CHAPTER 1

MECHANICAL DESIGN AND FABRICATION

Every scientific apparatus requires a mechanical structure, even a device that is fundamentally electronic or optical in nature. The design of this structure determines to a large extent the usefulness of the apparatus. It follows that a successful scientist must acquire many of the skills of the mechanical engineer in order to proceed rapidly with an experimental investigation.

The designer of research apparatus must strike a balance between the makeshift and the permanent. Too little initial consideration of the expected performance of a machine may frustrate all attempts to get data. Too much time spent planning can also be an error, since the performance of a research apparatus is not entirely predictable. A new machine must be built and operated before all the shortcomings in its design are apparent.

The function of a machine should be specified in some detail before design work begins. One must be realistic in specifying the job of a particular device. The introduction of too much flexibility can hamper a machine in the performance of its primary function. On the other hand, it may be useful to allow space in an initial design for anticipated modifications. Problems of assembly and disassembly should be considered at the outset, since research equipment rarely functions properly at first and often must be taken apart and reassembled repeatedly.

Make a habit of studying the design and operation of machines. Learn to visualize in three dimensions the size and positions of the parts of an instrument in relation to one another.

Before beginning a design, learn what has been done before. It is a good idea to build and maintain a library of commercial catalogs in order to be familiar with what is available from outside sources. Too many scientific designers waste time and money on the reinvention of the wheel and the screw. Use nonstandard parts only when their advantages justify the great cost of one-off construction in comparison with mass production. Consider modifications of a design that will permit the use of standardized parts. An evening spent leafing through the catalog of one of the major tool and hardware suppliers can be remarkably educational – catalogs from McMaster-Carr or W. M. Berg, for example, each list over 200 000 standard fasteners, bearings, gears, mechanical and electrical parts, tools etc.

Become aware of the available range of commercial services. In most big cities, specialty job shops perform such operations as casting, plating, and heat-treating inexpensively. In many cases it is cheaper to have others provide these services rather than attempt them oneself. Some of the thousands of suppliers of useful services, as well as manufacturers of useful materials, are noted throughout the text.

In the following sections we discuss the properties of materials and the means of joining materials to create a machine. The physical principles of mechanical design are presented. These deal primarily with controlling the motion of one part of a machine with respect to another, both where motion is desirable and where it is not. There are also sections on machine tools and on mechanical drawing. The former is mainly intended to provide enough information to enable the scientist to make intelligent use of the services of a machine shop. The latter is presented in sufficient detail to allow effective communication with people in the shop.

1.1 TOOLS AND SHOP PROCESSES

A scientist must be able to make proper use of hand tools to assemble and modify research apparatus. A successful experimentalist should be able to perform elementary operations safely with a drill press, lathe, and milling machine in order to make or modify simple components. Even when a scientist works with instruments that are fabricated and maintained by research technicians and machinists, an elementary knowledge of machine-tool operations will allow the design of apparatus that can be constructed with efficiency and at reasonable cost. The following is intended to familiarize the reader with the capabilities of various tools. Skill with machine tools is best acquired under the supervision of a competent machinist.

1.1.1 Hand Tools

A selection of hand tools for the laboratory is given in Table 1.1. A research scientist in physics or chemistry will have use for most of these tools, and if possible should have the entire set in the lab. The tool set outlined in Table 1.1 is not too expensive for any scientist to have on hand.

A laboratory scientist should adopt a craftsman-like attitude toward tools. Far less time is required to find and use the proper tool for a job than will be required to repair the damage resulting from using the wrong one.

1.1.2 Machines for Making Holes

Holes up to about 25 mm (1 in.) diameter are made using a *twist drill* (Figure 1.1) in a drill press. A *boring bar*

Table 1.1 Tool Set for Laboratory Use

Screwdrivers:
- No. 1, 2, and 3 drivers for slotted-head screws
- No. 1, 2, and 3 Phillips screwdrivers
- Allen (hex) drivers for socket-head screws, both a fractional set (1/16–1/4 in.) and a metric set (1.5–10 mm)
- Nut drivers for hex-head screws and nuts, both fractional (1/8–1/2 in.) and metric (4–11 mm)
- Set of jeweller's screwdrivers

Wrenches:
- Combination box and open-end wrenches, both a fractional set (3/8–1 in.) and a metric set (10–19 mm)
- 3/8 in. square-drive ratcheting socket driver with both fractional (3/8–7/8 in.) and metric (10–19 mm) socket sets
- Adjustable wrenches (small, medium, and large)
- Pipe wrench

Pliers:
- Slip-joint pliers
- Channel-locking pliers
- Large and small needle-nose pliers
- Large and small diagonal cutters
- Small flush cutters
- Hemostats

Hammers:
- Small and medium ball-peen hammers
- Soft-faced hammer with plastic or rubber inserts

