Section **13**

Manufacturing Processes

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13.1 FOUNDRY PRACTICE AND EQUIPMENT
by Michael K. Madsen
Expanded by Staff

BASIC STEPS IN MAKING SAND CASTINGS

The basic steps involved in making sand castings are:

1. **Patternmaking**. Patterns are required to make molds. The mold is made by packing molding sand around the pattern. The mold is usually made in two parts so that the pattern can be withdrawn. In horizontal molding, the top half is called the **cope,** and the bottom half is called the **drag**. In vertical molding, the leading half of the mold is called the **swing,** and the back half is called the **ram**. When the pattern is withdrawn from the molding material (sand or other), the imprint of the pattern provides the cavity when the mold parts are brought together. The mold cavity, together with any internal cores (see below) as required, is ultimately filled with molten metal to form the casting.

2. If the casting is to be hollow, additional patterns, referred to as **core boxes,** are needed to shape the sand forms, or **cores,** that are placed in the mold cavity to form the interior surfaces of castings. Thus the void between the mold and core eventually becomes the casting.

3. **Molding** is the operation necessary to prepare a mold for receiving the metal. It consists of ramming sand around the pattern placed in a support, or **flask,** removing the pattern, setting cores in place, cutting the **feeding system** to direct the metal if this feeding system is not a part of the pattern, removing the pattern, and closing the mold.

4. **Melting** and **pouring** are the processes of preparing molten metal of the proper composition and temperature and pouring this into the mold from transfer **ladles**.

5. **Cleaning** is all the operations required to remove the **gates** and **risers** that constitute the feeding system and to remove the adhering sand, scale, and other foreign material that must be removed before the casting is ready for shipment or other processing. Inspection follows, to check for defects in the casting as well as to ensure that the casting has the dimensions specified on the drawing and/or specifications. Inspection for internal defects may be quite involved, depending on the quality specified for the casting (see Sec. 5.4.). The inspected and accepted casting sometimes is used as is, but often it is subject to further processing which may include heat treatment, painting, other surface treatment (e.g., hot-dip galvanizing), and machining. Final operations may include electrodeposited plated metals for either cosmetic or operational requirements.

PATTERNS

Since patterns are the forms for the castings, the casting can be no better than the patterns from which it is made. Where close tolerances or smooth casting finishes are desired, it is particularly important that patterns be carefully designed, constructed, and finished.

Patterns serve a variety of functions, the more important being (1) to shape the mold cavity to produce castings, (2) to accommodate the characteristics of the metal cast, (3) to provide accurate dimensions, (4) to provide a means of getting liquid metal into the mold (gating system), and (5) to provide a means to support cores.

Usual allowances built into the pattern to ensure dimensional accuracy include the following: (1) **Draft,** the taper on the vertical walls of the casting which is necessary to extract the pattern from the mold without disturbing the mold walls. (2) **Shrinkage allowance,** a correction to compensate for the solidification shrinkage of the metal and its contraction during cooling. These allowances vary with the type of metal and size of casting. Typical allowances for cast iron are $\frac{1}{10}$ to $\frac{5}{32}$ in/ft; for steel, $\frac{1}{8}$ to $\frac{1}{4}$ in/ft; and for aluminum, $\frac{1}{16}$ to $\frac{5}{32}$ in/ft. A designer should consult appropriate references (AFS, ''Cast Metals Handbook''; ASM, ''Casting Design Handbook''; ''Design of Ferrous Castings'') or the foundry. These allowances also include a size tolerance for the process so that the casting is dimensionally correct. (See also Secs. 6.1, 6.3, and 6.4.) Table 13.1.1 lists additional data for some commonly cast metals. (3) **Machine finish allowance** is necessary if machining operations are to be used so that stock is provided for machining. Tabulated data are available in the references cited for shrinkage allowances. (4) If a casting is prone to distortion, a pattern may be intentionally distorted to compensate. This is a **distortion allowance**.

Patterns vary in complexity, depending on the size and number of castings required. **Loose patterns** are single prototypes of the casting and are used only when a few castings are needed. They are usually constructed of wood, but metal, plaster, plastics, urethanes, or other suitable material may be used. With advancements in solids modeling utilizing computers, CAD/CAM systems, and laser technology, rapid prototyping is possible and lends itself to the manufacture of protype patterns from a number of materials, including dense wax paper, or via stereolithographic processes wherein a laser-actuated polymerized plastic becomes the actual pattern or a prototype for a pattern or a series of patterns. The gating system for feeding the casting is cut into the sand by hand. Some loose patterns may be split into two parts to facilitate molding.

Gated patterns incorporate a gating system along with the pattern to eliminate hand cutting.

Match-plate patterns have the cope and drag portions of the pattern mounted on opposite sides of a wooden or metal plate, and are designed to speed up the molding process. Gating systems are also usually attached. These patterns are generally used with some type of molding machine and are recommended where a large number of castings are required.

For fairly large castings or where an increase in production rate is desired, the patterns can be mounted on separate pattern plates, which are referred to as **cope- and drag-pattern** plates. They are utilized in horizontal or vertical machines. In horizontal molding machines, the pattern plates may be used on separate machines by different workers,

Table 13.1.1 Average Linear Shrinkage of Castings

Bar iron, rolled	1:55	Cast iron	1:96	Steel, puddled	1:72
Bell metal	1:65	Gun metal	1:134	Steel, wrought	1:64
Bismuth	1:265	Iron, fine grained	1:72	Tin	1:128
Brass	1:65	Lead	1:92	Zinc, cast	1:624
Bronze	1:63	Steel castings	1:50	8 Cu + 1 Sn (by weight)	1:13

and then combined into completed molds on the molding floor prior to pouring. In vertical machines, the pattern plates are used on the same machine, with the flaskless mold portions pushed out one behind the other. Vertical machines result in faster production rates and provide an economic edge in overall casting costs.

Special Patterns and Devices   For extremely large castings, **skeleton** patterns may be employed. Large molds of a symmetric nature may be made for forming the sand mold by **sweeps,** which provide the contour of the casting through the movement of a template around an axis.

Follow boards are used to support irregularly shaped, loose patterns which require an irregular parting line between cope and drag. A **master pattern** is used as an original to make up a number of similar patterns that will be used directly in the foundry.

MOLDING PROCESSES AND MATERIALS

(See Table 13.1.2)

Molding Processes

Green Sand   Most castings are made in **green sand,** i.e., sand bonded with clay or bentonite and properly tempered with water to give it **green strength**. Miscellaneous additions may be used for special properties. This method is adaptable to high production of small- or medium-sized castings because the mold can be poured immediately after forming, and the sand can be reused and reprocessed after the casting has solidified.

Dry Sand Molds   These molds are made with green sand but are baked prior to use. The surface is usually given a refractory wash before baking to prevent erosion and to produce a better surface finish. Somewhat the same effects are obtained if the mold is allowed to **air-dry** by leaving it open for a period of time before pouring, or it is **skin-dried** by using a torch, infrared lamps, or heating elements directed at the mold cavity surface.

Core molding makes use of assembled cores to construct the mold. The sand is prepared by mixing with oil, or cereal, forming in core boxes, and baking. This process is used where the intricacy of the casting requires it.

Carbon Dioxide Process Molds   These molds are made in a manner similar to the green sand process but use sand bonded with sodium silicate. When the mold is finished, carbon dioxide gas is passed through the sand to produce a very hard mold with many of the advantages of dry sand and core molds but requiring no baking.

Floor and Pit Molding   When large castings are to be produced, these may be cast either directly on the floor of the foundry or in pits in the floor which serve as the flask. **Loam molding** is a variation of floor molding in which molding material composed of 50 percent sand and 50 percent clay (approx) is troweled onto a brickwork surface and brought to dimension by use of patterns, sweeps, or templates.

Shell Molding   Sand castings having close dimensional tolerances, and smooth finish can be produced by a process using a synthetic resin binder. The sand and resin mixture is dumped onto a preheated metal pattern, which causes the resin in the mixture to set as a thin shell over the pattern. When the shell has reached the proper thickness, the excess sand is removed by rotating the pattern to dump out the sand. The remaining shell is then cured on the pattern and subsequently removed by stripping it off, using mold release pins which have been properly spaced and that are mechanically or hydraulically made to protrude through the pattern. Mating shell halves are bonded, suitably backed by loose sand or other material, and then ready for metal to be poured. Current practice using shell molds has produced castings in excess of 1,000 lb, but often the castings weigh much less.

Plaster Molds   Plaster or plaster-bonded molds are used for casting certain aluminum or copper base alloys. Dimensional accuracy and excellent surface finish make this a useful process for making rubber tire molds, match plates, etc.

A variation of this method of molding is the **Antioch process,** using mixtures of 50 percent silica sand, 40 percent gypsum cement, 8 percent talc, and small amounts of sodium silicate, portland cement, and magnesium oxide. These dry ingredients are mixed with water and poured over the pattern. After the mixture is poured, the mold is steam-treated in an autoclave and then allowed to set in air before drying in an oven. When the mold has cooled it is ready for pouring. Tolerances of ± 0.005 in (± 0.13 mm) on small castings and ± 0.015 in (± 0.38 mm) on large castings are obtained by this process.

A problem presented by plaster molds lies in inadequate permeability in the mold material consistent with the desired smooth mold cavity surface. A closely related process, the **Shaw process,** provides a solution. In this process, a refractory aggregate is mixed with a gelling agent and then poured over the pattern. Initial set of the mixture results in a rubbery consistency which allows it to be stripped from the pattern but

Table 13.1.2   Design and Cost Features of Basic Casting Methods

Design and cost features	Process					
	Sand casting	Shell-mold casting	Permanent-mold casting	Plaster-mold casting	Investment casting	Die casting
Choice of materials	Wide—ferrous and nonferrous	Wide—except for low-carbon steels	Restricted—brass, bronze, aluminum, some gray iron	Narrow—brass, bronze, aluminum	Wide—includes hard-to-forge and machine materials	Narrow—zinc, aluminum, brass, magnesium
Complexity	Considerable	Moderate	Moderate	Considerable	Greatest	Considerable
Size range	Great	Limited	Moderate	Moderate	Moderate	Moderate
Minimum section, in	$3/32$	$1/16$	0.100	0.010	0.010	0.025
Tolerances, in ft*	$1/16-1/8$	$1/32-3/32$	$1/32-7/64$	$1/32-5/64$	0.003–0.006	$1/32-1/16$
Surface smoothness, μin, rms	250–300	150–200	90–125	90–125	90–125	60–125
Design feature remarks	Basic casting method of industry	Considered to be good low-cost casting method	Production economics with substantial quantities	Little finishing required	Best for parts too complicated for other casting methods	Most economical where applicable
Tool and die costs	Low	Low to moderate	Medium	Medium	Low to moderate	High
Optimum lot size	Wide—range from few pieces to huge quantities	More required than sand castings	Best when requirements are in thousands	From one to several hundred	Wide—but best for small quantities	Substantial quantities required
Direct labor costs	High	Moderate	Moderate	High	Very high	Low to medium
Finishing costs	High	Low	Low to moderate	Low	Low	Low
Scrap costs	Moderate	Low	Low	Low	Low	Low

* Closer at extra cost.
SOURCE: Cook, ''Engineered Castings,'' McGraw-Hill.

which is sufficiently strong to return to the shape it had when on the pattern. The mold is then ignited to burn off the volatile content in the set gel and baked at very high heat. This last step results in a hard, rigid mold containing microscopic cracks. The permeability of the completed mold is enhanced by the presence of the so-called microcrazes, while the mold retains the high-quality definition of the mold surface.

Two facts are inherent in the nature of sand molds: First, there may be one or few castings required of a given piece, yet even then an expensive wood pattern is required. Second, the requirement of removal of the pattern from the mold may involve some very intricate pattern construction. These conditions may be alleviated entirely by the use of the **full mold process,** wherein a foamed polystyrene pattern is used. Indeed, the foamed pattern may be made complete with a gating and runner system, and it can incorporate the elimination of draft allowance. In actual practice, the pattern is left in place in the mold and is instantly vaporized when hot metal is poured. The hot metal which vaporized the foam fills the mold cavity to the shape occupied previously by the foam pattern. This process is ideal for casting runs of one or a few pieces, but it can be applied to production quantities by mass-producing the foam patterns. There is extra expense for the equipment to make the destructible foam patterns, but often the economics of the total casting process is quite favorable when compared with resorting to a reusable pattern. There are particular instances when the extreme complexity of a casting can make a hand-carved foam pattern financially attractive.

The **lost-wax, investment, or precision-casting, process** permits the accurate casting of highly alloyed steels and of nonferrous alloys which are impossible to forge and difficult to machine. The procedure consists of making an accurate metal die into which the wax or plastic patterns are cast. The patterns are assembled on a sprue and the assembly sprayed, brushed, or dipped in a slurry of a fine-grained, highly refractory aggregate, and a proprietary bonding agent composed chiefly of ethyl silicate. This mixture is then allowed to set. The pattern is coated repeatedly with coarser slurries until a shell of the aggregate is produced around the pattern. The molds are allowed to stand until the aggregate has set, after which they are heated in an oven in an inverted position so that the wax will run out. After the wax is removed, the molds are baked in a preheat furnace. The molds may then be supported with loose sand and poured in any conventional manner.

There have been attempts in the past to use frozen mercury as a pattern. While mercury is a viable pattern material and can be salvaged totally for reuse, the inherent hazards of handling raw mercury have mitigated against its continued use to make patterns for investment castings.

All dimensions can be held to a tolerance of ± 0.005 in (± 0.13 mm) with some critical dimensions held to 0.002 in (0.05 mm). Most castings produced by this process are relatively small.

Faithful reproduction and accurate tolerances can also be attained by the **Shaw process;** see above. It combines advantages of dimensional control of precision molds with the ease of production of conventional molding. The process makes use of wood or metal patterns and a refractory mold bonded with an ethyl silicate base material. Since the mold is rubbery when stripped from the pattern, some back draft is permissible.

In the **cement-sand process** portland cement is used as the sand binder. A typical mixture has 11 percent portland cement, 89 percent silica sand, and water $4\frac{1}{2}$ to 7 percent of the total sand and cement. New sand is used for facing the mold and is backed with ground-up sand which has been rebonded. Cores are made of the same material. The molds and cores must airdry 24 to 72 h before pouring. The process can be used for either ferrous or nonferrous castings. This molding mixture practically eliminates the generation of gases, forms a hard surface which resists the erosive action of the metal, and produces castings with good surfaces and accurate dimensions. This process is seldom used, and then only for specific castings wherein the preparation of this type of mold outweighs many of its disadvantages.

Permanent-Mold Casting Methods

In the **permanent-mold casting method,** fluid metal is poured by hand into metal molds and around metal cores without external pressure. The molds are mechanically clamped together. Of necessity, the complexity of the cores must be minimal, inasmuch as they must be withdrawn for reuse from the finished casting. Likewise, the shape of the molds must be relatively simple, free of reentrant sections and the like, or else the mold itself will have to be made in sections, with attendant complexity.

Metals suitable for this type of casting are lead, zinc, aluminum and magnesium alloys, certain bronzes, and cast iron.

For making iron castings of this type, a number of metal-mold units are usually mounted on a turntable. The individual operations, such as coating the mold, placing the cores, closing the mold, pouring, opening the mold, and ejection of the casting, are performed as each mold passes certain stations. The molds are preheated before the first casting is poured. The process produces castings having a dense, fine-grained structure, free from shrink holes or blowholes. The tool changes are relatively low, and better surface and closer tolerances are obtained than with the sand-cast method. It does not maintain tolerances as close or sections as thin as the die-casting or the plaster-casting methods.

Yellow brasses, which are high in zinc, should not be cast by the permanent-mold process because the zinc oxide fouls the molds or dies.

The **semipermanent mold casting method** differs from the permanent mold casting in that sand cores are used, in some places, instead of metal cores. The same metals may be cast by this method. This process is used where cored openings are so irregular in shape, or so undercut, that metal cores would be too costly or too difficult to handle. The structure of the metal cast around the sand cores is like that of a sand casting. The advantages of permanent mold casting in tolerances, density, appearance, etc., exist only in the section cast against the metal mold.

Graphite molds may be used as short-run permanent molds since they are easier to machine to shape and can be used for higher-melting point alloys, e.g., steel. The molds are softer, however, and more susceptible to erosive damage. Steel railroad wheels may be made in these molds and can be cast by filling the mold by **low-pressure casting** methods.

In the **slush casting** process, the cast metal is allowed partially to solidify next to the mold walls to produce a thin section, after which the excess liquid metal is poured out of the permanent mold.

In **centrifugal casting** the metal is under centrifugal force, developed by rotating the mold at high speed. This process, used in the manufacture of bronze, steel, and iron castings, has the advantage of producing sound castings with a minimum of risers. In **true centrifugal castings** the metal is poured directly into a mold which is rotated on its own axis. Obviously, the shapes cast by this method must have external and internal geometries which are surfaces of revolution. The external cast surface is defined by the internal surface of the water-cooled mold; the internal surface of the casting results from the effective core of air which exists while the mold is spun and until the metal solidifies sufficiently to retain its cast shape. Currently, all cast-iron pipe intended for service under pressure (e.g., water mains) is centrifugally cast. The process is extended to other metals falling under the rubric of **tubular goods.**

In **pressure casting,** for asymmetrical castings which cannot be spun around their own axes, the mold cavities are arranged around a common sprue located on the neutral axis of the mold. The molds used in the centrifugal-casting process may be metal cores or dry sand, depending on the type of casting and the metal cast.

Die Casting machines consist of a basin holding molten metal, a metallic mold or die, and a metal transferring device which automatically withdraws molten metal from the basin and forces it under pressure into the die. Two forms of die casting machines are in general use. Lead, tin, and zinc alloys containing aluminum are handled in **piston machines.** Aluminum alloys and pure zinc, or zinc alloys free from aluminum, rapidly attack the iron in the piston and cylinder and require a different type of casting machine. The pressures in a piston machine range from a few hundred to thousands of lb/in^2.

The **gooseneck machine** has a cast-iron gooseneck which dips the molten metal out of the melting pot and transfers it to the die. The pressure is applied to the molten metal by compressed air after the gooseneck is brought in contact with the die. This machine, developed primarily for

aluminum alloys, is sometimes used for zinc-aluminum alloys, especially for large castings, but, owing to the lower pressure, the casting is likely to be less dense than when made in the piston machine. It is seldom used for magnesium alloys.

In **cold chamber machines** the molten-metal reservoir is separated from the casting machine, and just enough metal for one casting is ladled by hand into a small chamber, from which it is forced into the die under high pressure. The pressures, quite high, ranging from the low thousands to in excess of 10,000 lb/in^2, are produced by a hydraulic system connected to the piston in the hot metal chamber. The alloy is kept so close to its melting temperature that it is in a slushlike condition. The process is applicable to aluminum alloys, magnesium alloys, zinc alloys, and even higher-melting-point alloys like brasses and bronzes, since the pouring well, cylinder, and piston are exposed to the high temperature for only a short time.

All metal mold external pressure castings have close tolerances, sharp outlines and contours, fine smooth surface, and high rate of production, with low labor cost. They have a hard skin and a soft core, resulting from the rapid chilling effect of the cold metal mold.

The dies usually consist of two blocks of steel, each containing a part of the cavity, which are locked together while the casting is being made and drawn apart when it is ready for ejection. One-half of the die (next to the ejector nozzle) is stationary; the other half moves on a carriage. The dies are preheated before using and are either air- or water-cooled to maintain the desired operating temperature. Die life varies with the alloy and dimensional tolerances required. Retractable and removable metal cores are used to form internal surfaces. Inserts can be cast into the piece by placing them on locating pins in the die.

A wide range of sizes and shapes can be made by these processes, including threaded pieces and gears. Holes can be accurately located. The process is best suited to large-quantity production.

A historic application of the process was for typesetting machines such as the linotype. Although now they are obsolescent and rarely found in service, for a long time the end products of typesetting machines were a prime example of a high-quality die-cast metal product.

MOLDING EQUIPMENT AND MECHANIZATION

Flasks may be filled with sand by hand shoveling, gravity feed from overhead hoppers, continuous belt feeding from a bin, sand slingers, and, for large molds, by an overhead crane equipped with a grab bucket.

Hand ramming is the simplest method of compacting sand. To increase the rate, pneumatic rammers are used. The method is slow, the sand is rammed in layers, and it is difficult to gain uniform density.

More uniform results and higher production rates are obtained by **squeezing machines**. Hand-operated squeezers were limited to small molds and are obsolete; **air-operated machines** permit an increase in the allowable size of molds as well as in the production rate. These machines are suitable for shallow molds. Squeezer molding machines produce greatest sand density at the top of the flask and softest near the parting line of pattern. Air-operated machines are also applied in vertical molding processes using flaskless molds. Horizontal impact molding sends shock waves through the sand to pack the grains tightly.

In **jolt molding machines** the pattern is placed on a platen attached to the top of an air cylinder. After the table is raised, a quick-release port opens, and the piston, platen, and mold drop free against the top of the cylinder or striking pads. The impact packs the sand. The densities produced by this machine are greatest next to the parting line of the pattern and softest near the top of the flask. This procedure can be used for any flask that can be rammed on a molding machine. As a separate unit, it is used primarily for medium and large work. Where plain jolt machines are used on large work, it is usual to ram the top of the flask manually with an air hammer.

Jolt squeeze machines use both the jolt and the squeeze procedures. The platen is mounted on two air cylinders: a small cylinder to jolt and a large one to squeeze the mold. They are widely used for small and medium work, and with match-plate or gated patterns. Pattern-stripping devices can be incorporated with jolt or squeezer machines to permit

mechanical removal of the pattern. Pattern removal can also be accomplished by using jolt-rockover-draw or jolt-squeeze-rollover-draw machines.

The **sand slinger** is the most widely applicable type of ramming machine. It consists of an impeller mounted on the end of a double-jointed arm which is fed with sand by belt conveyors mounted on the arm. The impeller rotating at high speed gives sufficient velocity to the sand to ram it in the mold by impact. The head may be directed to all parts of the flask manually on the larger machines and may be automatically controlled on smaller units used for the high-speed production of small molds.

Vibrators are used on all pattern-drawing machines to free the pattern from the grip of the sand before drawing. Their use reduces mold damage to a minimum when the pattern is removed, and has the additional advantage of producing castings of more uniform size than can be secured by hand rapping the pattern. Pattern damage is also kept to a minimum. Vibrators are usually air-operated, but some electrically operated types are in use.

Flasks generally consist of two parts: the upper section, called the **cope,** and the bottom section, the **drag**. When more than two parts are used, the intermediate sections are called **cheeks**. Flasks are classified as tight, snap, and slip. **Tight flasks** are those in which the flask remains until the metal is poured. **Snap flasks** are hinged on one corner and have a locking device on the diagonally opposite corner. In use, these flasks are removed as soon as the mold is closed. **Slip flasks** are of solid construction tapered from top to bottom on all four sides so that they can be removed as soon as the mold is closed. Snap or slip flasks permit the molder to make any number of molds with one flask. Before pouring snap- or slip-flask molds, a wood or metal pouring jacket is placed around the mold and a weight set on the top to keep the cope from lifting. The cope and drag sections on all flasks are maintained in proper alignment by flask pins and guides.

Tight flasks can be made in any size and are fabricated of wood, rolled steel, cast steel, cast iron, magnesium, or aluminum. Wood, aluminum, and magnesium are used only for small- and medium-sized flasks. Snap and slip flasks are made of wood, aluminum, or magnesium, and are generally used for molds not over 20 by 20 in (500 mm by 500 mm).

Mechanization of Sand Preparation

In addition to the various types of molding machines, the modern foundry makes use of a variety of equipment to handle the sand and castings.

Sand Preparation and Handling   Sand is prepared in **mullers,** which serve to mix the sand, bonding agent, and water. **Aerators** are used in conjunction to loosen the sand to make it more amenable to molding. **Sand cutters** that operate over a heap on the foundry floor may be used instead of mullers. Delivery of the sand to the molding floor may be by means of dump or scoop trucks or by belt conveyors. At the molding floor the molds may be placed on the floor or delivered by conveyors to a pouring station. After pouring, the castings are removed from the flasks and adhering sand at a **shakeout** station. This may be a mechanically operated jolting device that shakes the loose sand from flask and casting. The used sand, in turn, is returned to the storage bins by belt conveyor or other means. Small castings may be poured by using **stack-molding** methods. In this case, each flask has a drag cavity molded in its upper surface and a cope cavity in its lower surface. These are stacked one on the other to a suitable height and poured from a common sprue.

There is an almost infinite variety of equipment and methods available to the foundry, ranging from simple, work-saving devices to completely mechanized units, including completely automatic molding machines. Because of this wide selection available, the degree to which a foundry can be mechanized depends almost entirely on the economics of the operations, rather than the availability or lack of availability of a particular piece of equipment.

MOLDING SAND

Molding sand consists of silica grains held together by some bonding material, usually clay or bentonite.

Grain size greatly influences the surface finish of a casting. The proper grain size is determined by the size of the casting, the quality of surface required, and the surface tension of the molten metal. The grain size should be approximately uniform when maximum permeability is desired.

Naturally bonded sands are mixtures of silica and clay as taken from the pits. Modification may be necessary to produce a satisfactory mixture. This type of sand is used in gray iron, ductile iron, malleable iron, and nonferrous foundries (except magnesium).

Synthetically bonded sands are produced by combining clay-free silica sand with clay or bentonite. These sands can be compounded to suit foundry requirements. They are more uniform than naturally bonded sands but require more careful mixing and control. Steel foundries, gray iron and malleable iron foundries, and magnesium foundries use this type of sand.

Special additives may be used in addition to the basic sand, clay, and water. These include cereals, ground pitch, sea coal, gilsonite, fuel oil, wood flour, silica flour, iron oxide, pearlite, molasses, dextrin, and proprietary materials. These all serve the purpose of altering specific properties of the sand to give desired results.

The properties of the sand that are of major interest to the foundry worker are **permeability,** or the venting power, of the sand; **green compressive strength; green shear strength; deformation,** or the sand movement under a given load; **dry compressive strength;** and **hot strength,** i.e., strength at elevated temperatures. Several auxiliary tests are often made, including moisture content, clay content, and grain-size determination.

The foundry engineer or metallurgist who usually is entrusted with the control of the sand properties makes the adjustments required to keep it in good condition.

Facing sands, for giving better surface to the casting, are used for gray iron, malleable iron, steel, and magnesium castings. The iron sands usually contain **sea coal,** a finely ground coal which keeps the sand from adhering to the casting by generating a gas film when in contact with the hot metal. Steel facings contain silica flour or other very fine highly refractory material to form a dense surface which the metal cannot readily penetrate.

Mold washes are coatings applied to the mold or core surface to improve the finish of the casting. They are applied either wet or dry. The usual practice is to brush or spray the wet mold washes and to brush or rub on the dry ones. Graphite or silica flour mixed with clay and molasses water is frequently used. The washes are mixed usually with water-base or alcohol-base solvent solutions that require oven drying time, during which not only does the wash set, but also the excess moisture is removed from the washed coating.

Core Sands and Core Binders

Green sand cores are made from standard molding-sand mixtures, sometimes strengthened by adding a binder, such as dextrin, which hardens the surface. Cores of this type are very fragile and are usually made with an arbor or wires on the inside to facilitate handling. Their collapsibility is useful to prevent hot tearing of the casting.

Dry sand cores are made from silica sand and a binder (usually oil) which hardens under the action of heat. The amount of oil used should be the minimum which will produce the necessary core strength.

Core binders are either organic, such as core oil, which are destroyed under heat, or inorganic, which are not destroyed.

Organic Binders The main organic binder is **core oil.** Pure linseed oil is used extensively as one of the basic ingredients in blended-oil core binders. These consist primarily of linseed oil, resin, and a thinner, such as high-grade kerosene. They have good wetting properties, good workability, and better oxidation characteristics than straight linseed oil.

Corn flour produces good green strength and dry strength when used in conjunction with oil. Cores made with this binder are quick drying in the oven and burn out rapidly and completely in the mold.

Dextrin produces a hard surface and weak center because of the migration of dextrin and water to the surface. Used with oil, it produces a hard smooth surface but does not produce a green bond as good as that with corn flour.

Commercial **protein binders,** such as gelatin, casein, and glues, im-

prove flowability of the sand, have high binding power, rapid drying, fair resistance to moisture, and low burning-out point, with only a small volume of gas evolved on burning. They are used where high collapsibility of the core is essential.

Other binders include paper-mill by-products, which absorb moisture readily, have high dry strength, low green strength, high gas ratio, and high binding power for clay materials.

Coal tar pitch and **petroleum pitch** flow with heat and freeze around the grains on cooling. These compounds have low moisture absorption rates and are used extensively for large iron cores. They can be used effectively with impure sands.

Wood and **gum rosin, plastic resins,** and rosin by-products are used to produce collapsibility in cores. They must be well ground. They tend to cake in hot weather, and large amounts are required to get desired strength.

Plastics of the **urea-** and **phenol-formaldehyde** groups and **furan resins** are being used for core binders. They have the advantage of low-temperature baking, collapse readily, and produce only small amounts of gas. These can be used in **dielectric baking ovens** or in the **shell molding, hot box, or air setting** processes for making cores.

Inorganic binders include fire clay, southern bentonite, western bentonite, and iron oxide.

Cores can also be made by mixing sand with sodium silicate. When this mixture is in the core box, it is infiltrated with CO_2, which causes the core to harden. This is called the CO_2 **process**.

Core-Making Methods

Cores are made by the methods employed for sand molds. In addition, **core blowers** and **extrusion machines** are used.

Core blowers force sand into the core box by compressed air at about 100 lb/in². They can be used for making all types of small- and medium-sized cores. The cores produced are very uniform, and high production rates are achieved.

Screw feed machines are used largely for plain cylindrical cores of uniform cross section. The core sand is extruded through a die onto a core plate. The use of these machines is limited to the production of stock cores, which are cut to the desired length after baking.

Core Ovens Core oven walls are constructed of inner and outer layers of sheet metal separated by rock wool or Fiberglas insulation and with interlocked joints. Combustion chambers are refractory-lined, and the hot gases are circulated by fans. They are designed for operating at temperatures suitable for the constituents in the core body. Time at baking temperatures will, likewise, vary with the composition of the core.

Core driers are light skeleton cast iron or aluminum boxes, the internal shape of which conforms closely to the cope portion of the core. They are used to support, during baking, cores which cannot be placed on a flat plate.

Chaplets are metallic pieces inserted into the mold cavity which support the core. Long unsupported cores will be subject to flotation force as the molten metal fills the mold and may break if the resulting flexural stresses are excessive. Likewise, the liquid forces imposed on cores as metal flows through the mold cavity may cause cores to shift. The chaplets interposed within the mold cavity are placed to alleviate these conditions. They are generally made of the same material as that being cast; they melt and blend with the metal as cast, and they remain solid long enough for the liquid forces to equilibrate through the mold cavity.

CASTING ALLOYS

In general, the types of alloys that can be produced as wrought metals can also be prepared as castings. Certain alloys, however, cannot be forged or rolled and can only be used as cast.

Ferrous Alloys

Steel Castings (See Sec. 6.3.) Steel castings may be classified as:
1. Low carbon (C < 0.20 percent). These are relatively soft and not readily heat-treatable.
2. Medium carbon (0.20 percent < C < 0.50 percent). These cast-

ings are somewhat harder and amenable to strengthening by heat treatment.

3. High carbon (C > 0.50 percent). These steels are used where maximum hardness and wear resistance are desired.

In addition to the classification based on carbon content, which determines the maximum hardness obtainable in steel, the castings can be also classified as **low alloy** content (≤ 8 percent) or **high alloy** content (> 8 percent).

Low-alloy steels behave essentially as plain carbon steels but have a higher **hardenability,** which is a measure of ability to be hardened by heat treatment. High-alloy steels are designed to produce some specific property, like corrosion resistance, heat resistance, wear resistance, or some other special property.

Malleable Iron Castings   The carbon content of malleable iron ranges from about 2.00 to 2.80 percent and may reach as high as 3.30 percent if the iron is melted in a cupola. Silicon ranging from 0.90 to 1.80 percent is an additional alloying element required to aid the annealing of the iron. As cast, this iron is hard and brittle and is rendered soft and malleable by a long heat-treating or annealing cycle. (See also Sec. 6.3)

Gray Iron Castings   Gray iron is an alloy of iron, carbon, and silicon, containing a higher percentage of these last two elements than found in malleable iron. Much of the carbon is present in the elemental form as graphite. Other elements present include manganese, phosphorus, and sulfur. Because the properties are controlled by proper proportioning of the carbon and silicon and by the cooling rate of the casting, it is usually sold on the basis of specified properties rather than composition. The carbon content will usually range between 3.00 and 4.00 percent and the silicon will be between 1.00 and 3.00 percent, the higher values of carbon being used with the lower silicon values (usually), and vice versa. As evidence of the fact that gray iron should not be considered as a material having a single set of properties, the ASTM and AFS codify gray cast iron in several classes, with accompanying ranges of tensile strengths available. The high strengths are obtained by proper adjustment of the carbon and silicon contents or by alloying. (See also Sec. 6.3.)

An important variation of gray iron is **nodular iron,** or **ductile iron,** in which the graphite appears as nodules rather than as flakes. This iron is prepared by treating the metal in the ladle with additives that usually include magnesium in alloy form. Nodular iron can exceed 100,000 lb/in^2 (690 MN/m^2) as cast and is much more ductile than gray iron, measuring about 2 to 5 percent elongation at these higher strengths, and even higher percentages if the strength is lower. (See Sec. 6.3.)

Nonferrous Alloys

Aluminum-Base Castings   Aluminum is alloyed with copper, silicon, magnesium, zinc, nickel, and other elements to produce a wide variety of casting alloys having specific characteristics of foundry properties, mechanical properties, machinability, and/or corrosion resistance. Alloys are produced for use in sand casting, permanent mold casting, or die casting. Some alloys are heat-treatable using **solution** and **age-hardening** treatments. (See also Sec. 6.4.)

Copper-Base Alloys   The alloying elements used with copper include zinc (brasses), tin (bronzes), nickel (nickel bronze), aluminum (aluminum bronze), silicon (silicon bronze), and beryllium (beryllium bronze). The brasses and tin bronzes may contain lead for machinability. Various combinations of zinc and tin, or of tin or zinc with other elements, are also available. With the exception of some of the aluminum bronzes and beryllium bronze, most of the copper-base alloys cannot be hardened by heat treatment. (See also Sec. 6.4.)

Special Casting Alloys   Other metals cast in the foundry include **magnesium-base alloys** for light weight, **nickel-base alloys** for high-temperature applications, **titanium-base alloys** for strength-to-weight ratio, etc. The magnesium-base alloys require special precautions during melting and pouring to avoid burning. (See Sec. 6.4.)

MELTING AND HEAT TREATING FURNACES

There are several types of **melting furnaces** used in conjunction with metal casting. Foundry furnaces used in melting practice for ferrous

castings are predominantly **electric arc** (direct and indirect), **induction,** and **crucible** for small operations. For cast iron, **cupolas** are still employed, although in ever-decreasing quantities. The previous widespread use of open-hearth furnaces is now relegated to isolated foundries and is essentially obsolete. In general, ferrous foundries' melting practice has become based largely on electric-powered furnaces. **Duplexing** operations are still employed, usually in the form of cupola/induction furnace, or cupola/electric arc furnace.

In nonferrous foundries, electric arc, induction, and crucible furnaces predominate. There are some residual installations which use air furnaces, but they are obsolete and found only in some of the older, small foundries which cater to unique clients.

Vacuum melting and metal refining were fostered by the need for extremely pure metals for high-temperature, high-strength applications (e.g., gas-turbine blades). Vacuum melting is accomplished in a furnace located in an evacuated chamber; the source of heat is most often an electric arc and sometimes induction coils. Gases entrained in the melt are removed, the absence of air prevents oxidation of the base metals, and a high degree of metal purity is retained in the molten metal and in the casting ultimately made from that vacuum-melted metal. The mold is also enclosed in the same evacuated chamber.

The vacuum melting and casting process is very expensive because of the nature of the equipment required, and quantities of metal handled are relatively small. The economics of the overall process are justified by the design requirements for highest-quality castings for ultimately very demanding service.

Annealing and **heat-treating furnaces** used to process castings are the type usually found in industrial practice. (See Secs. 7.3. and 7.5.)

CLEANING AND INSPECTION

Tumbling barrels consist of a power-driven drum in which the castings are tumbled in contact with hard iron stars or balls. Their impact removes the sand and scale.

In **air-blast cleaning units,** compressed air forces silica sand or chilled iron shot into violent contact with the castings, which are tumbled in a barrel, rotated on a table, or passed between multiple orifices on a conveyor. Large rooms are sometimes utilized, with an operator directing the nozzle. These machines are equipped with hoppers and elevators to return the sand or shot to the magazine. Dust-collecting systems are required.

In **centrifugal-blast cleaning units,** a rotating impeller is used to impart the necessary velocity to the chilled iron shot or abrasive grit. The velocities are not so high as with air, but the volume of abrasive is much greater. The construction is otherwise similar to the air blast machine.

Water in large volume at pressures of 250 to 600 lb/in^2 is used to remove sand and cores from medium and large castings.

High-pressure water and sand cleaning (Hydroblast) employs high pressure water mixed with molding sand which has been washed off the casting. A sand classifier is incorporated in the sand reclamation system.

Pneumatic chipping hammers may be used to clean large castings where the sand is badly burned on and for deep pockets.

Removal of Gates and Risers and Finishing Castings   The following tabulation shows the most generally used methods for removing gates and risers (marked R) and for finishing (marked F).

Steel: Oxyacetylene (R) hand hammer or sledge (R), grinders (F), chipping hammer, (F), and machining (F).

Cast iron: Chipping hammer (R, F), hand hammer or sledge (R), abrasive cutoff (R), power saw (R), and grinders (F).

Malleable iron: Hand hammer or sledge (R), grinders (F), shear (F), and machining (F).

Brass and bronze: Chipping hammer (R, F), shear (R, F), hand hammer or sledge (R), abrasive cutoff (R), power saw (R), belt sanders (F), grinders (F), and machining (F).

Aluminum: Chipping hammer (R), shear (R), hand hammer or sledge (R), power saw (R), grinders (F), and belt sander (F).

Magnesium: Band saw (R), machining (F), and flexible-shaft machines with steel burr cutters (F).

Casting Inspection

(See Sec. 5.4)

Castings are inspected for dimensional accuracy, hardness, surface finish, physical properties, internal soundness, and cracks. For **hardness** and for **physical properties,** see Sec. 6.

Internal soundness is checked by cutting or breaking up pilot castings or by nondestructive testing using X-ray, gamma ray, etc.

Destructive testing tells only the condition of the piece tested and does not ensure that other pieces not tested will be sound. It is the most commonly used procedure at the present time.

