory.*

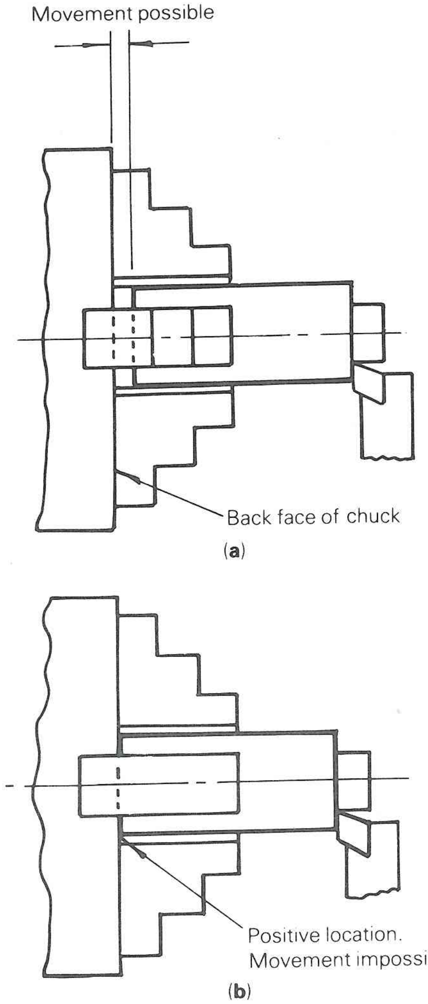

Figure 4.4 *Positive location of a turned component:* (a) *unsatisfactory and* (b) *satisfactory.*

Figure 4.5a shows a component that is to be machined on a vertical machining center and the datum in the *X* and *Y* axes that the programmer has established as a basis for the part program.

The machine setter will be informed of the position of the datum, either by written instructions or possibly by messages included as part of the program and visually displayed on the machine control unit, and he or she will be required to set the work-holding device, which in turn provides the precise location for the component, accordingly.

To illustrate the need for accurate component location, again consider Figure 4.5. Clearly a workpiece positioned as shown in (b) will not have the same