Files:
- Second-cut, flat, half-round, and round files with handles
- Smooth-cut, flat, half-round, and round files with handles
- Six-piece Swiss-Pattern file set

Miscellaneous:
- Dial caliper or micrometer
- Forceps
- Sheet-metal shears
- Hacksaw
- Tubing cutter
- Center punch
- Scriber
- Small machinist's square
- Steel scale
- Divider
- Tapered hand reamer
- Tap wrench with:
  - 4-40 to 1/4-20 UNC and 3×0.6 to 12×1.75 metric tap sets
  - 1/8 to 1/2 NPT or 6 mm to 15 mm BPST (metric) pipe thread tap sets
- Electric hand drill motor or small drill press
- Drills, 1/16–1/2 in. in 1/32 in. increments, in drill index
- Drills, Nos. 1–60, in drill index
- Small bench vise

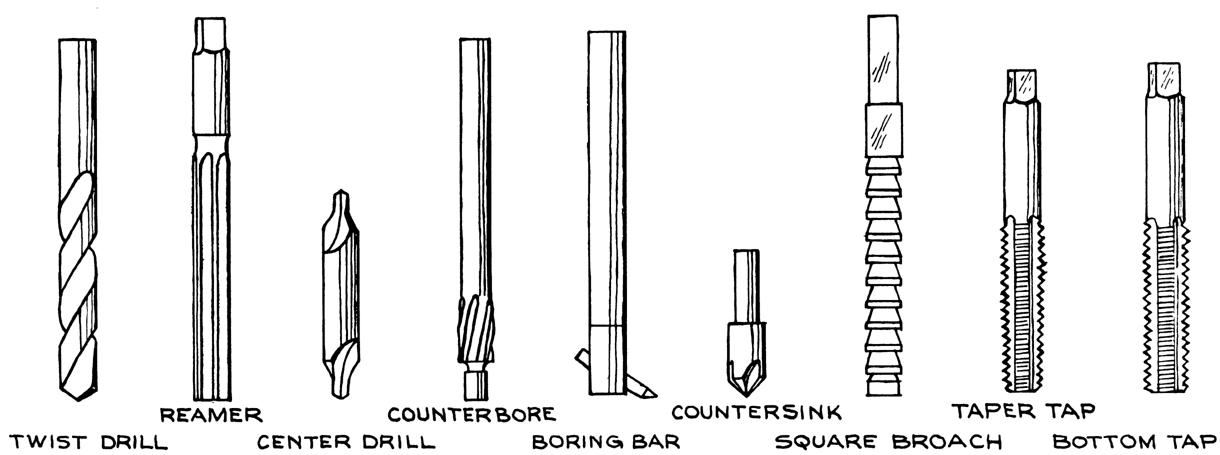

Figure 1.1 Tools for making and shaping holes.

(Figure 1.1) is used in a lathe or vertical milling machine to bore out a drilled hole to make a large hole. Of course, a hole can be drilled with a twist drill in a handheld drill motor; this method, although convenient, is not very accurate and should only be employed when it is not possible to mount the work on the drill press table.

Twist drills are available in fractional inch sizes and metric sizes as well as in number and letter series of sizes at intervals of only a few thousandths of an inch. Sizes designated by common fractions are available in 1/64 in. increments in diameters from 1/64 to 1 3/4 in., in 1/32 in. increments in diameters from 1 3/4 to 2 1/4 in., and in 1/16 in. increments in diameters from 2 1/4 to 3 1/2 in; metric sizes are available in 0.05 mm increments in diameters from 1.00 mm to 2.50 mm, in 0.10 mm increments from 2.50 mm to 10.00 mm, and in 0.50 mm increments from 10.00 mm to 17.50 mm. Number drill sizes are given in Appendix 1.1. The included angle at the point of a drill is 118°. A designer should always choose a hole size that can be drilled with a standard-size drill, and the shape of the bottom of a blind hole should be taken to be that left by a standard drill unless another shape is absolutely necessary.

If many holes of the same size are to be drilled, it may be worthwhile to alter the drill point to provide the best performance in the material that is being drilled. In very hard materials the included angle of the point should be increased to as much as 140°. For soft materials such as plastic or fiber it should be decreased to about 90°. Many shops maintain a set of drills with points specially ground for drilling in brass. The included angle of such a drill is 118°, but the cutting edge is ground so that its face is parallel to the axis of the drill in order to prevent the drill from digging in.

A drilled hole can be located to within about 0.3 mm (0.01 in.) by scribing two intersecting lines and making a punch mark at the intersection. The indentation made by the punch holds the drill point in place until the cutting edges first engage the material to be drilled. With care, locational accuracy of 0.03 mm (.001 in.) can be achieved in a milling machine or jig borer. Locational error is primarily a result of the drill's flexing as it first enters the material being drilled. This causes the point of the drill to wander off the center of rotation of the machine driving the drill; the hole should be started with a *center drill* (Figure 1.1) that is short and stiff. Once the hole is started, drilling is completed with the chosen twist drill.