X-ray, gamma ray, and other methods have made possible the nondestructive checking of castings to determine internal soundness on all castings produced. Shrinks, cracks, tears, and gas holes can be determined and repairs made before the castings are shipped.

Magnetic powder tests (Magnaflux) are used to locate structural discontinuities in iron and steel except austenitic steels, but they are not applicable to most nonferrous metals or their alloys. The method is most useful for the location of surface discontinuities, but it may indicate subsurface defects if the magnetizing force is sufficient to produce a leakage field at the surface.

In this test a magnetic flux is induced in ferromagnetic material. Any abrupt discontinuity in its path results in a local flux leakage field. If finely divided particles of ferromagnetic material are brought into the vicinity, they offer a low reluctance path to the leakage field and take a position that outlines approximately its effective boundaries. The casting to be inspected is magnetized and its surface dusted with the magnetic powder. A low velocity air stream blows the excess powder off and leaves the defect outlined by the powder particles. The powder may be applied while the magnetizing current is flowing (**continuous method**) or after the current is off (**residual method**). It may be applied dry or suspended in a light petroleum distillate similar to kerosene. Expert interpretation of the tests is necessary.

CASTING DESIGN

Design for the best utilization of metal in the cast form requires a knowledge of metal solidification characteristics, foundry practices, and the metallurgy of the metal being used. Metals exhibit certain peculiarities in the formation of solid metal during freezing and also undergo shrinkage in the liquid state during the freezing process and after freezing, and the casting must be designed to take these factors into consideration. Knowledge concerning the freezing process will also be of assistance in determining the fluidity of the metal, its resistance to **hot tearing,** and its tendency to evolve dissolved gases. For economy in production, casting design should take into consideration those factors in molding and coring that will lead to the simplest procedures. Elimination of expensive cores, irregular parting lines, and deep drafts in the casting can often be accomplished with a slight modification of the original design. Combination of the foregoing factors with the selection of the right metal for the job is important in casting design. Consultation between the design engineer and personnel at the foundry will result in well-designed castings and cost-effective foundry procedures. Initial guidance may be had from the several references cited and from updated professional literature, which abounds in the technical journals. Trade literature, as represented by the publications issued by the various generic associations, will be useful in assessing potential problems with specific casting designs. Generally, time is well spent in these endeavors before an actual design concept is reduced to a set of dimensional drawings and/or specifications.

13.2   PLASTIC WORKING OF METALS
by Rajiv Shivpuri

(See also Secs. 5 and 6)

REFERENCES: Crane, ''Plastic Working of Metals and Power Press Operations,'' Wiley. Woodworth, ''Punches, Dies and Tools for Manufacturing in Presses,'' Henley. Jones, ''Die Design and Die Making Practice,'' Industrial Press. Stanley, ''Punches and Dies,'' McGraw-Hill. DeGarmo, ''Materials and Processes in Manufacturing,'' Macmillan. ''Modern Plastics Encyclopedia and Engineers Handbook,'' Plastics Catalogue Corp., New York. ''The Tool Engineers Handbook,'' McGraw-Hill. Bridgman, ''Large Plastic Flow and Fracture,'' McGraw-Hill. ''Cold Working of Metals,'' ASM. Pearson, ''The Extrusion of Metals,'' Wiley.

STRUCTURE

Yieldable structural forces between the particles composing a material to be worked are the key to its behavior. Simple internal structures contain only a single element, as pure copper, silver, or iron. Relatively more difficult to work are the solid solutions in which one element tends to distribute uniformly in the structural pattern of another. Thus silver and gold form a continuous series of solid-solution alloys as their proportions vary. Next are alloys in which strongly bonded molecular groups dispersed through or along the grain boundaries of softer metals offer increasing resistance to working, as does iron carbide (Fe_3C) in solution in iron.

Bonding forces are supplied by electric fields characteristic of individual atoms. These forces in turn are subject to modification by temperature as energy is added, increasing electron activity.

The **particles** which constitute an atom are so small that most of its volume is empty space. For a similar energy state, there is some rough uniformity in the outside size of atoms. In general, therefore, the more complex elements have their larger number of particles more densely packed and so are heavier. For each element, the energy pattern of its electric charges in motion determines the field characteristics of that atom and which of the orderly arrangements it will seek to assume with relation to others like it in the orderly crystalline form.

Space lattice is the term used to describe the orderly arrangement of rows and layers of atoms in the crystalline form. This orderly state is also described as balanced, unstrained, or **annealed**. The working or deforming of materials distorts the orderly arrangement, unbalancing the forces between atoms. Cubic patterns or space lattices characterize the more ductile or workable materials. Hexagonal and more complex patterns tend to be more brittle or more rigid. Flaws, irregularities, or distortions, with corresponding unbalanced strains among adjacent atoms, may occur in the pattern or along grain boundaries. **Slip-plane** movements in working to new shapes tend to slide the once orderly layers of atoms within the grain-boundary limitations of individual crystals. Such sliding movement tends to take place at 45° to the direction of the applied load because much higher stresses are required to pull atoms directly apart or to push them straight together.

Chemical combinations, in liquid or solid solutions, or molecular compounds depend upon relative field patterns of elements or upon actual displacement of one or more electrons from the outer orbit of a donor element to the outer orbit of a receptor element. Thus the molecules of hard iron carbide, Fe_3C, may be held in solid solution in soft pure iron (ferrite) in increasing proportions up to 0.83 percent of carbon in iron, which is described as **pearlite**. Zinc may occupy solid-solution positions in the copper space lattice up to about 45 percent, the range of the ductile red and yellow brasses.

Thermal Changes   Adding heat (energy) increases electron activity

and therefore also the mobility of the atom. Probability of brittle failure at low temperatures usually becomes less as temperature increases. Transition temperatures from one state to another differ for different elements. Thermal transitions therefore become more complex as such differing elements are combined in alloys and compounds. As temperatures rise, a **stress-relieving** range is reached at which the most severely strained atoms are able to ease themselves around into less strained positions. At somewhat higher temperatures, **annealing** or **recrystallization** of worked or distorted structure takes place. Old grain boundaries disappear and small new grains begin to grow, aligning nearby atoms into their orderly lattice pattern. The more severely the material has been worked, the lower is the temperature at which recrystallization begins. Grain growth is more rapid at higher temperatures. In working materials above their recrystallization range, as in forging, the relief of interatomic strains becomes more nearly spontaneous as the temperature is increased. **Creep** takes place when materials are under some stress above the recrystallization range, and the thermal mobility permits individual atoms to ease around to relieve that stress with an accompanying gradual change of shape. Thus a wax candle droops due to gravity on a hot day. Lead, which recrystallizes below room temperature, will creep when used for roofing or spouting. Steels in rockets and jet engines begin to creep around 1,300 to 1,500°F (704 to 815°C). Creep is more rapid as the temperature rises farther above the recrystallization range.

PLASTICITY

Plasticity is that property of materials which commends them to the mass-production techniques of pressure-forming desired shapes. It is understood more easily if several types of plasticity are considered.

Crystoplastic describes materials, notably metals, which can be worked in the stable crystalling state, below the recrystallization range. Metals which crystallize in the cubic patterns have a wider plastic range than those of hexagonal pattern. Alloying narrows the range and increases the resistance to working. Tensile or compressive testing of an annealed specimen can be used to show the plastic range which lies between the initial yield point and the point of ultimate tensile or compressive failure.

The **plastic range,** as of an annealed metal, is illustrated in Fig. 13.2.1. Changing values of **true stress** are determined by dividing the applied load at any instant by the cross-section area at that instant. As material is worked, a progressive increase in elastic limit and yield point registers the slip-plane movement or work hardening which has taken place and the consequent reduction in residual plasticity. This changing yield point or resistance, shown in Fig. 13.2.1, is divided roughly into three characteristic ranges. The contour of the lower range can be varied by nonuniformity of grain sizes or by small displacements resulting from prior direction of working. Random large, soft grains yield locally under slight displacement, with resulting **surface markings,** described as *orange peel, alligator skin,* or *stretcher strain markings.* These can be
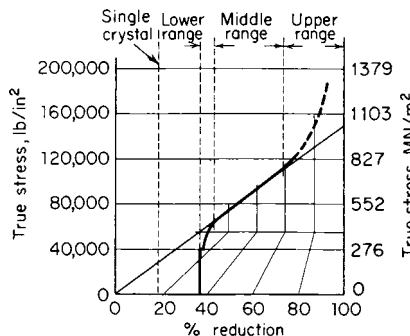
Fig. 13.2.1   Three ranges of crystoplastic work hardening of a low-carbon steel. *(ASME, 1954, W. S. Wagner, E. W. Bliss Co.)*

prevented by preparatory roller leveling, which gives protection in the case of steel for perhaps a day, or by a 3 to 5 percent temper pass of cold-rolling, which may stress relieve in perhaps 3 months, permitting recurrent trouble. The middle range covers most drawing and forming operations. Its upper limit is the point of normal tensile failure. The upper range requires that metal be worked primarily in compression to inhibit the start of tensile fracture. Severe extrusion, spring-temper rolling, and music-wire drawing use this range.

Dispersion hardening of metal alloys by heat treatment (see Fig. 13.2.2) reduces the plastic range and increases the resistance to work hardening. Figure 13.2.2 also shows the common methods of plotting change of true stress against **percentage of reduction**—e.g., reduction of thickness in rolling or compressive working, of area in wire drawing, ironing, or tensile testing, or of diameter in cup drawing or reducing operations—and against **true strain,** which is the natural logarithm of change of area, for convenience in higher mathematics.
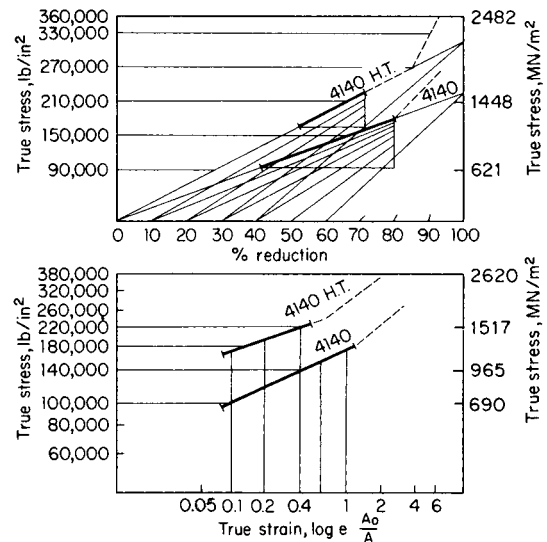
Fig. 13.2.2   High-range plasticity (dotted) of an SAE 4140 steel, showing the effect of dispersion hardening. Two plotting methods. *(ASME, 1958, Crane and Wagner, E. W. Bliss Co.)*

For metals, thermoplastic working is usually described as **hot working,** except for tin and lead, which recrystallize below room temperature. Hot-worked samples may be etched to show **flow lines,** which are usually made up of old-grain boundaries. Where these show, recrystallization has not yet taken place, and some work hardening is retained to improve physical properties. Zinc and magnesium, which are typical of the hexagonal-structure metals, take only small amounts of cold working but can be drawn or otherwise worked severely at rather moderate temperatures [Zn, 200 to 400°F (90 to 200°C); Mg, 500 to 700°F (260 to 400°C)]. Note that, although hexagonal-pattern metals are less easily worked than cubic-pattern metals, they are for that same reason structurally more rigid for a similar relative weight. Advantageous forging temperatures change with alloy composition: copper, 1,800 to 1,900°F (980 to 1,040°C); red brass, Cu 70, Zn 30, 1,600 to 1,700°F (870 to 930°C); yellow brass, Cu 60, Zn 40, 1,200 to 1,500°F (650 to 815°C). See Sec. 6 for general physical properties of metals.

Substantially pure iron shows an increasing elastic limit and decreasing plasticity with increasing amounts of work hardening by cold-rolling. The rate at which such work hardening takes place is greatly increased, and the remaining plasticity reduced, as alloying becomes more complex.

In **steels,** the mechanical working range is conventionally divided into cold, warm, and hot working. Figure 13.2.3 is a plot of flow stress, limit strain, scale factor, and dimensional error for different values of forging
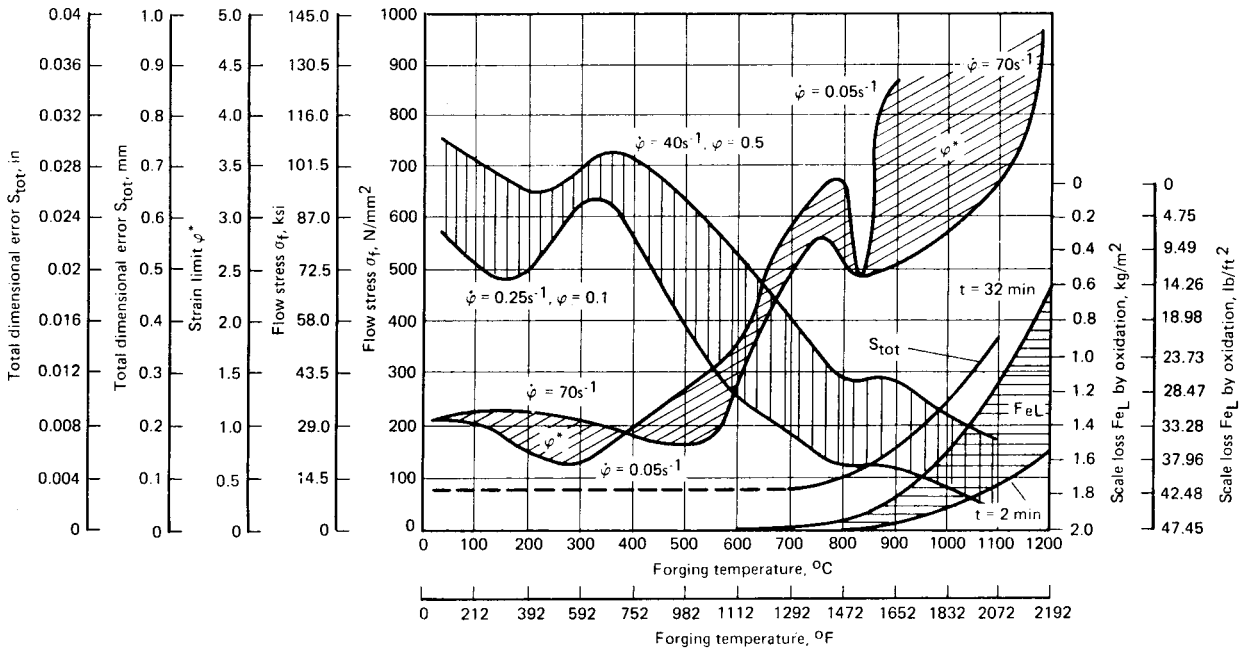
Fig. 13.2.3 Effect of forging temperature on forgeability and material properties. Material: AISI 1015 steel. ϕ = strain rate; ϕ^* = limiting strain; σ_f = flow stress; S_{tot} = dimensional error; Fe_L = scale loss. *(K. Lange, "Handbook of Metal Forming," McGraw-Hill, 1985.)*

temperature and for two different strain rates. The **flow stress** is the resistance to deformation. As the temperature rises from room temperature to 2,072°F (1,100°C), the flow stress decreases first gradually and then rapidly to about 25 percent of its value [cold working 114 ksi (786 MPa) and hot working 28 ksi (193 MPa) at a strain of 0.5 and strain rate of 40 per second].

One measure of workability is the **strain limit**. As the temperature rises, the strain limit for the 70-in (in · s) strain rate (typical of mechanical press forging) decreases slightly up to 500°C (932°F), rises until 750°C (1,382°F), drops rapidly at 800°C (1,472°F) (often called *blue brittleness*), and beyond 850°C (1,562°F) increases rapidly to hot forging temperature of 1,100°C (2,012°F). Therefore, substantial advantages of low material resistance (low tool pressures and press loads) and excellent workability (large flow without material failure) can be realized in the hot-working range. Hot-working temperatures, however, also mean poor dimensional tolerance (total dimensional error), poor surface finish, and material loss due to scale buildup. Forging temperatures above 1,300°C (2,372°F) can lead to **hot shortness** manifested by melting at the grain boundaries.

PLASTIC-WORKING TECHNIQUES

In the **metalworking** operations, as distinguished from metal cutting, material is forced to move into new shapes by plastic flow. **Hot-working** is carried on above the recovery temperature, and spontaneous recovery, or annealing, occurs about as fast as the properties of the material are altered by the deformation. This process is limited by the chilling of the material in the tools, scaling of the material, and the life of the tools at the required temperatures. **Cold-working** is carried on at room temperature and may be applied to most of the common metals. Since, in most cases, no recovery occurs at this temperature, the properties of the metal are altered in the direction of increasing strength and brittleness throughout the working process, and there is consequently a limit to which cold-working may be carried without danger of fracture.

A convenient way of representing the action of the common metals when cold-worked consists of plotting the actual stress in the material against the percentage reduction in thickness. Within the accuracy required for shop use, the relationship is linear, as in Fig. 13.2.4. The

lower limit of stress shown is the yield point at the softest temper, or anneal, commercially available, and the upper limit is the limit of tensile action, or the stress at which fracture, rather than flow, occurs. This latter value does not correspond to the commercially quoted "tensile strength" of the metal, but rather to the "true tensile strength," which is the stress that exists at the reduced section of a tensile specimen at fracture and which is higher than the nominal value in inverse proportion to the reduction of area of the material.
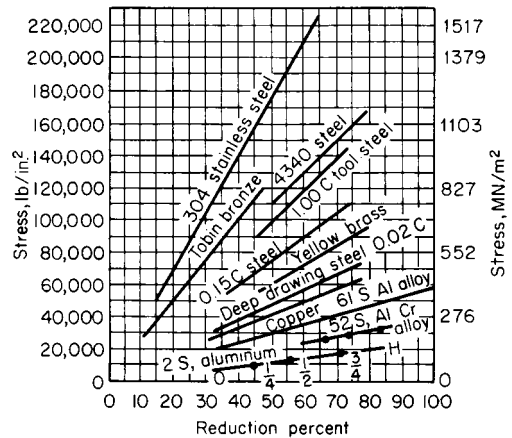
Fig. 13.2.4 Plastic range chart of commonly worked metals.

As an example of the construction and use of the cold-working plots shown in Fig. 13.2.4, the action of a very-low-carbon deep-drawing steel has been shown in Fig. 13.2.5. Starting with the annealed material with a yield point of 35,000 lb/in² (240 MN/m²), the steel was drawn to successive reductions of thickness up to about 58 percent, and the corresponding stresses plotted as the heavy straight line. The entire graph was then extrapolated to 100 percent reduction, giving the **modu-**

lus of strain hardening as indicated, and to zero stress so that all materials might be plotted on the same graph. Lines of equal reduction are slanting lines through the point marking the modulus of strain hardening at theoretical 100 percent reduction. Starting at any initial condition of previous cold work on the heavy line, a percentage reduction from this condition will be indicated by a horizontal traverse to the slanting reduction line of corresponding magnitude and the resulting increase in stress by the vertical traverse from this point to the heavy line.
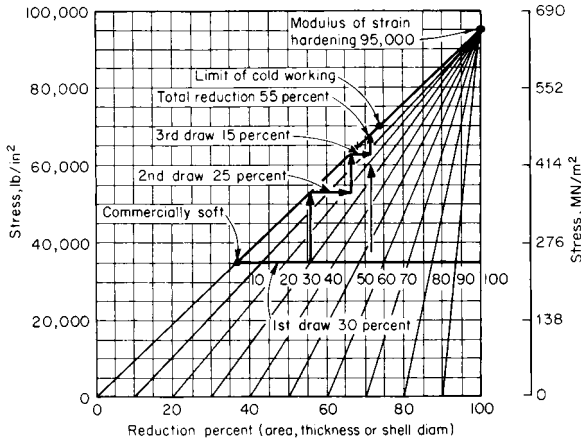

Fig. 13.2.5 Graphical solution of a metalworking problem.

The traverse shown involved three draws from the annealed condition of 30, 25, and 15 percent each, and resulting stresses of 53,000, 63,000, and 68,000 lb/in² (365, 434, and 469 MN/m²). After the initial 30 percent reduction, the next 25 percent uses $(1.00 - 0.30) \times 0.25$, or 17.5 percent more of the cold-working range; the next 15 percent reduction

uses $(1.00 - 0.30 - 0.175) \times 0.15$, or about 8 percent of the original range, totaling $30 + 17.5 + 8 = 55.5$ percent. This may be compared with the test value percent reduction in area for the particular material. The same result might have been obtained, die operation permitting, by a single reduction of 55 percent, as shown. Any appreciable reduction beyond this point would come dangerously close to the limit of plastic flow, and consequently an anneal is called for before any further work is done on the piece.

Figure 13.2.6 shows the approximate **true stress** vs. **true strain** plot of common plastic range values, for comparison with Fig. 13.2.4. In metal forming, a convenient way of representing the resistance of metal to deformation and flow is the **flow stress** σ, also known as the **logarithmic stress** or **true stress**. For most metals, flow stress is a function of the amount of deformation at cold-working temperatures (strain $\bar{\varepsilon}$) and the deformation rate at hot-working temperatures (strain rate $\dot{\bar{\varepsilon}}$). This relationship is often given as a power-law curve; $\sigma = K\bar{\varepsilon}^n$ for cold forming and $\sigma = C\dot{\bar{\varepsilon}}^m$ for hot forming. For commonly used materials, the values of the strength coefficients K and C and hardening coefficients n and m are given in Tables 13.2.1a and b.

A practical manufacturing method of judging relative plasticity is to compute the ratio of initial yield point to the ultimate tensile strength as developed in the tensile test. Thus a General Motors research memo listed steel with a 0.51 **yield/tensile ratio** [22,000 lb/in² (152 MN/m²) yp/43,000 lb/in² (296 MN/m²) ultimate tensile strength] as being suitable for really severe draws of exposed parts. When the ratio reaches about 0.75, the steel should be used only for flat parts or possibly those with a bend of not more than 90°. The higher ratios obviously represent a narrowing range of workability or residual plasticity.

ROLLING OPERATIONS

Rolling of sheets, coils, bars, and shapes is a primary process using plastic ranges both above and below recrystallization to prepare metals for further working or for fabrication. Metal squeezed in the bit area of
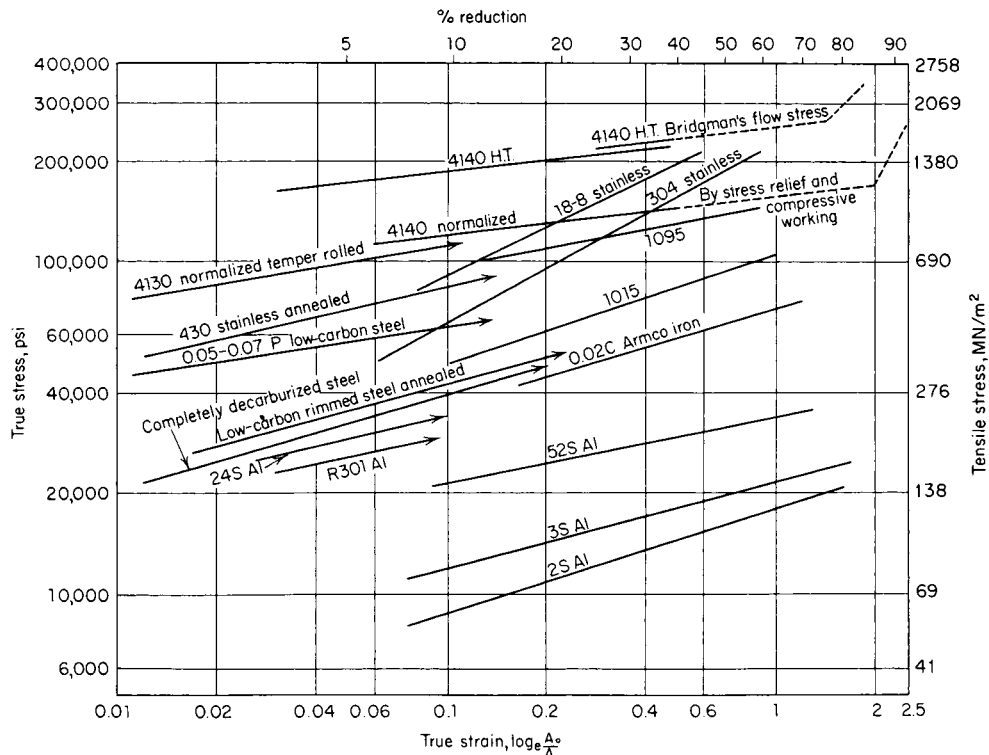

Fig. 13.2.6 True stress vs. true strain curves for typical metals. *(Crane and Hauf, E. W. Bliss Co.)*

Table 13.2.1a   Manufacturing Properties of Steels and Copper-Based Alloys*
(Annealed condition)

Designation and composition, %	Liquidus/ solidus, °C	Usual temp., °C	Flow stress,† MPa			Workability‡	Flow stress,§ MPa		$\sigma_{0.2}$, MPa	TS, MPa	Elongation, %	q R.A., %	Annealing temp.,¶ °C
			at °C	C	m		K	n					
Steels:													
1008 (0.08 C), sheet	<1,250		1,000	100	0.1	A	600	0.25	180	320	40	70	850–900 (F)
1015 (0.15 C), bar	<1,250		800	150	0.1	A	620	0.18	300	450	35	70	850–900 (F)
			1,000	120	0.1								
			1,200	50	0.17								
1045 (0.45 C)	<1,150		800	180	0.07	A	950	0.12	410	700	22	45	790–870 (F)
			1,000	120	0.13								
~ 8620 (0.2 C, 1 Mn 0.4 Ni, 0.5 Cr, 0.4 Mo)			1,000	120	0.1	A			350	620	30	60	
D2 tool-steel (1.5 C, 12 Cr, 1 Mo)	900–1,080		1,000	190	0.13	B	1,300	0.3					880 (F)
H13 tool steel (0.4 C, 5 Cr 1.5 Mo, 1 V)			1,000	80	0.26	B							
302 ss (18 Cr, 9 Ni) (austenitic)	1,420/1,400	930–1,200	1,000	170	0.1	B	1,300	0.3	250	600	55	65	1,010–1,120 (Q)
410 ss (13 Cr) (martensitic)	1,530/1,480	870–1,150	1,000	140	0.08	C	960	0.1	280	520	30	65	650–800
Copper-base alloys:													
Cu (99.94%)	1,083/1,065	750–950	600	130 (48)	0.06 (0.17)	A	450	0.33	70	220	50	78	375–650
			900	41	0.2								
Cartridge brass (30 Zn)	955/915	725–850	600	100	0.24	A	500	0.41	100	310	65	75	425–750
			800	48	0.15								
Muntz metal (40 Zn)	905/900	625–800	600	38	0.3	A	800	0.5	120	380	45	70	425–600
			800	20	0.24								
Leaded brass (1 Pb, 39 Zn)	900/855	625–800	600	58	0.14	A	800	0.33	130	340	50	55	425–600
			800	14	0.20								
Phosphor bronze (5 Sn)	1,050/950		700	160	0.35	C	720	0.46	150	340	57		480–675
Aluminum bronze (5 Al)	1,060/1,050	815–870				A			170	400	65		425–850

* Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B, J. Eng. Ind.* **95**, 1973, p. 1009.
† Hot-working flow stress is for a strain of $\varepsilon = 0.5$. To convert to 1,000 lb/in², divide calculated stresses by 7.
‡ Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.
§ Cold-working flow stress is for moderate strain rates, around $\varepsilon = 1\ s^{-1}$. To convert to 1,000 lb/in², divide stresses by 7.
¶ Furnace cooling is indicated by F, quenching by Q.
SOURCE: Adapted from John A. Schey, *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1987.

Table 13.2.1b   Manufacturing Properties of Various Nonferrous Alloys[a]
(Annealed condition, except 6061-T6)

Designation and composition, %	Liquidus/ solidus, °C	Usual temp., °C	Flow stress,[b] MPa at °C	C	m	Workability[f]	Flow stress,[c] MPa K	n	$\sigma_{0.2}$, MPa	TS,[d] MPa	Elongation,[d] %	q R.A., %	Annealing temp.[e] °C
			Hot-working				Cold-working						
Light metals:													
1100 Al (99%)	657/643	250–550	300 500	60 14	0.08 0.22	A	140	0.25	35	90	35		340
Mn alloy (1 Mn)	649/648	290–540	400	35	0.13	A			100	130	14		370
~ 2017 Al (3.5 Cu, 0.5 Mg, 0.5 Mn)	635/510	260–480	400 500	90 36	0.12 0.12	B	380	0.15	100	180	20		415 (F)
5052 Al (2.5 Mg)	650/590	260–510	480	35	0.13	A	210	0.13	90	190	25		340
6061-0 (1 Mg, 0.6 Si, 0.3 Cu)	652/582	300–550	400 500	50 37	0.16 0.17	A	220	0.16	55	125	25	65	415 (F)
6061-T6	NA[g]	NA	NA	NA	NA	NA	450	0.03	275	310	8	45	
~ 7075 Al (6 Zn, 2 Mg, 1 Cu)	640/475	260–455	450	40	0.13	B	400	0.17	100	230	16		415
Low-melting metals:													
Sn (99.8%)	232	100–200				A				15	45	100	150
Pb (99.7%)	327	20–200	100	10	0.1	A				12	35	100	20–200
Zn (0.08% Pb)	417	120–275	75 225	260 40	0.1 0.1	A				130/170	65/50		100
High-temperature alloys:													
Ni (99.4 Ni + Co)	1,446/1,435	650–1250				A	140			440	45	65	650–760
Hastelloy × (47 Ni, 9 Mo, 22 Cr, 18 Fe, 1.5 Co; 0.6 W)	1,290	980–1200	1,150	~ 140	0.2	C			360	770	42		1,175
Ti (99%)	1,660	750–1,000	600 900	200 38	0.11 0.25	C A			480	620	20		590–730
Ti–6 Al–4 V	1,660/1,600	790–1,000	600 900	550 140	0.08 0.4	C A			900	950	12		700–825
Zirconium	1,852	600–1,000	900	50	0.25	A			210	340	35		500–800
Uranium (99.8%)	1,132	~ 700	700	110	0.1				190	380	4	10	

[a] Empty spaces indicate unavailability of data. Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B. J. Eng. Ind.* **95**, 1973, p. 1009.
[b] Hot-working flow stress is for a strain of $\varepsilon = 0.5$. To convert to 1,000 lb/in^2, divide calculated stresses by 7.
[c] Cold-working flow stress is for moderate strain rates, around $\dot{\varepsilon} = 1$ s^1. To convert to 1,000 lb/in^2, divide stresses by 7.
[d] Where two values are given, the first is longitudinal, the second transverse.
[d] Furnace cooling is indicated by F.
[f] Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.
[g] NA = Not applicable to the − T6 temper.
SOURCE: Adapted from John A. Schey, *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1987.

the rolls moves out lengthwise with very little spreading in width. This compressive working above the yield point of the metal may be aided in some cases by maintaining a substantial tensile strain in the direction of rolling.

A cast or forged billet or slab is preheated for the preliminary break-down stage of rolling, although considerable progress has been made in continuous casting, in which the molten metal is poured continuously into a mold in which the metal is cooled progressively until it solidifies (albeit still at high temperature), whence it is drawn off as a quasi-continuous billet and fed directly into the first roll pass of the rolling mill. The increased speed of operation and production and the increased efficiency of energy consumption are obvious. Most new mills, especially minimills, have incorporated continuous casting as the normal method of operation. A reversing hot mill may achieve 5,000 percent elongation of an original billet in a series of manual or automatic passes. Alternatively, the billet may pass progressively through, say, 10 hot mills in rapid succession. Such a production setup requires precise control so that each mill stand will run enough faster than the previous one to make up for the elongation of the metal that has taken place. Hot-rolled steel may be sold for many purposes with the black mill scale on it. Alternatively, it may be acid-pickled to remove the scale and treated with oil or lime for corrosion protection. To prevent scale from forming in hot-rolling, a nonoxidizing atmosphere may be maintained in the mill area, a highly special plant design.

Pack rolling of a number of sheets stacked together provides means of retaining enough heat to hot-roll thin sheets, as for high-silicon electric steels.

Cold-rolling is practical in production of thin coil stock with the more ductile metals. The number of passes or amount of reduction between anneals is determined by the rate of work hardening of the metal. Successive stands of cold-rolling help to retain heat generated in working. Tension provided by mill reels and between stands helps to increase the practical reduction per step. Bright annealing in a controlled atmosphere avoids surface pockmarks, which are difficult to get out. For high-finish stock, the rolls must be maintained with equal finish.

Protective coating is best exemplified by high-speed tinplate mills in which coil stock passes continuously through the necessary series of cleaning, plating, and heating steps. Zinc and other metals are also applied by plating but not on the same scale. **Clad** sheets (high-strength aluminum alloys with pure aluminum surface for protection against electrolytic oxidation) are produced by rolling together; e.g., an alloy-aluminum billet is hot-rolled together with plates of pure aluminum above and below it through a series of reducing passes, with precautions to ensure clean adhesion.

On the other hand, prevention of adhesion, as by a separating film, is essential in the final stages of **foil rolling,** where two coils may have to be rolled together. Such foil may then be **laminated** with suitable adhesive to paper backing materials for wrapping purposes. (See also Sec. 6.)

Shape-rolling of structural shapes and rails is usually a **hot** operation with roll-pass contours designed to distribute the displacement of metal in a series of steps dictated largely by experience. **Contour rolling** of relatively thin stock into tubular, channel, interlocking, or varied special cross sections is usually done cold in a series of roll stands for lengthwise bending and setting operations. There is also a wide range of simple bead-rolling, flange-rolling, and seam-rolling operations in relatively thin materials, especially in connection with the production of barrels, drums, and other containers.

Oscillating or **segmental rolling** probably developed first in the manually fed contour rolling of agricultural implements. In some cases, the suitably contoured pair of roll inserts or roll dies oscillates before the operator, to form hot or cold metal. In other cases, the rolls rotate constantly, toward the operator. The working contour takes only a portion of the circumference, so that a substantial clearance angle leaves a space between the rolls. This permits the operator to insert the blank to the tong grip between the rolls and against a fixed gage at the back. Then, as rotation continues, the roll dies grip and form the blank, moving it back to the operator. This process is sometimes automated; such units as **tube-reducing mills** oscillate an entire rolling-mill assembly and

feed the work over a mandrel and into the contoured rolls, advancing it and possibly turning it between reciprocating strokes of the roll stands for cold reduction, improved concentricity, and, if desired, the tapering or forming of special sections.

Spinning operations (Fig. 13.2.7) apply a rolling-point pressure to relatively limited-lot production of cup, cone, and disk shapes, from floor lamps and TV tube housings to car wheels and large tank ends. Where substantial metal thickness is required, powerful machines and hydraulic servo controls may be used. Some of the large, heavy sections and difficult metals are spun hot.
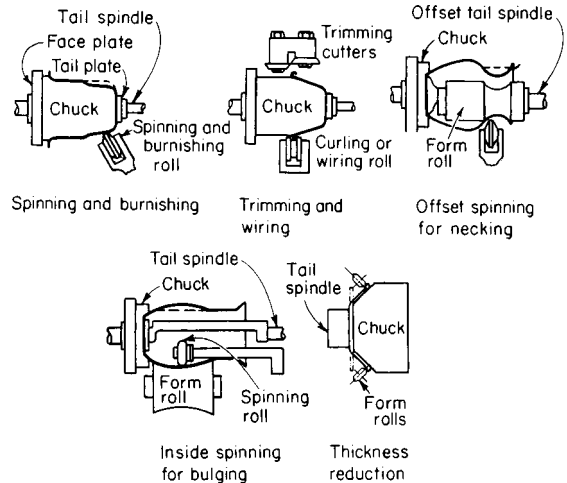

Fig. **13.2.7** Spinning operations.

Rolling operations are distinguished by the relatively rapid and continuous application of working pressure along a limited line of contact. In determining the working area, consider the lineal dimension (width of coil), the bit or reduction in thickness, and the roll-face deflection, which tends to increase the contact area. Approximations of rolling-mill load and power requirements have been worked out in literature of the AISE and ASME.

SHEARING

The shearing group of operations includes such **power press operations** as blanking, piercing, perforating, shaving, broaching, trimming, slitting, and parting. Shearing operations traverse the entire plastic range of metals to the point of failure.

The maximum pressure P, in pounds, required in shearing operations is given by the equation $P = \pi DtS = Lts$, where s is the resistance of the material to shearing, lb/in^2; t is the thickness of the material, in; L is the length of cut, in, which is the circumference of a round blank πD or the periphery of a rectangular or irregular blank. Approximate values of s are given in Table 13.2.2.

Shear (Fig. 13.2.8) is the advance of that portion of the shearing edge which first comes in contact with the material to be sheared over the last portion to establish contact, measured in the direction of motion. It should be a function of the thickness t. Shear reduces the maximum pressure because, instead of shearing the whole length of cut at once, the shearing action takes place progressively, shearing on only a portion of the length at any instant. The maximum pressure for any case where the shear is equal to or greater than t is given by $P_{max} = P_{av} t/\text{shear}$, where P_{av} is the average value of the pressure on a punch, with shear = t, from the time it strikes the metal to the time it leaves.

Distortion results from shearing at an angle (Fig. 13.2.8) and accordingly, in blanking, where the blank should be flat, the punch should be flat, and the shear should be on the die. Conversely, in hole punching, where the scrap is punched out, the die should be flat and the shear

**Table 13.2.2   Approximate Resistance to Shearing in Dies**

Material	Annealed state		Hard, cold-worked	
	Resistance to shearing, lb/in²*	Penetration to fracture, percent	Resistance to shearing, lb/in²*	Penetration to fracture, percent
Lead	3,500	50	Anneals at room temperature	
Tin	5,000	40	Anneals at room temperature	
Aluminum 2S, 3S	9,000–11,000	60	13,000–16,000	30
Aluminum 52S, 61S, 62S	12,000–18,000	· · ·	24,000–30,000	
Aluminum 75S	22,000	· · ·	46,000	
Zinc	14,000	50	19,000	25
Copper	22,000	55	28,000	30
Brass	33,000–35,000	50–55	52,000	25–30
Bronze 90–10	· · ·	· · ·	40,000	
Tobin bronze	36,000	25	42,000	
Steel 0.10C	35,000	50	43,000	38
Steel 0.20C	44,000	40	55,000	28
Steel 0.30C	52,000	33	67,000	22
Steel 0.40C	62,000	27	78,000	17
Steel 0.60C	80,000	20	102,000	9
Steel 0.80C	97,000	15	127,000	5
Steel 1.00C	115,000	10	150,000	2
Stainless steel	57,000	39		
Silicon steel	65,000	30		
Nickel	35,000	55		

*1,000 lb/in² = 6.895 MN/m².