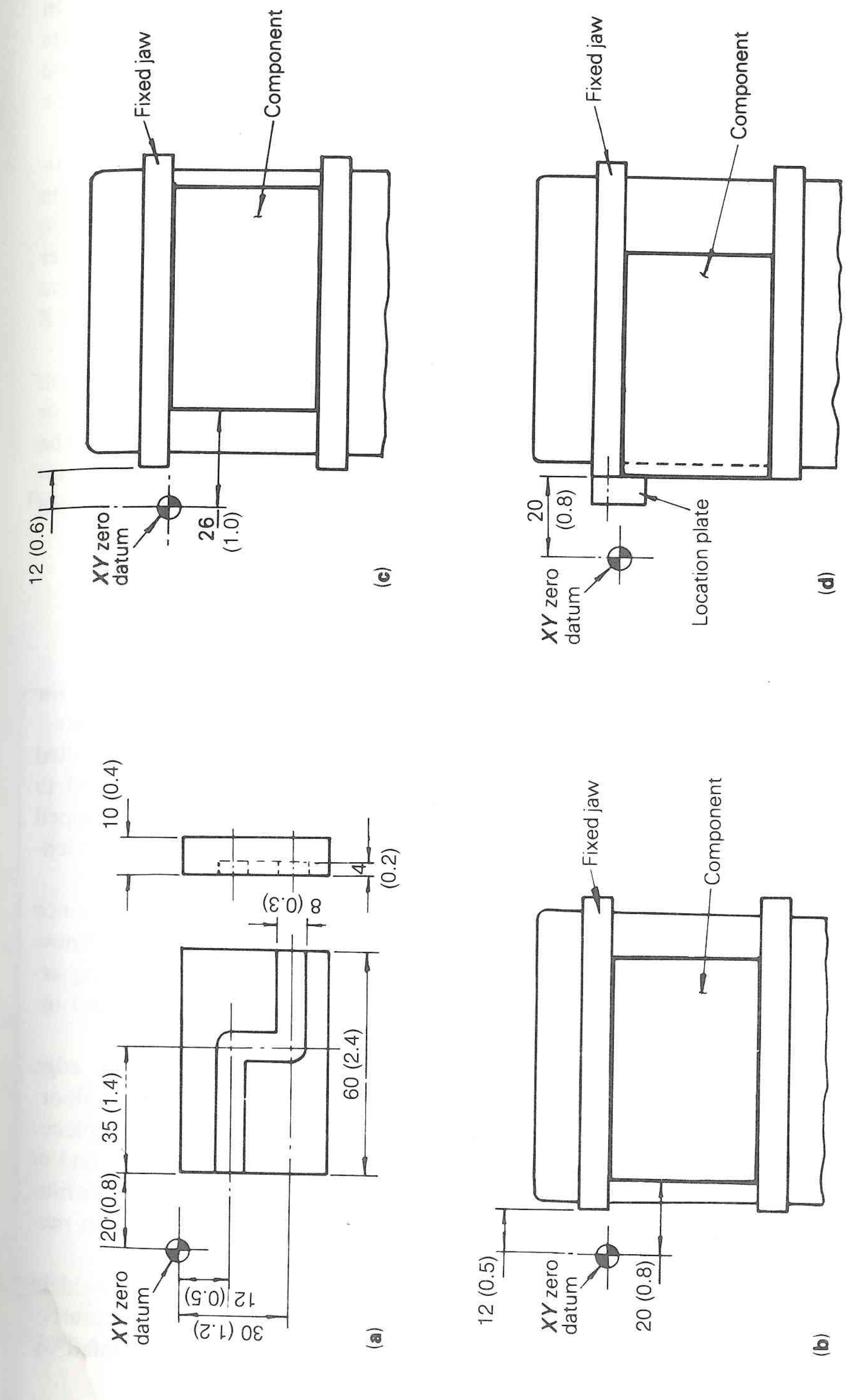

Figure 4.5 *Relationship between setting position and part program for a milled component:* (a) *component detail;* (b) *initial setting;* (c) *second setting;* (d) *setting position constant, no variation in component size. (Inch units are given in parentheses.)*

dimensional features in the X axis as the component position shown in (c). In this particular case the logical thing to do would be to place all components as shown in (d), thus using the end of the vice jaw as a locating position, and set the machine datum accordingly. A stop plate attached to the side of the fixed jaw is a method which can be used to ensure perfect location.

Figure 4.6 shows the use of a self-centering chuck where the back face provides the datum and location face in the Z axis and the self-centering action provides the datum and location in the X axis. The positioning of the workpiece to establish positive location in the X axis is automatic, but the machine setter will need to be informed that the work is to be located against the back face of the chuck to maintain the dimensional validity of the part program in the Z axis.

When the bar size is smaller than the machine spindle bore, accurate location may still be achieved by using a special part stop placed inside the chuck or spindle and against which the component is located prior to clamping. The internal stop is not removed before machining commences so the positive location is maintained. An alternative to using an internal stop is to use soft jaws bored to suit, with a shoulder acting as a stop.

THE USE OF GRID PLATES FOR MILLING AND DRILLING

A method of work holding and location that has gained wide acceptance for computer numerically controlled milling and drilling setups is the grid plate.

A grid plate is simply a base plate made of steel or cast iron that is drilled with a series of accurately positioned holes. These holes may be tapped to facilitate clamping, plain reamed to accommodate location dowels, or tapped and counterbored to provide for clamping and location. Each hole can be identified using the grid system illustrated in Figure 4.7.

The grid plate is attached to the machine table, often permanently, and since the part programmer can identify the exact position of any hole and will know the dimensions of any locating dowels or blocks used in the work-holding arrangement, he or she can establish datums when writing the program and instruct the machine setter accordingly.

The setting of a grid plate does not involve the use of dial indicators, edge finders, etc., and therefore is not demanding on manual skills on the shop floor. Once set, it provides for quick, simple, and accurate location of the workpiece.

It is often possible to load more than one component at each setting and at known pitches. By using the "zero shift" facility (see Chapter 6), the machining program can be repeated in a new position with a resulting saving in machine downtime.

Apart from clamping directly to the grid plate, components can be held in fixtures, vises, or a set of vises and fixtures, which themselves are accurately located and clamped in position. Complex shapes can be accommodated by

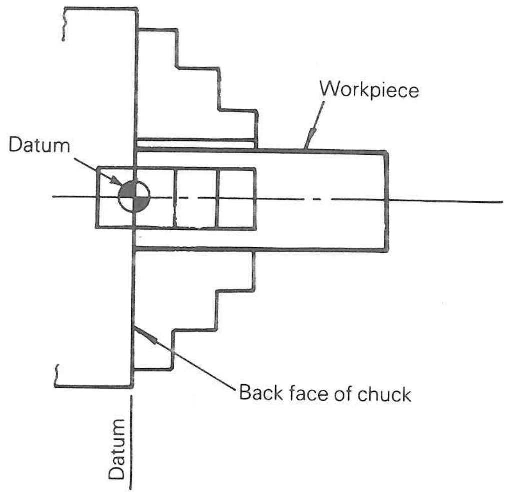

Figure 4.6 *Accurate location of a turned component providing constant datum position.*