A drill tends to produce a hole that is out-of-round and oversize by as much as 0.2 mm (.005 in.). Also, a drill point tends to deviate from a straight line as it moves through the material being drilled. This run-out can amount to 0.2 mm (.008 in.) for a 6 mm (1/4 in.) drill making a 25 mm (1 in.) deep hole; more for a smaller diameter drill. It is particularly difficult to make a round hole when drilling material that is so thin that the drill point breaks out on the under side before the shoulder

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enters the upper side. Clamping the work to a backup block of similar material alleviates the problem. When roundness and diameter tolerances are important, it is good practice to drill a hole slightly undersize and finish up with the correct size drill; better yet, the undersized hole can be accurately sized using a *reamer*.

Before drilling in a drill press, the location of the hole should be center-punched and the work should be securely clamped to the drill-press table. The drill should enter perpendicular to the work surface. When drilling curved or canted surfaces, it is best to mill a flat, perpendicular to the hole axis at the location of the hole.

The speed at which the drill turns is determined by the maximum allowable surface speed at the outer edge of the bit as well as the rate at which the drill is fed into the work. The rate at which a tool cuts is typically specified as meters per minute (m/min) or surface feet per minute (sfpm). Suggested tool speeds are given in Table 1.2. A drill (or any cutting tool) should be cooled and lubricated by flooding with soluble cutting oil, kerosene, or other cutting fluid. Brass or aluminum can be drilled without cutting oil if necessary.

A drilled hole that must be round and straight to close tolerances is drilled slightly undersize and then reamed using a tool such as is shown in Figure 1.1. Reamers with a round shank are meant to be grasped in the collet chuck of a milling machine; the reamer inserted after the drill is removed from the chuck without moving the work-piece on the bed of the milling machine. A reamer with a square shank is to be grasped in a tap handle for use by hand. A hand reamer has a slight initial taper to facilitate starting the cut. The diameter tolerance on a reamed hole can be 0.03 mm (.001 in.) or better. The chamfer (taper) tolerance can be kept to 0.0002 millimeter per millimeter (or 8 microinch per inch) or better. Tapered drill and reamer sets are available for preparing the tapered holes for standard taper pins used to secure one part to another with great and repeatable precision.

Table 1.2 Tool Speeds for High-speed Steel Tools (Speeds can be increased 2 × with carbide-tipped tools)

Material	m/min (sfpm)		
	Drill	Lathe	Mill
Aluminum	60 (200)	100 (300)	120 (400)
Brass	60 (200)	50 (150)	60 (200)
Cast iron	30 (100)	15 (50)	15 (50)
Carbon steel	25 (80)	30 (100)	20 (60)
Stainless steel	10 (30)	30 (100)	20 (60)
Copper	60 (200)	100 (300)	30 (100)
Plastics	30 (100)	60 (200)	60 (200)

A drilled hole can be threaded with a *tap* (shown in Figure 1.1). Cutting threads with a tap is usually carried out by hand. A tap has a square shank that is clamped in a tap handle. The tap is inserted in the hole and slowly turned, cutting as it goes. The tool should be lubricated and should be backed at least part way out of the hole after each full turn of cutting in order to clear metal chips from the tool. Taps are chamfered (tapered) on the end so that the first few teeth do not cut full depth. This makes for smoother cutting and better alignment. For more precise tapping the tap can be placed in a drill press with the work-piece held underneath. The drill chuck can be rotated by hand to start the tap off correctly, parallel to the hole. Some drill presses come with a foot-operated reversing mechanism so that with the drill operating at a slow speed the correct action of tap–reverse-tap can be carried out. The chamfer on a tap extends for nearly 10 teeth in a *taper tap*, 3 to 5 teeth on a *plug tap*, and 1 to 2 teeth on a *bottom tap*. The first two are intended for threading through a hole, the latter for finishing the threads in a blind hole. The hole to be threaded is drilled with a tap drill with a diameter specified to allow the tap to cut threads to about 75% of full depth. Appendix 1.1 gives tap drill sizes for American National and metric threads.

The head of a bolt can be recessed by enlarging the entrance of the bolt hole with a *counterbore* (shown in Figure 1.1).

A keyway slot can be added to a drilled hole or a drilled hole can be made square or hexagonal by shaping the hole with a *broach* (Figure 1.1). A broach is a cutting tool with a series of teeth of the desired shape, each successive cutting edge slightly larger than the one preceding. The broach can be driven through the hole by a hand-driven or hydraulic press. In some broaching machines the tool is pulled through the work. A broach can, at some expense, be ground to a nonstandard shape. The expense is probably only justified if many holes are to be broached.