NOTE: Available test data do not agree closely. The above table is subject to verification with closer control of metal analysis, rolling and annealing conditions, die clearances. In dinking dies, steel-rule dies, hollow cutters, etc., cutting-edge resistance is substantially independent of thickness: cotton glove cloth (stack, 2 or 3 in thick), 240 lb/in; kraft paper (stack tested, 0.20 in thick), 385 lb/in, celluloid [¹¹⁄₃₂ in thick, warmed in water to 120 to 150°F (49 to 66°C)], 300 lb/in.

should be on the punch. Where there are a number of punches, the effect of shear may be obtained by stepping the punches.

Crowding results during the plastic deformation period, before the fracture occurs, in any shearing operation. Accordingly, when small delicate punches are close to a large punch, they should be stepped shorter than the large punch by at least a third of the metal thickness.
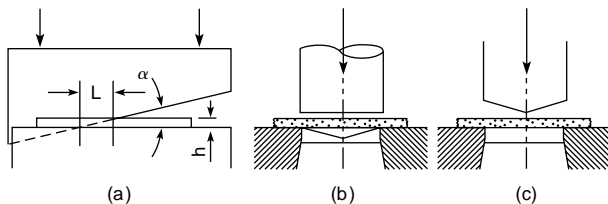
α = shearing angle
$t = h$ = thickness of sheet
L = shearing length

Fig. 13.2.8 Shearing forces can be reduced by providing a rake or shear on (*a*) the blades in a guillotine, (*b*) the die in blanking, (*c*) the punch in piercing. (*J. Schey, ''Introduction to Manufacturing Processes,'' McGraw-Hill, 1987.*)

Clearance between the punch and die is required for a clean cut and durability. An old rule of thumb places the clearance all around the punch at 8 to 10 percent of the metal thickness for soft metal and up to 12 percent for hard metal. Actually, hard metal requires less clearance for a clean fracture than soft, but it will stand more. In some cases, with delicate punches, clearance is as high as 25 percent. Where the hole diameter is important, the punch should be the desired diameter and the clearance should be added to the die diameter. Conversely, where the blank size is important, the die and blank dimensions are the same and clearance is deducted from the punch dimensions.

The **work per stroke** may be approximated as the product of the maximum pressure and the metal thickness, although it is only about 20 to 80 percent of that product, depending upon the clearance and ductility of the metal. Reducing the clearance causes secondary fractures and increases the work done. With sufficient clearance for a clean fracture, the work is a little less than the product of the maximum pressure, the metal thickness, and the percentage reduction in thickness at which the fracture occurs. Approximate values for this are given in Table 13.2.2. The **power required** may be obtained from the work per stroke plus a 10 to 20 percent friction allowance.

Shaving A sheared edge may be squared up roughly by shaving once, allowing for the shaving of mild sheet steel about 10 percent of the metal thickness. This allowance may be increased somewhat for thinner material and should be decreased for thicker and softer material. In making several cuts, the amount removed is reduced each time. For extremely fine finish a round-edged burnishing die or punch, say 0.001 or 0.0015 in tight, may be used. Aluminum parts may be blanked (as for impact extrusion) with a fine finish by putting a 30° bevel, approx one-third the metal thickness on the die opening, with a near metal-to-metal fit on the punch and die, and pushing the blank through the highly polished die.

Squaring shears for sheet or plate may have their blades arranged in either of the ways shown in Fig. 13.2.9. The square-edged blades in Fig. 13.2.9*a* may be reversed to give four cutting edges before they are reground. Single-edged blades, as shown in Fig. 13.2.9*b*, may have a clearance angle on the side where the blades pass, to reduce the working friction. They may also be ground at an angle or rake, on the face which comes in contact with the metal. This reduces the bending and conse-
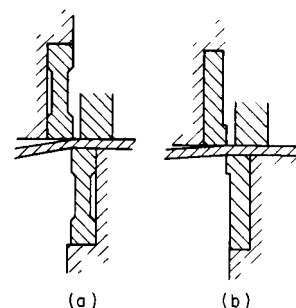

Fig. 13.2.9 Squaring shears.

quent distortion at the edge. Either type of blade distorts also in the other direction owing to the angle of shear on the length of the blades (see Fig. 13.2.8). Cutting speed is 3 to 30 ft/min (1 to 10 m/min), depending in part upon the thickness of the material.

Circular cutters for slitters and circle shears may also be square-edged (on most slitters) or knife-edged (on circle shears). According to one rule, their diameter should be not less than 70 times the metal thickness. Cutting speeds vary from 50 to 200 ft/min (17 to 65 m/min), depending largely upon metal thickness (inverse proportion).

Knife-edge hollow cutters working against end-grain maple blocks represent an old practice in cutting leather, rubber, and cloth in multiple thicknesses. **Steel-rule dies,** made up of knife-edge hard-steel strip economically mounted against a steel plate in a wood matrix with rubber strippers and cutting against hard saw-steel plates, extend the practice to corrugated-carton production and even some limited-lot metal cutting.

Higher precision is often required in **finish shearing** operations on sheet material. For ease of subsequent operations and assembly, the cut edges should be clean (acceptable burr heights and good surface finish) and perpendicular to the sheet surface. The processes include precision or fine blanking, negative clearance blanking, counterblanking, and shaving, as shown in Fig. 13.2.10. By these methods either the plastic behavior of material is suppressed, or the plastically deformed material is removed.
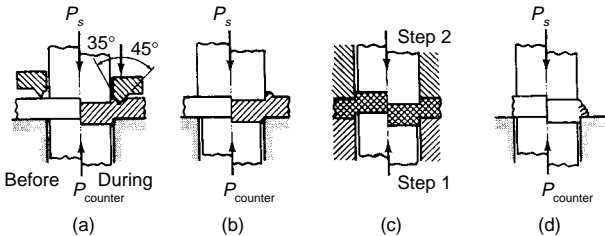
Fig. 13.2.10 Parts with finished edges can be produced by (a) precision blanking, (b) negative-clearance blanking, (c) counterblanking, (d) shaving a previously sheared part. (J. Schey, ''Introduction to Manufacturing Processes,'' McGraw-Hill, 1987.)

BENDING

The bending group of operations is performed in **presses** (variety), **brakes** (metal furniture, cornices, roofing), **bulldozers** (heavy rolled sections), **multiple-roll forming machines** (molding, etc.), **draw benches** (door trim, molding, etc.), **forming rolls** (cylinders), and **roll straighteners** (strips, plates).

Spring back, due to the elasticity of the metal and amount of the bend, may be compensated for by overbending or largely prevented by striking the metal at the radius with a **coining** (i.e., squeezing, as in production of coins) pressure sufficient to set up compressive stresses to counterbalance surface tensile stresses. A very narrow bead may be used to localize the pinch where needed and minimize danger to the press in squeezing on a large area. Under such conditions, good sharp bends in V dies have been obtained with two to four times the pressure required to shear the metal across the same section.

These are illustrated in Fig. 13.2.11, where P_b is the **bending load** on the press brake, W_b is the width of the die support, and P_{counter} is the counterload. The bending load can be obtained from

$$P_b = wt^2(\text{UTS})/W_b$$

where t and w are the sheet thickness and width, respectively, and UTS is the ultimate tensile strength of the sheet material.

Bending Allowance The thickness of the metal over a small radius or a sharp corner is 10 or 15 percent less than before bending because the metal moves more easily in tension than in compression. For the same reason the neutral axis of the metal moves in toward the center of the corner radius. Therefore, in figuring the length of blank L to be allowed for the bend up to an inside radius r of two or three times the
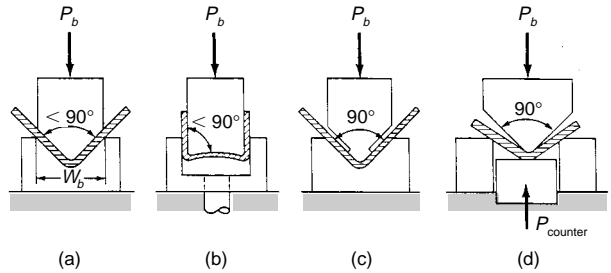
Fig. 13.2.11 Springback may be neutralized or eliminated by (a), (b) overbending; (c) plastic deformation at the end of the stroke; (d) subjecting the bend zone to compression during bending. [Part (d) after V. Kupka, T. Nakagawa, and H. Tyamoto, CIRP 22:73–74 (1973).] (Source: J. Schey, ''Introduction to Manufacturing Processes,'' McGraw-Hill, 1987.)

metal thickness t, the length may be figured closely as along a neutral line at $0.4t$ out from the inside radius. Thus, with reference to Fig. 13.2.12, for any angle a in deg and other dimensions in inches, $L = (r + 0.4t)2\pi a/360 = (r + 0.4t)a/57.3$.

The factor $0.4t$, which locates the neutral axis, is subject to some variation (say 0.35 to $0.45t$) according to radius, condition of metal, and angle. In figuring allowances for sharp bends, note that the metal builds up on the compression side of the corner. Therefore, in locating the neutral axis consider an inside radius r of about $0.05t$ as a minimum.

Roll straighteners work on the principle of bending the metal beyond its elastic limit in one direction over rolls small enough in diameter, in proportion to the metal thickness, to give a permanent set, and then

Fig. 13.2.12 Bending allowance.

taking that bend out by repeatedly reversing it in direction and reducing it in amount. Metal is also straightened by gripping and stretching it beyond its elastic limit and by hammering; the results of the latter operation depend entirely upon the skill of the operator.
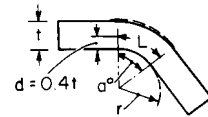
For approximating **bending loads,** the beam formula may be used but must be very materially increased because of the short spans. Thus, for a span of about 4 times the depth of section, the bending load is about 50 percent more than that indicated by the beam formula. It increases from this to nearly the shearing resistance of the section where some **ironing** (i.e., the thinning of the metal when clearance between punch and die is less than the metal thickness) occurs. Where hit-home dies do a little coining to ''set'' the bend, the pressure may range from two or three times the shearing resistance, with striking beads and proper care, up to very much higher figures.

The work to roll-bend a sheet or plate t in thick with a volume of V in^3, into curved shape of radius r in, is given as $W = CS(t/r)V/48$ ft · lb, in which S is the tensile strength and C is an experience factor between 1.4 and 2.

The **equipment for bending** consists of mechanical presses for short bends, press brakes (mechanical and hydraulic) for long bends, and roll formers for continuous production of profiles. The bends are achieved by bending between tools, wiping motion around a die corner, or bending between a set of rolls. These bending actions are illustrated in Fig. 13.2.13. Complex shapes are formed by repeated bending in simple tooling or by passing the sheet through a series of rolls which progressively bend it into the desired profile. Roll forming is economical for continuous forming for large production volume. Press brakes can be computer-controlled with synchronized feeding and bending as well as spring-back compression.

DRAWING

Drawing includes operations in which metal is pulled or drawn, in suitable containing tools, from flat sheets or blanks into cylindrical cups or rectangular or irregular shapes, deep or shallow. It also includes reduc-
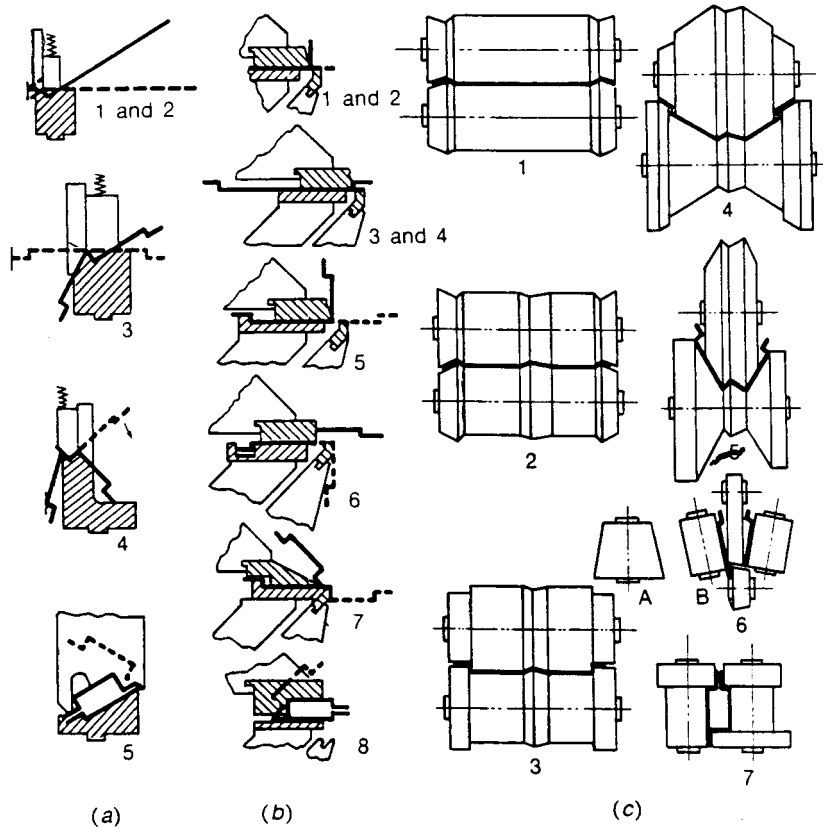
Fig. 13.2.13   Complex profiles formed by a sequence of operations on (*a*) press brakes, (*b*) wiping dies, (*c*) profile rolling. *(After Oehler; Biegen, Hanser Verlag, Munich, 1963.) Source: J. Schey, ''Introduction to Manufacturing Processes,'' McGraw-Hill, 1987.*

ing operations on shells, tube, wire, etc., in which the metal being drawn is pulled through dies to reduce the diameter or size of the shape. All drawing and reducing operations, by an applied tensile stress in the material, set up circumferential compressive stresses which crowd the metal into the desired shape. The relation of the shape or diameter before drawing to the shape or diameter after drawing determines the magnitude of the stresses. Excessive draws or reductions cause thinning or tearing out near the bottom of a shell. Severe cold-drawing operations require very ductile material and, in consequence of the amount of plastic deformation, harden the metal rapidly and necessitate annealing to restore the ductility for further working.

The **pressure used in drawing** is limited to the load to shear the bottom of the shell out, except in cases where the side wall is ironed thinner, when wall friction makes somewhat higher loads possible. It is less than this limit for round shells which are shorter than the limiting height and also for rectangular shells. Drawing occurs only around the corner radii of rectangular shells, the straight sides being merely free bending.

A **holding pressure** is required in most initial drawing and some redrawing, to prevent the formation of wrinkles due to the circumferential compressive stresses. Where the blank is relatively thin compared with its diameter, the blank-holding pressure for round work is likely to vary up to about one-third of the drawing pressure. For material heavy enough to provide sufficient internal resistance to wrinkling, no pressure is required. Where a drawn shape is very shallow, the metal must be stretched beyond its elastic limit in order to hold its shape, making it necessary to use higher blank-holding loads, often in excess of the drawing pressure. To grip the edges sufficiently to do this, it is often advisable to use **draw beads** on the blank-holding surfaces if sufficient pressure is available to form these beads.

In sheet/deep-drawing practice, the punch force P can be approximated by

$$P = \pi D_p t_0 (\text{UTS})(D_0/D_p - 0.7)$$

where t_0 is the blank thickness and D_0 and D_p are the diameters of the blank and the punch.

The blank holder pressure for avoiding defects such as wrinkling of bottom/wall tear-out is kept at 0.7 to 1.0 percent of the sum of the yield and the UTS of the material. Punch/die clearances are chosen to be 7 to 14 percent greater than the sheet blank thickness t_0. The die corner radii are chosen to avoid fracture at the die corner from puckering or wrinkling. Recommended values of D_0/t_0 for deep-drawn cups are 6 to 15 for cups without flange and 12 to 30 for cups with flange. These values will be smaller for relatively thick sheets and larger for very thin blank thickness. For deeper-drawn cups, they may be redrawn or reverse-drawn, the latter process taking advantage of strain softening on reverse drawing. When the material has marked strain-hardening propensities, it may be necessary to subject it to an intermediate annealing process to restore some of its ductility and to allow progression of the draws to proceed.

Some shells, which are very thick or very shallow compared with their diameter, do not require a blank holder. Blank-holding pressure may be obtained through toggle, crank, or cam mechanisms built into the machine or by means of air cylinders, spring-pressure attachments, or rubber bumpers under the bolster plate. The length of car springs should be about 18 in/in (18 cm/cm) of draw to give a fairly uniform drawing pressure and long life. The use of car springs has been largely superseded by hydraulic and pneumatic cushions. Rubber bumpers may be figured on a basis of about 7.5 lb/in^2 (50 kN/m^2) of cross-sectional

area per 1 percent of compression. In practice they should never be loaded beyond 20 percent compression, and as with springs, the greater the length relative to the working stroke, the more uniform is the pressure.

Dimensions of Drawn Shells   The smallest and deepest round shell that can be drawn from any given blank has a diameter d of 65 to 50 percent of the blank diameter D. The height of these shells is $h = 0.35d$ to $0.75d$, approximately. Higher shells have occasionally been drawn with ductile material and large punch and die radii. Greater thickness of material relative to the diameter also favors deeper drawing.

The area of the bottom and of the side walls added together may be considered as equal to the area of the blank for approximations. If the punch radius is appreciable, the area of a neutral surface about $0.4t$ out from the inside of the shell may be taken for approximations. Accurate blank sizes may be obtained only by trial, as the metal tends to thicken toward the top edge and to get thinner toward the bottom of the shell wall in drawing.

Approximate diameters of blanks for shells are given by the expression $\sqrt{d^2 + 4dh}$, where d is the diameter and h the height of the shell.

In **redrawing** to smaller diameters and greater depths the amount of reduction is usually decreased in each step. Thus in double-action redrawing with a blank holder, the successive reductions may be 25, 20, 16, 13, 10 percent, etc. This progression is modified by the relative thickness and ductility of the metal. Single-action redrawing without a blank holder necessitates smaller steps and depends upon the shape of the dies and punches. The steps may be 19, 15, 12, 10 percent, etc. Smaller reductions per operation seem to make possible greater total reductions between annealings.

Rectangular shells may be drawn to a depth of 4 to 6 times their corner radius. It is sometimes desirable, where the sheet is relatively thin, to use draw beads at the corners of the shell or near reverse bends in irregular shapes to hold back the metal and assist in the prevention of wrinkles.

Work in drawing is approximately the product of the length of the draw, and the maximum punch pressure, as the load rises quickly to the peak, remains fairly constant, and drops off sharply at the end of the draw unless there is stamping or wall friction. To this, add the work of blank holding which, in the case of cam and toggle pressure, is the product of the blank-holding pressure and the spring of the press at the pressure (which is small). For single-action presses with spring, rubber, or air-drawing attachments it is the product of the average blank-holding pressure and the length of draw.

Rubber-die forming, especially of the softer metals and for limited-lot production, uses one relatively hard member of metal, plaster, or plastic with a hard powder filler to control contour. The mating member may be a rubber or neoprene mattress or a hydraulically inflatable bag, confined and at 3,000 to 7,000 lb/in^2 (20 to 48 MN/m^2). Babbitt, oil, and water have also been used directly as the mobile member. A large hydraulic press is used, often with a sliding table or tables, and even static containers with adequate pumping systems.

Hot drawing above the recrystallization range applies single- and double-action drawing principles. For light gages of plastics, paper, and hexagonal-lattice metals such as magnesium, dies and punches may be heated by gas or electricity. For thick steel plate and heat-treatable alloys, the mass of the blank may be sufficient to hold the heat required.

Lubricants for Presswork   Many jobs may be done dry, but better results and longer life of dies are obtained by the use of a lubricant. Lard or sperm oil is used when punching iron, steel, or copper. Petroleum jelly is used for drawing aluminum. A soap solution is commonly used for drawing brass, copper, or steel. One manufacturer uses 90 percent mineral oil, 5 percent rosin, and 5 percent oleic acid for light work and an emulsion of a mineral oil, degras, and a pigment consisting of chalk, sulfur, or lithopone for heavy work. (See also Sec. 6.)

For heavy drawing operations and extrusion, steels may have a zinc phosphate coating bonded on, and a zinc or sodium stearate bonded to that, to withstand pressures over 300,000 lb/in^2 (2,070 MN/m^2). An

Table 13.2.3   Typical Lubricants* and Friction Coefficients in Plastic Deformation

Workplace material	Working	Forging Lubricant	μ	Extrusion† lubricant	Wire drawing Lubricant	μ	Rolling Lubricant	μ	Sheet metalworking Lubricant	μ
Sn, Pb, Zn alloys		FO-MO	0.05	FO or soap	FO	0.05	FA-MO or MO-EM	0.05 0.1	FO-MO	0.05
Mg alloys	Hot or warm	GR and/or MoS$_2$	0.1–0.2	None			MO-FA-EM	0.2	GR in MO or dry soap	0.1–0.2
Al alloys	Hot	GR or MoS$_2$	0.1–0.2	None			MO-FA-EM	0.2		
	Cold	FA-MO or dry soap	0.1 0.1	Lanolin or soap on PH	FA-MO-EM, FA-MO	0.1 0.03	1–5% FA in MO(1–3)	0.03	FO, lanolin, or FA-MO-EM	0.05–0.1
Cu alloys	Hot	GR	0.1–0.2	None (or GR)			MO-EM	0.2		
	Cold	Dry soap, wax, or tallow	0.1	Dry soap or wax or tallow	FO-soap-EM, MO	0.1 0.03	MO-EM	0.1	FO-soap-EM or FO-soap	0.05–0.1
Steels	Hot	GR	0.1–0.2	GL (100–300), GR			None or GR-EM	ST‡ 0.2	GR	0.2
	Cold	EP-MO or soap, on PH	0.1 0.05	Soap on PH	Dry soap or soap on PH	0.05 0.03	10% FO-EM	0.05	EP-MO, EM, soap, or polymer	0.05–0.1
Stainless steel, Ni and alloys	Hot	GR	0.1–0.2	GL (100–300)			None	ST‡	GR	0.2
	Cold	CL-MO or soap on PH	0.1 0.05	CL-MO or soap on PH	Soap on PH or CL-MO	0.03 0.05	FO-CL-EM or CL-MO	0.1 0.05	CL-MO, soap, or polymer	0.1
Ti alloys	Hot	GL or GR	0.2	GL (100–300)					GR, GL	0.2
	Cold	Soap or MO	0.1	Soap on PH	Polymer	0.1	MO	0.1	Soap or polymer	0.1

* Some more frequently used lubricants (hyphenation indicates that several components are used in the lubricant):
   CL = chlorinated paraffin
   EM = emulsion; listed lubricating ingredients are finely distributed in water
   EP = ''extreme-pressure'' compounds (containing S, Cl, and P)
   FA = fatty acids and alcohols, e.g., oleic acid, stearic acid, stearyl alcohol
   FO = fatty oils, e.g., palm oil and synthetic palm oil
   GL = glass (viscosity at working temperature in units of poise)
   GR = graphite; usually in a water-base carrier fluid
   MO = mineral oil (viscosity in parentheses, in units of centipoise at 40°C).
   PH = phosphate (or similar) surface conversion, providing keying of lubricant
† Friction coefficients are misleading for extrusion and therefore are not quoted here.
‡ The symbol ST indicates sticking friction.
SOURCE: John A. Schey, *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1987.

anodized coating for aluminum may be used as a host for the lubricant. It is reported that such a chemical treatment plus a lacquer or plastic coating and a lubricant is effective for severe ironing operations.

The problem is to prevent local pressure welding from starting as galling or pickup, with resulting scratching, by maintaining a fluid film separation between metal surfaces. At moderate pressures, almost any viscous liquid lubricant will do the job. Rust protection and easy removal of the lubricant are often major factors in the choice.

Lubricants for metalworking are often classified based on their interface friction coefficient, which depends on the workpiece material and the lubricant being used. The **interface friction coefficient** μ is often defined as the ratio of the friction force to the normal force at the interface. Typical values of μ for different workpiece-lubricant pairs are included in Table 13.2.3.

Shock-wave forming for limited lots is developing in several ways. **Explosive forming,** especially for large-area drawn or formed shapes, usually requires one metal contour-control die immersed in a large container of fluid, or even in a lake or pond. Explosives manufacturers have developed means of computing the charge and the distance that it should be suspended above the blank to be formed. The space back of the blank in the die has to be evacuated. A blank-holding ring to minimize wrinkle formation in the flange area is bolted very tightly to the die, with an O-ring seal to prevent leakage.

Electrohydraulic forming is similar to explosive forming except that the shock wave is imparted electrically from a large battery of capacitors. **Magnetic forming** uses the same source of power but does not require a fluid medium. A flexible pancake coil delivers the magnetic shock pulse.

usually the least severe of the squeezing group. Tolerances are ordinarily closer than for the milling operations which are supplanted. When extremely close tolerances are required, say plus or minus one-thousandth of an inch (0.025 mm), arrange substantial size blocks to take half or two-thirds of the total load. These take up uniformly the bearing-oil films and any slight deflection of the bed and bolster and minimize the error in springback due to variation in thickness, hardness, and area of the rough forging or casting. The usual amount left for squeezing is $\frac{1}{32}$ to $\frac{1}{16}$ in (0.8 to 1.6 mm). Presses may be selected for this service on a basis of 60 to 80 tons/in^2 (830 to 1,100 MN/m^2), although 100 tons/in^2 (1,380 MN/m^2) is more often used in the automobile trade for reserve capacities. When figuring from experimental results obtained in testing machines, the recorded loads are usually doubled in selecting a press, in order to allow for the difference among the speed of the machines, the positive action, and a safety margin.

Swaging or **cold forging** involves squeezing of the blank to an appreciably different shape. Success in performing such operations on steel usually depends upon squeezing a relatively small area with freedom to flow without restraint. Dies for this work must usually be substantially backed up with hardened steel plates. The edge of the blank after coining is usually ragged and must be trimmed for appearance.

Hot forging is similar in certain respects to the above but permits much greater movement of metal. Hot forging may be done in drop hammers, percussion presses, power presses, or forging machines, when dies are used, or in steam hammers, helve hammers, or hydraulic presses, on plain anvils.

The pressure exerted by hydraulic presses and steam hammer for jobbing work should be about as follows:

Ingot diam, in*	5	8	12	16	24	36	48	60	72
Press, tons†	100	200	400	600	1,000	1,500	2,000	3,000	4,000
Hammer, tons†	½	1	3	5	10	20	40	80	120

* 1 in = 2.54 cm.
† 1 ton = 8.9 kN.

BULK FORMING

The squeezing group of operations are those in which the metal is worked in compression. Resultant tensile strains occur, however; in cases where the metal is thin compared with its area and there is an appreciable movement of the metal, there results a pyramiding of pressure toward the center of the die which may prove serious. The metal is incompressible (beyond about 1 percent), and consequently, to reduce the thickness of any volume of metal in the center of the blank, its area must be increased, which involves spreading or stretching all the metal around it. The surrounding metal acts like shrunk bands and offers a resistance increasing toward the center and often many times the compressive resistance of the material.

Squeezing operations and particularly the squeezing of steel are practically the severest of all press operations. They may be divided into four general classifications according to severity, although in every group there will be found examples of working to the limit of what the die steels will stand, which may be taken at about 100 tons/in^2. The severer operations, such as cold bottom extrusion and wall extrusion, are limited to the softer metals. Squeezing operations ordinarily require pressure through a very short distance, the pressure starting at the compressive yield strength of the material over the surface being squeezed and rising to a maximum at bottom stroke. This maximum is greatest when the metal is thin compared with its area or when the die is entirely closed as for coining. Care must be taken, on all squeezing operations, in the setting of presses and avoidance of double blanks or extra-heavy blanks as the presses must be stiff. In squeezing solidly across bottom center the mechanical advantage is such that a small difference in thickness or setup can make a very large difference in pressure exerted. For this reason high-speed self-contained hydraulic presses, with automatic pressure-control and size blocks, are now finding favor for some of this work.

Sizing, or the flattening or surfacing of parts of forgings or castings, is

Drop hammers are rated according to weight of ram. For carbon steel they may be selected on a basis of 50 to 55 lb of ram weight per square inch of projected area (3.5 to 3.9 kg/cm^2) of the forging, including as much of the flash as is squeezed. This allowance should be increased to 60 lb/in^2 (4.2 kg/cm^2) for 0.20 carbon steel, 70 lb/in^2 (4.9 kg/cm^2) for 0.30 carbon steel, and up to about 130 lb/in^2 (9.2 kg/cm^2) for tungsten steel.

In figuring the **forging pressure,** multiply the projected area of the forging, including the portion of the flash that is squeezed, by approximately one-third of the cold compressive strength of the material. Another method gives the forging pressure at three to four times the compressive strength of the material at forging temperatures times the projected area, for presses; or at ten times the compressive strength at forging temperatures times the projected area, for hammers. The pressure builds up to a rather high figure at bottom stroke owing to the cooling of the metal particularly in the flash and to the small amount of relief for excess metal which the flash allows.

For **brass press forgings** a good mixture is about Cu, 59; Zn, 39; Pb, 2 percent forged at 1,300 to 1,400°F (700 to 760°C). The power curve in press forging rises sharply, from the compressive strength at forging heat times the projected area of the slug to three or more times that quantity at bottom stroke. A large flash area assists in driving the metal into deep die recess.

In **heading operations,** hot or cold, the length of wire or rod that can be gathered into a head, without side restraint, in a single operation, is limited to three times the diameter. In coining and then heading large heads, cold, wire of about 0.08 carbon must be used to avoid excessive strain-hardening.

Forging Dies   Drop-forge dies are usually of steel or steel castings. A good all-around grade of **steel** is a 0.60 percent carbon open-hearth. Dies of this steel will forge mild steel, copper, and tool steel satisfactorily if the number of forgings required is not too large. For a large

number of tool-steel forgings, tool-steel dies of 0.80 to 0.90 percent carbon may be used and for extreme conditions, 3½ percent nickel steel.

Die blocks of alloy steels have special value for the production of drop forgings in large quantities. Widely used die materials and their recommended hardness are listed in Table 13.2.4. For a typical hot-working steel, the relationship between the hardness and the UTS is

HRC	UTS, ksi (MPa)
30	140 (960)
40	185 (1,250)
50	250 (1,700)
60	350 (2,400)

The pressure on dies can be kept as high as 80 percent of the above values. For higher tool pressures, carbide (tungsten carbide is the most common) die material is used. Carbides can withstand very high compressive pressures but have poor tensile properties. Consequently, carbide dies and inserts are always kept under compression, often by the use of shrink rings. These are some design guidelines for punches and dies:

1. *Long punch.* The punch pressure should be kept below the buckling stress σ_b

$$\sigma_b = \sigma_y \left[1 - \left(\frac{4\sigma_y}{\pi^2 E} \right) \left(\frac{L_p}{D_p} \right)^2 \right]$$

where σ_y is the yield stress of the punch material, E the elastic modulus 30,000 ksi (210 GPa) for steel and 50,000 ksi (350 GPa) for tungsten carbide, L_p is the punch length and D_p is the punch diameter.

2. *Short punch.* The failure mode is plastic upset. Therefore, the punch pressure should be kept less than the yield stress of the punch

Table 13.2.4 Typical Die Materials for Deformation Processes*

Process	Al, Mg, and Cu alloys		Steels and Ni alloys	
	Die material† and HRC for working			
Hot forging	6G	30–40	6G	35–45
	H12	48–50	H12	40–56
Hot extrusion	H12	46–50	H12	43–47
Cold extrusion:				
Die	W1, A2	56–58	A2, D2	58–60
	D2	58–60	WC	
Punch	A2, D2	58–60	A2, M2	64–65
Shape drawing	O1	60–62	M2	62–65
	WC		WC	
Cold rolling	O1	55–65	O1, M2	56–65
Blanking	Zn alloy		As for Al, and	
	W1	62–66	M2	60–66
	O1	57–62	WC	
	A2	57–62		
	D2	58–64		
Deep drawing	W1	60–62	As for Al, and	
	O1	57–62	M2	60–65
	A2	57–62	WC	
	D2	58–64		
Press forming	Epoxy/metal powder		As for Al	
	Zn alloy			
	Mild steel			
	Cast iron			
	O1, A2, D2			

* Compiled from ''Metals Handbook,'' 9th ed., vol. 3, American Society for Metals, Metals Park, Ohio, 1980.

† Die materials mentioned first are for lighter duties, shorter runs. Tool steel compositions, percent (representative members of classes):

  6 G (prehardened die steel): 0.5 C, 0.8 Mn, 0.25 Si, 1 Cr, 0.45 Mo, 0.1 V
  H12 (hot-working die steel): 0.35 C, 5 Cr, 1.5 Mo, 1.5 W, 0.4 V
  W1 (water-hardening steel): 0.6–1.4 C
  O1 (oil-hardening steel): 0.9 C, 1 Mn, 0.5 Cr
  A2 (air-hardening steel): 1 C, 5 Cr, 1 Mo
  D2 (cold-working die steel): 1.5 C, 12 Cr, 1 Mo
  M2 (Mo high-speed steel): 0.85 C, 4 Cr, 5 Mo, 6.25 W, 2 V
  WC (tungsten carbide)

SOURCE: John A. Schey, *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1987.

material [180 ksi (1,200 MPa) for steel and 500 ksi (3,000 MPa) for tungsten carbide].

3. *Flat platen.* Flat platens fail by plastic yielding. A common formula for calculating acceptable maximum platen pressure p is

$$p = \sigma_y \text{ (diameter of platen / diameter of workpiece)}$$

4. *Die cavity.* The die pressures in a deep cavity (impression) are much higher than in a flat platen (die), resulting in die burst-out. A more conservative value of 150 ksi (1,000 MPa) is used for acceptable die pressure. If shrink rings are used, higher values of 250 ksi (1,700 MPa) for steels and 400 ksi (2,700 MPa) for tungsten carbide can be used for the inner insert.

For large massive dies or for intermittent service, chrome-nickel-molybdenum alloys are preferred. In closed die work, where the dies must dissipate considerable heat, the tungsten steels are preferred, with resulting increase in wear resistance but decrease in toughness.

For very large pieces with deep impressions, **cast-steel** dies are sometimes used. For large dies likely to spring in hardening, 0.85 **carbon steel** high in manganese is sometimes used unhardened.

Good **die-block proportions** for width and depth are as follows:

Width, in (cm)	8 (20)	10 (24)	12 (30)	14 (36)
Depth, in (cm)	6 (15)	7 (18)	7 (18)	7 or 8 (18 or 20)

For ordinary work, 1½ in (4 cm) of metal between impression and edge of block is sufficient.

Dimensions of **dovetailed die shanks:** for hammers up to 1,200 lb (550 kg) 4 in (10 cm) wide and 1⅛ in (3 cm) deep, with sides dovetailed at angles of 6° with the vertical; for hammers from 1,200 to 3,000 lb (550 to 1,360 kg) in size, 6 in (15 cm) wide and 1½ in (4 cm) deep, with 6° angles.

The **minimum draft for the impressions** is 7°, although for parts difficult to draw this may be increased up to 15°. It is not uncommon to have several drafts in the same impression.

Open-hearth and tool-steel **dies** are **hardened** by heating in a carbonizing box packed in charcoal and dipping face downward over a jet of brine. The jet is allowed to strike into the impression, thus freeing the face of steam and producing uniform hardness. After hardening, they are drawn in an oil bath to a temperature of 500 to 550°F (260 to 290°C).

The forging production per pair of dies is largely affected by the size and shape of the impression, the material forged, the material in the dies, the quality of heating of stock to be forged, and the care exercised in use. It may vary from a few hundred pieces to 50,000 or more. A normal **life** for a pair of dies under average conditions may be 20,000 pieces.

Coining, Stamping, and Embossing The metal is well confined in closed dies in which it is forced to flow to fill the shape. The U.S. Mint gives the following pressures; silver quarter, 100 tons/in² (1,380 MN/m²); nickel (0.25 Ni, 0.75 Cu), 90 tons/in² (1,240 MN/m²); copper cent, 40 tons/in² (550 MN/m²). In stamping designs, lettering, etc., in sheet metal the thickness is so little compared with the area that there is practically no relief for excess pressure. Where sharp designs are required, as in stamping panels, the dies should be arranged to strike on a narrow line [say ⅟₃₂ in (0.8 mm)] around the outline. If a sharp design is not obtained, it is often best to correct deflection in the machine by shimming or more substantial backing. Increasing the pressure only aggravates the condition and may break the press. General practice for light overall stamping is to allow 5 to 10 tons/in² (68 to 132 MN/m²) of area that is to be stamped, except in areas where the yield point must be exceeded.

Extrusion is the severest of the squeezing processes. The metal is forced to flow rapidly through an orifice, being otherwise confined and subject largely to the laws of hydraulics, with allowances for restraint of flow and for work hardening. Power-press **impact extrusion** began with tin and lead collapsible tubes. It has been extended to the backward and forward extrusion of aluminum, brass, and copper in pressure ranges of

30 to 60 or more tons/in² (413 to 825 MN/m²), and mild steel at pressures up to 165 tons/in² (2,275 MN/m²). Hot impact extrusion of steel, as in projectile piercing, ranges from about 25 to 50 tons/in² (345 to 690 MN/m²). **Forward extrusion** of long tubes, rods, and shapes usually performed hot in hydraulic presses has been extended from the softer metals to the extrusion of steels. Most work is done horizontally because of the lengths of the extrusions. Some vertical mechanical-press equipment is used in hot extrusion of steel tubing.

EQUIPMENT FOR WORKING METALS

The **mass production** industries use an extremely wide variety of machines to force materials to flow plastically into desired shapes (as compared with the more gradual methods of obtaining shapes by cutting away surplus material in machine tools). The application of working pressure may use hydraulic, pneumatic, mechanical, or electric means to apply pressing, hammering, or rolling forces. Mechanically and hydraulically actuated devices cover much the same range. In general, the mechanical equipment is faster, easier to maintain, and more efficient to operate by reason of energy-storing flywheels. The hydraulic equipment is more flexible and more easily adjusted to limited lots in pressure, positions, and strokes. Mechanical handling or feeding devices incorporated in or serving many of these more or less specialized machines further extend their productivity.

Power presses consist of a frame or substantial construction with devices for holding the dies or tools and a moving member or slide for actuating one portion of the dies. This slide usually receives its movement from a crankshaft furnished with a clutch for intermittent operation and a flywheel to supply the sudden power requirement. **Hydraulic presses** have no crankshaft, clutch, or flywheel but employ rams actuated by pumps.