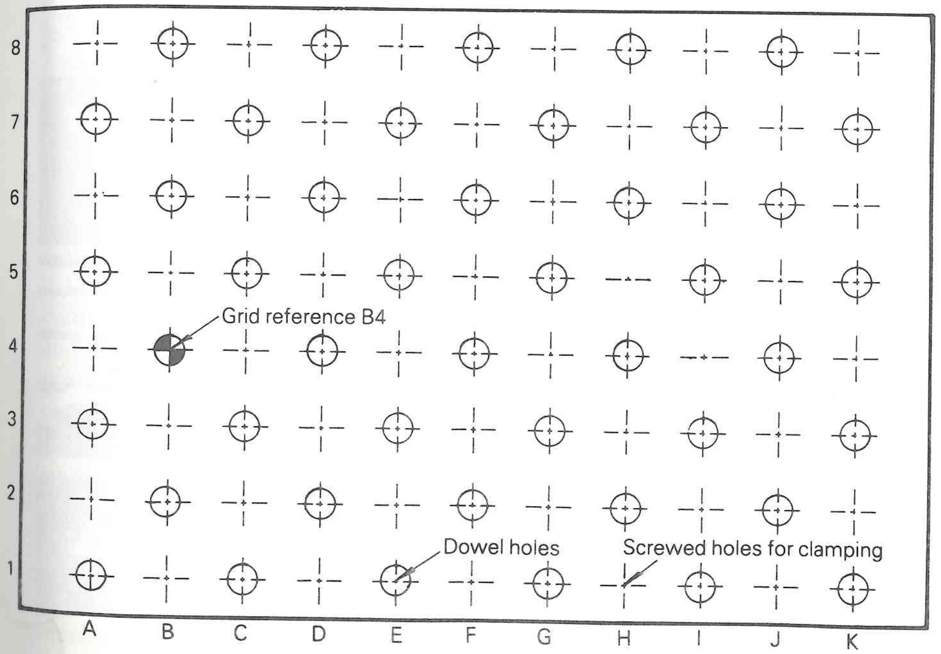

Figure 4.7 *Principle of grid plate location.*

using specially shaped locators, while fixtures can be provided with locating devices so that they may be accurately located and clamped in a known position.

Through cutting is possible by using stepped locators that raise the workpiece from the grid plate.

Examples of commercially available grid plates for both horizontal and vertical applications are shown in Figures 4.8 and 4.9.

THE USE OF ROTARY TABLES AND INDEXERS FOR MILLING AND DRILLING

Many of the conventional uses of a rotary table have become redundant with the introduction of numerical control. Radial profiles are now achieved by circular interpolation, and the positioning of holes or slots in angular relationship to each other, possibly using polar coordinates, has been reduced to nothing more complex than a simple one-block data entry in the machine program. Circular interpolation and polar coordinates are discussed in more detail in Chapter 6.

Rotary tables are still used on horizontal machines for rotating work to facilitate machining in a new position in the vertical plane. An angle of rotation of 90°, for example, permits machining on four sides of a cube, but the indexer can be used to rotate the work through much smaller angles. An angle of rotation as small as 1° or 360 circular positions are common.