1.1.3 The Lathe

A lathe (Figure 1.2) is used to produce a surface of revolution such as a cylindrical or conical surface. The work to

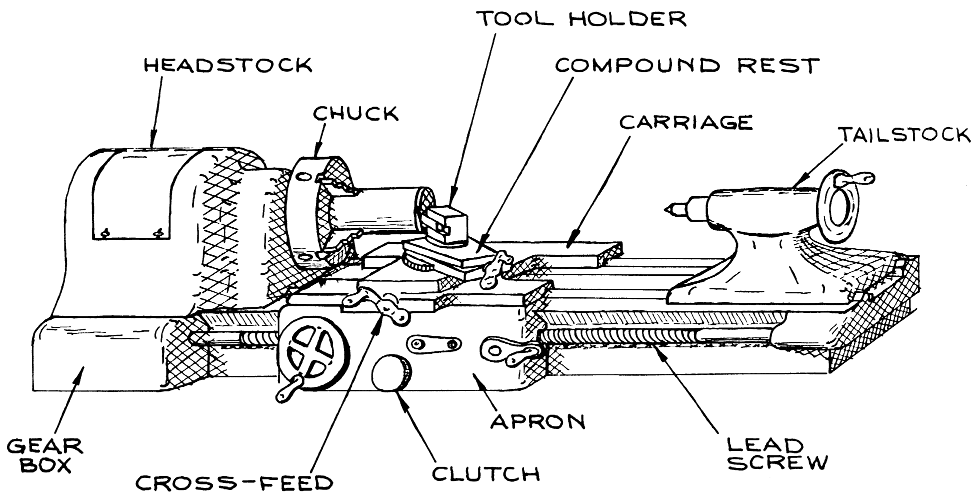

Figure 1.2 A lathe.

be turned is grasped by a *chuck* that is rotated by the driving mechanism within the lathe *headstock.* Long pieces are supported at the free end by a center mounted in the *tailstock.* A cutting tool held atop the lathe carriage is brought against the work as it turns. As shown in Figure 1.2, the *tool holder* is clamped to the *compound rest* mounted to a rotatable table atop the *cross-feed* that in turn rests on the *carriage.* The carriage can be moved parallel to the axis of rotation along slides or ways on the lathe bed. A cylindrical surface is produced by moving the carriage up or down the ways, as in the first cut illustrated in Figure 1.3. Driving the cross-feed produces a face perpendicular to the axis of rotation; driving the tool with the compound-rest screw produces a conical surface.

Most lathes have a *lead screw* along the side of the lathe bed. This screw is driven in synchronization with the rotating chuck by the motor drive of the lathe. A groove running the length of the lead screw can be engaged by a clutch in the carriage *apron* to provide power to drive either the carriage or the cross-feed in order to produce a long uniform cut. When cutting threads the lead screw can be engaged by a split nut in the apron to provide uniform motion of the carriage.

A variety of attachments are available for securing work to the spindle in the headstock. Most convenient is the three-jaw chuck. All three jaws are moved inward and outward by a single control so that a cylinder placed in the chuck is automatically centered. A four-jaw chuck with independently controlled jaws is used to grasp a workpiece that is not cylindrical or to hold a cylindrical piece off center. Large irregular work can be bolted to a face plate that is attached to the lathe spindle. Small round pieces can be grasped in a *collet chuck.* A collet is a slotted tube with an inner diameter of the same size as the work and a slightly tapered outer surface. The work is clamped

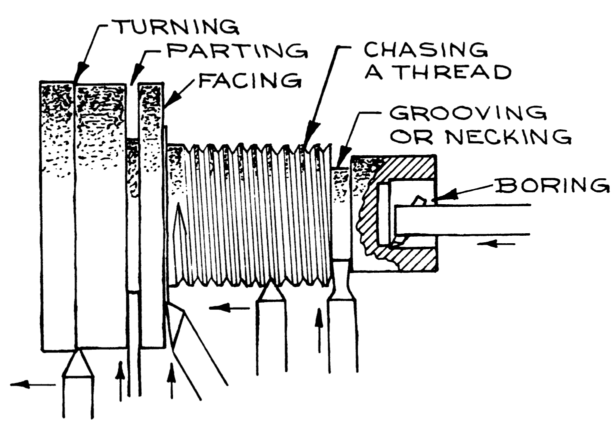

Figure 1.3 Cuts made on a lathe.

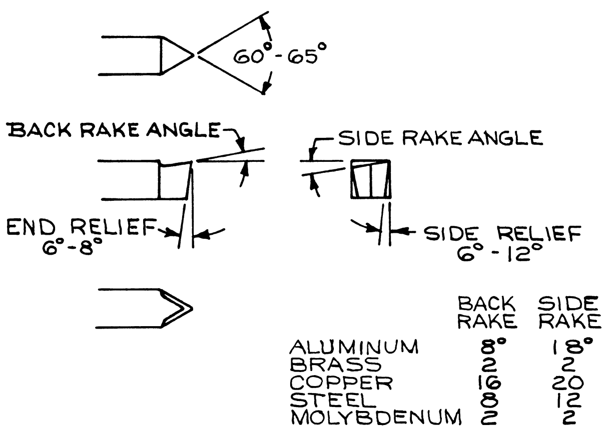

Figure 1.4 Tool angles for a right-cutting round-nose tool. A right-cutting tool has its cutting edge on the right when viewed from the point end.