The crankshaft is ordinarily the limiting factor in the pressure capacity of the machine and accordingly is often taken as the basis for tonnage ratings. There is no uniform basis for this rating, owing to variations in shaft proportions and materials and in the different relative severity of various press operations. The following valuation is tentative and is based on the shaft diameter in the main bearings. The bending strength is figured at a section through the center of the crankpin and the combined bending and torsional strength at the inside ends of the main bearings, taking the bending fulcrum at a distance out from these points equal to one-third the length of the main bearings. In the case of double-crank presses and twin-drive arrangements, the relative proportion of the torsional load must be varied to suit, but, except in the cases of long strokes, it is usually small. The working strength is based upon a stress in the extreme fibers of 28,000 lb/in² (193 MN/m²). The limit bearing capacities are taken approximately at 5,000 lb/in² (35 MN/m²) on the crankpins and 2,500 lb/in² (18 MN/m²) average over the main bearings for ordinary steel on cast-iron press bearings with proper grooving. On the knuckle-joint-type presses with hardened tool-steel bearing surfaces and flood lubrication, the bearings will take up to about 30,000 lb/in² (207 MN/m²). On eccentric-type shafts where the main bearings support right up to the oversize pin on each side, the limiting factor is the bearing load. The shaft is practically in shear, so that it has a considerable overload capacity (about $7d^2$ tons). In Table 13.2.5, uniform-diameter single crankshafts are those in which for manufacturing reasons the diameter is the same at the crankpin and at the main bearings. Other crank shafts have an oversize crankpin to balance the bending load at the center with the combined bending and torsional load at the side. The strength of the shaft is figured at midstroke, and the stroke and tonnage capacity are given in terms of the diameter d at the main bearings. Where the working load comes on only near the bottom stroke, the shaft press capacity may be figured as if the stroke were shorter in proportion.

Table 13.2.5 gives the rated capacities of a series of power presses as a function of the shaft diameter.

The speed of operation of the press depends upon the energy requirement and the crankpin velocity. The latter determines the velocity of impact on the tools. In blanking, the blow varies directly with the con-

Table 13.2.5   Power-Press Shaft Capacities

Type of press crankshaft	Max stroke, in*	Capacity tons†
Single crank, single drive, uniform diameter	d‡	$2.8d^2$
Single crank, single drive, oversize crankpin	d	$3.5d^2$
Single crank, single drive, oversize crankpin	$2d$	$2.2d^2$
Single crank, single drive, oversize crankpin	$3d$	$1.6d^2$
Single crank, twin drive, oversize crankpin	$2d$	$3.5d^2$
Single crank, twin drive, oversize crankpin	$3d$	$2.7d^2$
Double crank, single drive, oversize crankpin	$0.75d$	$5.5d^2$
Double crank, single drive, oversize crankpin	d	$4.4d^2$
Double crank, single drive, oversize crankpin	$2d$	$2.5d^2$
Double crank, single drive, oversize crankpin	$3d$	$1.7d^2$
Double crank, twin drive, oversize crankpin	$1.5d$	$5.5d^2$
Double crank, twin drive, oversize crankpin	$3d$	$3.2d^2$
Single eccentric, single or twin drive	$0.5d$	$4.3d^2$

* 1 in = 2.54 cm.
† 1 ton = 8.9 kN.
‡ d = shaft diameter in main bearing.
SOURCE: F. W. Bliss Co.

tact speed and the thickness and hardness of the material. In drawing operations the variation depends upon contact speed, ductility of material, lubrication, etc.

The energy required per stroke is practically the product of the average load and the working distance, plus friction allowance, assumed at about 16 percent. On short-stroke operations, such as blanking, the working energy is supplied almost entirely by slowing down the flywheel; motor or belt pull serves merely to return the flywheel to speed during the large part of the cycle in which no work is done. In drawing operations, the working period is considerable, and in many cases the belt takes the largest part of the working load. In this case, add to the available flywheel energy, the work done by the belt. This amounts, for example, to 70 lb/in of width of the belt (123 N/cm), multiplied by the ratio of the belt velocity to the crankpin velocity, multiplied by the length of the working stroke on the crank circle in feet. The maximum flywheel slowdown has been assumed as up to 10 percent for continuous operation and up to 20 percent for intermittent operation. The following formula is based upon average press-flywheel proportions and a slowdown of 10 percent. The result may be doubled for 20 percent slowdown.

The flywheel capacity per stroke at 10 percent slowdown in inch-tons equals $WD^2N^2/5,260,000,000$, where W is the weight of the flywheel, lb, D is the diameter, in, and N is rotation speed, r/min. (See Sec. 8.2.)

The difference between nongeared and geared presses is only in speed of operation and the relatively greater flywheel capacity.

Press frames are designed for stiffness and usually have considerable excess strength. Good practice is to figure cast-iron sections for a stress of about 2,000 to 3,000 lb/in² (13.8 to 20.6 MN/m²). **C-frame presses** are subjected to an appreciable arc spring amount ordinarily of between 0.0005 and 0.002 in/ton (1.5 and 6 mm/MN), because the center of gravity of the frame section is a considerable distance back of the working centerline of the press. **Straight-sided presses** eliminate that portion of the spring or deflection which is on an arc. **Built-up frame presses** are held together with steel tie rods shrunk in under an initial tension in excess of the working load so that they minimize stretch in that portion of the press.

Power presses are built in a very wide variety of styles and sizes with shafts ranging from 1- to 21-in (2.5- to 53-cm) diam. Over a large part of this range they are built with C frames for convenience, straight-sided frames for heavier and thinner work, eccentric shafts for heavy forgings and stampings, double crankshafts for wide jobs, four-point presses for large panel work, underdrive presses in high-production plants where repairs to presses would interfere with flow of production, and knuckle-join presses for intensely high pressures at the very bottom of the stroke. All these are classified as single-action presses and are used for most of the operations previously discussed.

Double-action presses combine the functions of blank holding with drawing. In the smaller sizes, such presses have cams mounted on the

cheeks of the crankshaft to actuate the outer or blank-holding slide. In larger machines, toggle mechanisms are provided to actuate the outer slide, with the advantage that the blank-holding load is taken on the frame instead of the crankshaft. Both of these types afford a considerable power saving over single-action presses equipped with drawing attachments, because the latter must add the blank-holding pressure to the working load for the full depth of the draw.

Types of presses include **foot presses,** in which the pendulum type has the lowest mechanical advantage and the longest stroke; the **lever type,** which has higher mechanical advantage and shorter strokes; **toggle** or **knuckle type,** which has the highest mechanical advantage and works through the shortest stroke with considerable advantage obtainable from the use of tie rods on fine stamping or embossing work; long-stroke rack and pinion-driven presses; triple-action drawing presses; cam-actuated presses; etc.

Screw presses consist of a conventional frame and a slide which is forced down by a steep pitch screw on the upper end of which is a flywheel or weight bar. Hand-operated machines are used for die testing and for small production stamping, embossing, forming, and other work requiring more power than foot presses. Power-driven screw presses are built with a friction drive for the flywheel and automatic control to limit the stroke. Such presses are built in comparatively large sizes and used to a considerable extent for press forging. They lack the accuracy and speed of power presses built for this work but have a safety factor which power presses have not, in that their action is not positive. In this they closely resemble a drop hammer, although their motion is slower. The energy available for work in these presses is $\frac{1}{2}I_f v^2 + \frac{1}{2}I_s v^2$, in which I_f is the moment of inertia of the flywheel, I_s is the moment of inertia of the spindle, and v is the angular velocity of both.

Self-contained fast-acting **hydraulic presses** are being increasingly used. Equipped with motor-driven variable-displacement oil hydraulic pumps, the speed and pressure of the operating ram or rams are under instant and automatic control; this is particularly advantageous for deep drawing operations. The punch can be brought into initial contact with the work without shock and moved with a uniform controlled velocity through the drawing portion of the cycle. The drawing of stainless steels and alloy aluminums (in which the control of drawing speed is vital), as well as the hot drawing of magnesium, is best done on hydraulic presses.

The hydraulic press is used on the rubber pad, or *Guerin,* process of blanking or forming metals, in which a laminated-rubber pad replaces one half—usually the female half—of a die. In forming aluminum the practice has developed of using inexpensive dies of soft metal, vulcanized fiber, plastic, wood, or plaster; and cast dies in industries which, like the aircraft industry, require short runs on many different sizes of shapes and parts.

The older accumulator type of hydraulic-press construction is still used for hot extrusion and some forging work.

Drop Hammers or Presses Small belt-lift and board-lift drop presses were used for variety of sheet-metal operations on hardware, cutlery, silverware, etc. Board-lift drop hammers with heads weighing up to 5,000 lb (22 kN) were widely used in the production of steel drop forgings. The energy available for work is the product of the weight of the ram and the length of fall (see below). The following table gives the shaft diameters of trimming presses (for removing the flash) ordinarily used with drop hammers for trimming the same range of forgings:

Helve hammers are usually belt-driven and carry the hammer face or swage on the end of a beam. The belt is provided with a tightening device, treadle-controlled, permitting the operator to regulate the number and speed of the blows. They were **used for general** and duplicate **forging,** welding, plating drawing, swaging, collaring, spindle making, etc.

Strap hammers carry the hammer slung from a strap, usually of leather. The control and operation are the same as for the helve type. They were **adapted for general work**.

Board Drop Hammer Let W = work of blow, ft · lb; H = weight of hammer and die, lb; g = acceleration due to gravity ($l = 32.3$ ft/s^2); h = actual hammer stroke, ft; and v = terminal velocity of hammer, ft/s. Then, if the hammer and die fall of their own weight, $W = (H/g)v^2/2 = Hh = 0.015\ Hv^2$ (approx).

Although now obsolete and found only in a few locations, the hammers described above largely have been supplanted by steam or air (pneumatic) hammers. These latter utilize fluid pressure inside a piston to raise and propel the hammer with greater striking velocity, allowing for better control and permitting a higher production rate.

Steam hammers may be divided into **three classes**. In the first, the hammer is lifted by steam and drops of its own weight; in the second, steam is admitted above the piston and through its expansion increases the force of the blow; in the third, live steam is admitted above the piston throughout the stroke and the force of the blow is from combined weight of the falling hammer and the pressure of the steam.

In the **first class,** that of the single-acting steam hammer, part of the force of the steam is used to accelerate the lifting motion, continuing after the steam has been cut off as long as the pressure under the piston $> H$. These hammers are **used** only **for very large work**. The **weight of the hammer** ranges from 25 to 125 tons (220 to 1,110 kN). The disadvantage of this type lies in the fact that the height of the clearance under the piston is directly dependent upon the thickness of the piece of work.

In the **second class,** in which steam is admitted above the piston and allowed to expand, there is an economy in steam consumption, a greater acceleration of the hammer head, and a large number of blows per unit of time.

In the **third class,** live steam is admitted above the piston. Here the **weight of the hammer head** varies from 1 to 25 tons (9 to 1,100 kN). The control is such that the weight of the hammer itself is available for light blows, and for heavier blows steam is admitted above the piston.

In comparatively small hammers where the head weighs 150 to 2,000 lb (670 to 8,900 N), up to 350 **blows per min** can be obtained, depending on the length of the stroke and the tightness of the stuffing box. These hammers are provided with an automatic reversing gear. The **number and force of the blows** can be regulated by throttling the steam, changing the center position of the operating valve, and changing the back lash in the operating gear. The frame of these hammers is usually C-shaped.

The **anvil** in small hammers is usually a single casting. In large hammers it is usually divided into upper and lower anvil blocks. In smaller hammers the anvil is connected with the shears and upper part of the machine. In the larger hammers, however, this is not the case, as the concussions tend to injure the hammer mechanism. For good practice the **weight of the anvil** ($= Q$) for hammers used in forging iron is at least eight times the weight of the hammer head; for forging steel, at least twelve times.

Drop-Hammer Ram Weights and Suitable Trimming-Press Shaft Diameters

Ram weight, lb*	600	800	1,000	1,200	1,500	2,000	2,500	3,000	5,000	8,000
Press shaft diam. in†	½	4	4½	5	5½	6	6½	7	8	9

* 1,000 lb = 4,450 N.
† 1 in = 2.54 cm.
SOURCE: F. W. Bliss Co.

The pressure Q_1 exerted by the anvil block on the surface which it supports is assumed to be as follows: for blooming hammers, $Q_1 = (30 \text{ to } 60)hH + Q$; for billet-forging hammers, $Q_1 = (60 \text{ to } 95)h + Q$; for hammers for steel forging, $Q_1 = (95 \text{ to } 125)hH + Q$.

Pneumatic Hammers   A self-contained type of pneumatic forge hammer (the Bêché) has an air-operated ram with an air-compressing cylinder integral with the frame. The ram is raised by admitting compressed air beneath the ram piston; at the same time a partial vacuum is caused above it. The ram is forced down by a reversal of this action.

The **terminal velocity** (velocity at ram-workpiece contact) of the steam, pneumatic, or hydraulic assisted hammer can be calculated as follows:

$$v = \left[2hg \left(1 + \frac{Ap_m}{H} \right) \right]^{0.5}$$

where A is the area of the piston and p_m the mean pressure in the drive cylinder. The hammer energy is often calculated by dividing the energy required for plastic work by the mechanical efficiency of the hammer.

Hydraulic presses are energized by pressurized liquid, usually oil. They can deliver high tonnage but are slow. Due to large die chilling (heat loss to dies) present in hydraulic press forging, they are not usually used for hot forging, except in isothermal forging, where slow speed and large die-workpiece contact times are not a major limitation. They are specially suited to sheet metal forming operations, where slower ram speeds produce lower impact loads, speeds can be varied during the stroke, and multiple actions can be obtained for blank holder and die cushion operation.

Hammers and presses are often selected based on their characteristics such as energy, ram mass (t_{up}), force or tonnage, ram speed (stroking rate), stroke length, bed area, and mechanical efficiency. The characteristics for various hammers and presses are summarized in Table 13.2.6.

Rotary motion is used **for working sheet metal** in a variety of machines, including bending rolls (three rolls); rolling straighteners with five, seven, or more rolls; roll forming machines, in which a series of rolls in successive pairs are used to bend the strip material step by step to some desired shape; a series of two-spindle and multiple-spindle machines used for rolling beads, threads, knurls, flanges, and trimming or curling the edges of drawn shells of cylinders; seaming machines for double seaming, crimping, curling, and other operations in the production of tin cans, pieced tinware, etc.; and spinning machines for spinning, burnishing, trimming, curling, shape forming, and thickness reduction. Various production spinning operations and tool arrangements are shown in Fig. 13.2.7.

Plate-Straightening Machines   The **horsepower required** for plate-straightening machines operating on steel plate is shown in Table 13.2.7.

Power required for angle-iron-straightening machines: for 4-in angles, 12 hp; for 6-in, 18 hp; for 8-in, 25 hp.

Power or hydraulic presses are used to straighten **large rolled sections**. The presses make 20 to 30 strokes per min, and the amount of flexure is regulated by inserting wedges or pieces of flat iron. The beams are supported on rolls so they can be easily handled. The **power required for presses** of this kind is as follows:

Depth of girder, in*	4	6	8	10	12	16	20	24
Horsepower (approx)†	3	4	7	11	13	19	23	35

* 1 in = 2.54 cm.
† 1 hp = 0.746 kW.

Horizontal plate-bending machines consist of two stationary rolls and a third vertical adjustable upper roll which can be fitted obliquely for taper bending and is held in bearings with spherical seats. The diameter of the rolls can be determined approximately from the equation $r^2 = bt$, in which r is the radius of the roll, b the width of the plate or sheet, and t its thickness, all in inches.

The **power requirements** of horizontal plate and sheet bending machines are shown in Table 13.2.8.

Vertical plate-bending machines have a hydraulically operated piston which moves an upper and a lower pair of rolls between inclined surfaces of the stationary upright and the crosshead. The bending is done piece by piece against a second stationary upright. Heavy ship plates are rigidly clamped down and bent by a roll operated by two hydraulic pistons. For angular bends or for the production of warped surfaces, the pistons can be operated independently or together. In vertical machines, angles and other rolled shapes are bent between suitably shaped rolls. Pipes are filled with sand to prevent flattening when being bent. For

Table 13.2.6   Characteristics of Hammers and Presses*

Equipment type	Energy,† kN · m	Ram mass, kg	Force,‡ kN	Speed, m/s	Strokes per min	Stroke, m	Bed area, m × m	Mechanical efficiency
Hammers								
Mechanical	0.5–40	30–5,000		4–5	350–35	0.1–1.6	0.1 × 0.1 to 0.4 × 0.6	0.2–0.5
Steam and air	20–600	75–17,000 (25,000)		3–8	300–20	0.5–1.2	0.3 × 0.4 to (1.2 × 1.8)	0.05–0.3
Counterblow	5–200 (1,250)			3–5	60–7		0.3 × 0.4 to (1.8 × 5)	0.2–0.7
Herf	15–750			8–20	<2			0.2–0.6
Presses								
Hydraulic, forging			100–80,000 (800,000)	<0.5	30–5	0.3–1 (3)	0.5 × 0.5 to (3.5 × 8)	0.1–0.6
Hydraulic, sheet metalworking			10–40,000	<0.5	130–20	0.1–1	0.2 × 0.2 to 2 × 6	0.5–0.7
Hydraulic, extrusion			1,000–50,000 (200,000)	<0.5	<2	0.8–5	0.06–0.6 diam. container	0.5–0.7
Mechanical, forging			10–80,000	<0.5	130–10	0.1–1	0.2 × 0.2 to 2 × 3	0.2–0.7
Horizontal upsetter			500–30,000 (1–9 in diam)	<1	90–15	0.05–0.4	0.2 × 0.2 to 0.8 × 1	0.2–0.7
Mechanical, sheet metalworking			10–20,000	<1	180–10	0.1–0.8	0.2 × 0.2 to 2 × 6	0.3–0.7
Screw			100–80,000	<1	35–6	0.2–0.8	0.2 × 0.3 to 0.8 × 1	0.2–0.7

* From a number of sources, chiefly A. Geleji, *Forge Equipment, Rolling Mills and Accessories,* Akademiai Kiado, Budapest, 1967.
† Multiply number in column by 100 to get m · kg, by 0.73 to get 10^3 lbf · ft.
‡ Divide number by −10 to get tons. Numbers in parentheses indicate the largest sizes, available in only a few places in the world.
SOURCE: John A. Schey, *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1987.

Table 13.2.7   Power Requirement for Plate-Straightening Machines (Steel)

Thickness of plate, in*	0.25	0.4	0.6	0.8	1.0	1.2	1.4	1.6
Width of plate, in*	48.0	52.0	60.0	72.0	88.0	102.0	120.0	140.0
Diameter of rolls, in*	5.0	8.0	10.0	12.0	13.0	14.0	15.0	16.0
Horsepower (approx)†	6.0	8.0	12.0	20.0	30.0	55.0	90.0	130.0

* 1 in = 2.54 cm.
† 1 hp = 0.746 kW.

Table 13.2.8   Power Requirement for Plate and Sheet Bending Machines (Steel)

Thickness of plate, in*	0.5	0.6	0.8	1	1.2
Horsepower for plate 120 in wide†	10.0	12.0	18.0	27.0	40.0
Horsepower for plate 240 in wide†	30.0	30.0	40.0	55.0	75.0

* 1 in = 2.54 cm.
† 1 hp = 0.746 kW.

some work, pipes are bent hot between suitable forms operated by hydraulic pressure.

The **rotary swaging machines** for tapering, closing in, and reducing tubes, rods, and hollow articles is essentially a cage carrying a number of rollers and revolving at high speed; e.g., 14 rolls in a cage revolving at 600 r/min will strike 8,400 blows per min on the work.

A rapid succession of light blows is applied to a considerable variety of commercial **riveting** operations such as pneumatic riveting. Another method of riveting, described as spinning, involves rotating small rollers rapidly over the top of the rivet and at the same time applying pressure. Neither of these methods involves pressures as intense as those used in riveting by direct pressure, either hot or cold. Power presses and C-frame riveters, employing hydraulic pressure or air pressure of 80 to 100 lb/in² (550 to 690 kN/m²), are designed to apply 150,000 lb/in² (1,035 MN/m²) on the cross section of the body of the rivet for hot-working and 300,000 lb/in² (2,070 MN/m²) for cold-working. The pieces joined should be pressed together by a pressure 0.3 to 0.4 times that used in riveting.

13.3   WELDING AND CUTTING
by Omer W. Blodgett and Duane K. Miller

REFERENCES: From the American Welding Society (AWS): ''Welding Handbook'' (six volumes); ''Structural Welding Code''; ''Filler Metal Specifications,'' ''Welding Terms and Definitions''; ''Brazing Manual''; ''Thermal Spraying''; ''Welding of Chromium-Molybdenum Steels.'' From the Lincoln Arc Welding Foundation: Blodgett, ''Design of Weldments''; Blodgett, ''Design of Welded Structures.'' ''Procedure Handbook of Welding,'' The Lincoln Electric Co. ''Safety in Welding and Cutting,'' ANSI. ''Welding and Fabrication Data Book,'' Penton Pub. Co. AISI, ''Steel Construction Manual—ASD,'' 9th ed., and ''Steel Construction Manual—LRFD,'' 2d ed.

INTRODUCTION

Welded connections and assemblies represent a very large group of fabricated steel components, and only a portion of the aspects of their design and fabrication is treated here. The welding process itself is complex, involving heat and liquid-metal transfer, chemical reactions, and the gradual formation of the welded joint through liquid-metal deposition and subsequent cooling into the solid state, with attendant metallurgical transformations. Some of these items are treated in greater detail in the references and other extensive professional literature, as well as in Secs. 6.2, 6.3, and 13.1.

The material in this section will provide the engineer with an overview of the most important aspects of welded design. In order that the resulting welded fabrication be of adequate strength, stiffness, and utility, the designer will often collaborate with engineers who are experts in the broad area of design and fabrication of weldments.

ARC WELDING

Arc welding is one of several **fusion processes** for joining metal. By the generation of intense heat, the juncture of two metal pieces is melted and mixed—directly or, more often, with an intermediate molten **filler metal**. Upon cooling and solidification, the resulting welded joint metallurgically bonds the former separate pieces into a continuous structural assembly (a **weldment**) whose strength properties are basically those of the individual pieces before welding.

In arc welding, the intense heat needed to melt metal is produced by an **electric arc**. The arc forms between the workpieces and an electrode that is either manually or mechanically moved along the joint; conversely, the work may be moved under a stationary electrode. The **electrode** generally is a specially prepared rod or wire that not only conducts electric current and sustains the arc, but also melts and supplies **filler metal** to the joint; this constitutes a **consumable electrode. Carbon** or **tungsten electrodes** may be used, in which case the electrode serves only to conduct electric current and to sustain the arc between tip and workpiece, and it is not consumed; with these electrodes, any filler metal required is supplied by rod or wire introduced into the region of the arc and melted there. Filler metal applied separately, rather than via a consumable electrode, does not carry electric current.

Most steel welding operations are performed with consumable electrodes.

Welding Process Fundamentals

Heat and Filler Metal   An ac or dc power source fitted with necessary controls is connected by a work cable to the workpiece and by a ''hot'' cable to an electrode holder of some type, which, in turn, is electrically connected to the welding electrode (Fig. 13.3.1). When the circuit is energized, the flow of electric current through the electrode heats the electrode by virtue of its electric resistance. When the electrode tip is touched to the workpiece and then withdrawn to leave a gap between the electrode and workpiece, the arc jumping the short gap presents a further path of high electric resistance, resulting in the generation of an extremely high temperature in the region of the sustained arc. The temperature reaches about 6,500°F, which is more than adequate to melt most metals. The heat of the arc melts both base and filler metals, the latter being supplied via a consumable electrode or separately. The puddle of molten metal produced is called a **weld pool,** which solidifies

as the electrode and arc move along the joint being welded. The resulting weldment is metallurgically bonded as the liquid metal cools, fuses, solidifies, and cools. In addition to serving its main function of supplying heat, the arc is subject to adjustment and/or control to vary the proper transfer of molten metal to the weld pool, remove surface films in the weld region, and foster gas-slag reactions or other beneficial metallurgical changes.
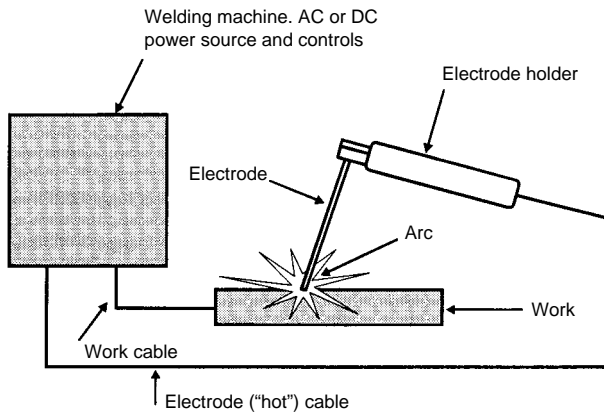

Fig. 13.3.1   Typical welding circuit.

Filler metal composition is generally different from that of the weld metal, which is composed of the solidified mix of both filler and base metals.

Shielding and Fluxing   High-temperature molten metal in the weld pool will react with oxygen and nitrogen in ambient air. These gases will remain dissolved in the liquid metal, but their solubility significantly decreases as the metal cools and solidifies. The decreased solubility causes the gases to come out of solution, and if they are trapped in the metal as it solidifies, **cavities,** termed **porosities,** are left behind. This is always undesirable, but it can be acceptable to a limited degree depending on the specification governing the welding.

Smaller amounts of these gases, particularly nitrogen, may remain dissolved in the weld metal, resulting in drastic reduction in the physical properties of otherwise excellent weld metal. **Notch toughness** is seriously degraded by nitrogen inclusions. Accordingly, the molten metal must be shielded from harmful atmospheric gas contaminants. This is accomplished by gas shielding or slag shielding or both.

Gas shielding is provided either by an external supply of gas, such as carbon dioxide, or by gas generated when the electrode flux heats up. **Slag shielding** results when the flux ingredients are melted and leave behind a slag to cover the weld pool, to act as a barrier to contact between the weld pool and ambient air. At times, both types of shielding are utilized.

In addition to its primary purpose to protect the molten metal, the shielding gas will significantly affect arc behavior. The shielding gas may be mixed with small amounts of other gases (as many as three others) to improve arc stability, puddle (weld pool) fluidity, and other welding operating characteristics.

In the case of shielded-metal arc welding (SMAW), the ''stick'' electrode is covered with an extruded coating of flux. The arc heat melts the flux and generates a gaseous shield to keep air away from the molten metal, and at the same time the flux ingredients react with deleterious substances, such as surface oxides on the base metal, and chemically combine with those contaminants, creating **a slag** which floats to the surface of the weld pool. That slag crusts over the newly solidified hot metal, minimizes contact between air and hot metal while the metal cools, and thereby inhibits the formation of surface oxides on the newly deposited weld metal, or weld bead. When the temperature of the weld bead decreases, the slag, which has a glassy consistency, is chipped off to reveal the bright surface of the newly deposited metal. Minimal sur-

face oxidation will take place at lower temperatures, inasmuch as oxidation rates are greatly diminished as ambient conditions are approached.

Fluxing action also aids in wetting the interface between the base metal and the molten metal in the weld pool edge, thereby enhancing uniformity and appearance of the weld bead.

Process Selection Criteria

Economic factors generally dictate which welding process to use for a particular application. It is impossible to state which process will always deliver the most economical welds, because the variables involved are significant in both number and diversity. The variables include, but are not limited to, steel (or other base metal) type, joint type, section thickness, production quantity, joint access, position in which the welding is to be performed, equipment availability, availability of qualified and skilled welders, and whether the welding will be done in the field or in the shop.

Shielded Metal Arc Welding

The **SMAW** process (Fig. 13.3.2), commonly known as **stick welding,** or **manual welding,** is the most popular and widespread welding process. It is versatile, relatively simple to do, and very flexible in being applied. To those casually acquainted with welding, **arc welding** usually means **shielded-metal arc welding.** SMAW is used in the shop and in the field for fabrication, erection, maintenance, and repairs. Because of the relative inefficiency of the process, it is seldom used for fabrication of major structures. SMAW has earned a reputation for providing high-quality welds in a dependable fashion. It is, however, inherently slower and more costly than other methods of welding.
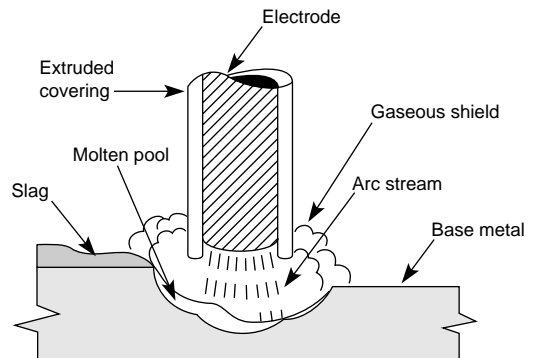

Fig. 13.3.2   SMAW process.

SMAW may utilize either direct current (dc) or alternating current (ac). Generally speaking, direct current is used for smaller electrodes, usually less than $\frac{3}{16}$-in diameter. Larger electrodes utilize alternating current to eliminate undesirable arc blow conditions.

Electrodes used with alternating current must be designed specifically to operate in this mode, in which current changes direction 120 times per second with 60-Hz power. All ac electrodes will operate acceptably on direct current. The opposite is not always true.

Flux Cored Arc Welding (FCAW)

In **FCAW,** the arc is maintained between a continuous tubular metal electrode and the weld pool. The tubular electrode is filled with flux and a combination of materials that may include metallic powder(s). FCAW may be done automatically or semiautomatically. FCAW has become the workhorse in fabrication shops practicing semiautomatic welding. Production welds that are short, change direction, are difficult to access, must be done out of position (e.g., vertical or overhead), or are part of a short production run generally will be made with semiautomatic FCAW.

When the application lends itself to automatic welding, most fabricators will select the submerged arc process (see material under

''SAW''). Flux cored arc welding may be used in the automatic mode, but the intensity of arc rays from a high-current flux cored arc, as well as a significant volume of smoke, makes alternatives such as submerged arc more desirable.

Advantages of FCAW FCAW offers two distinct advantages over SMAW. First, the electrode is continuous and eliminates the built-in starts and stops that are inevitable with SMAW using stick electrodes. An economic advantage accrues from the increased operating factor; in addition, the reduced number of arc starts and stops largely eliminates potential sources of weld discontinuities. Second, increased amperages can be used with FCAW. With SMAW, there is a practical limit to the amount of current that can be used. The covered electrodes are 9 to 18 in long, and if the current is too high, electric resistance heating within the unused length of electrode will become so great that the coating ingredients may overheat and ''break down.'' With continuous flux cored electrodes, the tubular electrode is passed through a contact tip, where electric current is transferred to the electrode. The short distance from the contact tip to the end of the electrode, known as electrode extension or ''**stickout**,'' inhibits heat buildup due to electric resistance. This electrode extension distance is typically 1 in for flux cored electrodes, although it may be as much as 2 or 3 in in some circumstances.

Smaller-diameter flux cored electrodes are suitable for all-position welding. Larger electrodes, using higher electric currents, usually are restricted to use in the flat and horizontal positions. Although the equipment required for FCAW is more expensive and more complicated than that for SMAW, most fabricators find FCAW much more economical than SMAW.

FCAW Equipment and Procedures Like all wire-fed welding processes, FCAW requires a power source, wire feeder, and gun and cable assembly (Fig. 13.3.3). The power supply is a dc source, although either electrode positive or electrode negative polarity may be used. The four primary variables used to determine welding procedures are voltage, wire feed speed, electrode extension, and travel speed. For a given wire feed speed and electrode extension, a specified amperage will be delivered to maintain stable welding conditions.
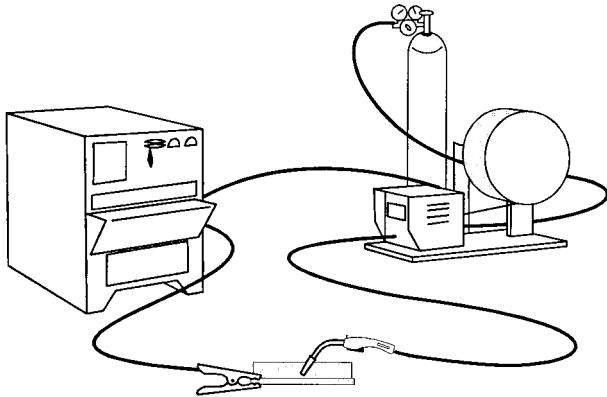

Fig. 13.3.3 FCAW and GMAW equipment.

As wire feed speed is increased, amperage will be increased. On some equipment, the wire feed speed control is called the amperage control, which, despite its name, is just a rheostat that regulates the speed of the dc motor driving the electrode through the gun. The most accurate way, however, to establish welding procedures is to refer to the **wire feed speed (WFS),** since electrode extension, polarity, and electrode diameter will also affect amperage. For a fixed wire feed speed, a shorter electrical stick-out will result in higher amperages. If procedures are set based on the wire feed speed, the resulting amperage verifies that proper electrode extensions are being used. If amperage is used to set welding procedures, an inaccurate electrode extension may go undetected.

Self-Shielded and Gas-Shielded FCAW Within the category of FCAW, there are two specific subsets: **self-shielded flux core arc welding (FCAW-ss)** (Fig. 13.3.4) and **gas-shielded flux core arc welding (FCAW-g)** (Fig. 13.3.5). Self-shielded flux cored electrodes require no external shielding gas. The entire shielding system results from the flux ingredients contained in the tubular electrode. The gas-shielded variety of flux cored electrode utilizes, in addition to the flux core, an externally supplied shielding gas. Often, CO_2 is used, although other mixtures may be used.
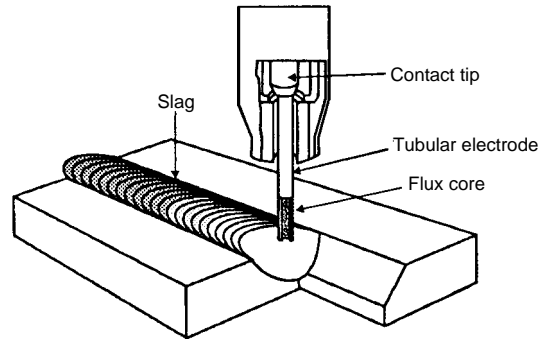

Fig. 13.3.4 Self shielded FCAW.

Both these subsets of FCAW are capable of delivering weld deposits featuring consistency, high quality, and excellent mechanical properties. Self-shielded flux cored electrodes are ideal for field welding operations, for since no externally supplied shielding gas is required, the process may be used in high winds without adversely affecting the
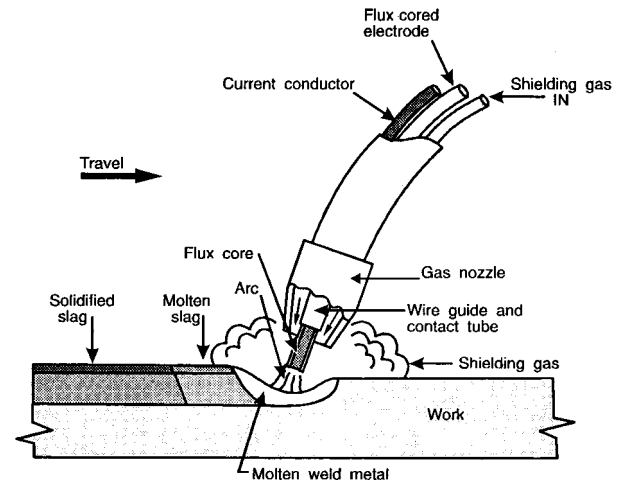

Fig. 13.3.5 Gas shielded FCAW.

quality of the weld metal deposited. With any gas-shielded processes, wind shields must be erected to preclude wind interference with the gas shield. Many fabricators with large shops have found that self-shielded flux core welding offers advantages when the shop door can be left open or fans are used to improve ventilation.

Gas-shielded flux cored electrodes tend to be more versatile than self-shielded flux cored electrodes and, in general, provide better arc action. Operator acceptance is usually higher. The gas shield must be protected from winds and drafts, but this is not difficult for most shop fabrication. Weld appearance is very good, and quality is outstanding. Higher-strength gas-shielded FCAW electrodes are available, but current practice limits self-shielded FCAW deposits to a strength of 80 ksi or less.

Submerged Arc Welding (SAW)

Submerged arc welding differs from other arc welding processes in that a blanket of fusible granular flux is used to shield the arc and molten metal (Fig. 13.3.6). The arc is struck between the workpiece and a bare-wire electrode, the tip of which is submerged in the flux. The arc is completely covered by the flux and it is not visible; thus the weld is made without the flash, spatter, and sparks that characterize the open-arc processes. The flux used develops very little smoke or visible fumes.
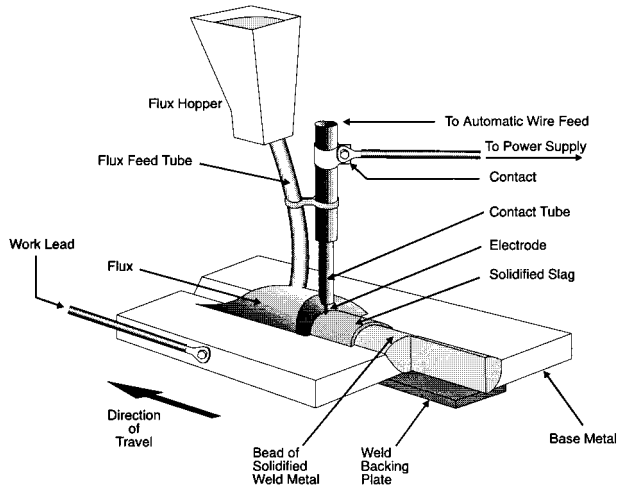
Fig. 13.3.6   SAW process.

Typically, the process is operated fully automatically, although semi-automatic operation is possible. The electrode is fed mechanically to the welding gun, head, or heads. In semiautomatic welding, the welder moves the gun, usually equipped with a flux-feeding device, along the joint.

Flux may be fed by gravity flow from a small hopper atop the torch and then through a nozzle concentric with the electrode, or through a nozzle tube connected to an air-pressurized flux tank. Flux may also be applied in advance of the welding operation or ahead of the arc from a hopper run along the joint. Many fully automatic installations are equipped with a vacuum system to capture unfused flux left after welding; the captured, unused flux is recycled for use once more.

During welding, arc heat melts some of the flux along with the tip of the electrode. The electrode tip and the welding zone are always shielded by molten flux and a cover layer of unfused flux. The electrode is kept a short distance above the workpiece. As the electrode progresses along the joint, the lighter molten flux rises above the molten metal to form slag. The weld metal, having a higher melting (freezing) point, solidifies while the slag above it is still molten. The slag then freezes over the newly solidified weld metal, continuing to protect the metal from contamination while it is very hot and reactive with atmospheric oxygen and nitrogen. Upon cooling and removal of any unmelted flux, the slag is removed from the weld.

Advantages of SAW   High currents can be used in SAW, and extremely high heat input can be developed. Because the current is applied to the electrode a short distance above the arc, relatively high amperages can be used on small-diameter electrodes. The resulting extremely high current densities on relatively small-cross-section electrodes permit high rates of metal deposition.