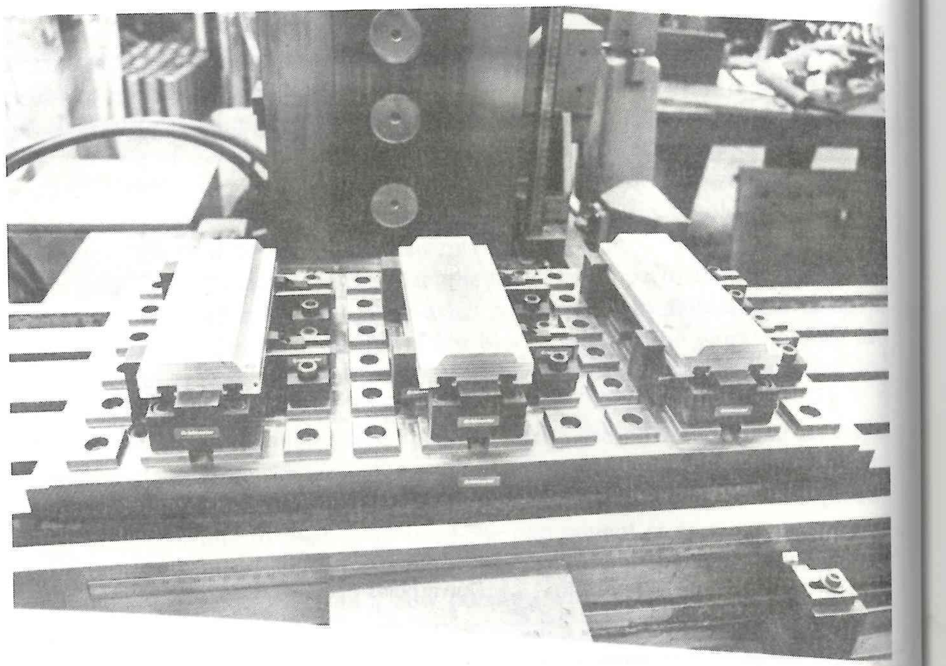

Figure 4.8 *Grid plate showing three components in position.*

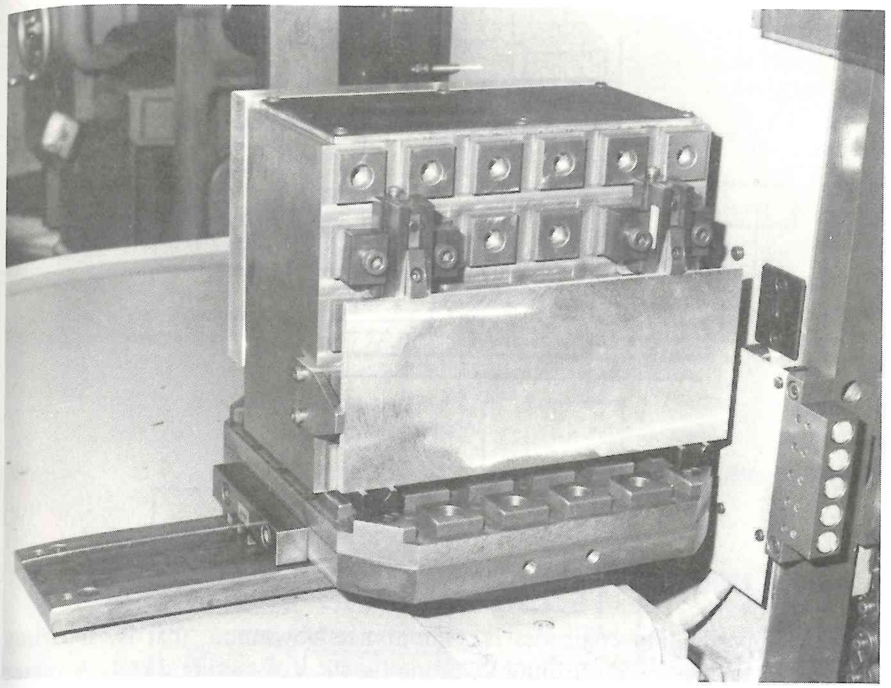

Figure 4.9 *Vertical application of a grid plate.*

Rotary tables of this type may be attached to the machine bed in the normal way or be a built-in feature of the machine table, as illustrated in Figure 4.10.

Conventional dividing heads are also redundant as far as computer numerical control is concerned. They have been replaced by indexers, fully programmable and controlled via the machining program. Simple versions allow up to 24 positions, or increments of 15°, rather like the direct indexing plate fitted to conventional dividing heads.

For more complex indexing or where continual rotation is required, for example when cutting a helix, a rather more sophisticated version is needed, with up to 360,000 positions and feedrate controls. Some of these devices are capable of rotating in two planes. (Rather confusingly, they are referred to as "tilting rotary tables" by one manufacturer.) When the two-axis version is used in conjunction with three axes of table movement, thus providing a five-axis machining capability, it permits the production of components so complex that they may well be incapable of being produced by conventional means.

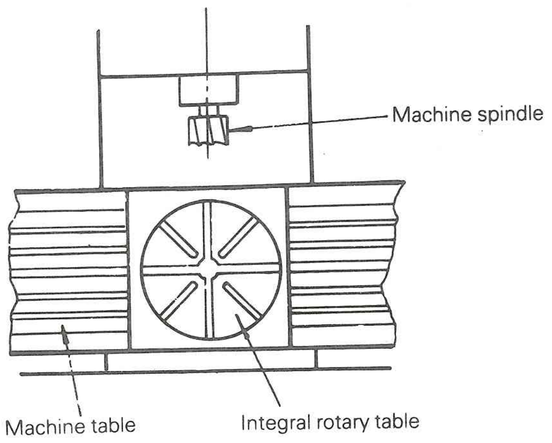

Figure 4.10 *Integral rotary table.*

THE USE OF PALLETS FOR MILLING AND DRILLING

An aim of production engineers is to minimize downtime, that is, the time when the machine is not fulfilling its prime function of cutting metal. A major source of downtime is work loading and unloading. The use of preloaded pallets considerably improves the situation.

A pallet is simply a table, which, like the grid plate, is provided with a series of holes or slots to facilitate location and clamping of the component. Pallets are fitted to the machines, shown in Figures 2.1b and 3.14, and can be shuttled in and out of the machining area.

The most simple arrangement will involve the use of just two pallets. A workpiece is located and clamped on the first pallet in a position predetermined by the part programmer and the pallet is then moved into the machining position. As machining is taking place, the second pallet is loaded. When machining of the first component is complete, the pallets are interchanged and, as the second component is being machined, the first pallet is unloaded and reloaded with another component.

Pallets can be interchanged in several ways. Two such methods, one involving a shuttle system and the other a rotary movement, are illustrated in Figures 4.11a and 4.11b. Some machining systems involve more than two pallets (see Chapter 9).