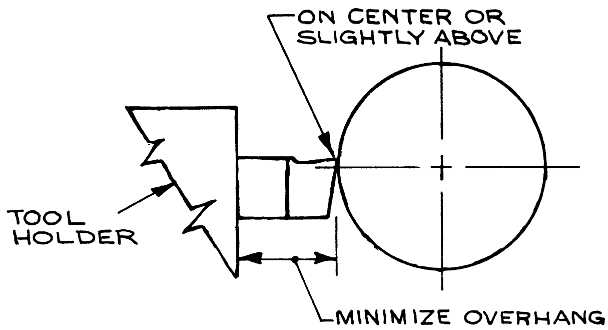

Figure 1.5 Placement of tool with respect to the work in a lathe.

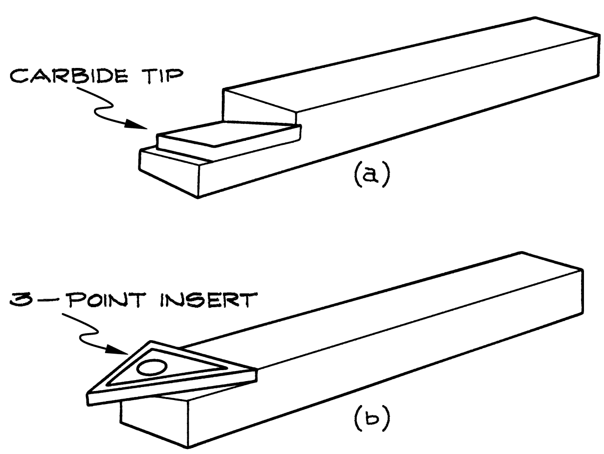

Figure 1.6 (a) Single-point carbide-tipped lathe tool. (b) Lathe tool with replaceable carbide insert. The insert has three cutting points.

in the collet by a mechanism that draws the collet into a sleeve mounted in the lathe spindle.

The cutting tool largely determines the quality of work produced in a lathe. The efficiency of the tool bit used in a lathe depends upon the shape of the cutting edge and the placement of the tool with respect to the work-piece. A cutting tool must be shaped to provide a good compromise between sharpness and strength. The sharpness of the cutting edge is determined by the *rake angles* indicated in Figure 1.4. The indicated *relief angles* are required to prevent the noncutting edges and surfaces of the tool from interfering with the work. Placement of the tool in relation to the work-piece is illustrated in Figure 1.5.

In the past, a machinist was obliged to grind tool steel stock to the required shape to made a tool bit. Now virtually all work is done with prepared tool bits. These may be simply ground-to-shape tool bits. Especially sharp, robust tools are available with sintered tungsten carbide (so-called ‘‘carbide’’) or diamond tips. Many tools are made with replaceable carbide inserts. The insert, which is clamped to the end of the tool, is triangular or square to provide three or four cutting edges by rotating the insert in its holder. Examples are illustrated in Figure 1.6.

As in drilling, the cutting speed for turning in a lathe depends upon the material being machined. Cutting speeds for high-speed steel tools are given in Table 1.2. Modern carbide- and ceramic-tipped cutters are much faster than tool-steel bits; they also produce a cleaner, more precise cut. Typically, a cut should be 0.1 to 0.3 mm (.003–.010 in.) deep, although much deeper cuts are permissible for rough work if the lathe and work-piece can withstand the stress.

Holes in the center of a work-piece may be drilled by placing a twist drill in the tailstock and driving the drill into the rotating work with the hand-wheel drive of the tailstock. The hole should first be located with a *center drill* (Figure 1.1), or the drill point will wander off center.

A drill, a lathe tool, or a milling cutter is usually bathed with a cutting fluid to cool the tool and to produce a smooth cut. Cutting fluids include soluble oils, mineral oils, and base oils. *Soluble oils* form emulsions when mixed with water and are used for cutting both ferrous and nonferrous metals, when cooling is most important. *Mineral oils* are petroleum products including paraffin oils and kerosene. They are typically used for light, high-speed cutting. *Base oils* are inorganic or fatty oils with or without sulfur-containing additives. Base oils are called for when making heavy cuts in ferrous materials.

Tolerances of 0.1 mm (.004 in.) can be maintained with ease when machining parts in a lathe. Diameters accurate to ±0.01 mm (±.0004 in.) can be obtained by a skilled operator at the expense of considerable time. Any modern lathe will maintain a straightness tolerance of 0.4 mm/m (0.005 in/ft) provided the work-piece is stiff enough not to spring away from the cutting tool.