The insulating flux blanket above the arc prevents rapid escape of heat and concentrates it in the welding zone. Not only are the electrode and base metal melted rapidly, but also fusion is deep into the base metal. Deep penetration allows the use of small welding grooves, thus minimizing the amount of filler metal to be deposited and permitting fast welding speeds. Fast welding, in turn, minimizes the total heat input

to the assembly and thus tends to limit problems of heat distortion. Even relatively thick joints can be welded in one pass with SAW.

Versatility of SAW   SAW can be applied in more ways than other arc welding processes. A single electrode may be used, as is done with other wire feed processes, but it is possible to use two or more electrodes in submerged arc welding. Two electrodes may be used in parallel, sometimes called **twin arc welding,** employing a single power source and one wire drive. In **multiple-electrode SAW,** up to five electrodes can be used thus, but most often, two or three arc sources are used with separate power supplies and wire drives. In this case, the lead electrode usually operates on direct current while the trailing electrodes operate on alternating current.

Gas Metal Arc Welding (GMAW)

Gas metal arc welding utilizes the same equipment as FCAW (Figs. 13.3.3 and 13.3.7); indeed, the two are similar. The major differences are: (1) GMAW uses a solid or metal cored electrode, and (2) GMAW leaves no residual slag.

GMAW may be referred to as **metal inert gas (MIG),** solid wire and gas, **miniwire** or **microwire welding.** The shielding gas may be carbon
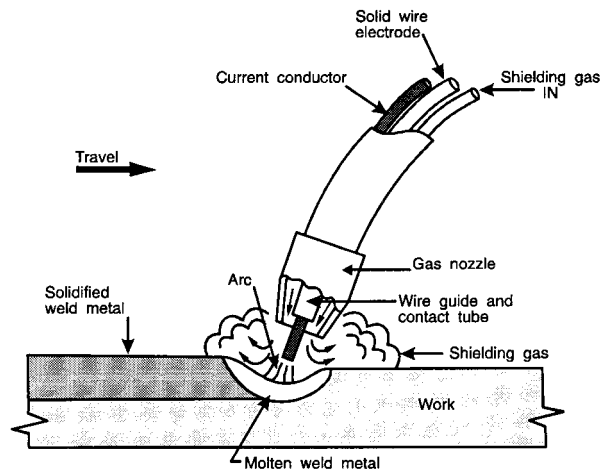

Fig. 13.3.7   GMAW welding process.

dioxide or blends of argon with CO_2 or oxygen, or both. GMAW is usually applied in one of four ways: short arc transfer, globular transfer, spray arc transfer, and pulsed arc transfer.

Short arc transfer is ideal for welding thin-gage materials, but generally is unsuitable for bridge fabrication purposes. In this mode of transfer, a small electrode, usually of 0.035- to 0.045-in diameter, is fed at a moderate wire feed speed at relatively low voltages. The electrode contacts the workpiece, resulting in a short circuit. The arc is actually quenched at this point, and very high current will flow through the electrode, causing it to heat and melt. A small amount of filler metal is transferred to the welding done at this time.

The cycle will repeat itself when the electrode short-circuits to the work again; this occurs between 60 and 200 times per second, creating a characteristic buzz. This mode of transfer is ideal for sheet metal, but results in significant fusion problems if applied to thick sections, when **cold lap** or **cold casting** results from failure of the filler metal to fuse to the base metal. This is unacceptable since the welded connection will have virtually no strength. Caution must be exercised if the short arc transfer mode is applied to thick sections.

Spray arc transfer is characterized by high wire feed speeds at relatively high voltages. A fine spray of molten filler metal drops, all smaller in diameter than the electrode, is ejected from the electrode toward the work. Unlike with short arc transfer, the arc in spray transfer is maintained continuously. High-quality welds with particularly good appearance are obtained. The shielding gas used in spray arc transfer is

composed of at least 80 percent argon, with the balance either carbon dioxide or oxygen. Typical mixtures would include 90-10 argon-CO_2, and 95-5 argon-oxygen. Relatively high arc voltages are used with spray arc transfer. Gas metal spray arc transfer welds have excellent appearance and evidence good fusion. However, due to the intensity of the arc, spray arc transfer is restricted to applications in the flat and horizontal positions.

Globular transfer is a mode of gas metal arc welding that results when high concentrations of carbon dioxide are used. Carbon dioxide is not an inert gas; rather, it is active. Therefore, GMAW that uses CO_2 may be referred to as **MAG,** for **metal active gas**. With high concentrations of CO_2 in the shielding gas, the arc no longer behaves in a spraylike fashion, but ejects large globs of metal from the end of the electrode. This mode of transfer, while resulting in deep penetration, generates relatively high levels of spatter, and weld appearance can be poor. Like the spray mode, it is restricted to the flat and horizontal positions. Globular transfer may be preferred over spray arc transfer because of the low cost of CO_2 shielding gas and the lower level of heat experienced by the operator.

Pulsed arc transfer is a relatively new development in GMAW. In this mode, a background current is applied continuously to the electrode. A pulsing peak current is applied at a rate proportional to the wire feed speed. With this mode of transfer, the power supply delivers a pulse of current which, ideally, ejects a single droplet of metal from the electrode. The power supply then returns to a lower background current to maintain the arc. This occurs between 100 and 400 times per second. One advantage of pulsed arc transfer is that it can be used out of position. For flat and horizontal work, it will not be as fast as spray arc transfer. However, when it is used out of position, it is free of the problems associated with gas metal arc short-circuiting mode. Weld appearance is good, and quality can be excellent. The disadvantages of pulsed arc transfer are that the equipment is slightly more complex and is more costly.

Metal cored electrodes comprise another new development in GMAW. This process is similar to FCAW in that the electrode is tubular, but the core material does not contain slag-forming ingredients. Rather, a variety of metallic powders are contained in the core, resulting in exceptional alloy control. The resulting weld is slag-free, as are other forms of GMAW.

The use of metal cored electrodes offers many fabrication advantages. Compared to spray arc transfer, metal cored electrodes require less amperage to obtain the same deposition rates. They are better able to handle mill scale and other surface contaminants. When used out-of-position, they offer greater resistance to the cold lapping phenomenon so common with short arc transfer. Finally, metal cored electrodes permit the use of amperages higher than may be practical with solid electrodes, resulting in higher metal deposition rates.

The weld properties obtained from metal cored electrode deposits can be excellent, and their appearance is very good. Filler metal manufacturers are able to control the composition of the core ingredients, so that mechanical properties obtained from metal cored deposits can be more consistent than those obtained with solid electrodes.

Electroslag/Electrogas Welding (ESW/EGW)

Electroslag and **electrogas welding** (Figs. 13.3.8 and 13.3.9) are closely related processes that allow high deposition welding in the vertical plane. Properly applied, these processes offer tremendous savings over alternative, out-of-position methods and, in many cases, savings over flat-position welding. Although the two processes have similar applications and mechanical setup, there are fundamental differences in the arc characteristics.

Electroslag and electrogas are mechanically similar in that both utilize **copper dams,** or shoes, that are applied to either side of a square-edged butt joint. An electrode or multiple electrodes are fed into the joint. Usually, a starting sump is applied for the beginning of the weld. As the electrode is fed into the joint, a puddle is established that progresses vertically. The water-cooled copper dams chill the weld metal and prevent its escape from the joint. The weld is completed in one pass.
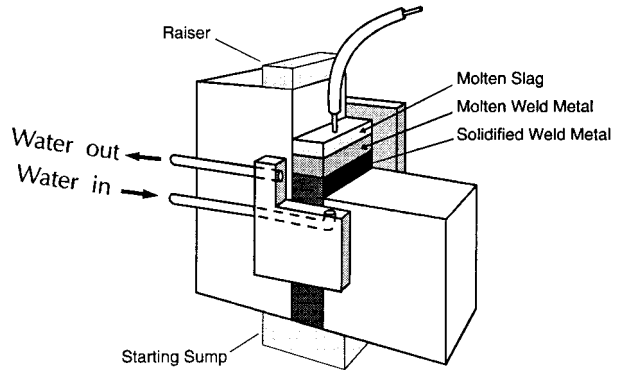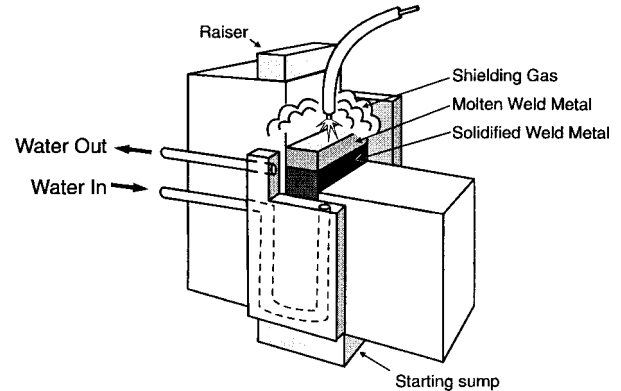

Fig. 13.3.8 ESW process.

Fig. 13.3.9 EGW process.

Gas Tungsten Arc Welding (GTAW)

The **gas tungsten arc welding** process (Fig. 13.3.10), colloquially called **TIG welding,** uses a nonconsumable tungsten electrode. An arc is established between the tungsten electrode and the workpiece, resulting in heating of the base metal. If required, a filler metal is used. The weld area is shielded with an inert gas, usually argon or helium. GTAW is ideally suited to weld nonferrous materials such as stainless steel and aluminum, and is very effective for joining thin sections.

Highly skilled welders are required for GTAW, but the resulting weld quality can be excellent. The process is often used to weld exotic materials. Critical repair welds as well as root passes in pressure piping are typical applications.
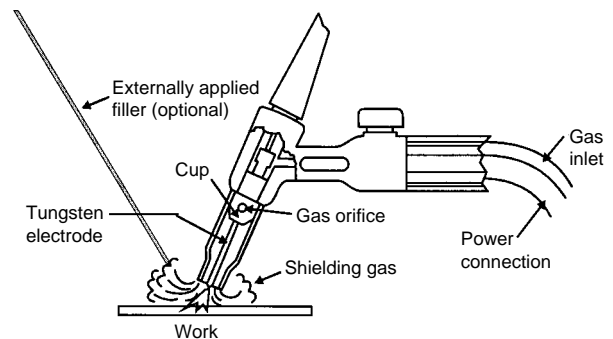

Fig. 13.3.10 Gas tungsten arc welding (GTAW).

Plasma Arc Welding (PAW)

Plasma arc welding is an arc welding process using a constricted arc to generate very high, localized heating. PAW may utilize either a transferred or a nontransferred arc. In the **transferred arc mode,** the arc occurs between the electrode and the workpiece, much as in GTAW, the primary difference being the constriction afforded by the secondary gases and torch design. With the **nontransferred arc** mode, arcing is contained within the torch between a tungsten electrode and a surrounding nozzle.

The constricted arc results in higher localized arc energies than are experienced with GTAW, resulting in faster welding speeds. Applications for PAW are similar to those for GTAW. The only significant disadvantage of PAW is the equipment cost, which is higher than that for GTAW.

Most PAW is done with the transferred arc mode, although this mode utilizes a nontransferred arc for the first step of operation. An arc and plasma are initially established between the electrode and the nozzle. When the torch is properly located, a switching system will redirect the arc toward the workpiece. Since the arc and plasma are already established, transferring the arc to the workpiece is easily accomplished and highly reliable. For this reason, PAW is often preferred for automated applications.

GAS WELDING AND BRAZING

The heat for **gas welding** is supplied by burning a mixture of oxygen and a suitable combustible gas. The gases are mixed in a torch which controls the welding flame.

Acetylene is almost universally used as the combustible gas because of its high flame temperature. This temperature, about 6,000°F (3,315°C), is so far above the melting point of all commercial metals that it provides a means for the rapid localized melting essential in welding. The oxyacetylene flame is also used in cutting ferrous metals.

A **neutral flame** is one in which the fuel gas and oxygen combine completely, leaving no excess of either fuel gas or oxygen. The neutral flame has an inside portion, consisting of a brilliant cone $\frac{1}{16}$ to $\frac{3}{4}$ in (1.6 to 19.1 mm) long, surrounded by a faintly luminous envelope flame. When fuel gas is in excess, the flame consists of three easily recognizable zones: a sharply defined inner cone, an intermediate cone of whitish color, and the bluish outer envelope. The length of the intermediate cone is a measure of the amount of excess fuel gas. This **flame is reducing,** or **carburizing**.

When oxygen is in excess in the mixture, the flame resembles the neutral flame, but the inner cone is shorter, is ''necked in'' on the sides, is not so sharply defined, and acquires a purplish tinge. A slightly **oxidizing flame** may be used in braze welding and bronze surfacing, and a more strongly oxidizing flame is sometimes used in gas-welding brass, bronze, and copper. A disadvantage of a strongly oxidizing flame is that it can oxidize the surface of the base metal and thereby prevent fusion of the filler metal to the base metal.

In **braze welding,** coalescence is produced by heating above 840°F (450°C) and by using a nonferrous filler metal having a melting point below that of the base metals. Braze welding with brass (bronze) rods is used extensively on cast iron, steel, copper, brass, etc. Since it operates at temperatures lower than base metal melting points, it is used where control of distortion is necessary or lower base metal temperatures during welding are desired. Braze-welded joints on mild steel, made with rods of classifications RCuZn-B and RBCuZn-D, will show transverse tensile values of 60,000 to 70,000 lb/in^2 (414 to 483 MPa). Joint designs for braze welding are similar to those used for gas and arc welding.

In braze welding it is necessary to remove rust, grease, scale, etc., and to use a suitable flux to dissolve oxides and clean the metal. Sometimes rods are used with a flux coating applied to the outside. Additional flux may or may not be required, notwithstanding the flux coating on the rods. The parts are heated to red heat [1,150 to 1,350°F (621 to 732°C)], and the rod is introduced into the heated zone. The rod melts first and ''tins'' the surfaces, following which additional filler metal is added.

Welding rods for oxyacetylene braze welding are usually of the copper-zinc (60 Cu-40 Zn) analysis. Additions of tin, manganese, iron, nickel, and silicon are made to improve the mechanical properties and usability of the rods.

Brazing is another one of the general groups of welding processes, consisting of the torch, furnace, induction, dip, and resistance brazing. Brazing may be used to join almost all metals and combinations of dissimilar metals, but some combinations of dissimilar metals are not compatible (e.g., aluminum or magnesium to other metals). In brazing, coalescence is produced by heating above 840°F (450°C) but below the melting point of the metals being joined. The nonferrous filler metal used has a melting point below that of the base metal, and the filler metal is distributed in the closely fitted lap or butt joints by capillary attraction. Clean joints are essential for satisfactory brazing. The use of a flux or controlled atmosphere to ensure surface cleanliness is necessary. Filler metal may be hand-held and fed into the joint (face feeding), or preplaced as rings, washers, shims, slugs, etc.

Brazing with the silver-alloy filler metals previously was known as **silver soldering** and **hard soldering. Braze welding** should not be confused with brazing. Braze welding is a method of welding employing a filler metal which melts below the welding points of the base metals joined, but the filler metal *is not* distributed in the joint by capillary attraction. (See also Sec. 6.)

Torch brazing uses acetylene, propane, or other fuel gas, burned with oxygen or air. The combination employed is governed by the brazing temperature range of the filler metal, which is usually above its liquidus. Flux with a melting point appropriate to the brazing temperature range and the filler metal is essential.

Furnace brazing employs the heat of a gas-fired, electric, or other type of furnace to raise the parts to brazing temperature. Fluxes may be used, although reducing or inert atmospheres are more common since they eliminate postbraze cleaning necessary with fluxes.

Induction brazing utilizes a high-frequency current to generate the necessary heat in the part by induction. Distortion in the brazed joint can be controlled by current frequency and other factors. Fluxes or gaseous atmospheres must be used in induction bearing.

Dip brazing involves the immersion of the parts in a molten bath. The bath may be either molten brazing filler metal or molten salts, which most often are brazing flux. The former is limited to small parts such as electrical connections; the latter is capable of handling assemblies weighing several hundred pounds. The particular merit of dip brazing is that the entire joint is completed all at one time.

Resistance brazing utilizes standard resistance-welding machines to supply the heat. Fluxes or atmospheres must be used, with flux predominating. Standard spot or projection welders may be used. Pressures are lower than those for conventional resistance welding.

RESISTANCE WELDING

In resistance welding, coalescence is produced by the heat obtained from the electric resistance of the workpiece to the flow of electric current in a circuit of which the workpiece is a part, and by the application of pressure. The specific processes include **resistance spot welding, resistance seam welding, and projection welding**. Figure 13.3.11 shows diagrammatic outlines of the processes.

The resistance of the welding circuit should be a maximum at the interface of the parts to be joined, and the heat generated there must reach a value high enough to cause localized fusion under pressure.

Electrodes are of copper alloyed with such metals as molybdenum and tungsten, with high electrical conductivity, good thermal conductivity, and sufficient mechanical strength to withstand the high pressures to which they are subjected. The electrodes are water-cooled. The resistance at the surfaces of contact between the work and the electrodes must be kept low. This may be accomplished by using smooth, clean work surfaces and a high electrode pressure.

In **resistance spot welding** (Fig. 13.3.11), the parts are lapped and held in place under pressure. The size and shape of the electrodes control the size and shape of the welds, which are usually circular.

Designing for spot welding involves six elements: tip size, edge distance, contacting overlap, spot spacing, spot weld shear strength, and

electrode clearance. For mild steel, the diameter of the tip face, in terms of sheet thickness t, may be taken as $0.1 + 2t$ for thin material, and as $\sqrt{t}$ for thicker material; all dimensions in inches. Edge distance should be sufficient to provide enough metal around the weld to retain it when in the molten condition. Contacting overlap is generally taken as the diameter of the weld nugget plus twice the minimum edge distance. Spot spacing must be sufficient to ensure that the welding current will not shunt through the previously made weld.
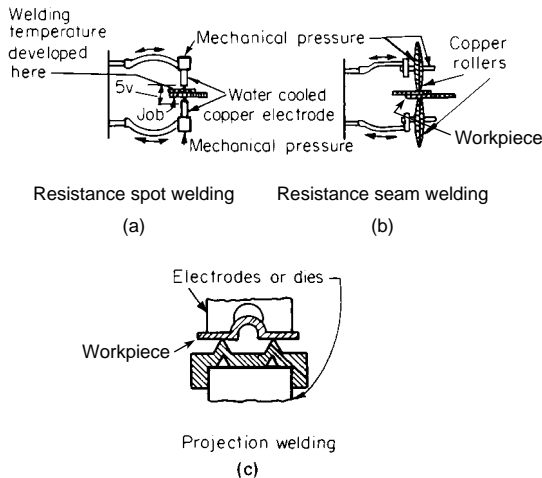

Fig. 13.3.11   (*a*) Resistance spot; (*b*) resistance seam; (*c*) projection welding.

Resistance spot welding machines vary from small, manually operated units to large, elaborately instrumented units designed to produce high-quality welds, as on aircraft parts. Portable gun-type machines are available for use where the assemblies are too large to be transported to a fixed machine. Spot welds may be made singly or in multiples, the latter generally made on special purpose machines. Spacing of electrodes is important to avoid excessive shunting of welding current.

The **resistance seam welding process** (Fig. 13.3.11) produces a series of spot welds made by circular or wheel type electrodes. The weld may be a series of closely spaced individual spot welds, overlapping spot welds, or a continuous weld nugget. The weld shape for individual welds is rectangular, continuous welds are about 80 percent of the width of the roll electrode face.

A **mash weld** is a seam weld in which the finished weld is only slightly thicker than the sheets, and the lap disappears. It is limited to thicknesses of about 16 gage and an overlap of 1½ times the sheet thickness. Operating the machine at reduced speed, with increased pressure and noninterrupted current, a strong quality weld may be secured that will be 10 to 25 percent thicker than the sheets. The process is applicable to mild steel but has limited use on stainless steel; it cannot be used on nonferrous metals. A modification of this technique employs a straight butt joint. This produces a slight depression at the weld, but the strength is satisfactory on some applications, e.g., for the production of some electric-welded pipe and tubing.

Cleanliness of sheets is of even more importance in seam welding than in spot welding. Best results are secured with cold-rolled steel, wiped clean of oil; the next best with pickled hot-rolled steel. Grinding or polishing is sometimes performed, but not sand- or shot-blasting.

In **projection welding** (Fig. 13.3.11), the heat for welding is derived from the localization of resistance at predetermined points by means of projections, embossments, or the intersections of elements of the assembly. The projections may be made by stamping or machining. The process is essentially the same as spot welding, and the projections seem to concentrate the current and pressure. Welds may be made singly or in multiple with somewhat less difficulty than is encountered in spot welding. When made in multiple, all welds may be made simulta-

neously. The advantages of projection welding are (1) the heat balance for difficult assemblies is readily secured, (2) the results are generally more uniform, (3) a closer spacing of welds is possible, and (4) electrode life is increased. Sometimes it is possible to projection-weld joints that could not be welded by other means.

OTHER WELDING PROCESSES

Electron Beam Welding (EBW)

In **electron beam welding,** coalescence of metals is achieved by heat generated by a concentrated beam of high-velocity electrons impinging on the surfaces to be joined. Electrons have a very small mass and carry a negative charge. An electron beam gun, consisting of an emitter, a bias electrode, and an anode, is used to create and accelerate the beam of electrons. Auxiliary components such as beam alignment, focus, and deflection coils may be used with the electron beam gun; the entire assembly is referred to as the electron beam gun column.

The advantages of the process arise from the extremely high energy density in the focused beam which produces deep, narrow welds at high speed, with minimum distortion and other deleterious heat effects. These welds show superior strength compared with those made utilizing other welding processes for a given material. Major applications are with metals and alloys highly reactive to gases in the atmosphere or those volatilized from the base metal being welded.

A disadvantage of the process lies in the necessity for providing precision parts and fixtures so that the beam can be precisely aligned with the joint to ensure complete fusion. Gapped joints are not normally welded because of fixture complexity and the extreme difficulty of manipulating filler metal into the tiny, rapidly moving, weld puddle under high vacuum. When no filler metal is employed, it is common to use the keyhole technique. Here, the electron beam makes a hole entirely through the base metal, which is subsequently filled with melted base metal as the beam leaves the area. Other disadvantages of the process arise from the cost, complexity, and skills required to operate and maintain the equipment, and the safety precautions necessary to protect operating personnel from the X-rays generated during the operation.

Laser Beam Welding and Cutting

By using a laser, energy from a primary source (electrical, chemical, thermal, optical, or nuclear) is converted to a beam of coherent electromagnetic radiation at ultraviolet, visible, or infrared frequency. Because high-energy laser beams are coherent, they can be highly concentrated to provide the high energy density needed for welding, cutting, and heat-treating metals.

As applied to welding, **pulsed** and continuously operating solid-state **lasers** and lasers that produce **continuous-wave (cw) energy** have been developed to the point that multikilowatt laser beam equipment based on CO_2 is capable of full-penetration, single-pass welding of steel to ¾-in thickness.

Lasers do not require a vacuum in which to operate, so that they offer many of the advantages of electron beam welding but at considerably lower equipment cost and higher production rates. Deep, narrow welds are produced at high speeds and low heat input, thus duplicating the excellent weld properties and minimal heat effects obtained from electron beam welding in some applications. The application of lasers to metals—for cutting or welding—coupled with computerized control systems, allows their use for complex shapes and contours.

Solid-State Welding

Solid-state welding encompasses a group of processes in which the weld is effected by bringing clean metal surfaces into intimate contact under certain specific conditions. In **friction welding,** one part is rotated at high speed with respect to the other, under pressure. The parts are heated, but not to the melting point of the metal. Rotation is stopped at the critical moment of welding. Base metal properties across the joint show little change because the process is so rapid. **Ultrasonic welding** employs mechanical vibrations at ultrasonic frequencies plus pressure to effect the

intimate contact between faying surfaces needed to produce a weld. (See also Sec. 12.) The welding tool is essentially a transducer that converts electric frequencies to ultra-high-frequency mechanical vibrations. By applying the tip of the tool, or anvil, to a small area in the external surface of two lapped parts, the vibrations and pressure are transmitted to the faying surfaces. Foils, thin-gage sheets, or fine wires can be spot- or seam-welded to each other or to heavier parts.

Explosion Welding

Explosion welding utilizes extremely high pressures to join metals, often with significantly different properties. For example, it may used to clad a metal substrate, such as steel, with a protective layer of a dissimilar metal, such as aluminum. Since the materials do not melt, two metals with significantly different melting points can be successfully welded by explosion welding. The force and speed of the explosion are directed to cause a series of progressive shock waves that deform the faying surfaces at the moment of impact. A magnified section of the joint reveals a true weld with an interlocking waveshape and, usually, some alloying.

THERMAL CUTTING PROCESSES

Oxyfuel Cutting (OFC)   Oxyfuel cutting (Fig. 13.3.12) is used to cut steels and to prepare bevel and vee grooves. In this process, the metal is heated to its ignition temperature, or kindling point, by a series of preheat flames. After this temperature is attained, a high-velocity stream of pure oxygen is introduced, which causes oxidation or ''burning'' to occur. The force of the oxygen steam blows the oxides out of the joint, resulting in a clean cut. The oxidation process also generates additional thermal energy, which is radially conducted into the surrounding steel, increasing the temperature of the steel ahead of the cut. The next portion of the steel is raised to the kindling temperature, and the cut proceeds.

Carbon and low-alloy steels are easily cut by the oxyfuel process. Alloy steels can be cut, but with greater difficulty than mild steel. The level of difficulty is a function of the alloy content. When the alloy content reaches the levels found in stainless steels, oxyfuel cutting cannot be used unless the process is modified by injecting flux or iron-rich powders into the oxygen stream. Aluminum cannot be cut with the oxyfuel process. Oxyfuel cutting is commonly regarded as the most economical way to cut steel plates greater than $\frac{1}{2}$ in thick.

A variety of **fuel gases** may be used for oxyfuel cutting, with the choice largely dependent on local economics; they include natural gas, propane, acetylene, and a variety of proprietary gases offering unique advantages. Because of its role in the primary cutting stream, oxygen is always used as a second gas. In addition, some oxygen is mixed with the fuel gas in proportions designed to ensure proper combustion.

Plasma Arc Cutting (PAC)   The plasma arc cutting process (Fig. 13.3.13) was developed initially to cut materials that do not permit the use of the oxyfuel process: stainless steel and aluminum. It was found, however, that plasma arc cutting offered economic advantages when applied to thinner sections of mild steel, especially those less than 1 in thick. Higher travel speed is possible with plasma arc cutting, and the volume of heated base material is reduced, minimizing metallurgical changes as well as reducing distortion.

PAC is a thermal and mechanical process. To utilize PAC, the material is heated until molten and expelled from the cut with a high-velocity stream of compressed gas. Unlike oxyfuel cutting, the process does not rely on oxidation. Because high amounts of energy are introduced
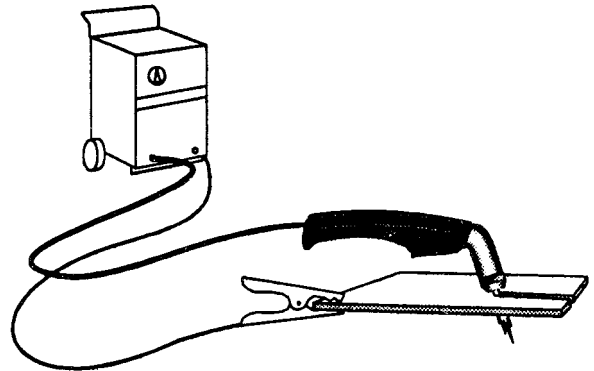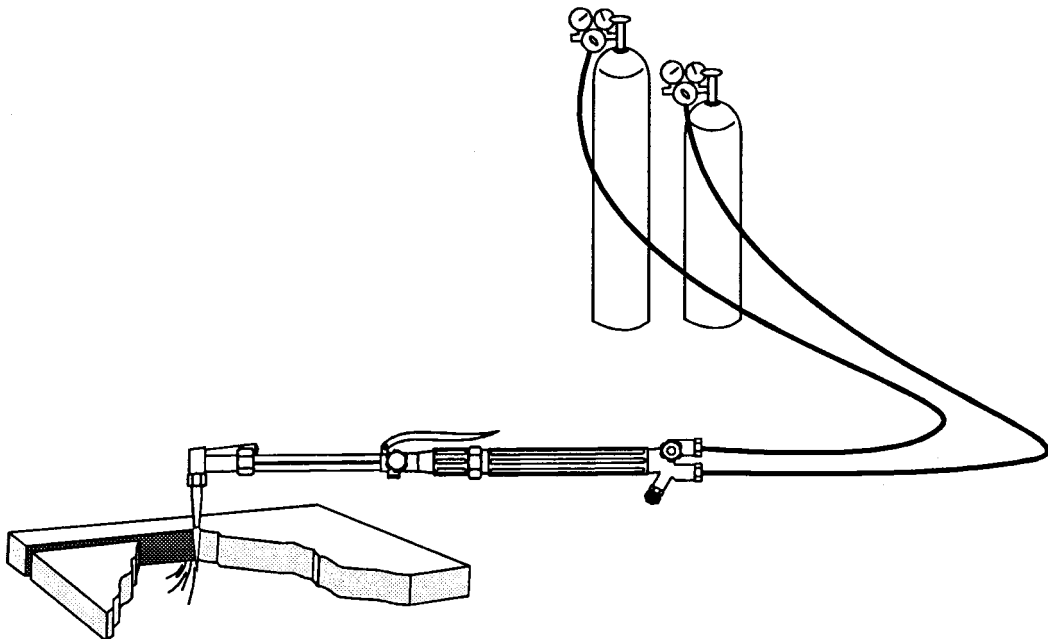

Fig. 13.3.13   Plasma arc cutting process.
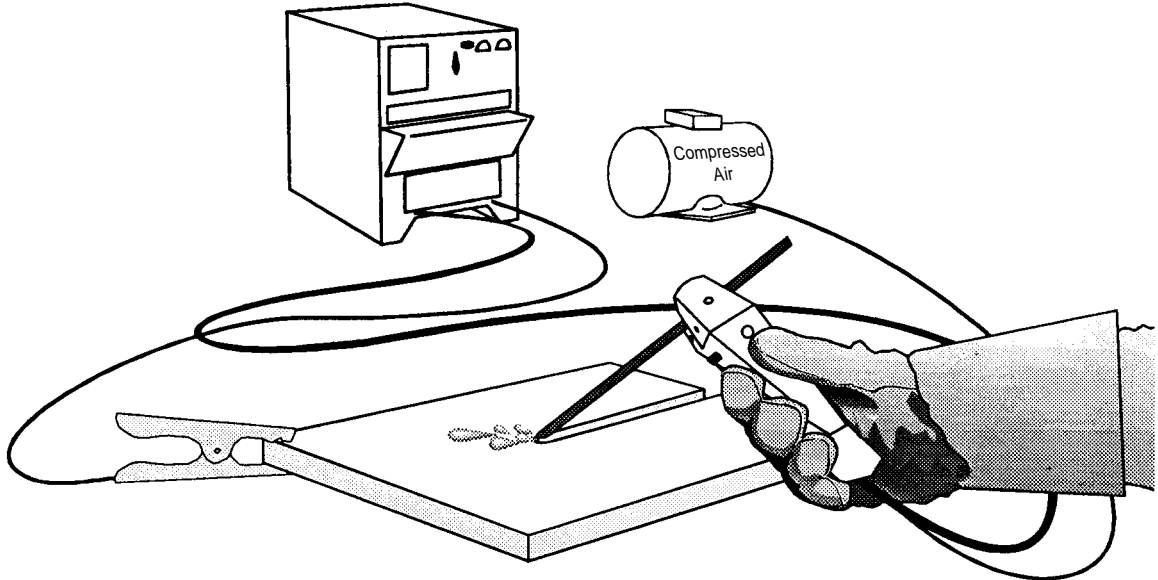

Fig. 13.3.12   Oxyfuel cutting.

Fig. **13.3.14** Air arc gouging.

through the arc, PAC is capable of extremely high-speed cutting. The thermal energy generated during the oxidation process with oxyfuel cutting is not present in plasma; hence, for thicker sections, PAC is not economically justified. The use of PAC to cut thick sections usually is restricted to materials that do not oxidize readily with oxyfuel.

Air Arc Gouging (AAG) The air carbon arc gouging system (Fig. 13.3.14) utilizes an electric arc to melt the base material; a high-velocity jet of compressed air subsequently blows the molten material away. The air carbon gouging torch looks much like a manual electrode holder, but it uses a carbon electrode instead of a metallic electrode. Current is conducted through the base material to heat it. A valve in the torch handle permits compressed air to flow through two air ports. As the air hits the molten material, a combination of oxidation and expulsion of metal takes place, leaving a smooth cavity behind. The air carbon arc gouging system is capable of removing metal at a much higher rate than can be deposited by most welding processes. It is a powerful tool used to remove metal at low cost.

Plasma Arc Gouging A relatively new development is the application of plasma arc equipment for gouging. The process is identical to plasma arc cutting, but the small-diameter orifice is replaced with a larger one, resulting in a broader arc. More metal is heated, and a larger, broader stream of hot, high-velocity plasma gas is directed toward the workpiece. When the torch is inclined to the work surface, the metal can be removed in a fashion similar to air carbon arc gouging. The applications of the process are similar to those of air carbon arc gouging.

DESIGN OF WELDED CONNECTIONS

A **welded connection** consists of two or more pieces of base metal joined by weld metal. Design engineers determine joint type and generally specify weld type and the required throat dimension. Fabricators select the specific joint details to be used.

Joint Types

When pieces of steel are brought together to form a **joint,** they will assume one of the five configurations presented in Fig. 13.3.15. Joint types are descriptions of the relative positions of the materials to be joined and do not imply a specific type of weld.

Weld Types

Welds fall into three categories: fillet welds, groove welds, and plug and slot welds (Fig. 13.3.16). Plug and slot welds are used for connections that transfer small loads.
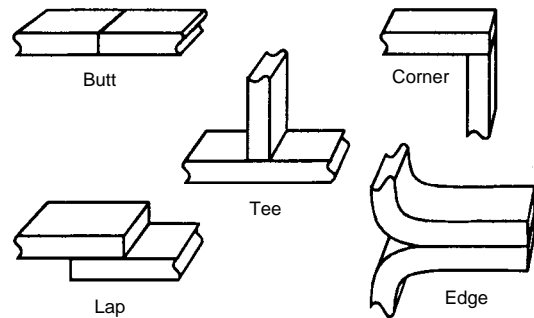

Fig. **13.3.15** Joint types.

Many engineers will see or have occasion to use standard welding symbols. A detailed discussion of their proper use is found in AWS documents. A few are shown in Fig. 13.3.17.

Fillet Welds Fillet welds have a triangular cross section and are applied to the surface of the materials they join. By themselves, fillet welds do not fully fuse the cross-sectional areas of parts they join, although it is still possible to develop full-strength connections with fillet welds. The size of a fillet weld is usually determined by measuring the leg, even though the weld is designed by specifying the required throat. For equal-legged, flat-faced fillet welds applied to plates that are oriented 90° apart, the throat dimension is found by multiplying the leg size by 0.707 (for example, sin 45°).
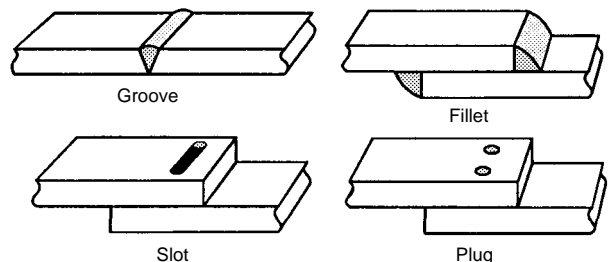

Fig. **13.3.16** Major weld types.

Basic Weld Symbols*								
Back bead	Fillet	Plug or slot	Groove or butt					
			V	Bevel	U	J	Flare V	Flare Bevel

Supplementary Weld Symbols*					
Backing	Spacer	Weld all around	Field weld	Contour	
				Flush	Convex

* See AWS publications for a complete listing.

Fig. 13.3.17   Some welding symbols commonly used. *(AWS)*

Groove Welds   Groove welds comprise two subcategories: complete joint penetration (CJP) groove welds and partial joint penetration (PJP) groove welds (Fig. 13.3.18). By definition, CJP groove welds have a throat dimension equal to the thickness of the material they join; a PJP groove weld is one with a throat dimension less than the thickness of the materials joined.

An **effective throat** is associated with a PJP groove weld. This term is used to differentiate between the depth of groove preparation and the probable depth of fusion that will be achieved. The **effective throat** on a PJP groove weld is abbreviated by E. The required **depth of groove preparation** is designated by a capital S. Since the designer may not
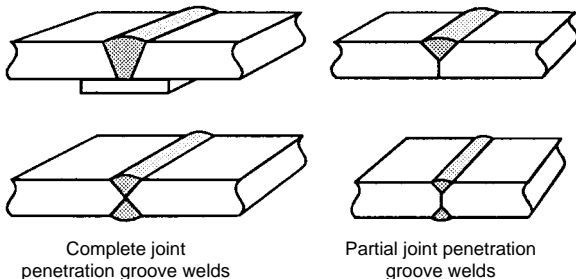

Complete joint
penetration groove welds

Partial joint penetration
groove welds

Fig. 13.3.18   Types of groove welds.

know which welding process a fabricator will select, it is necessary only to specify the dimension for E. The fabricator then selects the welding process, determines the position of welding, and applies the appropriate S dimension, which will be shown on the shop drawings. In most cases, both the S and E dimensions will appear on the welding symbols of shop drawings, with the effective throat dimension shown in parentheses.

Sizing of Welds

Overwelding is one of the major factors of welding cost. Specifying the correct size of weld is the first step in obtaining low-cost welding. It is important, then, to have a simple method to figure the proper amount of weld to provide adequate strength for all types of connections.

In terms of their application, welds fall into two general types: primary and secondary. **Primary welds** are critical welds that directly transfer the full applied load at the point at which they are located. These welds must develop the full strength of the members they join. Complete joint penetration groove welds are often used for these connections. **Secondary welds** are those that merely hold the parts together to

form a built-up member. The forces on these welds are relatively low, and fillet welds are generally utilized in these connections.

Filler Metal Strength   **Filler metal strength** may be classified as matching, undermatching, or overmatching. **Matching filler metal** has the same, or slightly higher, minimum specified yield and tensile strength as the base metal. CJP groove welds in tension require the use of matching weld metal—otherwise, the strength of the welded connection will be lower than that of the base metal. **Undermatching filler metal** deposits welds of a strength lower than that of the base metal. Undermatching filler metal may be deposited in fillet welds and PJP groove welds as long as the designer specifies a throat size that will compensate for the reduction in weld metal strength. An **overmatching filler metal** deposits weld metal that is stronger than the base metal; this is undesirable unless, for practical reasons, lower-strength filler metal is unavailable for the application. When overmatching filler metal is used, if the weld is stressed to its maximum allowable level, the base metal can be overstressed, resulting in failure in the fusion zone. Designers must ensure that connection strength, including the fusion zone, meets the application requirements.