WORK SUPPORT FOR TURNING OPERATIONS

Most turned components are relatively small. The work-holding arrangements used in their production are conventional, that is, chucks and collets are used and there is no need for further work support. Because of this, a number of the smaller turning centers available do not have tailstocks. They are no longer essential for drilling, reaming, etc., as this work is carried out from the turret.

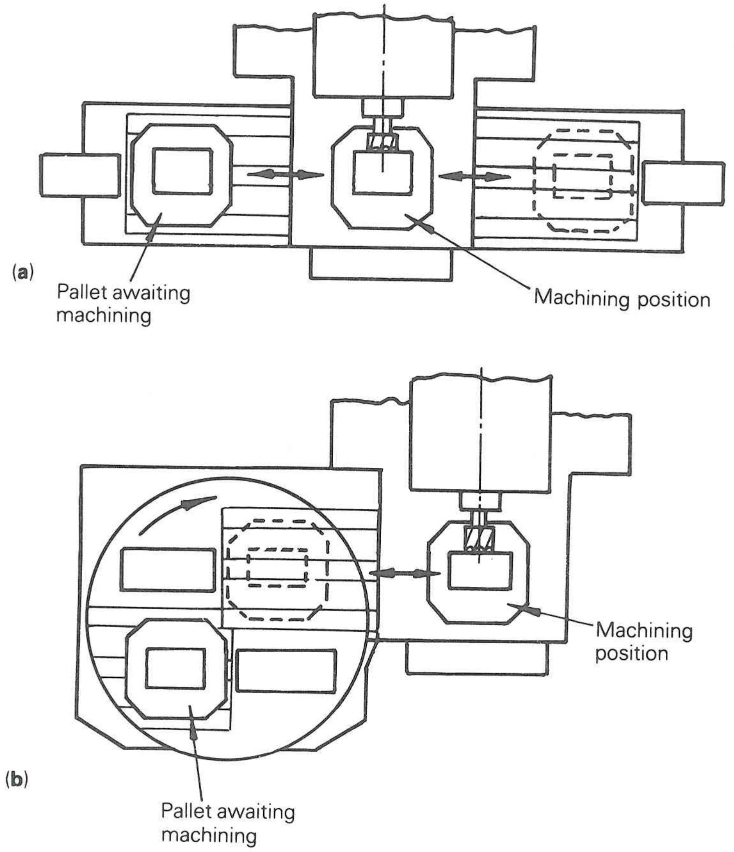

Figure 4.11 *Pallet shuttles:* (a) *linear and* (b) *rotary.*

When the capacity of the machine is such that the work overhang can be considerable, then tailstock support becomes essential. It is also necessary, of course, for turning between centers. Figure 4.12 illustrates a tailstock being used on a computer numerically controlled turning center.

On some machines the tailstock is very similar to that of a conventional center lathe. It is positioned and clamped solely by manual intervention. On others, it is partially controlled, being manually positioned and clamped on the machine bed but with a programmable hydraulic quill movement. Some machines provide for a fully programmable tailstock, that is, both its position along the bed and the quill movement, together with the necessary clamping, can be included in the part program and automatically controlled.