1.1.4 Milling Machines

Milling, as a machine-tool operation, is the converse of lathe turning. In milling the work-piece is brought into contact with a rotating cutter. Typical milling cutters are illustrated in Figure 1.7. A *plain milling cutter* has teeth only on the periphery and is used for milling flat surfaces. A *side milling cutter* has cutting edges on the periphery and either one or both ends so that it can be used to mill a channel or groove. An *end mill* is rotated about its long axis and has cutters on both the end and sides. There are also a number of specially shaped cutters for milling dovetail slots, T-slots, and Woodruff key-slots. A *fly cutter* is another useful milling tool. It consists of a cylinder with a single, movable cutting edge and is used for cutting round holes and milling large flat surfaces. Radial saws are also used in milling machines for cutting narrow grooves and for parting off. Ordinary milling cutters are made of tough, hard steel known as high-speed steel. Other alloys are used as well, frequently with coatings of titanium nitride (TiN) or titanium carbonitride (TiCN) for a harder surface and improved lubricity. Both carbide-tipped cutters and tools with replaceable carbide inserts are available. Solid carbide end mills can be had for about twice the cost of high-speed steel mills.

There are two basic types of milling machine. The *plain miller* has a horizontal shaft, or *arbor,* on which a cutter is mounted. The work is attached to a movable bed below the cutter. The plain miller is typically used to produce a flat surface or a groove or channel. It is not much used in the fabrication of instrument components. The *vertical mill* has a vertical spindle located over the bed. Milling cutters can be mounted to an arbor in the spindle of the vertical

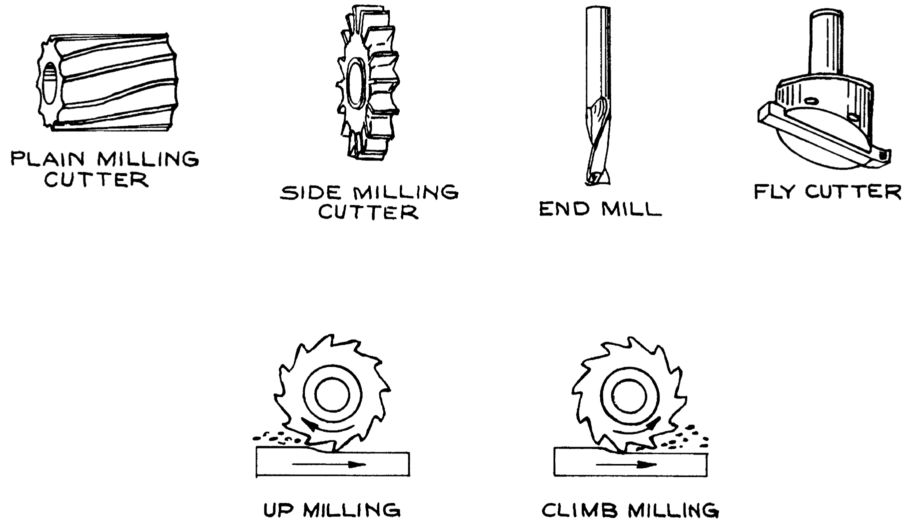

Figure 1.7 Milling cutters.

mill, or a collet chuck for grasping an end mill can replace the arbor. Motion of the mill bed in three dimensions is controlled by hand-wheels. Big machines may have power-driven beds. An essential accessory for a vertical mill is a rotating table so that the work-piece can be rotated under the cutter for cutting circular grooves and for milling a radius at the intersection of two surfaces.

The two possible cutting operations are illustrated in Figure 1.7. *Climb milling,* in which the cutting edge enters the work from above, has the advantage of producing a cleaner cut. Also, climb milling tends to hold the work flat and deposits chips behind the direction of the cut. There is however a danger of pulling the work into the cutter and damaging both the work and the tool. *Up milling* is preferred when the work cannot be securely mounted and when using older, less rigid machines. Cutter speeds are given in Table 1.2.

Dimensional accuracy of ± 0.1 mm ($\pm .004$ in.) is easily achieved in a milling operation; flatness and squareness of much higher precision are easily maintained. Both the mill operator and the designer specifying a milled surface should be aware that milled parts tend to curl after they are unclamped from the mill bed. This problem is particularly acute with thin pieces of metal. It can be alleviated somewhat if cuts are taken alternately on one side and then the other, finishing up with a light cut on each side.

The vertical milling machine is the workhorse of the model shop where instruments are fabricated. A scientist contemplating the design of a new instrument should become familiar with the milling machine's capability and, if possible, gain at least rudimentary skill in its operation.

Two electronic innovations have significantly increased the utility and ease of operation of the milling machine: the electronic digital position readout and computer control of the motion of the mill arbor and the mill bed.