In welding high-strength steel, it is generally desirable to utilize undermatching filler metal for secondary welds. High-strength steel may require additional preheat and greater care in welding because there is an increased tendency to crack, especially if the joint is restrained. Undermatching filler metals such as E70 are the easiest to use and are preferred, provided the weld is sized to impart sufficient strength to the joint.

Allowable Strength of Welds under Steady Loads   A structure, or **weldment,** is as strong as its weakest point, and ''allowable'' weld strengths are specified by the American Welding Society (AWS), the American Institute of Steel Construction (AISC), and various other professional organizations to ensure that a weld will deliver the mechanical properties of the members being joined. Allowable weld strengths are designated for various types of welds for steady and fatigue loads.

CJP groove welds are considered **full-strength welds,** since they are capable of transferring the equivalent capacity of the members they join. In calculations, such welds are allowed the same stress as the plate, provided the proper strength level of weld metal is used (e.g., matching filler metal). In such CJP welds, the mechanical properties of the weld metal must at least match those of the base metal. If the plates joined are of different strengths, the weld metal strength must at least match the strength of the weaker plate.

Figure 13.3.19 illustrates representative applications of PJP groove welds widely used in the economical welding of very heavy plates. PJP groove welds in heavy material will usually result in savings in weld metal and welding time, while providing the required joint strength. The
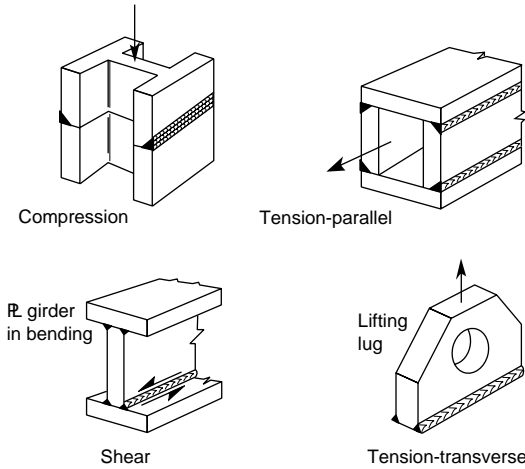
Fig. 13.3.19 Applications of partial joint penetration (PJP) groove welds.

Table 13.3.1 Minimum Fillet Weld Size ω or Minimum Throat of PJP Groove Weld t_e

Material thickness of thicker part joined, in	ω or t_e, in
*To ¼ incl.	⅛
Over ¼ to ½	3/16
Over ½ to ¾	¼
†Over ¾ to 1½	5/16
Over 1½ to 2¼	⅜
Over 2¼ to 6	½
Over 6	⅝

Not to exceed the thickness of the thinner part.
* Minimum size for bridge application does not go below 3/16 in.
† For minimum fillet weld size, table does not go above 5/16-in fillet weld for over ¾-in material.

faster cooling and increased restraint, however, justify establishment of a minimum effective throat t_e (see Table 13.3.1).

Other factors must be considered in determining the allowable stress on the throat of a PJP groove weld. Joint configuration is one. If a V, J, or U groove is specified, it is assumed that the welder can easily reach the bottom of the joint, and the effective weld throat t_e equals the depth of the groove. If a bevel groove with an included angle of 45° or less is specified and SMAW is used, ⅛ in is deducted from the depth of the prepared groove in defining the effective throat. This does not apply to the SAW process because of its deeper penetration capabilities. In the case of GMAW or FCAW, the ⅛-in reduction in throat only applies to bevel grooves with an included angle of 45° or less in the vertical or overhead position.

Weld metal subjected to compression in any direction or to tension parallel to the axis of the weld should have the same allowable strength as the base metal. Matching weld metal must be used for compression, but is not necessary for tension parallel loading.

The existence of tension forces transverse to the axis of the weld or shear in any direction requires the use of weld metal allowable strengths that are the same as those used for fillet welds. The selected weld metal may have mechanical properties higher or lower than those of the metal being joined. If the weld metal has lower strength, however, its allowable strength must be used to calculate the weld size or maximum allowable weld stress. For higher-strength weld metal, the weld allowable strength may not exceed the shear allowable strength of the base metal.

The AWS has established the **allowable shear value** for weld metal in a fillet or PJP bevel groove weld as

$$\tau = 0.30 \times \text{electrode min. spec. tensile strength} = 0.30 \times \text{EXX}$$

and has proved it valid from a series of fillet weld tests conducted by a special Task Committee of AISC and AWS.

Table 13.3.2 lists the allowable shear values for various weld metal strength levels and the more common fillet weld sizes. These values are for equal-leg fillet welds where the effective throat t_e equals $0.707 \times$ leg size ω. With the table, one can calculate the allowable unit force per lineal inch f for a weld size made with a particular electrode type. For example, the allowable unit force per lineal inch f for a ½-in fillet weld made with an E70 electrode is

$$f = 0.707\omega\tau = 0.707(\tfrac{1}{2}\text{ in})(0.30)(70\text{ ksi}) = 7.42\text{ kips/in in}$$

The minimum allowable sizes for fillet welds are given in Table 13.3.1. When materials of different thickness are joined, the minimum fillet weld size is governed by the thicker material; but this size need not exceed the thickness of the thinner material unless it is required by the calculated stress.

Table 13.3.2 Allowable Loads for Various Size Fillet Welds

	60*	70*	80	90*	100	110*	120
	Strength level of weld metal (EXX)						
	Allowable shear stress on throat, ksi (1,000 lb/in²), of fillet weld or PJP weld						
$\tau =$	18.0	21.0	24.0	27.0	30.0	33.0	36.0
	Allowable unit force on fillet weld, kips/lin in						
$f =$	12.73ω	14.85ω	16.97ω	19.09ω	21.21ω	23.33ω	25.45ω
Leg size ω, in	Allowable unit force for various sizes of fillet welds, kips/lin in						
1	12.73	14.85	16.97	19.09	21.21	23.33	25.45
⅞	11.14	12.99	14.85	16.70	18.57	20.41	22.27
¾	9.55	11.14	12.73	14.32	15.92	17.50	19.09
⅝	7.96	9.28	10.61	11.93	13.27	14.58	15.91
½	6.37	7.42	8.48	9.54	10.61	11.67	12.73
7/16	5.57	6.50	7.42	8.35	9.28	10.21	11.14
⅜	4.77	5.57	6.36	7.16	7.95	8.75	9.54
5/16	3.98	4.64	5.30	5.97	6.63	7.29	7.95
¼	3.18	3.71	4.24	4.77	5.30	5.83	6.36
3/16	2.39	2.78	3.18	3.58	3.98	4.38	4.77
⅛	1.59	1.86	2.12	2.39	2.65	2.92	3.18
1/16	0.795	0.930	1.06	1.19	1.33	1.46	1.59

* Fillet welds actually tested by the joint AISC-AWS Task Committee.

Connections under Simple Loads   For a **simple tensile, compressive or shear load,** the imposed load is divided by weld length to obtain applied force, *f*, in pounds per lineal inch of weld. From this force, the proper leg size of the fillet weld or throat size of groove weld is found.

For **primary welds in butt joints,** groove welds must be made through the entire plate, in other words, **100 percent penetration**. Since a butt joint with a properly made CJP groove has a strength equal to or greater than that of the plate, there is no need to calculate the stress in the weld or to attempt to determine its size. It is necessary only to utilize matching filler metal.

With fillet welds, it is possible to have a weld that is either too large or too small; therefore, it is necessary to be able to determine the proper weld size.

Parallel fillet welds have forces applied parallel to their axis, and the throat is stressed only in shear. For an equal-legged fillet, the maximum shear stress occurs on the 45° throat.

Transverse fillet welds have forces applied transversely, or at right angles to their axis, and the throat is stressed by combined shear and normal (tensile or compressive) stresses. For an equal-legged fillet weld, the maximum shear stress occurs on the 67½° throat, and the maximum normal stress occurs on the 22½° throat.

Connections Subject to Horizontal Shear   A weld joining the flange of a beam to its web is stressed in horizontal shear (Fig. 13.3.20). A designer may be accustomed to specifying a certain size fillet weld for a given plate thickness (e.g., leg size about three-fourths of the plate thickness) in order that the weld develop full plate strength. This particular joint between flange and web is an exception to this rule. In order to
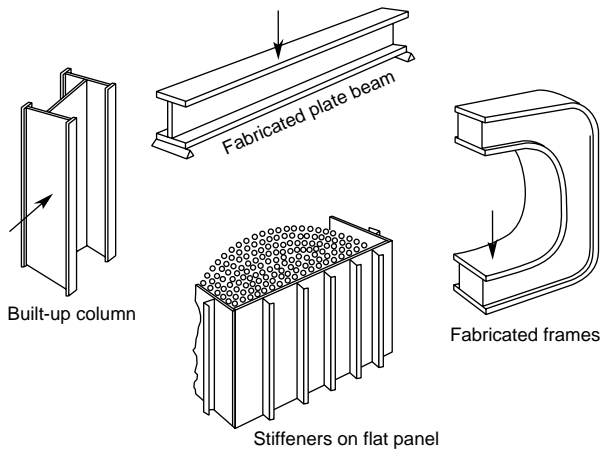

Fabricated plate beam

Built-up column

Fabricated frames

Stiffeners on flat panel

Fig. 13.3.20   Examples of welds stressed in horizontal shear.

prevent web buckling, a lower allowable shear stress is usually used, which results in the requirement for a thicker web. The welds are in an area next to the flange where there is no buckling problem, and no reduction in allowable load is applied to them. From a design standpoint, these welds may be very small; their actual size sometimes is determined by the minimum size allowed by the thickness of the flange plate, in order to ensure the proper slow cooling rate of the weld on the heavier plate.

General Rules about Horizontal Shear   Aside from joining the flanges and web of a beam, or transmitting any unusually high force between the flange and web at right angles to the assembly (e.g., bearing supports, lifting lugs), the weld between flange and web serves to transmit the horizontal shear forces; the weld size is determined by the magnitude of the shear forces. In the analysis of a beam, a shear diagram is useful to depict the amount and location of welding required between the flange and web (Fig. 13.3.21).

Figure 13.3.21 shows that (1) members with applied transverse loads are subject to bending moments; (2) changes in bending moments cause

horizontal shear forces; and (3) horizontal shear forces require welds to transmit them between the flange and web of the beam.

NOTE: (1) Shear forces occur only when the bending moment is changing. (2) It is quite possible for portions of a beam to have little or no shear—i.e., the middle portions of the beams 1 and 2, within which the bending moment is constant. (3) When there is a difference in shear along the length of the beam, the shear forces are usually greatest at the ends of the beam (see beam 3), so that when web stiffeners are used, they are welded continuously when placed at the ends and welded intermittently when placed elsewhere along the length of the beam. (4) Fixing beam ends will alter the moment diagram to reduce the maximum moment; i.e., the bending moment is lower in the middle, but is now introduced at the ends. For the uniform loading configuration in beam 3, irrespective of the end conditions and their effect on bending moments and their location, the shear diagram will remain unchanged, and the amount of welding between flange and web will remain the same.
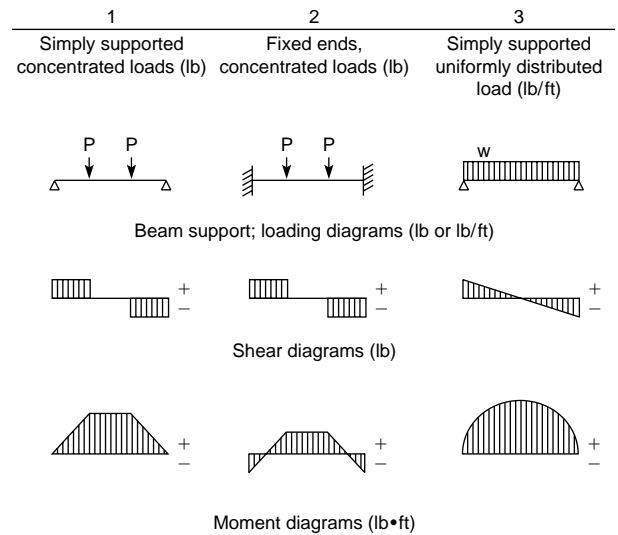

1	2	3
Simply supported concentrated loads (lb)	Fixed ends, concentrated loads (lb)	Simply supported uniformly distributed load (lb/ft)

Beam support; loading diagrams (lb or lb/ft)

Shear diagrams (lb)

Moment diagrams (lb·ft)

Fig. 13.3.21   Shear and moment diagrams.

Application of Rules to Find Weld Size   Horizontal shear forces acting on the weld joining flange and web (Fig. 13.3.22) may be found from the following formula:

$$f = \frac{Vay}{In} \qquad \text{lb/lin in}$$

where *f* = force on weld, lb/lin in; *V* = total shear on section at a given position along beam, lb; *a* = area of flange held by weld, in²; *y* = distance between center of gravity of flange area and neutral axis of whole section, in; *I* = moment of inertia of whole section, in⁴; and *n* = number of welds joining flange to web.

Locate Welds at Point of Minimum Stress   In Fig. 13.3.23*a*, shear force is high because the weld lies on the neutral axis of the section,
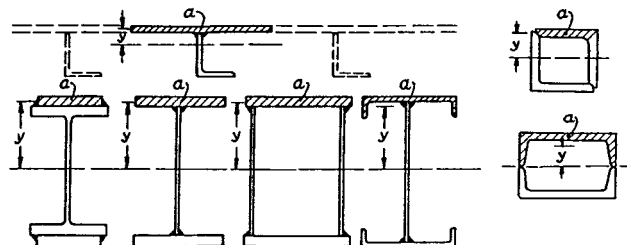

Fig. 13.3.22   Area of flange held by weld.

where the horizontal shear force is maximum. In Fig. 3.3.23*b*, the shear force is resisted by the channel webs, not the welds. In this last case, the shear formula above does not enter into consideration; for the configuration in Fig. 13.3.23*b*, full-penetration welds are not required.
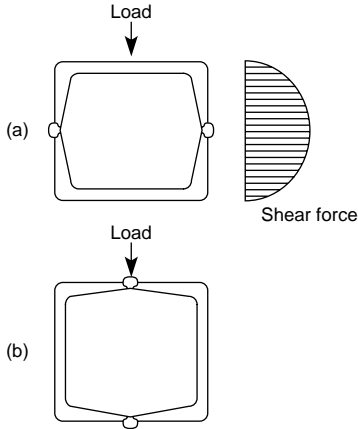

Fig. 13.3.23   Design options for placement of welds. (*a*) Welds at neutral axis; (*b*) welds at outer fibers.

Determine Length and Spacing of Intermittent Welds   If intermittent fillet welds are used, read the weld size as a decimal and divide this by the actual size used. Expressed as a percentage, this will give the length of weld to be used per unit length. For convenience, Table 13.3.3 lists various intermittent weld lengths and distances between centers for given percentages of continuous welds; or

$$\% = \frac{\text{calculated leg size (continuous)}}{\text{actual leg size used (intermittent)}}$$

Connections Subject to Bending or Twisting   The problem here is to determine the properties of the welded connection in order to check the stress in the weld without first knowing its leg size. One approach suggests assuming a certain weld leg size and then calculating the stress in the weld to see if it is over- or understressed. If the result is too far off, the assumed weld leg size is adjusted, and the calculations repeated. This iterative method has the following disadvantages:

1. A decision must be made as to throat section size to be used to determine the property of the weld. Usually some objection can be raised to any throat section chosen.

2. The resulting stresses must be combined, and for several types of loading, this can become rather complicated.

Table 13.3.3   Length and Spacing of Intermittent Welds

Continuous weld, %	Length of intermittent welds and distance between centers, in		
75	—	3–4	—
66	—	—	4–6
60	—	3–5	—
57	—	—	4–7
50	2–4	3–6	4–8
44	—	—	4–9
43	—	3–7	—
40	2–5	—	4–10
37	—	3–8	—
33	2–6	3–9	4–12
30	—	3–10	—
25	2–8	3–12	—
20	2–10	—	—
16	2–12	—	—

Proposed Method   The following is a simple method used to determine the correct amount of welding required to provide adequate strength for either a bending or a torsion load. In this method, the weld is treated as a line, having no area but having a definite length and cross section. This method offers the following advantages:

1. It is not necessary to consider throat areas.

2. Properties of the weld are easily found from a table without knowledge of weld leg size.

3. Forces are considered per unit length of weld, rather than converted to stresses. This facilitates dealing with combined-stress problems.

4. Actual values of welds are given as force per unit length of weld instead of unit stress on throat of weld.

Visualize the welded connection as a line (or lines), following the same outline as the connection but having no cross sectional area. In Fig. 13.3.24, the desired area of the welded connection A_w can be represented by just the length of the weld. The stress on the weld cannot be determined unless the weld size is assumed; but by following the proposed procedure which treats the weld as a line, the solution is more direct, is much simpler, and becomes basically one of determining the force on the weld(s).
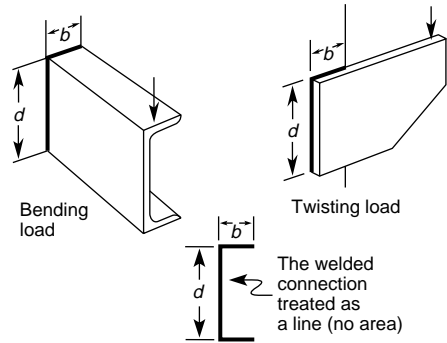

Fig. 13.3.24   Treating the weld as a line.

Use Standard Formulas to Find Force on Weld   Treat the **weld as a line**. By inserting this property of the welded connection into the standard design formula used for a particular type of load (Table 13.3.4*a*), the unit force on the weld is found in terms of pounds per lineal inch of weld.

Normally, use of these standard design formulas results in a **unit stress**, lb/in², but with the weld treated as a line, these formulas result in a **unit force** on the weld, in lb/lin in.

For problems involving bending or twisting loads, Table 13.3.4*c* is used. It contains the section modulus S_w and polar moment of inertia J_w of some 13 typical welded connections with the weld treated as a line. For any given connection, two dimensions are needed: width b and depth d. Section modulus S_w is used for welds subjected to bending; polar moment of inertia J_w for welds subjected to twisting. Section modulus S_w in Table 13.3.4*c* is shown for symmetric and unsymmetric connections. For unsymmetric connections, S_w values listed differentiate between top and bottom, and the forces derived therefrom are specific to location, depending on the value of S_w used.

When one is applying more than one load to a welded connection, they are combined vectorially, but must occur at the same location on the welded joint.

Use Allowable Strength of Weld to Find Weld Size   Weld size is obtained by dividing the resulting unit force on the weld by the allowable strength of the particular type of weld used, obtained from Table 13.3.5 (steady loads) or Table 13.3.6 (fatigue loads). For a joint which has only a transverse load applied to the weld (either fillet or butt weld), the allowable transverse load may be used from the applicable table. If part of the load is applied parallel (even if there are transverse loads in addition), the allowable parallel load must be used.

Applying the System to Any Welded Connection

1. Find the position on the welded connection where the combination of forces will be maximum. There may be more than one which must be considered.

2. Find the value of each of the forces on the welded connection at this point. Use Table 13.3.4a for the standard design formula to find the force on the weld. Use Table 13.3.4c to find the property of the weld treated as a line.

3. Combine (vectorially) all the forces on the weld at this point.

4. Determine the required weld size by dividing this value (step 3) by the allowable force in Table 13.3.5 or 13.3.6.

Sample Calculations Using This System The example in Fig. 13.3.25 illustrates the application of this procedure.

Summary

The application of the following guidelines will ensure effective welded connections:

1. Properly select weld type.

2. Use CJP groove welds only where loading criteria mandate.

3. Consider the cost of joint preparation vs. welding time when you select groove weld details.

4. Double-sided joints reduce the amount of weld metal required. Verify welder access to both sides and that the double-sided welds will not require overhead welding.

5. Use intermittent fillet welds where continuous welds are not required.

6. On corner joints, prepare the thinner member.

7. Strive to obtain good fit-up and do not overweld.

8. Orient welds and joints to facilitate flat and horizontal welding wherever possible.

9. Use the minimum amount of filler metal possible in a given joint.

10. Always ensure adequate access for the welder, welding apparatus, and inspector.

Step 1
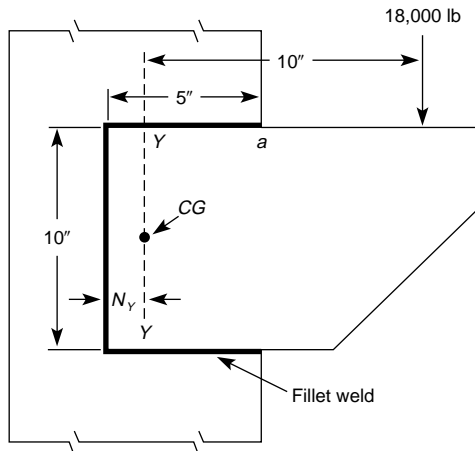
Properties of weld treated as a line
(Table 13.3.4c)
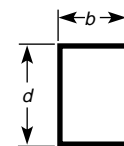
$$N_Y = \frac{b^2}{2b + d} = \frac{5^2}{2 \times 5 + 10} = 1.25 \text{ in}$$

$$J_w = \frac{(2b + d)^3}{12} - \frac{b^2(b + d)^2}{(2b + d)} = \frac{(2 \times 5 + 10)^3}{12} - \frac{5^2(5 + 10)^2}{(2 \times 5 + 10)} = 385.9 \text{ in}^3$$

$$A_w = 20 \text{ in}$$

Step 2 (Table 13.3.4a)

Twisting (horizontal component)

$$f_h = \frac{T\,C_h}{J_w} = \frac{(180,000)(5)}{(385.9)} = 2340 \text{ lb/in}$$

Twisting (vertical component)

$$f_v = \frac{T\,C_v}{J_w} = \frac{(180,000)(3.75)}{(385.9)} = 1750 \text{ lb/in}$$

Vertical shear

$$f_s = \frac{P}{A_w} = \frac{180,000}{20} = 900 \text{ lb/in}$$

Step 3

$$f_R = \sqrt{f_v^2 + f_h^2} = \sqrt{.2340^2 + 2650^2} = 3540 \text{ lb/in}$$
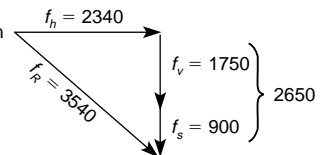
Step 4 (Assume E60 electrodes; Table 13.3.2)

$$\omega = \frac{3540}{12,730} = 0.278 \text{ in or } \tfrac{5}{16} \text{ in leg fillet weld}$$

Fig. 13.3.25 Sample problem: Find the fillet weld size required for the connection shown.

Table 13.3.4   Treating a Weld as a Line

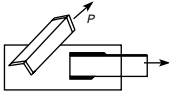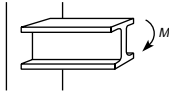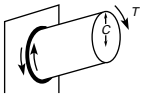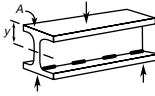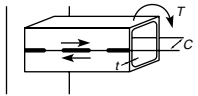| Type of loading		Standard design formula	Treating the weld as a line
		Stress lb/in^2	Force, lb/in
Primary welds transmit entire load at this point			
	Tension or compression	$\sigma = \dfrac{P}{A}$	$f = \dfrac{P}{A_w}$
	Vertical shear	$\sigma = \dfrac{V}{A}$	$f = \dfrac{V}{A_w}$
	Bending	$\sigma = \dfrac{M}{S}$	$f = \dfrac{M}{S_w}$
	Twisting	$\sigma = \dfrac{TC}{J}$	$f = \dfrac{TC}{J_w}$
Secondary welds hold section together—low stress			
	Horizontal shear	$\tau = \dfrac{VA_y}{It}$	$f = \dfrac{VA_y}{In}$
	Torsion horizontal shear*	$\tau = \dfrac{T}{2At}$	$f = \dfrac{T}{2A}$

A = area contained within median line.
* Applies to closed tubular section only.

(*a*) Design formulas used to determine forces on a weld

b = width of connection, in
d = depth of connection, in
A = area of flange material held by welds in horizontal shear, in^2
y = distance between center of gravity of flange material and N.A. of whole section, in
I = moment of inertia of whole section, in.^{4}
C = distance of outer fiber, in
t = thickness of plate, in
J = polar moment of inertia of section, in.^{4}
P = tensile or compressive load, lb
V = vertical shear load, lb

M = bending moment, in·lb
T = twisting moment, in·lb.
A_w = length of weld, in
S_w = section modulus of weld, in^2
J_w = polar moment of inertia of weld, in^3
N_x = distance from x axis to face
N_y = distance from y axis to face
S = stress in standard design formula, lb/in^2
f = force in standard design formula when weld is treated as a line, lb/in
n = number of welds

(*b*) Definition of terms

Allowable Fatigue Strength of Welds

The performance of a weld under **cyclic stress** is an important consideration, and applicable specifications have been developed following extensive research by the American Institute of Steel Construction (AISC). Although sound weld metal has about the same fatigue strength as unwelded metal, the change in section induced by the weld may lower the fatigue strength of the welded joint. In the case of a CJP groove weld, reinforcement, any undercut, lack of penetration, or a crack will act as a notch; the notch, in turn, is a **stress raiser** which results in reduced fatigue strength. A fillet weld used in lap or tee joints provides an abrupt change in section; that geometry introduces a stress raiser and results in reduced fatigue strength.

The initial AISC research was directed toward bridge structure components; Table 13.3.6 illustrates a few such combinations. Similar details arise with other classes of fabricated metal products subjected to repeated loading, such as presses, transportation equipment, and material handling devices. The principles underlying fatigue performance are relatively independent of a particular application, and these data shown can be applied to the design of weldments other than for bridge construction.

Table 13.3.6 is abstracted from an extensive tabulation in the AISC ''Manual of Steel Construction,'' 9th ed. The table also lists the variation of allowable range of stress vs. number of stress cycles for cyclic loading. A detailed discussion of the solution of fatigue-loaded welded joints is beyond the scope of this section. The reader is referred to the basic reference cited above and to the references at the head of this section in pursuing the procedures recommended to solve problems involving welded assemblies subjected to fatigue loads.

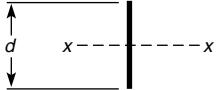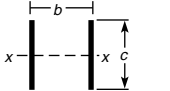Table 13.3.4   Treating a Weld as a Line   (*Continued*)
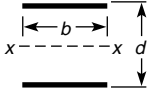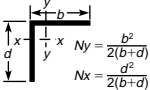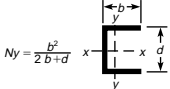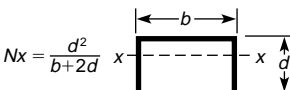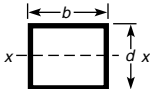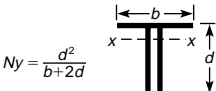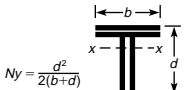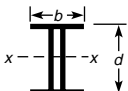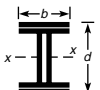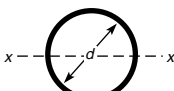
Outline of welded joint b = width d = depth	Bending (about horizontal axis $x - x$)	Twisting
d x----|----x	$S_w = \dfrac{d^2}{6}$ in^2	$J_w = \dfrac{d^3}{12}$ in^3
$\vdash b \dashv$ x--|--|-x c	$S_w = \dfrac{d^2}{3}$	$J_w = \dfrac{d(3b^2 + d^2)}{6}$
$\vdash b \dashv$ x------x d	$S_w = bd$	$J_w = \dfrac{b^3 + 3bd^2}{6}$
y, b; x-x; d; $Ny = \dfrac{b^2}{2(b+d)}$ $Nx = \dfrac{d^2}{2(b+d)}$	$S_w = \dfrac{4bd + d^2}{6} = \dfrac{d^2(4b + d)}{6(2b + d)}$ top bottom	$J_w = \dfrac{(b + d)^4 - 6b^2d^2}{12(b + d)}$
b; $Ny = \dfrac{b^2}{2\,b+d}$ x--x d; y	$S_w = bd + \dfrac{d^2}{6}$	$J_w = \dfrac{(2b + d)^3}{12} - \dfrac{b^2(b + d)^2}{2b + d}$
b; $Nx = \dfrac{d^2}{b+2d}$ x------x d	$S_w = \dfrac{2bd + d^2}{3} = \dfrac{d^2(2b + d)}{3(b + d)}$ top bottom	$J_w = \dfrac{(b + 2d)^3}{12} - \dfrac{d^2(b + d)^2}{b + 2d}$
b; x----d x	$S_w = bd + \dfrac{d^2}{3}$	$J_w = \dfrac{(b + d)^3}{6}$
b; x--x d; $Ny = \dfrac{d^2}{b+2d}$	$S_w = \dfrac{2bd + d^2}{3} = \dfrac{d^2(2b + d)}{3(b + d)}$ top bottom	$J_w = \dfrac{(b + 2d)^3}{12} - \dfrac{d^2(b + d)^2}{b + 2d}$
b; x--x d; $Ny = \dfrac{d^2}{2(b+d)}$	$S_w = \dfrac{4bd + d^2}{3} = \dfrac{4bd^2 + d^3}{6b + 3d}$ top bottom	$J_w = \dfrac{d^3(4b + d)}{6(b + d)} + \dfrac{b^3}{6}$
b; x--x d	$S_w = bd + \dfrac{d^2}{3}$	$J_w = \dfrac{b^3 + 3bd^2 + d^3}{6}$
b; x--x d	$S_w = 2bd + \dfrac{d^2}{3}$	$J_w = \dfrac{2b^3 + 6bd^2 + d^3}{6}$
x--d--x	$S_w = \dfrac{\pi d^2}{4}$	$J_w = \dfrac{\pi d^3}{4}$
x, d, y, x; $\vdash D \dashv$	$I_w = \dfrac{\pi_d}{2}\left(D^2 + \dfrac{d^2}{2}\right)$ $S_w = \dfrac{I_w}{c}$ where $c = \dfrac{\sqrt{D^2 + d^2}}{2}$	

(*c*) Properties of welded connections

Table 13.3.5a Allowable Stresses on Weld Metal

Type of weld stress	Permissible stress*	Required strength level†‡
Complete penetration groove welds		
Tension normal to effective throat	Same as base metal	Matching weld metal must be used. See table below.
Compression normal to effective throat	Same as base metal	Weld metal with a strength level equal to or one classification (10 ksi) less than matching weld metal may be used.
Tension or compression parallel to axis of weld	Same as base metal	Weld metal with a strength level equal to or less than matching weld metal may be used.
Shear on effective throat	0.30 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.40 × yield stress of base metal	
Partial penetration groove welds		
Compression normal to effective throat	Designed not to bear—0.50 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.60 × yield stress of base metal Designed to bear. Same as base metal	Weld metal with a strength level equal to or less than matching weld metal may be used.
Tension or compression parallel to axis of weld§	Same as base metal	
Shear parallel to axis of weld	0.30 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.40 × yield stress of base metal	
Tension normal to effective throat¶	0.30 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.60 × yield stress of base metal	
Fillet welds§		
Stress on effective throat, regardless of direction of application of load	0.30 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.40 × yield stress of base metal	Weld metal with a strength level equal to or less than matching weld metal may be used
Tension or compression parallel to axis of weld	Same as base metal	
Plug and slot welds		
Shear parallel to faying surfaces	0.30 × nominal tensile strength of weld metal (ksi) except stress on base metal shall not exceed 0.40 × yield stress of base metal	Weld metal with a strength level equal to or less than matching weld metal may be used

* For matching weld metal, see AISC Table 1.17.2 or AWS Table 4.1.1 or table below.
† Weld metal, one strength level (10 ksi) stronger than matching weld metal may be used when using alloy weld metal on A242 or A588 steel to match corrosion resistance or coloring characteristics (Note 3 of Table 4.1.4 or AWS D1.1).
‡ Fillet welds and partial penetration groove welds joining the component elements of built-up members (ex. flange to web welds) may be designed without regard to the axial tensile or compressive stress applied to them.
§ Cannot be used in tension normal to their axis under fatigue loading (AWS 2.5). AWS Bridge prohibits their use on any butt joint (9.12.1.1), or any splice in a tension or compression member (9.17), or splice in beams or girders (9.21), however, are allowed on corner joints parallel to axial force of components of built-up members (9.12.1.2 (2). Cannot be used in girder splices (AISC 1.10.8).
¶ AWS D1.1 Section 9 Bridges–reduce above permissible stress allowables of weld by 10%.
SOURCE: Abstracted from AISC and AWS data, by permission. Footnotes refer to basic AWS documents as indicated.

Table 13.3.5b Matching Filler and Base Metals*

Weld metal	60 or 70	70	80	100	110
Type of steel	A36; A53, Gr. B; A106, Gr. B; A131, Gr. A, B, C, CS, D, E; A139, Gr. B; A381, Gr. Y35; A500, Gr. A, B; A501; A516, Gr. 55, 60; A524, Gr. I, II; A529; A570, Gr. D.E; A573, Gr. 65; A709, Gr. 36; API 5L, Gr. B; API 5LX Gr. 42; ABS, Gr. A, B, D, CS, DS, E	A131, Gr. AH32, DH32, EH32, AH36, DH36, EH36; A242; A441; A516, Gr. 65; 70; A537, Class 17; A572, Gr. 42, 45, 50, 55; A588 (4 in and under); A595, Gr. A, B, C; A606; A607, Gr. 45, 50, 55; A618; A633, Gr. A, B, C, D (2½ in and under); A709, Gr. 50, 50W; API 2H; ABS Gr. AH32, DH32, EH32, AH36, DH36, EH36.	A572, Gr. 60, 65; A537, Class 2; A63, Gr. E	A514 (over 2½ in (63 mm)]; A709, Gr. 100, 100W [2½ to 4 in (63 to 102 mm)]	A514 [2½ in (63 mm) and under]; A517; A709, Gr. 100, 100W [2½ in (63 mm) and under]

* Abstracted from AISC and AWS data, by permission

Figure 13.3.26 is a **modified Goodman diagram** for a CJP groove butt weld with weld reinforcement left on. The category is C, and the life is 500,000 to 2 million cycles (see Table 13.3.6). The vertical axis shows maximum stress σ_{max}, and the horizontal axis shows minimum stress σ_{min}, either positive or negative. A steady load is represented by the 45° line to the right, and a complete reversal by the 45° line to the left. The region to the right of the vertical line ($K = 0$) represents tensile loading. The fatigue formulas apply to welded butt joints in plates or other joined members. The region to the left of this line represents cycles going into compressive loading.

The fatigue formulas are meant to reduce the allowable stress as cyclic loads are encountered. The resulting allowable fatigue stress

Table 13.3.6   AISC Fatigue Allowable Stresses for Cyclic Loading

Base metal–no attachments–rolled or clean surfaces

(A)

Base metal–built-up plates or shapes–connected by continuous complete penetration groove welds or fillet welds–without attachments. Note: don't use this as a fatigue allowable for the fillet weld to transfer a load. See (F) for that case.

(B)

Base metal and weld metal at full penetration groove welds–changes thickness or width not to exceed a slope of 1 in 2½ (22°). Ground flush and inspected by radiography or ultrasound (B).

For A514 steel (B′)

Base metal and weld metal at full penetration groove welds–changes in thickness or width not to exceed a slope of 1 in 2½ (22°) Weld reinforcement not removed inspected by radiography or ultrasound.

(C)

Longitudinal loading
Base metal–full penetration groove weld
Weld termination ground smooth
Weld reinforcement not removed
Not necessarily equal thickness

$2 < a < 12$ b or 4 in	(D)
$a > 12b$ or 4 in when $b \pm 1$ in	(E)
$a > 12b$ or 4 in when $b > 1$ in	(E′)

Weld metal of continuous or intermittent longitudinal or transverse fillet welds.

(F)

Category	Allowable Stress Range, σ_{sr} Ksi			
	20,000 to 100,000 ~	100,000 to 500,000 ~	500,000 to 2×10^6 ~	Over 2×10^6 ~
A	63	37	24	24
B	49	29	18	16
B′	39	23	15	12
C	35	21	13	10 (Note 1)
D	28	16	10	7
E	22	13	8	5
E′	16	9	6	3
F	15	12	9	8

Note 1: Flexural stress range of 12 ksi permitted at toe of stiffener welds on flanges.

Allowable fatigue stress:

$$\sigma_{max} = \frac{\sigma_{sr}}{1 - K} \quad \text{for normal stress } \sigma \qquad \tau_{max} = \frac{\tau_{sr}}{1 - K} \quad \text{for shear stress } \tau$$

but shall not exceed steady allowables

σ_{max} or τ_{max} = maximum allowable fatigue stress
σ_{sr} or τ_{sr} = allowable range of stress from table above

$$K = \frac{\sigma_{min}}{\sigma_{max}} = \frac{M_{min}}{M_{max}} = \frac{F_{min}}{F_{max}} = \frac{\tau_{min}}{\tau_{max}} = \frac{V_{min}}{V_{max}}$$

where S = shear, T = tension, R = reversal, M = stress in metal, and W = stress in weld.

should not exceed the usual steady load allowable stress. For this reason, these fatigue curves are cut off with horizontal lines representing the steady load allowable stress for the particular type of steel used. In Fig. 13.3.26, A36 steel with E60 or E70 weld metal is cut off at 22 ksi; A441 steel with E70 weld metal at 30 ksi; and A514 with E110 weld metal at either 54 or 60 ksi, depending on plate thickness.

Figure 13.3.27 is a modification of Fig. 13.3.26, where the horizontal axis represents the range K of the cyclic stress. Here, two additional

strength levels of weld metal have been added—E80 and E90—along with equivalent strength levels of steel. Note that for a small range in stress of $K = 0.6$ to 1.0, higher-strength welds and steels show increased allowable fatigue stress. However, as the stress range increases—lower values of K—the increase is not as great, and below $K = +0.35$ all combinations of weld and steel strengths exhibit the same allowable fatigue stress.