If a fully programmed tailstock movement is to be used, it is essential that,

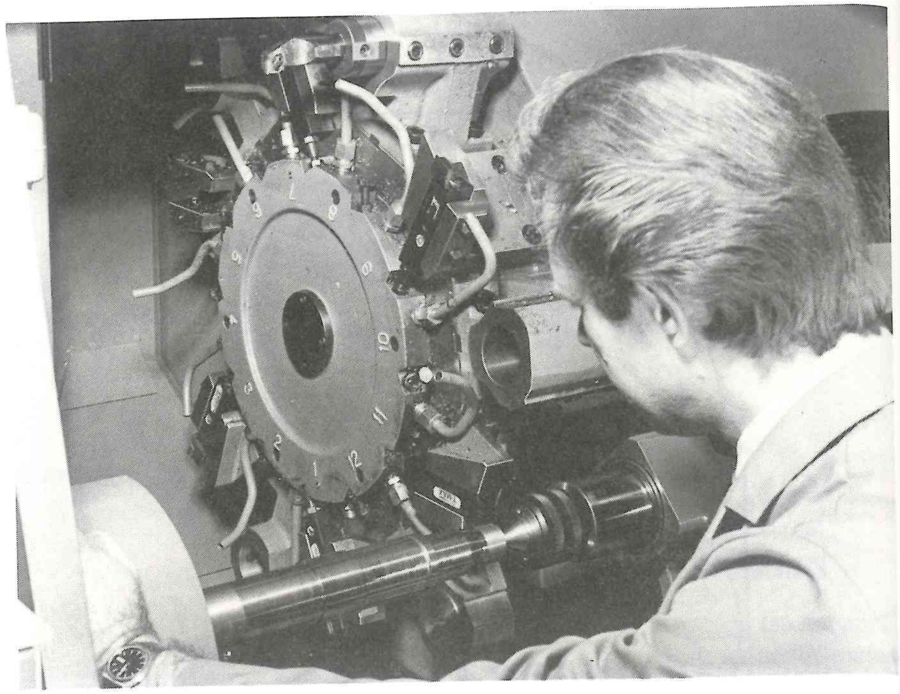

Figure 4.12 *Use of a tailstock for work support on a turning center.*

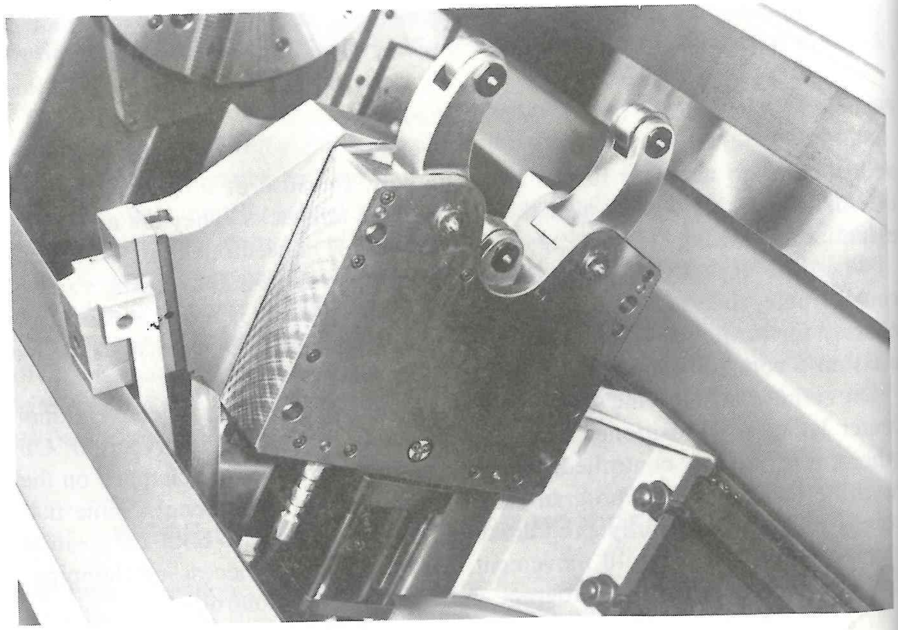

Figure 4.13 *Bar steady rest providing pressure-controlled support.*

as the quill moves forward, the workpiece is in the correct position, that is, on center in order to receive the center support. Acknowledging that this condition may be difficult to obtain, some manufacturers offer hydraulic self-centering steady rest to position the work prior to the tailstock movement being made.

Steady rests are also available to prevent the deflection of slender work, these being located on the machine bed in a manner similar to the way steady rests are used on conventional lathes. Two types of steady rests are illustrated in Figures 4.13 and 4.14.

WORK LOADING FOR TURNING OPERATIONS

Work loading into turning centers may be manual or automatic. The choice of method to be used will be affected by various factors such as component size, component shape, and quantity required.