All machine tools suffer from backlash in the mechanical controls. In a milling machine the position of the mill bed is read off vernier scales on the hand-wheels that drive the screws that position the bed. In addition to the inconvenience caused by this sort of readout, the operator must realize that reversing the direction of rotation of the hand-wheel does not instantly reverse the direction of travel of the bed, owing to inevitable clearances between the threads of the drive screw and the nut that it engages. This backlash must be accounted for in even the roughest work. The problem is entirely obviated by the fitting of electronic position sensors on the bed that read out in inches or millimeters on displays mounted to the machine. This simple innovation significantly increases the speed of operation for a skilled operator, while at the same time reducing the number of errors. These displays invariably improve the quality of work of a relatively unskilled operator.

Even modest shops now use milling machines in which the bed and arbor are driven by electric motors under computer control – CNC (computer numerical control) machines. Most modern machinists, working from mechanical drawings provided by the designer, can efficiently program these machines. The time required is frequently offset by time saved by the machine operating under computer control, so in many instances it is quite reasonable to use a CNC machine for one-off production. This is particularly true when a complex sequence of bed and arbor motions is required to turn out a part. Conversely, when a CNC machine is available, the designer can contemplate many more complex shapes in a design than would be economically feasible to produce with manually controlled machines. An additional advantage for the instrument designer is that complex parts can initially be turned out in an inexpensive material, such as polyethylene, to check shape and fit before the final part is machined from some expensive material.

The ultimate application of computer-controlled machines is for them to be operated directly by programs produced by the software the designer employs in the process of preparing the engineering drawings. This is the integration of computer-aided design (CAD) with computer-aided manufacturing (CAM) in a so-called CAD/CAM system. At present, however, this mode of fabrication is not usually practical for the scientist-designer. The time involved in learning to use sophisticated CAD/CAM software, as well as its cost, cannot be justified. In addition, few model shops have machines that can be operated by the output of high-level CAD programs.

Mills and lathes are both relatively powerful machines. One cannot expect the machine to stop should rotating parts of the machine get caught on loose clothing, such as a shirt cuff or necktie, or, worse, on a limb or digit. Initial operation of these machines should be under the guidance of a competent instructor. One must always be certain that the machine is in proper operating condition and that the work in the machine is securely clamped to the bed (of the milling machine) or by the jaws (of the lathe chuck); a loose work-piece can become a projectile. Metal chips may come flying off the cutting tool; eye protection is mandatory.

1.1.5 Electrical Discharge Machining (EDM)

A spark between an electrode and a work-piece will remove material from the work as a consequence of highly localized heating and various electron- and ion-impact phenomena. As improbable as it may seem, the process of spark erosion has been developed into an efficient and very precise method for machining virtually any material that conducts electricity. In electrical discharge machining (EDM), the electrode and the work-piece are immersed in a dielectric oil or de-ionized water, a pulsed electrical potential is applied between the electrode and the work, and the two are brought into close proximity until sparking occurs. The dielectric fluid is continuously circulated to remove debris and to cool the work. The position of the work-piece is controlled by a computer servo that maintains the required gap and moves the work-piece into the electrode to obtain the desired cut.

There are two types of electrical discharge machines: the *plunge* or *die-sinking EDM* and the *wire EDM*. The plunge EDM is used to make a hole or a well. The electrode is the male counterpart to the female concavity produced in the work. The electrode is machined from graphite, tungsten, or copper. Making the electrode in the required shape is a significant portion of the entire cost of the process. The electrode for wire EDM is typically a vertically traveling copper or copper-alloy wire 0.05 to 0.4 mm (.002 to .012 in.) in diameter. The wire is eroded as cutting progresses. It comes off a spool to be fed through the work and is discarded after a single pass. With two-dimensional horizontal (XY) control of the work-piece, a cutting action analogous to that of a bandsaw is obtained. XYZ-control permits the worktable to be tilted up to 20° so that conical surfaces can be generated.

In an EDM process, the cavity or *kerf* is always larger than the electrode. This *overcut* is highly predictable and may be as small as 0.03 mm (.001 in.) for wire EDM. As a consequence, an accuracy of ±0.03 mm (±.001 in.) is routine and an accuracy of ±.003 mm (±.0001 in.) is possible. Furthermore, EDM produces a very high-quality finish; a surface roughness less than 0.0003 mm (12 micro-inches) RMS (root mean squared) is routinely obtained. Part of the reason for the great accuracy obtained in EDM is that there is no force applied to the work and hence no possibility of the work-piece being deflected from the cutting tool. There is no work-hardening and no residual stress in the material being cut. The efficacy of EDM is independent of the hardness of the material of the work. Tool steel, conductive ceramics such as graphite and carbide, and refractory metals such as tungsten are cut with the same ease as soft aluminum. A particular advantage is that the material can be heat treated before fabrication since very little heat is generated in the cutting operation.