Figure 13.3.28 represents the same welded joint as in Fig. 13.3.27.
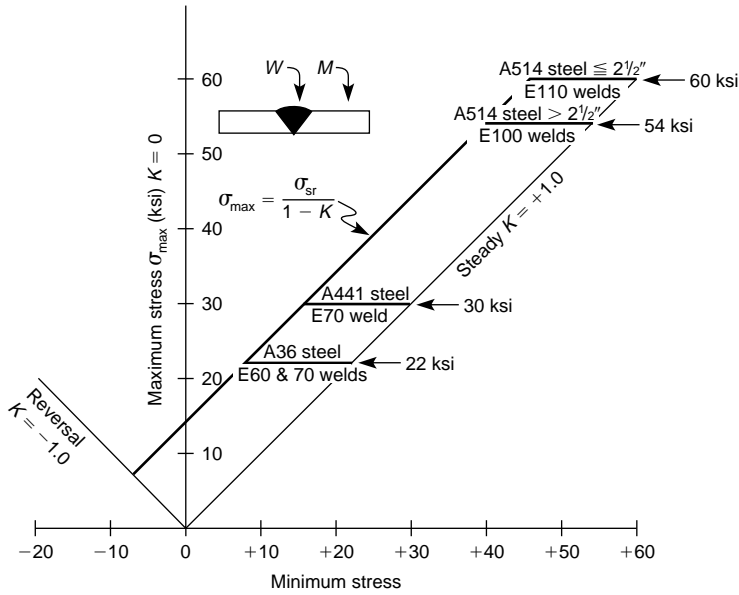
Fig. 13.3.26   Modified Goodman diagram for butt weld. [Butt weld and plate, weld reinforcement left on. Category C; 500,000 to 2,000,000 cycles (see Table 13.3.6).]

Fig. 13.3.27   Fatigue allowable for groove weld. [Butt weld and plate, weld reinforcement left on. Category C; 500,000 to 2,000,000 cycles (see Table 13.3.6).]

but with a lower life of 20,000 to 100,000 cycles. Here, the higher-strength welds and steels have higher allowable fatigue stresses and over a wider range. A conclusion can be drawn that the wider the range of cycling, the less useful the application of a high-strength steel. When there is a complete stress reversal, there is not much advantage in using a high-strength steel.

BASE METALS FOR WELDING

Introduction

When one is considering welding them, the nature of the base metals must be understood and recognized, i.e., their chemical composition, mechanical properties, and metallurgical structure. Cognizance of the
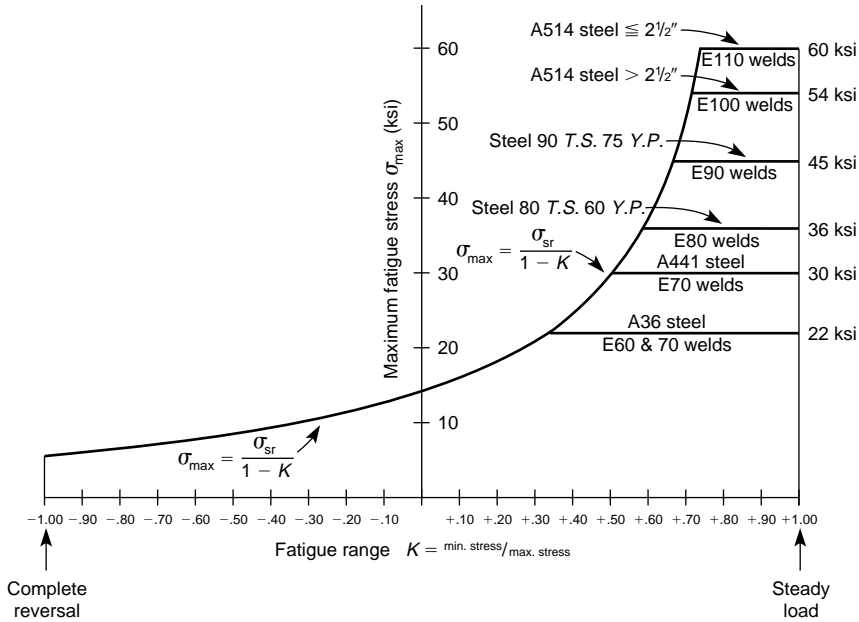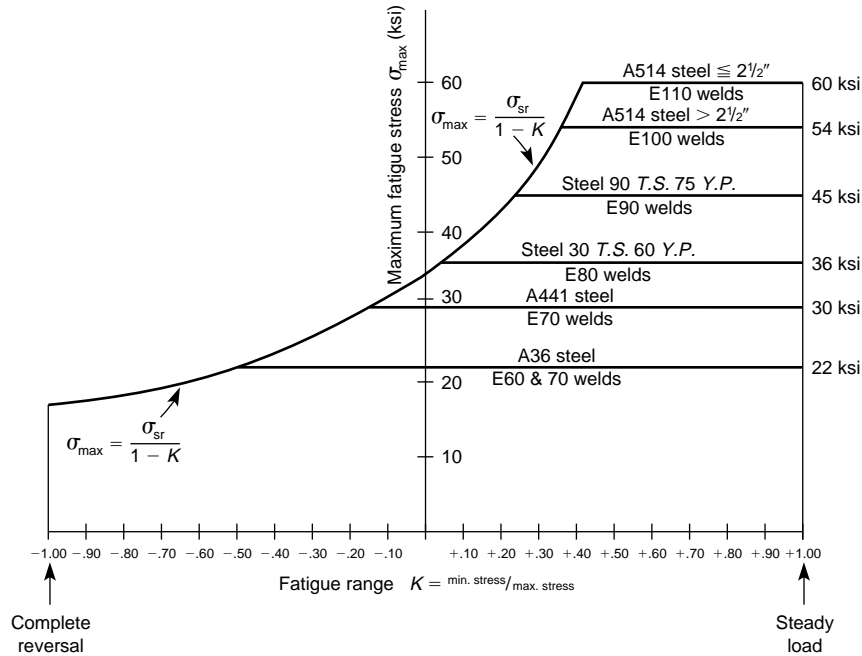
Fig. 13.3.28   Fatigue allowable for groove weld. [Butt weld and plate, weld reinforcement left on. Category C; 20,000 to 100,000 cycles (see Table 13.3.6).]

mechanical properties of the base metal will guide the designer to ensure that the weld metal deposited will have properties equal to those of the base metal; knowledge of the chemical composition of the base metal will affect the selection of the filler metal and/or electrode; finally, the metallurgical structure of the base metal as it comes to the welding operation (hot-worked, cold-worked, quenched, tempered, annealed, etc.) will affect the weldability of the metal and, if it is weldable, the degree to which the final properties are as dictated by design requirements. Welding specifications may address these matters, and base metal suppliers can provide additional data as to the weldability of the metal.

In some cases, the identity of the base metal is absolutely not known. To proceed to weld such metal may prove disastrous. Identification may be aided by some general characteristics which may be self-evident: carbon steel (oxide coating) vs. stainless steel (unoxidized); brush-finished aluminum (lightweight) vs. brush-finished Monel metal (heavy); etc. Ultimately, it may become necessary to subject the unknown metal to chemical, mechanical, and other types of laboratory tests to ascertain its exact nature.

Steel

Low-Carbon Steels   (Carbon up to 0.30 percent)   Steels in this class are readily welded by most arc and gas processes. Preheating is unnecessary unless parts are very heavy or welding is performed below 32°F (0°C). Torch-heating steel in the vicinity of welding to 70°F (21°C) offsets low temperatures. Postheating is necessary only for important structures such as boilers, pressure vessels, and piping. GTAW is usable only on killed steels; rimmed steels produce porous, weak welds. Resistance welding is readily accomplished if carbon is below 0.20 percent; higher carbon requires heat-treatment to slow the cooling rate and avoid hardness. Brazing with BAg, BCu, and BCuZn filler metals is very successful.

Medium-Carbon Steels   (Carbon from 0.30 to 0.45 percent)   This class of steel may be welded by the arc, resistance, and gas processes. As the rapid cooling of the metal in the welded zone produces a harder structure, it is desirable to hold the carbon as near 0.30 percent as possible. These hard areas are proportionately more brittle and difficult to machine. The cooling rate may be diminished and hardness decreased by preheating the metal to be welded above 300°F (149°C) and preferably to 500°F (260°C). The degree of preheating depends on the thickness of the section. Subsequent heating of the welded zone to 1,100 to 1,200°F (593 to 649°C) will restore ductility and relieve thermal strains. Brazing may also be used, as noted for low-carbon steels above.

High-Carbon Steels   (Carbon from 0.45 to 0.80 percent)   These steels are rarely welded except in special cases. The tendency for the metal heated above the critical range to become brittle is more pronounced than with lower- or medium-carbon steels. Thorough preheating of metal, in and near the welded zone, to a minimum of 500°F is essential. Subsequent annealing at 1,350 to 1,450°F (732 to 788°C) is also desirable. Brazing is often used with these steels, and is combined with the heat treatment cycle.

Low-Alloy Steels   The weldability of low-alloy steels is dependent upon the analysis and the hardenability, those exhibiting low hardenability being welded with relative ease, whereas those of high hardenability requiring preheating and postheating. Sections of 1/4 in (6.4 mm) or less may be welded with mild-steel filler metal and may provide joint strength approximating base metal strength by virtue of alloy pickup in the weld metal and weld reinforcement. Higher-strength alloys require filler metals with mechanical properties matching the base metal. Special alloys with creep-resistant or corrosion-resistant properties must be welded with filler metals of the same chemical analysis. Low-hydrogen-type electrodes (either mild- or alloy-steel analyses) permit the welding of alloy steels, minimizing the occurrence of under-head cracking.

Stainless Steel

Stainless steel is an iron-base alloy containing upward of 11 percent chromium. A thin, dense surface film of chromium oxide which forms on stainless steel imparts superior corrosion resistance; its passivated nature inhibits scaling and prevents further oxidation, hence the appellation ''stainless.'' (See Sec. 6.2.)

There are five types of stainless steels, and depending on the amount and kind of alloying additions present, they range from fully austenitic to fully ferritic. Most stainless steels have good weldability and may be

welded by many processes, including arc welding, resistance welding, electron and laser beam welding, and brazing. With any of these, the joint surfaces and any filler metal must be clean.

The coefficient of thermal expansion for the austenitic stainless steels is 50 percent greater than that of carbon steel; this must be taken into account to minimize distortion. The low thermal and electrical conductivity of austenitic stainless steel is generally helpful. Low welding heat is required because the heat is conducted more slowly from the joint, but low thermal conductivity results in a steeper thermal gradient and increases distortion. In resistance welding, lower current is used because electric resistivity is higher.

Ferritic Stainless Steels   Ferritic stainless steels contain 11.5 to 30 percent Cr, up to 0.20 percent C, and small amounts of ferrite stabilizers, such as Al, Nb, Ti, and Mo. They are ferritic at all temperatures, do not transform to austenite, and are not hardenable by heat treatment. This group includes types 405, 409, 430, 442, and 446. To weld ferritic stainless steels, filler metals should match or exceed the Cr level of the base metal.

Martensitic Stainless Steels   Martensitic stainless steels contain 11.4 to 18 percent Cr, up to 1.2 percent C, and small amounts of Mn and Ni. They will transform to austenite on heating and, therefore, can be hardened by formation of martensite on cooling. This group includes types 403, 410, 414, 416, 420, 422, 431, and 440. Weld cracks may appear on cooled welds as a result of martensite formation. The Cr and C content of the filler metal should generally match these elements in the base metal. Preheating and interpass temperature in the 400 to 600°F range is recommended for welding most martensitic stainless steels. Steels with over 0.20 percent C often require a postweld heat treatment to avoid weld cracking.

Austenitic Stainless Steels   Austenitic stainless steels contain 16 to 26 percent Cr, 10 to 24 percent Ni and Mn, up to 0.40 percent C, and small amounts of Mo, Ti, Nb, and Ta. The balance between Cr and Ni + Mn is normally adjusted to provide a microstructure of 90 to 100 percent austenite. These alloys have good strength and high toughness over a wide temperature range, and they resist oxidation to over 1,000°F. This group includes types 302, 304, 310, 316, 321, and 347. Filler metals for these alloys should generally match the base metal, but for most alloys should also provide a microstructure with some ferrite to avoid hot cracking. Two problems are associated with welding austenitic stainless steels: sensitization of the weld-heat-affected zone and hot cracking of weld metal.

Sensitization is caused by chromium carbide precipitation at the austenitic grain boundaries in the heat-affected zone when the base metal is heated to 800 to 1,600°F. Chromium carbide precipitates remove chromium from solution in the vicinity of the grain boundaries, and this condition leads to intergranular corrosion. The problem can be alleviated by using low-carbon stainless-steel base metal (types 302L, 316L, etc.) and low-carbon filler metal. Alternately, there are **stabilized stainless-steel** base metals and filler metals available which contain alloying elements that react preferentially with carbon, thereby not depleting the chromium content in solid solution and keeping it available for corrosion resistance. Type 321 contains titanium and type 347 contains niobium and tantalum, all of which are stronger carbide formers than chromium.

Hot cracking is caused by low-melting-point metallic compounds of sulfur and phosphorus which penetrate grain boundaries. When present in the weld metal or heat-affected zone, they will penetrate grain boundaries and cause cracks to appear as the weld cools and shrinkage stresses develop. Hot cracking can be prevented by adjusting the composition of the base metal and filler metal to obtain a microstructure with a small amount of ferrite in the austenite matrix. The ferrite provides ferrite-austenite boundaries which control the sulfur and phosphorus compounds and thereby prevent hot cracking.

Precipitation-Hardening Stainless Steels   Precipitation-hardening (PH) stainless steels contain alloying elements such as aluminum which permit hardening by a solution and aging heat treatment. There are three categories of PH stainless steels: martensitic, semiaustenitic, and austenitic. Martensitic PH stainless steels are hardened by quenching from the austenitizing temperature (around 1,900°F) and then aging between 900 and 1,150°F. Semiaustenitic PH stainless steels do not transform to martensite when cooled from the austenitizing temperature because the martensite transformation temperature is below room temperature. Austenitic PH stainless steels remain austenitic after quenching from the solution temperature, even after substantial amounts of cold work.

If maximum strength is required to martensitic PH and semiaustenitic PH stainless steels, matching, or nearly matching, filler metal should be used, and before welding, the work pieces should be in the annealed or solution-annealed condition. After welding, a complete solution heat treatment plus an aging treatment is preferred. If postweld solution treatment is not feasible, the components should be solution-treated before welding and then aged after welding. Thick sections of highly restrained parts are sometimes welded in the overaged condition. These require a full heat treatment after welding to attain maximum strength properties.

Austenitic PH stainless steels are the most difficult to weld because of hot cracking. Welding is preferably done with the parts in solution-treated condition, under minimum restraint and with minimum heat input. Filler metals of the Ni-Cr-Fe type, or of conventional austenitic stainless steel, are preferred.

Duplex Stainless Steels   Duplex stainless steels are the most recently developed type of stainless steel, and they have a microstructure of approximately equal amounts of ferrite and austenite. They have advantages over conventional austenitic and ferritic stainless steels in that they possess higher yield strength and greater stress corrosion cracking resistance. The duplex microstructure is attained in steels containing 21 to 25 percent Cr and 5 to 7 percent Ni by hot-working at 1,832 to 1,922°F, followed by water quenching. Weld metal of this composition will be mainly ferritic because the deposit will solidify as ferrite and will transform only partly to austenite without hot working or annealing. Since hot-working or annealing most weld deposits is not feasible, the metal composition filler is generally modified by adding Ni (to 8 to 10 percent); this results in increased amounts of austenite in the as-welded microstructure.

Cast Iron

Even though cast iron has a high carbon content and is a relatively brittle and rigid material, welding can be performed successfully if proper precautions are taken. Optimum conditions for welding include the following: (1) A weld groove large enough to permit manipulation of the electrode or the welding torch and rod. The groove must be clean and free of oil, grease, and any foreign material. (2) Adequate preheat, depending on the welding process used, the type of cast iron, and the size and shape of the casting. Preheat temperature must be maintained throughout the welding operation. (3) Welding heat input sufficient for a good weld but not enough to superheat the weld metal; i.e., welding temperature should be kept as low as practicable. (4) Slow cooling after welding. Gray iron may be enclosed in insulation, lime, or vermiculite. Other irons may require postheat treatment immediately after welding to restore mechanical properties. ESt and ENiFe identify electrodes of steel and of a nickel-iron alloy. Many different welding processes have been used to weld cast iron, the most common being manual shielded metal-arc welding, gas welding, and braze welding.

Aluminum and Aluminum Alloys

(See Sec. 6.4)

The **properties** that distinguish the **aluminum alloys** from other metals determine which welding processes can be used and which particular procedures must be followed for best results. Among the welding processes that can be used, choice is further dictated by the requirements of the end product and by economic considerations.

Physical properties of aluminum alloys that most significantly affect all welding procedures include low melting-point range, approx 900 to 1,215°F (482 to 657°C), high thermal conductivity (about two to four times that of mild steel), high rate of thermal expansion (about twice that of mild steel), and high electrical conductivity (about 3 to 5 times that of mild steel). Interpreted in terms of welding, this means that,

when compared with mild steel, much higher welding speeds are demanded, greater care must be exercised to avoid distortion, and for arc and resistance welding, much higher current densities are required.

Aluminum alloys are not quench-hardenable. However, weld cracking may result from excessive shrinkage stresses due to the high rate of thermal contraction. To offset this tendency, welding procedures, where possible, require a fast weld cycle and a narrow-weld zone, e.g., a highly concentrated heat source with deep penetration, moving at a high rate of speed. Shrinkage stresses can also be reduced by using a filler metal of lower melting point than the base metal. The filler metal ER4043 is often used for this purpose.

Welding procedures also call for the removal of the thin, tough, transparent film of aluminum oxide that forms on and protects the surface of these alloys. The oxide has a melting point of about 3,700°F (2,038°C) and can therefore exist as a solid in the molten weld. Removal may be by chemical reduction or by mechanical means such as machining, filing, rubbing with steel wool, or brushing with a stainless-steel wire brush. Most aluminum is welded with GTAW or GMAW. GTAW usually uses alternating current, with argon as the shielding gas. The power supply must deliver high current with balanced wave characteristics, or deliver high-frequency current. With helium, weld penetration is deeper, and higher welding speeds are possible. Most welding, however, is done using argon because it allows for better control and permits the welder to see the weld pool more easily.

GMAW employs direct current, electrode positive in a shielding gas that may be argon, helium, or a mixture of the two. In this process, the welding arc is formed by the filler metal, which serves as the electrode. Since the filler metal is fed from a coil as it melts in the arc, some arc instability may arise. For this reason, the process does not have the same precision as the GTAW process for welding very thin gages. However, it is more economical for welding thicker sections because of its higher deposition rates.

Copper and Copper Alloys

In welding **commercially pure copper,** it is important to select the correct type. Electrolytic, or ''tough-pitch,'' copper contains a small percentage of copper oxide, which at welding heat leads to oxide embrittlement. For welded assemblies it is recommended that deoxidized, or oxygen-free, copper be used and that welding rods, when needed, be of the same analysis. The preferred processes for welding copper are GTAW and GMAW; manual SMAW can also be used. It is also welded by oxyacetylene method and braze-welded; brazing with brazing filler metals conforming to BAg, BCuP, and RBCuZn-A classifications is also employed. The high heat conductivity of copper requires special consideration in welding; generally higher welding heats are necessary together with concurrent supplementary heating. (See also Sec. 6.4.)

Copper alloys are extensively welded in industry. The specific procedures employed are dependent upon the analysis, and reference should be made to the AWS Welding Handbook. Filler metals for welding copper and its alloys are covered in AWS specifications.

SAFETY

Welding is safe when sufficient measures are taken to protect the welder from potential hazards. When these measures are overlooked or ignored, welders can be subject to electric shock; overexposure to radiation, fumes, and gases; and fires and explosion. Any of these can be fatal. Everyone associated with welding operations should be aware of the potential hazards and help ensure that safe practices are employed. Infractions must be reported to the appropriate responsible authority.

NOTE: Oxygen is incorrectly called **air** in some fabricating shops. Air from the atmosphere contains only 21 percent oxygen and obviously is different from the 100 percent pure oxygen used for cutting. The unintentional confusion of oxygen with air has resulted in fatal accidents. When compressed oxygen is inadvertently used to power air tools, e.g., an explosion can result. While most people recognize that fuel gases are dangerous, the case can be made that oxygen requires even more careful handling.

Information about welding safety is available from American Welding Society, P.O. Box 351040, Miami, FL 33135.

13.4 MATERIAL REMOVAL PROCESSES AND MACHINE TOOLS
by Serope Kalpakjian

REFERENCES: ''Machining,'' ASM Handbook, vol. 16, ASM International. ''Machining,'' Tool and Manufacturing Engineers Handbook, vol. 1, Society of Manufacturing Engineers. ''Machining Data Handbook,'' 3d ed., Machinability Data Center. ''Machinery's Handbook,'' Industrial Press. ''Metal Cutting Tool Handbook,'' 7th ed., United States Cutting Tool Institute. Boothroyd and Knight, ''Fundamentals of Machining and Machine Tools,'' 2d ed., Marcel Dekker. Borkowski and Szymanski, ''Uses of Abrasives and Abrasive Tools,'' Ellis Horwood. Byers (ed.), ''Metalworking Fluids,'' Marcel Dekker. Endoy, ''Gear Hobbing, Shaping and Shaving,'' Society of Manufacturing Engineers. Farago, ''Abrasive Methods Engineering,'' 2 vols., Industrial Press. Gibbs and Crandell, ''An Introduction to CNC Machining and Programming,'' Industrial Press. Kalpakjian, ''Manufacturing Engineering and Technology,'' 3d ed., Addison-Wesley. King and Hahn, ''Handbook of Modern Grinding Technology,'' Chapman & Hall/Methuen. Krar and Ratterman, ''Superabrasives: Grinding and Machining with CBN and Diamond,'' McGraw-Hill. Lynch, ''Computer Numerical Control for Machining,'' McGraw-Hill. Malkin, ''Grinding Technology: Theory and Applications of Machining with Abrasives,'' Wiley. Maroney, ''A Guide to Metal and Plastic Finishing,'' Industrial Press. McGeough, ''Advanced Methods of Machining,'' Chapman & Hall. Meyers and Slattery, ''Basic Machining Reference Handbook,'' Industrial Press. Nachtman and Kalpakjian, ''Lubricants and Lubrication in Metalworking Operations,'' Marcel Dekker. Polywka and Gabrel, ''Programming of Computer Numerically Controlled Machines,'' Industrial Press. Shaw, ''Metal Cutting Principles,'' Oxford. Thyer, ''Computer Numerical Control of Machine Tools,'' 2d ed., Industrial Press. Trent, ''Metal Cutting,'' 4th ed., Butterworth Heinemann. Walsh, ''McGraw-Hill Machining and Metalworking Handbook.'' Weck, ''Handbook of Machine Tools,'' 4 vols., Wiley. Stephenson and Agapiou, ''Metal Cutting: Theory and Practice,'' Marcel Dekker. DeVries, ''Analysis of Material Removal Processes,'' Springer. ''Tool Materials,'' ASM Specialty Handbook, ASM International. Juneja, ''Fundamentals of Metal Cutting and Machine Tools,'' McGraw-Hill. Salmon, ''Modern Grinding Process Technology,'' McGraw-Hill. Benedict, ''Nontraditional Manufacturing Processes,'' Marcel Dekker. Webster et al., ''Abrasive Processes: Theory, Technology, and Practice,'' Marcel Dekker.

INTRODUCTION

Material removal processes, which include machining, cutting, grinding, and various nonmechanical chipless processes, are desirable or even necessary for the following basic reasons: (1) Closer dimensional tolerances, surface roughness, or surface-finish characteristics may be required than are available by casting, forming, powder metallurgy, and other shaping processes; and (2) part geometries may be too complex or too expensive to be manufactured by other processes. However, material removal processes inevitably waste material in the form of chips, production rates may be low, and unless carried out properly, the processes can have detrimental effects on the surface properties and performance of parts.

Traditional material removal processes consist of turning, boring,

drilling, reaming, threading, milling, shaping, planing, and broaching, as well as abrasive processes such as grinding, ultrasonic machining, lapping, and honing. Nontraditional processes include electrical and chemical means of material removal, as well as the use of abrasive jets, water jets, laser beams, and electron beams. This section describes the principles of these operations, the processing parameters involved, and the characteristics of the machine tools employed.

BASIC MECHANICS OF METAL CUTTING

The basic mechanics of chip-type machining processes (Fig. 13.4.1) are shown, in simplest two-dimensional form, in Fig. 13.4.2. A tool with a certain **rake angle** α (positive as shown) and **relief angle** moves along the surface of the workpiece at a depth t_1. The material ahead of the tool is sheared continuously along the **shear plane,** which makes an angle of ϕ
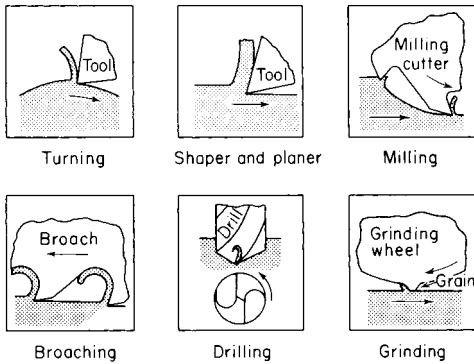

Fig. 13.4.1 Examples of chip-type machining operations.

with the surface of the workpiece. This angle is called the **shear angle** and, together with the rake angle, determines the chip thickness t_2. The ratio of t_1 to t_2 is called the **cutting ratio** r. The relationship between the shear angle, the rake angle, and the cutting ratio is given by the equation $\tan \phi = r \cos \alpha / (1 - r \sin \alpha)$. It can readily be seen that the shear angle is important in that it controls the thickness of the chip. This, in turn, has great influence on cutting performance. The **shear strain** that the material undergoes is given by the equation $\gamma = \cot \phi + \tan (\phi - \alpha)$. Shear strains in metal cutting are usually less than 5.
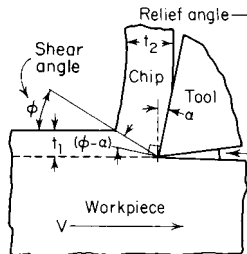

Fig. 13.4.2 Basic mechanics of metal cutting process.

Investigations have shown that the shear plane may be neither a plane nor a narrow zone, as assumed in simple analysis. Various formulas have been developed which define the shear angle in terms of such factors as the rake angle and the friction angle β. (See Fig. 13.4.3.)

Because of the large shear strains that the chip undergoes, it becomes hard and brittle. In most cases, the chip curls away from the tool. Among possible factors contributing to chip curl are nonuniform normal stress distribution on the shear plane, strain hardening, and thermal effects.

Regardless of the type of machining operation, some basic types of chips or combinations of these are found in practice (Fig. 13.4.4):

Continuous chips are formed by continuous deformation of the work-

piece material ahead of the tool, followed by smooth flow of the chip along the tool face. These chips ordinarily are obtained in cutting ductile materials at high speeds.

Discontinuous chips consist of segments which are produced by fracture of the metal ahead of the tool. The segments may be either loosely
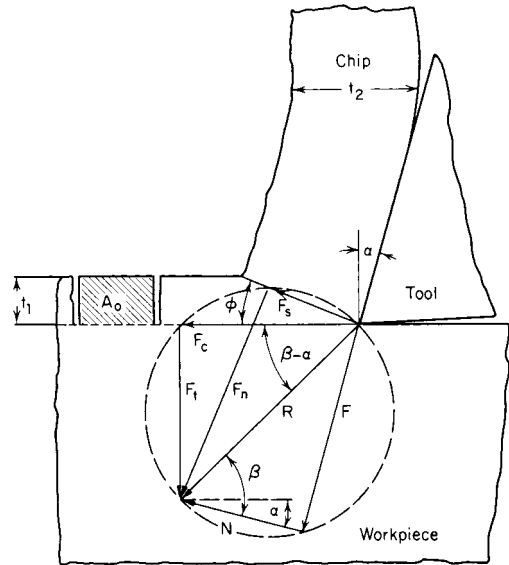
Fig. 13.4.3 Force system in metal cutting process.

connected to each other or unconnected. Such chips are most often found in the machining of brittle materials or in cutting ductile materials at very low speeds or low or negative rake angles.

Inhomogeneous (serrated) chips consist of regions of large and small strain. Such chips are characteristic of metals with low thermal conductivity or metals whose yield strength decreases sharply with temperature. Chips from titanium alloys frequently are of this type.

Built-up edge chips consist of a mass of metal which adheres to the tool face while the chip itself flows continuously along the face. This type of chip is often encountered in machining operations at low speeds and is associated with high adhesion between chip and tool and causes poor surface finish.

The **forces** acting on the cutting tool are shown in Fig. 13.4.3. The resultant force R has two components, F_c and F_t. The cutting force F_c in the direction of tool travel determines the amount of work done in cutting. The thrust force F_t does no work but, together with F_c, produces deflections of the tool. The resultant force also has two components on the shear plane: F_s is the force required to shear the metal along the shear plane, and F_n is the normal force on this plane. Two other force components also exist on the face of the tool: the friction force F and the normal force N.

Whereas the cutting force F_c is always in the direction shown in Fig. 13.4.3, the thrust force F_t may be in the opposite direction to that shown in the figure. This occurs when both the rake angle and the depth of cut are large, and friction is low.

From the geometry of Fig. 13.4.3, the following relationships can be derived: The **coefficient of friction** at the tool-chip interface is given by $\mu = (F_t + F_c \tan \alpha) / (F_c - F_t \tan \alpha)$. The **friction force** along the tool is $F = F_t \cos \alpha + F_c \sin \alpha$. The **shear stress** in the shear plane is $\tau = (F_c \sin \phi \cos \phi - F_t \sin^2 \phi) / A_0$, where A_0 is the cross-sectional area that is being cut from the workpiece.

The coefficient of friction on the tool face is a complex but important factor in cutting performance; it can be reduced by such means as the use of an effective cutting fluid, higher cutting speed, improved tool material and condition, or chemical additives in the workpiece material.

Fig. 13.4.4 Basic types of chips produced in metal cutting: (*a*) continuous chip with narrow, straight primary shear zone; (*b*) secondary shear zone at the tool-chip interface; (*c*) continuous chip with large primary shear zone; (*d*) continuous chip with built-up edge; (*e*) segmented or nonhomogeneous chip, (*f*) discontinuous chip. (*Source: After M. C. Shaw.*)

The net **power** consumed at the tool is $P = F_c V$. Since F_c is a function of tool geometry, workpiece material, and process vari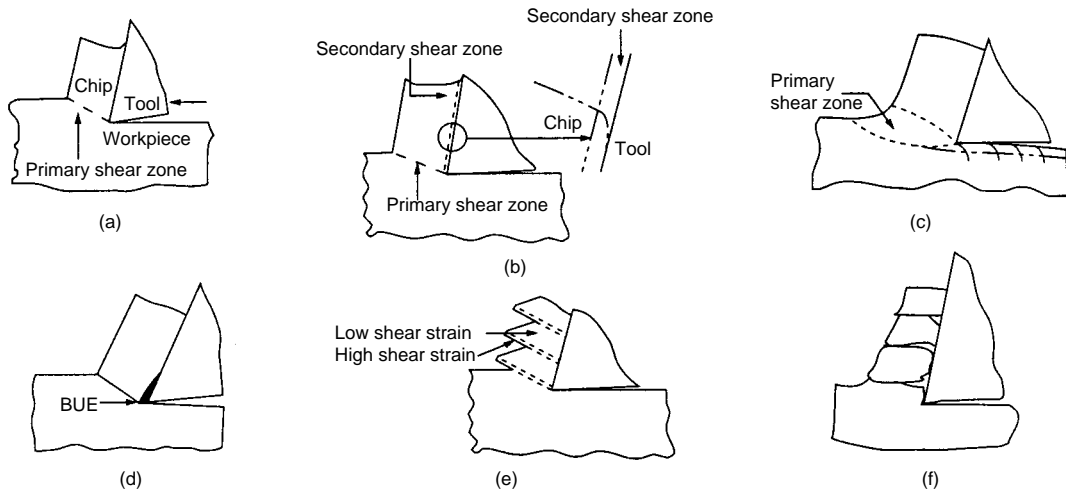ables, it is difficult reliably to calculate its value in a particular machining operation. Depending on workpiece material and the condition of the tool, **unit power** requirements in machining range between 0.2 hp·min/in³ (0.55 W·s/mm³) of metal removal for aluminum and magnesium alloys, to 3.5 for high-strength alloys. The power consumed is the product of unit power and rate of metal removal: $P = $ (unit power)(vol/min).

The power consumed in cutting is transformed mostly to **heat**. Most of the heat is carried away by the chip, and the remainder is divided between the tool and the workpiece. An increase in cutting speed or feed will increase the proportion of the heat transferred to the chip. It has been observed that, in turning, the average interface **temperature** between the tool and the chip increases with cutting speed and feed, while the influence of the depth of cut on temperature has been found to be limited. Interface temperatures to the range of 1,500 to 2,000°F (800 to 1,100°C) have been measured in metal cutting. Generally the use of a cutting fluid removes heat and thus avoids temperature buildup on the cutting edge.

In cutting metal at high speeds, the chips may become very hot and cause safety hazards because of long spirals which whirl around and become entangled with the tooling. In such cases, **chip breakers** are introduced on the tool geometry, which curl the chips and cause them to break into short sections. Chip breakers can be produced on the face of the cutting tool or insert, or are separate pieces clamped on top of the tool or insert.

A factor of great significance in metal cutting is **tool wear**. Many factors determine the type and rate at which wear occurs on the tool. The major critical variables that affect wear are tool temperature, type and hardness of tool material, grade and condition of workpiece, abrasiveness of the microconstituents in the workpiece material, tool geometry, feed speed, and cutting fluid. The type of wear pattern that develops depends on the relative role of these variables.

Tool wear can be classified as (1) flank wear (Fig. 13.4.5); (2) crater wear on the tool face; (3) localized wear, such as the rounding of the cutting edge; (4) chipping or thermal softening and plastic flow of the cutting edge; (5) concentrated wear resulting in a deep groove at the edge of a turning tool, known as **wear notch**.

In general, the wear on the flank or relief side of the tool is the most dependable guide for **tool life**. A wear land of 0.060 in (1.5 mm) on high-speed steel tools and 0.015 or 0.030 in (0.4 or 0.8 mm) for carbide tools is usually used as the endpoint. The cutting speed is the variable

Fig. 13.4.5 Types of tool wear in cutting.

which has the greatest influence on tool life. The relationship between tool life and cutting speed is given by the Taylor equation $VT^n = C$, where V is the cutting speed; T is the actual cutting time to develop a certain wear land, min; C is a constant whose value depends on workpiece material and process variables, numerically equal to the cutting speed that gives a tool life of 1 min; and n is the exponent whose value depends on workpiece material and other process variables. The recommended cutting speed for a high-speed steel tool is generally the one which produces a 60- to 120-min tool life. With carbide tools, a 30- to 60-min tool life may be satisfactory. Values of n range from 0.08 to 0.2 for high-speed steels, from 0.2 to 0.5 for carbides, and from 0.5 to 0.7 for ceramic tools.

When one is using tool-life equations, caution should be exercised in extrapolation of the curves beyond the operating region for which they are derived. In a log-log plot, tool life curves may be linear over a short cutting-speed range but are rarely linear over a wide range of cutting speeds. In spite of the considerable data obtained to date, no simple formulas can be given for quantitative relationships between tool life and various process variables for a wide range of materials and conditions.

An important aspect of machining on computer-controlled equipment is **tool-condition monitoring** while the machine is in operation with little or no supervision by an operator. Most state-of-the-art machine controls are now equipped with tool-condition monitoring systems. Two common techniques involve the use of (1) transducers that are installed on the tool holder and continually monitor torque and forces and (2) acoustic emission through a piezoelectric transducer. In both methods the signals are analyzed and interpreted automatically for tool wear or chipping, and corrective actions are taken before any significant damage is done to the workpiece.

A term commonly used in machining and comprising most of the items discussed above is **machinability**. This is best defined in terms of (1) tool life, (2) power requirement, and (3) surface integrity. Thus, a good machinability rating would indicate a combination of long tool life, low power requirement, and a good surface. However, it is difficult to develop quantitative relationships between these variables. Tool life is considered as the important factor and, in production, is usually ex-

pressed as the number of pieces machined between tool changes. Various tables are available in the literature that show the machinability rating for different materials; however, these ratings are relative. To determine the proper machining conditions for a given material, refer to the machining recommendations given later in this section.

The major factors influencing **surface finish** in machining are (1) the profile of the cutting tool in contact with the workpiece, (2) fragments of built-up edge left on the workpiece during cutting, and (3) vibration and chatter. Improvement in surface finish may be obtained to various degrees by increasing the cutting speed and decreasing the feed and depth of cut. Changes in cutting fluid, tool geometry, and material are also important; the microstructure and chemical composition of the material have great influence on surface finish.

As a result of mechanical working and thermal effects, **residual stresses** are developed on the surfaces of metals that have been machined or ground. These stresses may cause warping of the workpiece as well as affect the resistance to fatigue and stress corrosion. To minimize residual stresses, sharp tools, medium feeds, and medium depths of cut are recommended.

Because of plastic deformation, thermal effects, and chemical reactions during material removal processes, alterations of machined surfaces may take place which can seriously affect the **surface integrity** of a part. Typical detrimental effects may be lowering of the fatigue strength of the part, distortion, changes in stress-corrosion properties, burns, cracks, and residual stresses. Because of its great importance to manufacturing technology, particularly in critical aerospace components, surface integrity is now a recognized and rapidly developing subject. Surface control generally results in decreasing production rate and increasing costs. Improvements in surface integrity may be obtained by post-processing techniques such as polishing, sanding, peening, finish machining, and fine grinding.

Vibration in machine tools, a very complex behavior, is often the cause of premature tool failure or short tool life, poor surface finish, damage to the workpiece, and damage to the machine itself. Vibration may be **forced** or **self-excited**. The term **chatter** is commonly used to designate self-excited vibrations in machine tools. The excited amplitudes are usually very high and may cause damage to the machine. Although there is no complete solution to all types of vibration problems, certain measures may be taken. If the vibration is being forced, it may be possible to remove or isolate the forcing element from the machine. In cases where the forcing frequency is near a natural frequency, either the forcing frequency or the natural frequency may be raised or lowered. Damping will also greatly reduce the amplitude. Self-excited vibrations are generally controlled by increasing the stiffness and damping. (See also Sec. 5.)

Good machining practice requires a rigid setup. The machine tool must be capable of providing the **stiffness** required for the machining conditions used. If a rigid setup is not available, the depth of cut must be reduced. Excessive tool overhang should be avoided, and in milling, cutters should be mounted as close to the spindle as possible. The length of end mills and drills should be kept to a minimum. Tools with large

nose radius or with a long, straight cutting edge increase the possibility of chatter.

CUTTING-TOOL MATERIALS

A wide variety of **cutting-tool materials** are available. The selection of a proper material depends on such factors as the cutting operation involved, the machine to be used, the workpiece material, production requirements, cost, and surface finish and accuracy desired. The major qualities required in a cutting tool are (1) hot hardness, (2) impact toughness or mechanical shock resistance, and (3) wear resistance. (See Table 13.4.1 and Figs. 13.4.6 and 13.4.7.)