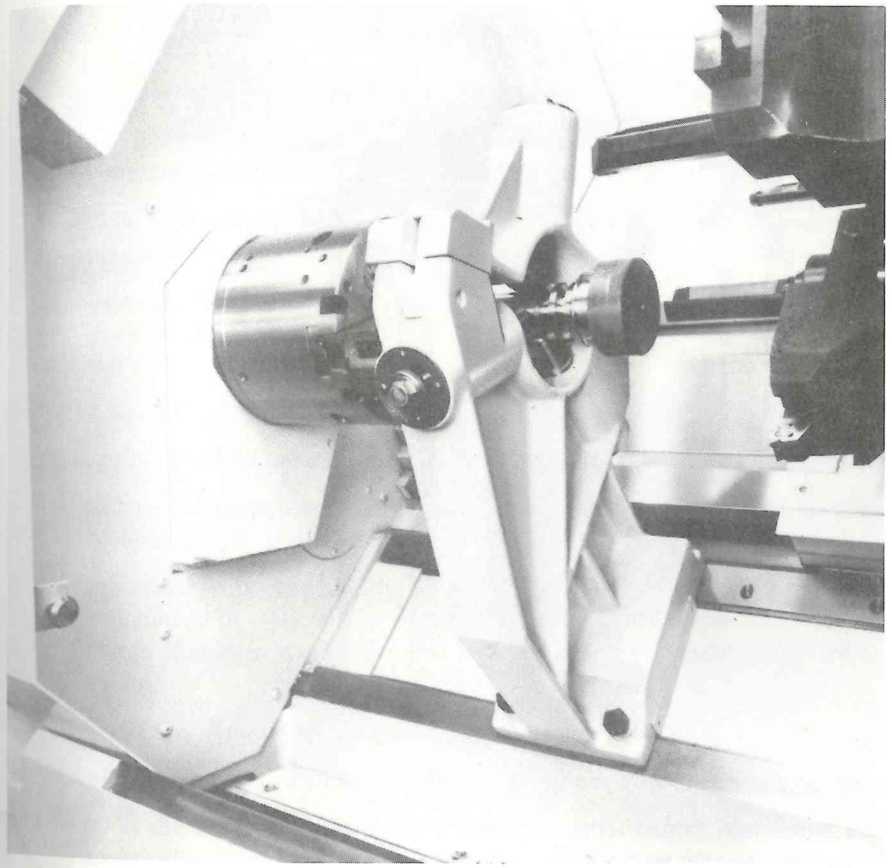

Figure 4.14 *Mechanically adjusted bar steady rest.*

Manual loading detracts from the benefits in terms of increased production rates and reduced labor costs inherent in computer numerically controlled machining. However, it is quite acceptable for small-batch production and indeed may be essential when the component shape is irregular, for example, a casting, or when nonstandard work-holding devices, such as a fixture clamped to a face plate, are being used.

When automatic loading is applicable, the cost of the necessary equipment is likely to be the determining factor in the final choice. The possibilities range from relatively inexpensive bar feeders to arrangements involving conveyors and robots.

Bar feeders have been applied to turning machines for many years. One of the disadvantages associated with earlier designs was that they were noisy in operation, the noise being created by the bar rotating in the feeder tube. Modern designs have eliminated this problem by various methods, perhaps the most successful one being where the bar is completely surrounded by oil. The bar is fed into the machine under pressure (hydraulic and pneumatic systems are available) when the work-holding device releases its grip. The bar extends to a preset stop located in the turret before the work-holding device closes again.

Figure 4.15 *Silent bar feeder. Bar is supported in oil.*

Bar feeders do not provide total automation, since they have to be reloaded manually from time to time. A modern bar feeder is shown in Figure 4.15.

Components that are too large for bar feeders to be suitable are often produced from preprepared "billets," that is, the material is supplied in short lengths, sometimes already faced to size. Material in this form, and partly machined components of similar size requiring further machining, are usually suitable for robot handling. Many machine manufacturers offer robot handling equipment as an optional extra, the robot being adaptable to various component shapes and sizes by fitting interchangeable end effectors (grippers).

QUESTIONS

1 Explain what is meant by positive location as applied to work holding.

2 Why is it especially important that components are positively located for computer numerically controlled machining operations?

3 Explain how a workpiece can be positively located in a self-centering power-operated chuck.

4 State three reasons why pneumatic or hydraulically operated work-holding devices are particularly suitable for use on computer numerically controlled machines.

5 List the advantages of the grid plate as a means of holding workpieces.

6 Describe how the positioning of a workpiece on a grid plate is identified.

7 How would components of irregular shape, such as castings or forgings, be held on a grid plate?

8 Much of the work carried out on a rotary table using conventional machines is achieved in other ways on computer numerically controlled machines. Quote examples where the facilities provided by a rotary table are still useful.

9 What is the main advantage of using preloaded pallets?

10 Describe two ways in which pallets are interchanged on a machining center.

11 Why is the accurate location of a pallet essential before machining commences?

12 Explain what is meant by a fully programmable tailstock as used on a turning center and briefly describe the alternative types of tailstock.

13 What is the main disadvantage of having manual work loading in a computer numerically controlled machining situation? Give an example of a situation where there is unlikely to be an economically viable alternative.

14 What are the advantages and disadvantages of using bar feeders for turning centers?

15 What are billets and what are the advantages in their use?

5

DATA PREPARATION AND INPUT TO MACHINE CONTROL UNITS

DATA PREPARATION

The preparation of numerical data prior to input to the machine control unit is referred to as programming. The extent of the preparation will depend on the complexity of the component. It is possible that the data necessary to produce a simple component may require nothing more than an examination of a detailed drawing followed by a direct manual entry to the control unit. On the other hand, programming very complex components may require computing facilities to determine appropriate tool paths. The vast majority of components require an approach similar to that outlined diagrammatically in Figure 5.1.

From the diagram it can be seen that the program is central to the whole process. It is compiled after taking into account a number of essential interrelated factors and then, having been compiled, it totally controls the machining process. Efficient programming requires considerable practical knowledge on the part of the programmer together with a full understanding of the control system to be employed.

The approach to programming must be methodical, and because of this it usually involves compiling a special form or listing the data on a computer screen, preferably followed by a checking process, before recording the data in a form acceptable to the machine control unit. Even at this late stage a further checking process, referred to as "program proving," is essential before a final commitment to machining is made.