A precision CNC electrical discharge machine may cost in excess of $100 000. As a consequence these machines are seldom found in the typical university model shop; the EDM machine has become, however, the workhorse of the tool-and-die industry. Owing to the cost of the machines and the fact that, once programmed, they can run virtually 24 hours a day, job shops are usually anxious to have outside work to keep the machines running full time and usually welcome scientists with one-off jobs.

1.1.6 Grinders

Grinders are used for the most accurate work and to produce the smoothest surface attainable in most machine shops. A grinding machine is similar to a plain milling machine except that a grinding wheel rather than a milling cutter is mounted on the rotating arbor. In most machines the work is clamped magnetically to the table and the table is raised until the work touches the grinding wheel. The table is automatically moved back and forth under the wheel at a fairly rapid rate. Many lathes incorporate, as an accessory, a grinder that can be mounted to the compound rest in place of the tool holder, so that cylindrical and conical surfaces can be finished by grinding.

Even the hardest steel can be ground, but grinding is seldom used to remove more than a small fraction of a millimeter (a few thousandths of an inch) of metal. For complicated pieces to be made of hardened bronze or steel, it is advantageous to soften the stock material by annealing, machine it slightly oversize with ordinary cutting tools, re-harden the material, and then grind the critical surfaces.

A flatness tolerance of ±0.003 mm (±.0001 in.) can be maintained in grinding operations. The average variation of a ground surface should not exceed 0.001 mm (50 microinches); a surface roughness less than 0.0003 mm (10 microinches) RMS is possible.

Safety is a primary concern in any grinding operation. Grinding wheels are typically held together with an inorganic ceramic cement. They are brittle and can fail catastrophically. Significant forces come into play when grinding: the centrifugal force on the spinning wheel; the force generated between the wheel and the work; and especially the shock produced when the wheel first contacts the work. A guard should enclose the wheel. The exposed portion of the wheel should be no more than necessary to carry out the operation at hand. The bearings and pilot shaft supporting the wheel must be in good condition; check for balance before spinning up; unbalanced forces can be destructive. The flanges clamping the grinding wheel to the drive shaft must be correct for the wheel in use. Wheel speed should not exceed that specified for the wheel. The wheel speed is usually specified as meters per minute (m/min) or surface feet per minute (sfpm), thus requiring the operator to calculate the rotational speed required to attain a specified linear speed at the outer circumference of the wheel. In general, the surface speed at the outer edge of an inorganic-bonded wheel should not exceed about 2000 m/min (6000 sfpm). In a dry grinding operation an exhaust system should be in place to carry away the considerable dust and metal residue that is generated. ANSI standards for safe grinding operations are given in condensed form in *Machinery's Handbook Pocket Companion*.[1]

1.1.7 Tools for Working Sheet Metal

Most machine shops are equipped with the tools necessary for making panels, brackets, and rectangular and cylindrical boxes of sheet metal. The basic sheet-metal processes are illustrated in Figure 1.8.

Sheet metal is cut in a guillotine *shear.* Shears are designed for making long straight cuts or for cutting out inside corners. A typical shear can make a cut a meter in length in sheet metal of up to 1.5 mm (1/16 in.) in thickness.

A *sheet-metal brake* is used to bend sheet stock. A typical instrument-shop brake can accommodate sheet stock at least a meter wide and up to 1.5 mm (1/16 in.) thick. The minimum bend radius is equal to the thickness of the sheet metal. Dimensional tolerances of 1 mm (.04 in.) can be maintained.

Sheet can be formed into a simple curved surface on a *sheet-metal roll.* The roll consists of three long parallel rollers, one above and two below. Sheet is passed between the upper roller and the two lower rollers. The upper roller is driven. The distance between the upper roller and the lower rollers is adjustable and determines the radius of the curve that is formed.

Holes can be punched in sheet metal. A sheet-metal punch consists of a *punch,* a *guide bushing,* and a *die.* The punch is the male part. The cross section of the punch determines the shape and size of the hole. The punch is a close fit into the die, so that sheet metal placed between the two is sheared by the edge of the punch as it is driven into the die. Round and square punches are available in standard sizes. A punch-and-die set to make a nonstandard hole can be fabricated, but the cost may be justified only if a large number of identical holes are required. On the other hand, a very precisely shaped hole can be made in a punch-and-die operation since the tools can be made with great precision.

Sheet metal can be embossed with a *stamp and die,* similar to a punch and die except that the die is somewhat larger than the stamp, so that the metal is formed into the die rather than sheared off at the edge.

Sheet metal can be formed into surfaces that are figures of revolution by *spinning*. The desired shape is first turned in hard wood in a lathe. A circular sheet-metal blank is then clamped against the wooden form by a rubber-faced rotating center mounted in the lathe tailstock. Then as the wooden form is rotated the sheet metal is gradually formed over the surface of the wood by pressing against the sheet with a blunt wooden or brass tool. Spinning requires few special tools and is economical for one-off production.

1.1.8 Casting

Sand casting is the most common process used for the production of a small number of cast parts. Although