DATA INPUT

Data can be entered into machine control units by the following methods:

1. Manual data input (MDI).
2. Conversational manual data input.
3. Perforated tape.
4. Magnetic tape.
5. Portable electronic data storage unit via an interfaced computer.
6. Magnetic disk via an interfaced computer.
7. Master computer (direct numerical control, DNC).

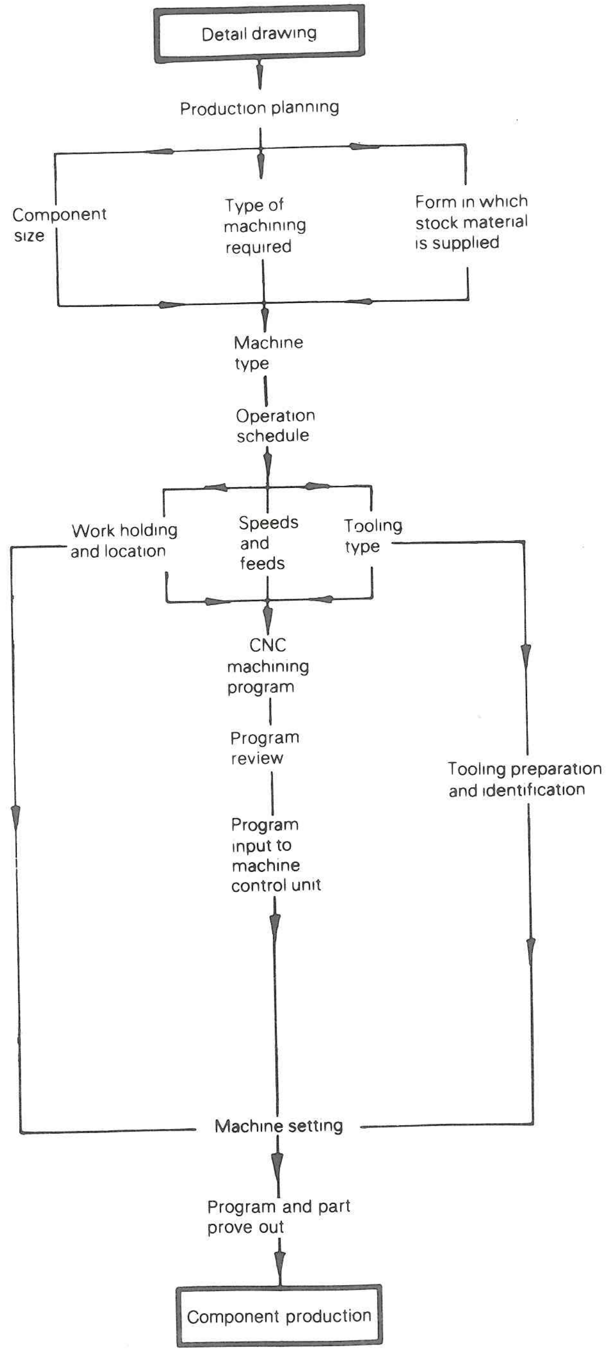

Figure 5.1 *Approach to data preparation.*

Manual Data Input

Manual data input is used when setting up the machine and editing programs, and for entering complete programs, although the latter should be restricted to relatively simple programs so that the machine is not idle for too long as the data entry is being made.

Manual Data Input to NC Machines To input data on noncomputerized control units the operator has to set dials, position switches, etc., before finally activating the machine tool to carry out the required movements. Only a limited amount of data can be entered at any one time. Data-recording facilities are often not available.

Manual Data Input to CNC Machines On computerized control units, by pressing the appropriate buttons on the control console a limited amount of data or a complete part program may be entered and the machine activated accordingly. The computer will retain the data and it can be transferred to a recording medium such as magnetic tape or disk and transferred back to the computer as and when required.

Conversational Manual Data Input

Conversational manual data input involves the operator pressing the appropriate keys on the control console in response to questions in everyday English, which appear on the visual display unit (CRT, cathode ray tube) screen. This method of manual data input is quicker than methods requiring the use of data codes, and manufacturers of these control units claim that to make the first chip takes one tenth of the time and that operator training is just a matter of hours as opposed to up to two weeks for nonconversational input.

The basis of conversational data input is the preprogramming of the computer with standard data stored in files within the computer memory, each item of data being numerically identified and called into the program by the appropriate operator response. Some machines maintain files of data from which the operator makes his or her final selections; other machines only ask questions to remind the operator what is needed.

Consider the turning of a bar of metal on a turning center. Before any consideration can be given to slide movements, the basic metal-cutting data would have to be ascertained. For example, the correct spindle speed and feed rate are of vital importance. The spindle speed is affected by the work diameter and the cutting speed. The cutting speed is related to the material being machined. The feed rate would depend on the depth of cut, tool type, and surface finish required. From this it can be seen that the necessary data to machine the metal successfully can be related to four factors:

(a) the material being cut;
(b) the material diameter;
(c) the surface finish required;
(d) the tool type.