Materials for cutting tools include high-speed steels, cast alloys, carbides, ceramics or oxides, cubic boron nitride, and diamond. Understanding the different types of **tool steels** (see Sec. 6.2) requires knowledge of the role of different alloying elements. These elements are
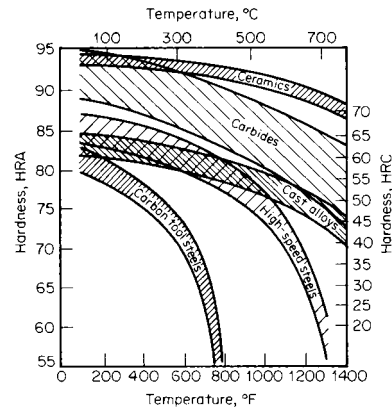
Fig. 13.4.6   Hardness of tool materials as a function of temperature.

added to (1) obtain greater hardness and wear resistance, (2) obtain greater impact toughness, (3) impart hot hardness to the steel such that its hardness is maintained at high cutting temperatures, and (4) decrease distortion and warpage during heat treating.

Carbon forms a carbide with iron, making it respond to hardening and thus increasing the hardness, strength, and wear resistance. The carbon content of tool steels ranges from 0.6 to 1.4 percent. **Chromium** is added to increase wear resistance and toughness; the content ranges from 0.25 to 4.5 percent. **Cobalt** is commonly used in high-speed steels to increase hot hardness so that tools may be used at higher cutting speeds and still maintain hardness and sharp cutting edges; the content ranges from 5 to 12 percent. **Molybdenum** is a strong carbide-forming element and increases strength, wear resistance, and hot hardness. It is always used in conjunction with other alloying elements, and its content ranges to 10 percent. **Tungsten** promotes hot hardness and strength; content ranges

Table 13.4.1   Characteristics of Cutting-Tool Materials

	High-speed steels	Cast cobalt alloys	Carbides	Coated carbides	Ceramics	Polycrystalline cubic boron nitride	Diamond
Hot hardness	────────────────	increasing	──→				
Toughness	←────────────────	increasing	──				
Impact strength	←────────────────	increasing	──				
Wear resistance	────────────────	increasing	──→				
Chipping resistance	←────────────────	increasing	──				
Cutting speed	────────────────	increasing	──→				
Thermal shock resistance	←────────────────	increasing	──				
Tool material cost	────────────────	increasing	──→				

NOTE: These tool materials have a wide range of compositions and properties; thus overlapping characteristics exist in many categories of tool materials.
SOURCE: After R Komandurr (ed.), ''Advances in Hard Material Tool Technology,'' Carnegie Press, Pittsburgh, PA.

from 1.25 to 20 percent. **Vanadium** increases hot hardness and abrasion resistance; in high-speed steels, it ranges from 1 to 5 percent.

High-speed steels are the most highly alloyed group among tool steels and maintain their hardness, strength, and cutting edge. With suitable procedures and equipment, they can be fully hardened with little danger of distortion or cracking. High-speed steel tools are widely used in operations using form tools, drilling, reaming, end-milling, broaching, tapping, and tooling for screw machines.

Fig. 13.4.7   Ranges of properties of various groups of tool materials.

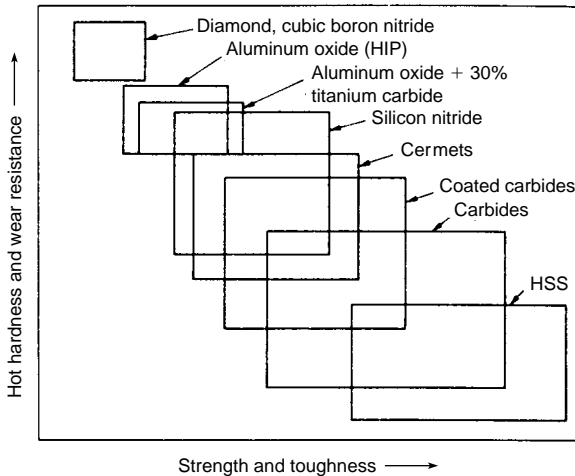**Cast alloys** maintain high hardness at high temperatures and have good wear resistance. Cast-alloy tools, which are cast and ground into any desired shape, are composed of cobalt (38 to 53 percent), chromium (30 to 33 percent), and tungsten (10 to 20 percent). These alloys are recommended for deep roughing operations at relatively high speeds and feeds. Cutting fluids are not necessary and are usually used only to obtain a special surface finish.

Carbides have metal carbides as key ingredients and are manufactured by powder-metallurgy techniques. They have the following properties which make them very effective cutting-tool materials: (1) high hardness over a wide range of temperatures; (2) high elastic modulus, 2 to 3 times that of steel; (3) no plastic flow even at very high stresses; (4) low thermal expansion; and (5) high thermal conductivity. Carbides are used in the form of inserts or tips which are clamped or brazed to a steel shank. Because of the difference in coefficients of expansion, brazing should be done carefully. The mechanically fastened tool tips are called **inserts** (Fig. 13.4.8); they are available in different shapes, such as square, triangular, circular, and various special shapes.

There are three general groups of carbides in use: (1) tungsten carbide with cobalt as a binder, used in machining cast irons and nonferrous abrasive metals; (2) tungsten carbide with cobalt as a binder, plus a solid solution of WC-TiC-TaC-NbC, for use in machining steels; and
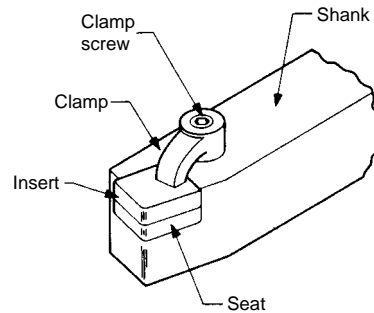
Fig. 13.4.8   Insert clamped to shank of a toolholder.

(3) titanium carbide with nickel and molybdenum as a binder, for use where cutting temperatures are high because of high cutting speeds or the high strength of the workpiece material. Carbides are classified by ISO and ANSI, as shown in Table 13.4.2 which includes recommendations for a variety of workpiece materials and cutting conditions. (See also Sec. 6.4.)

Coated carbides consist of conventional carbide inserts that are coated with a thin layer of titanium nitride, titanium carbide, or aluminum oxide. The coating provides additional wear resistance while maintaining the strength and toughness of the carbide tool. Coatings are also applied to high-speed steel tools, particularly drills and taps. The desirable properties of individual coatings can be combined and optimized

Table 13.4.2   Classification of Tungsten Carbides According to Machining Applications

ISO standard	ANSI classification no. (grade)	Materials to be machined	Machining operation	Type of carbide	Characteristics of	
					Cut	Carbide
K30-K40	C-1	Cast iron, nonferrous metals, and nonmetallic materials requiring abrasion resistance	Roughing	Wear-resistant grades; generally straight WC-Co with varying grain sizes	Increasing cutting speed	Increasing hardness and wear resistance
K20	C-2		General purpose		↑	↑
K10	C-3		Light finishing		↓	
K01	C-4		Precision finishing		Increasing feed rate	Increasing strength and binder content
P30-P50	C-5	Steels and steel alloys requiring crater and deformation resistance	Roughing	Crater-resistant grades; various WC–Co compositions with TiC and/or TaC alloys	Increasing cutting speed	Increasing hardness and wear resistance
P20	C-6		General purpose		↑	↑
P10	C-7		Light finishing		↓	
P01	C-8		Precision finishing		Increasing feed rate	Increasing strength and binder content

NOTE: The ISO and ANSI comparisons are approximate.

by using **multiphase coatings**. Carbide tools are now available with, e.g., a layer of titanium carbide over the carbide substrate, followed by aluminum oxide and then titanium nitride. Various alternating layers of coatings are also used, each layer being on the order of 80 to 400 μin (2 to 10 μm) thick. New developments in coatings include diamond, titanium carbonitride, chromium carbide, zirconium nitride, and hafnium nitride.

Stiffness is of great importance when using carbide tools. Light feeds, low speeds, and chatter are deleterious. No cutting fluid is needed, but if one is used for cooling, it should be applied in large quantities and continuously to prevent heating and quenching.

Ceramic, or **oxide,** inserts consist primarily of fine aluminum oxide grains which have been bonded together. Minor additions of other elements help to obtain optimum properties. Ceramic tools have very high abrasion resistance, are harder than carbides, and have less tendency to weld to metals during cutting. However, they lack impact toughness, and premature tool failure can result by chipping or general breakage. Ceramic tools have been found to be effective for high-speed, uninterrupted turning operations. Tool and setup geometry is important. Tool failures can be reduced by the use of rigid tool mountings and rigid machine tools. Included in oxide, cutting-tool materials are **cermets** (such as 70 percent aluminum oxide and 30 percent titanium carbide), combining the advantages of ceramics and metals.

Polycrystalline **diamond** is used where good surface finish and dimensional accuracy are desired, particularly on soft nonferrous materials that are difficult to machine. The general properties of diamonds are extreme hardness, low thermal expansion, high heat conductivity, and a very low coefficient of friction. The polycrystalline diamond is bonded to a carbide substrate. Single-crystal diamond is also used as a cutting tool to produce extremely fine surface finish on nonferrous alloys, such as copper-base mirrors.

Next to diamond, **cubic boron nitride (CBN)** is the hardest material presently available. Polycrystalline CBN is bonded to a carbide substrate and used as a cutting tool. The CBN layer provides very high wear resistance and edge strength. It is chemically inert to iron and nickel at elevated temperatures; thus it is particularly suitable for machining high-temperature alloys and various ferrous alloys. Both diamond and CBN are also used as abrasives in grinding operations.

CUTTING FLUIDS

Cutting fluids, frequently referred to as lubricants or coolants, comprise those liquids and gases which are applied to the cutting zone in order to facilitate the cutting operation. A cutting fluid is used (1) to keep the tool cool and prevent it from being heated to a temperature at which the hardness and resistance to abrasion are reduced; (2) to keep the workpiece cool, thus preventing it from being machined in a warped shape to inaccurate final dimensions; (3) through lubrication to reduce the power consumption, wear on the tool, and generation of heat; (4) to provide a good finish on the workpiece; (5) to aid in providing a satisfactory chip formation; (6) to wash away the chips (this is particularly desirable in deep-hole drilling, hacksawing, milling, and grinding); and (7) to prevent corrosion of the workpiece and machine tool.

Classification Cutting fluids may be classified as follows: (1) air blast, (2) emulsions, (3) oils, and (4) solutions. Cutting fluids are also classified as light-, medium-, and heavy-duty; light-duty fluids are for general-purpose machining.

Induced **air blast** may be used with internal and surface grinding and polishing operations. Its main purpose is to remove the small chips or dust, although some cooling is also obtained, especially in machining of plastics.

Emulsions consist of a soluble oil emulsified with water in the ratio of 1 part oil to 10 to 100 parts water, depending upon the type of product and the operation. Emulsions have surface-active or **extreme-pressure** additives to reduce friction and provide an effective lubricant film under high pressure at the tool-chip interface during machining. Emulsions are low-cost cutting fluids and are used for practically all types of cutting and grinding when machining all types of metals. The more concentrated mixtures of oil and water, such as 1:10, are used for broaching, threading, and gear cutting. For most operations, a solution of 1 part soluble oil to 20 parts water is satisfactory.

A variety of **oils** are used for metal cutting. They are used where lubrication rather than cooling is essential or on high-grade finishing cuts, although sometimes superior finishes are obtained with emulsions.

Oils generally used in machining are mineral oils with the following compositions: (1) straight mineral oil, (2) with fat, (3) with fat and sulfur, (4) with fat and chlorine, and (5) with fat, sulfur, and chlorine. The more severe the machining operation, the higher the composition of the oil. Broaching and tapping of refractory alloys and high-temperature alloys, for instance, require highly compounded oils. In order to avoid staining of the metal, aluminum and copper, for example, inhibited sulfur and chlorine are used.

Solutions are a family of cutting fluids that blend water and various chemical agents such as amines, nitrites, nitrates, phosphates, chlorine, and sulfur compounds. These agents are added for purposes of rust prevention, water softening, lubrication, and reduction of surface tension. Most of these chemical fluids are coolants but some are lubricants.

The **selection** of a cutting fluid for a particular operation requires consideration of several factors: the workpiece material, the difficulty of the machining operation, the compatibility of the fluid with the workpiece material and the machine tool components, surface preparation, method of application and removal of the fluid, contamination of the cutting fluid with machine lubricants, and the treatment of the fluid after use. Also important are the **biological** and **ecological** aspects of the cutting fluid used. There may be potential health hazards to operating personnel from contact with or inhalation of mist or fumes from some fluids. Recycling and waste disposal are also important problems to be considered.

Methods of Application The most common method is **flood cooling** in quantities such as 3 to 5 gal/min (about 10 to 20 L/min) for single-point tools and up to 60 gal/min (230 L/min) per cutter for multiple-tooth cutters. Whenever possible, multiple nozzles should be used. In **mist cooling** a small jet equipment is used to disperse water-base fluids as very fine droplets in a carrier that is generally air at pressures 10 to 80 lb/in^2 (70 to 550 kPa). Mist cooling has a number of advantages, such as providing high-velocity fluids to the working areas, better visibility, and improving tool life in certain instances. The disadvantages are that venting is required and also the cooling capability is rather limited.

MACHINE TOOLS

The general types of **machine tools** are lathes; turret lathes; screw, boring, drilling, reaming, threading, milling, and gear-cutting machines; planers and shapers; broaching, cutting-off, grinding, and polishing machines. Each of these is subdivided into many types and sizes. General items common to all machine tools are discussed first, and individual machining processes and equipment are treated later in this section.

Automation is the application of special equipment to control and perform manufacturing processes with little or no manual effort. It is applied to the manufacturing of all types of goods and processes, from the raw material to the finished product. Automation involves many activities, such as handling, processing, assembly, inspecting, and packaging. Its primary objective is to lower manufacturing cost through controlled production and quality, lower labor cost, reduced damage to work by handling, higher degree of safety for personnel, and economy of floor space. Automation may be partial, such as gaging in cylindrical grinding, or it may be complete.

The conditions which play a role in decisions concerning automation are rising production costs, high percentage of rejects, lagging output, scarcity of skilled labor, hazardous working conditions, and work requiring repetitive operation. Factors which must be carefully studied before deciding on automation are high initial cost of equipment, maintenance problems, and type of product (See also Sec. 16.)

Mass production with modern machine tools has been achieved through the development of self-contained **power-head** production units

and the development of **transfer** mechanisms. Power-head units, consisting of a frame, electric driving motor, gearbox, tool spindles, etc., are available for many types of machining operations. Transfer mechanisms move the workpieces from station to station by various methods. Transfer-type machines can be arranged in several configurations, such as a straight line or a U pattern. Various types of machine tools for mass production can be built from components; this is known as the **building-block** principle. Such a system combines flexibility and adaptability with high productivity. (See **machining centers.**)

Numerical control (NC), which is a method of controlling the motions of machine components by numbers, was first applied to machine tools in the 1950s. Numerically controlled machine tools are classified according to the type of cutting operation. For instance, in drilling and boring machines, the positioning and the cutting take place sequentially (point to point), whereas in die-sinking machines, positioning and cutting take place simultaneously. The latter are often described as **continuous-path** machines, and since they require more exacting specifications, they give rise to more complex problems. Machines now perform over a very wide range of cutting conditions without requiring adjustment to eliminate chatter, and to improve accuracy. Complex contours can be machined which would be almost impossible by any other method. A large variety of programming systems has been developed.

The control system in NC machines has been converted to computer control with various software. In **computer numerical control (CNC),** a microcomputer is a part of the control panel of the machine tool. The advantages of computer numerical control are ease of operation, simpler programming, greater accuracy, versatility, and lower maintenance costs.

Although numerical control of machine tools has many advantages such as high productivity and flexibility, it has certain limitations. Among these are high initial cost of equipment and the need for trained personnel and special maintenance.

Further developments in machine tools are **machining centers.** This is a machine equipped with as many as 200 tools and with an automatic tool changer (Fig. 13.4.9). It is designed to perform various operations on different surfaces of the workpiece, which is placed on a pallet capable of as much as five-axis movement (three linear and two rotational). Machining centers, which may be vertical or horizontal spindle, have flexibility and versatility that other machine tools do not have, and thus they have become the first choice in machine selection in modern manufacturing plants and shops. They have the capability of tool and part checking, tool-condition monitoring, in-process and postprocess gaging, and inspection of machined surfaces. **Universal machining centers** are the latest development, and they have both vertical and hori-
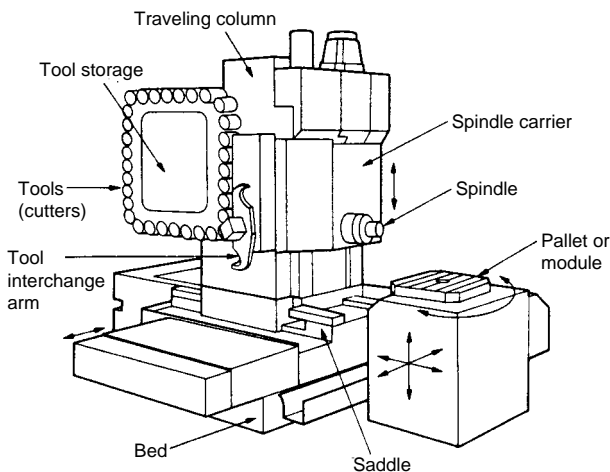
zontal spindles. **Turning centers** are a further development of computer-controlled lathes and have great flexibility. Many centers are now constructed on a **modular** basis, so that various accessories and peripheral equipment can be installed and modified depending on the type of product to be machined.

An approach to optimize machining operations is **adaptive control**. While the material is being machined, the system senses operating conditions such as forces, tool-tip temperature, rate of tool wear, and surface finish, and converts these data into feed and speed control that enables the machine to cut under optimum conditions for maximum productivity. Combined with numerical controls and computers, adaptive controls are expected to result in increased efficiency of metalworking operations.

With the advent of sophisticated computers and various software, modern manufacturing has evolved into **computer-integrated manufacturing (CIM)**. This system involves the coordinated participation of computers in all phases of manufacturing. **Computer-aided design** combined with **computer-aided manufacturing (CAD/CAM),** results in a much higher productivity, better accuracy and efficiency, and reduction in design effort and prototype development. CIM also involves the management of the factory, inventory, and labor, and it integrates all these activities, eventually leading to untended factories.

The highest level of sophistication is reached with a **flexible manufacturing system (FMS)**. Such a system is made of **manufacturing cells** and an automatic materials-handling system interfaced with a central computer. The manufacturing cell is a system in which CNC machines are used to make a specific part or parts with similar shape. The workstations, i.e., several machine tools, are placed around an **industrial robot** which automatically loads, unloads, and transfers the parts. FMS has the capability to optimize each step of the total manufacturing operation, resulting in the highest possible level of efficiency and productivity.

The proper design of **machine-tool structures** requires analysis of such factors as form and materials of structures, stresses, weight, and manufacturing and performance considerations. The best approach to obtain the ultimate in machine-tool accuracy is to employ both improvements in structural stiffness and compensation of deflections by use of special controls. The C-frame structure has been used extensively in the past because it provides ready accessibility to the working area of the machine. With the advent of computer control, the box-type frame with its considerably improved static stiffness becomes practical since the need for manual access to the working area is greatly reduced. The use of a box-type structure with thin walls can provide low weight for a given stiffness. The light-weight-design principle offers high dynamic stiffness by providing a high natural frequency of the structure through combining high static stiffness with low weight rather than through the use of large mass. (Dynamic stiffness is the stiffness exhibited by the system when subjected to dynamic excitation where the elastic, the damping, and the inertia properties of the structure are involved; it is a frequency-dependent quantity.)

TURNING

Turning is a machining operation for all types of metallic and nonmetallic materials and is capable of producing circular parts with straight or various profiles. The cutting tools may be single-point or form tools. The most common machine tool used is a **lathe;** modern lathes are computer-controlled and can achieve high production rates with little labor. The basic operation is shown in Fig. 13.4.10, where the workpiece is held in a chuck and rotates at N r/min; a cutting tool moves along the length of the piece at a feed f (in/r or mm/r) and removes material at a radial depth d, reducing the diameter from D_0 to D_f.

Lathes are generally considered to be the oldest member of machine tools, having been first developed in the late eighteenth century. The most common lathe is called an engine lathe because it was one of the first machines driven by Watt's steam engine. The basic lathe has the following main parts: bed, headstock, tailstock, and carriage. The types of lathes available for a variety of applications may be listed as follows: engine lathes, bench lathes, horizontal turret lathes, vertical lathes, and

Fig. 13.4.9 Schematic of a horizontal spindle machining center, equipped with an automatic tool changer. Tool magazines can store 200 different cutting tools. *(Source: Courtesy of Cincinnati Milacron, Inc.)*

automatics. A great variety of lathes and attachments are available within each category, also depending on the production rate required.

It is common practice to specify the size of an engine lathe by giving the **swing** (diameter) and the **distance between centers** when the tailstock is flush with the end of the bed. The maximum swing over the ways is usually greater than the nominal swing. The **length of the bed** is given frequently to specify the overall length of the bed. A lathe size is indicated thus: 14 in (356 mm) (swing) by 30 in (762 mm) (between centers) by 6 ft (1,830 mm) (length of bed). Lathes are made for light-, medium-, or heavy-duty work.

Geometric progression is used extensively in designing machine-tool feeds and speeds. Feeds in geometric progression are used on cylindrical grinders, boring mills, milling machines, drilling machines, etc.; but for screw-cutting lathes, the power feeds for thread cutting and turning must be in proportion to the pitch of threads to be cut.

All geared-head lathes, which are single-pulley (belt-driven or arranged for direct-motor drive through short, flat, or V belts, gears, or silent chain), increase the power of the drive and provide a means for obtaining 8, 12, 16, or 24 spindle speeds. The teeth may be of the spur, helical, or herringbone type and may be ground or lapped after hardening.
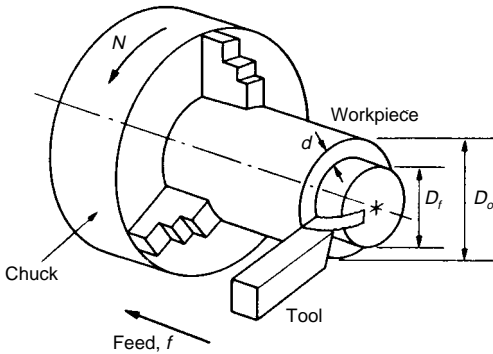

Fig. 13.4.10 A turning operation on a round workpiece held in a three-jaw chuck.

Variable speeds are obtained by driving with adjustable-speed dc shunt-wound motors with stepped field-resistance control or by electronics or motor-generator system to give speed variation in infinite steps. AC motors driving through infinitely variable speed transmissions of the mechanical or hydraulic type are also in general use.

Modern lathes, many of which are now computer-controlled (**turning centers),** are built with the speed capacity, stiffness, and strength capable of taking full advantage of new and stronger tool materials. The main drive-motor capacity of lathes ranges from fractional to more than 200 hp (150 kW). Speed preselectors, which give speed as a function of work diameter, are introduced, and variable-speed drives using dc motors with panel control are standard on many lathes. Lathes with contour facing, turning, and boring attachments are also available.

Tool Shapes for Turning

The standard **nomenclature** for single-point tools, such as those used on lathes, planers, and shapers, is shown in Fig. 13.4.11. Each tool consists of a shank and point. The point of a single-point tool may be formed by grinding on the end of the shank; it may be forged on the end of the shank and subsequently ground; a tip or insert may be clamped or brazed to the end of the shank (see Fig. 13.4.8). The **best tool shape** for each material and each operation depends on many factors. For specific information and recommendations, the various sources listed in the References should be consulted. See also Table 13.4.3.

Positive **rake angles** improve the cutting operation with regard to forces and deflection; however, a high positive rake angle may result in early failure of the cutting edge. Positive rake angles are generally used in lower-strength materials. For higher-strength materials, negative rake

angles may be used. **Back rake** usually controls the direction of chip flow and is of less importance than the **side rake**. The purpose of **relief angles** is to avoid interference and rubbing between the workpiece and tool flank surfaces. In general, they should be small for high-strength materials and larger for softer materials. Excessive relief angles may weaken the tool. The **side cutting-edge angle** influences the length of chip contact and the true feed. This angle is often limited by the workpiece geometry, e.g., the shoulder contour. Large angles are apt to cause tool chatter. Small **end cutting-edge angles** may create excessive force normal to the workpiece, and large angles may weaken the tool point. The purpose of the **nose radius** is to give a smooth surface finish and to obtain longer tool life by increasing the strength of the cutting edge. The nose radius should be tangent to the cutting-edge angles. A large nose radius gives a stronger tool and may be used for roughing cuts; however, large radii may lead to tool chatter. A small nose radius reduces forces and is therefore preferred on thin or slender workpieces.
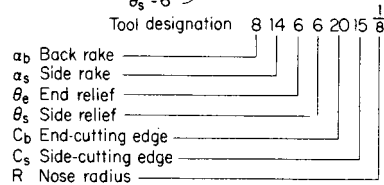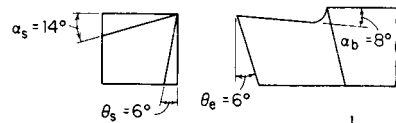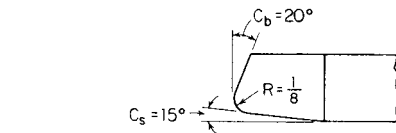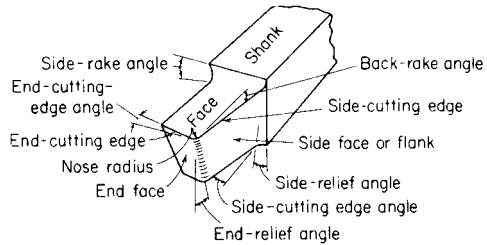
Fig. 13.4.11 Standard nomenclature for single-point cutting tools.

Turning Recommendations Recommendations for tool materials, depth of cut, feed, and cutting speed for turning a variety of materials are given in Table 13.4.4. The cutting speeds for high-speed steels for turning, which are generally M2 and M3, are about one-half those for uncoated carbides. A general **troubleshooting guide** for turning operations is given in Table 13.4.5.

Turret Lathes

Turret lathes are used for the production of parts in moderate quantities and produce interchangeable parts at low production cost. Turret lathes may be chucking, screw machine, or universal. The universal machine may be set up to machine bar stock as a screw machine or have the work held in a chuck. These machines may be semiautomatic, i.e., so arranged that after a piece is chucked and the machine started, it will complete the machining cycle automatically and come to a stop. They may be horizontal or vertical and single- or multiple-spindle; many of these lathes are now computer-controlled and have a variety of features.

Table 13.4.3   Recommend Tool Geometry for Turning (degrees)

	High-speed steel and cast-alloy tools					Carbide tools (inserts)				
Material	Back rake	Side rake	End relief	Side relief	Side and end cutting edge	Back rake	Side rake	End relief	Side relief	Side and end cutting edge
Aluminum alloys	20	15	12	10	5	0	5	5	5	15
Magnesium alloys	20	15	12	10	5	0	5	5	5	15
Copper alloys	5	10	8	8	5	0	5	5	5	15
Steels	10	12	5	5	15	−5	−5	5	5	15
Stainless steels, ferritic	5	8	5	5	15	0	5	5	5	15
Stainless steels, austenitic	0	10	5	5	15	0	5	5	5	15
Stainless steels, martensitic	0	10	5	5	15	−5	−5	5	5	15
High-temperature alloys	0	10	5	5	15	5	0	5	5	45
Refractory alloys	0	20	5	5	5	—	—	5	5	15
Titanium alloys	0	5	5	5	15	−5	−5	5	5	5
Cast irons	5	10	5	5	15	−5	−5	5	5	15
Thermoplastics	0	0	20–30	15–20	10	0	0	20–30	15–20	10
Thermosetting plastics	0	0	20–30	15–20	10	0	15	5	5	15

SOURCE: ''Matchining Data Handbook,'' published by the Machinability Data Center, Metcut Research Associates, Inc.

Table 13.4.4   General Recommendations for Turning Operations

		General-purpose starting conditions			Range for roughing and finishing		
Workpiece material	Cutting tool	Depth of cut, mm (in)	Feed mm/r (in/r)	Cutting speed, m/min (ft/min)	Depth of cut, mm (in)	Feed mm/r (in/r)	Cutting speed, m/min (ft/min)
Low-C and free-machining steels	Uncoated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	90 (300)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	60–135 (200–450)
	Ceramic-coated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	245–275 (800–900)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	120–425 (400–1,400)
	Triple-coated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	185–200 (600–650)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	90–245 (300–800)
	TiN-coated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	105–150 (350–500)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	60–230 (200–750)
	Al_2O_3 ceramic	1.5–6.3 (0.06–0.25)	0.25 (0.010)	395–440 (1,300–1,450)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	365–550 (1,200–1,800)
	Cermet	1.5–6.3 (0.06–0.25)	0.30 (0.012)	215–290 (700–950)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	105–455 (350–1,500)
Medium- and high-C steels	Uncoated carbide	1.2–4.0 (0.05–0.20)	0.30 (0.012)	75 (250)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	45–120 (150–400)
	Ceramic-coated carbide	1.2–4.0 (0.05–0.20)	0.30 (0.012)	185–230 (600–750)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	120–410 (400–1,350)
	Triple-coated carbide	1.2–4.0 (0.050–0.20)	0.30 (0.012)	120–150 (400–500)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	75–215 (250–700)
	TiN-coated carbide	1.2–4.0 (0.05–0.20)	0.30 (0.012)	90–200 (300–650)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	45–215 (150–700)
	Al_2O_3 ceramic	1.2–4.0 (0.05–0.20)	0.25 (0.010)	335 (1,100)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	245–455 (800–1,500)
	Cermet	1.2–4.0 (0.05–0.20)	0.25 (0.010)	170–245 (550–800)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	105–305 (350–1,000)
Cast iron, gray	Uncoated carbide	1.25–6.3 (0.05–0.25)	0.32 (0.013)	90 (300)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	75–185 (250–600)
	Ceramic-coated carbide	1.25–6.3 (0.05–0.25)	0.32 (0.013)	200 (650)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	120–365 (400–1,200)
	TiN-coated carbide	1.25–6.3 (0.05–0.25)	0.32 (0.013)	90–135 (300–450)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	60–215 (200–700)
	Al_2O_3 ceramic	1.25–6.3 (0.05–0.25)	0.25 (0.010)	455–490 (1,500–1,600)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	365–855 (1,200–2,800)
	SiN ceramic	1.25–6.3 (0.05–0.25)	0.32 (0.013)	730 (2,400)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	200–990 (650–3,250)
Stainless steel, austenitic	Triple-coated carbide	1.5–4.4 (0.06–0.175)	0.35 (0.014)	150 (500)	0.5–12.7 (0.02–0.5)	0.08–0.75 (0.003–0.03)	75–230 (250–750)
	TiN-coated carbide	1.5–4.4 (0.06–0.175)	0.35 (0.014)	85–160 (275–525)	0.5–12.7 (0.02–0.5)	0.08–0.75 (0.003–0.03)	55–200 (175–650)
	Cermet	1.5–4.4 (0.06–0.175)	0.30 (0.012)	185–215 (600–700)	0.5–12.7 (0.02–0.5)	0.08–0.75 (0.003–0.03)	105–290 (350–950)
High-temperature alloys, nickel base	Uncoated carbide	2.5 (0.10)	0.15 (0.006)	25–45 (75–150)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	15–30 (50–100)
	Ceramic-coated carbide	2.5 (0.10)	0.15 (0.006)	45 (150)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	20–60 (65–200)

Table 13.4.4 General Recommendations for Turning Operations (*Continued*)

Workpiece material	Cutting tool	General-purpose starting conditions			Range for roughing and finishing		
		Depth of cut, mm (in)	Feed mm/r (in/r)	Cutting speed, m/min (ft/min)	Depth of cut, mm (in)	Feed mm/r (in/r)	Cutting speed, m/min (ft/min)
High-temperature alloys, nickel base (*cont.*)	TiN-coated carbide	2.5 (0.10)	0.15 (0.006)	30–55 (95–175)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	20–85 (60–275)
	Al$_2$O$_3$ ceramic	2.5 (0.10)	0.15 (0.006)	260 (850)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	185–395 (600–1,300)
	SiN ceramic	2.5 (0.10)	0.15 (0.006)	215 (700)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	90–215 (300–700)
	Polycrystalline CBN	2.5 (0.10)	0.15 (0.006)	150 (500)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	120–185 (400–600)
Titanium alloys	Uncoated carbide	1.0–3.8 (0.04–0.15)	0.15 (0.006)	35–60 (120–200)	0.25–6.3 (0.01–0.25)	0.1–0.4 (0.004–0.015)	10–75 (30–250)
	TiN-coated carbide	1.0–3.8 (0.04–0.15)	0.15 (0.006)	30–60 (100–200)	0.25–6.3 (0.01–0.25)	0.1–0.4 (0.004–0.015)	10–100 (30–325)
Aluminum alloys, free-machining	Uncoated carbide	1.5–5.0 (0.06–0.20)	0.45 (0.018)	490 (1,600)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	200–670 (650–2,000)
	TiN-coated carbide	1.5–5.0 (0.06–0.20)	0.45 (0.018)	550 (1,800)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	60–915 (200–3,000)
	Cermet	1.5–5.0 (0.06–0.20)	0.45 (0.018)	490 (1,600)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	215–795 (700–2,600)
	Polycrystalline diamond	1.5–5.0 (0.06–0.20)	0.45 (0.018)	760 (2,500)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	305–3,050 (1,000–10,000)
High-silicon	Polycrystalline diamond	1.5–5.0 (0.06–0.20)	0.45 (0.018)	530 (1,700)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	365–915 (1,200–3,000)
Copper alloys	Uncoated carbide	1.5–5.0 (0.06–0.20)	0.25 (0.010)	260 (850)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	105–535 (350–1,750)
	Ceramic-coated carbide	1.5–5.0 (0.06–0.20)	0.25 (0.010)	365 (1,200)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	215–670 (700–2,200)
	Triple-coated carbide	1.5–5.0 (0.06–0.20)	0.25 (0.010)	215 (700)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	90–305 (300–1,000)
	TiN-coated carbide	1.5–5.0 (0.06–0.20)	0.25 (0.010)	90–275 (300–900)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	45–455 (150–1,500)
	Cermet	1.5–5.0 (0.06–0.20)	0.25 (0.010)	245–425 (800–1,400)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	200–610 (650–2,000)
	Polycrystalline diamond	1.5–5.0 (0.06–0.20)	0.25 (0.010)	520 (1,700)	0.4–7.5 (0.015–0.3)	0.15–0.75 (0.006–0.03)	275–915 (900–3,000)
Tungsten alloys	Uncoated carbide	2.5 (0.10)	0.2 (0.008)	75 (250)	0.25–5.0 (0.01–0.2)	0.12–0.45 (0.005–0.018)	55–120 (175–400)
	TiN-coated carbide	2.5 (0.10)	0.2 (0.008)	85 (275)	0.25–5.0 (0.01–0.2)	0.12–0.45 (0.005–0.018)	60–150 (200–500)
Thermoplastics and thermosets	TiN-coated carbide	1.2 (0.05)	0.12 (0.005)	170 (550)	0.12–5.0 (0.005–0.20)	0.08–0.35 (0.003–0.015)	90–230 (300–750)
	Polycrystalline diamond	1.2 (0.05)	0.12 (0.005)	395 (1,300)	0.12–5.0 (0.005–0.20)	0.08–1.35 (0.003–0.015)	150–730 (500–2,400)
Composites, graphite-reinforced	TiN-coated carbide	1.9 (0.075)	0.2 (0.008)	200 (650)	0.12–6.3 (0.005–0.25)	0.12–1.5 (0.005–0.06)	105–290 (350–950)
	Polycrystalline diamond	1.9 (0.075)	0.2 (0.008)	760 (2,500)	0.12–6.3 (0.005–0.25)	0.12–1.5 (0.005–0.06)	550–1,310 (1,800–4,300)

NOTE: Cutting speeds for high-speed-steel tools are about one-half those for uncoated carbides.
SOURCE: Based on data from Kennametal Inc.

Table 13.4.5 General Troubleshooting Guide for Turning Operations

Problem	Probable causes
Tool breakage	Tool material lacks toughness; improper tool angles; machine tool lacks stiffness; worn bearings and machine components; cutting parameters too high
Excessive tool wear	Cutting parameters too high; improper tool material; ineffective cutting fluid; improper tool angles
Rough surface finish	Built-up edge on tool; feed too high; tool too sharp, chipped, or worn; vibration and chatter
Dimensional variability	Lack of stiffness; excessive temperature rise; tool wear
Tool chatter	Lack of stiffness; workpiece not supported rigidly; excessive tool overhang

The basic principle of the turret lathe is that, with standard tools, setups can be made quickly so that combined, multiple, and successive cuts can be made on a part. By **combined** cuts, tools on the cross slide operate simultaneously with those on the turret, e.g., facing from the cross slide and boring from the turret. **Multiple** cuts permit two or more tools to operate from either or both the cross slide or turret. By **successive** cuts, one tool may follow another to rough or finish a surface; e.g., a hole may be drilled, bored, and reamed at one chucking. In the tool-slide machine only roughing cuts, such as turn and face, can be made in one machine. A second machine similarly tooled must be available to make the finishing cuts.

Ram-type turret lathes have the turret mounted on a ram which slides in a separate base. The base is clamped at a position along the bed to suit a long or short workpiece. A cross slide can be used so that combined cuts can be taken from the turret and the cross slide at the same time. Turret and cross slide can be equipped with manual or power feed. The short stroke of the turret slide limits this machine to comparatively short light work, in both small and quantity-lot production.

Saddle-type turret lathes have the turret mounted on a saddle which slides directly on the bed. Hence, the length of stroke is limited only by the length of bed. A separate square-turret carriage with longitudinal and transverse movement can be mounted between the head and the hex-turret saddle so that combined cuts from both stations at one time are possible. The saddle type of turret lathe generally has a large hollow vertically faced turret for accurate alignment of the tools.

Screw Machines

When turret lathes are set up for bar stock, they are often called **screw machines**. Turret lathes that are adaptable only to bar-stock work are constructed for light work. As with turret lathes, they have spring collets for holding the bars during machining and friction fingers or rolls to feed the bar stock forward. Some bar-feeding devices are operated by hand and others semiautomatically.

Automatic screw machines may be classified as single-spindle or multiple-spindle. Single-spindle machines rotate the bar stock from which the part is to be made. The tools are carried on a turret and on cross slides or on a circular drum and on cross slides. Multiple-spindle machines have four, five, six, or eight spindles, each carrying a bar of the material from which the piece is to be made. Capacities range from ⅓ to 6 in (3 to 150 mm) diam of bar stock.

Feeds of forming tools vary with the width of the cut. The wider the forming tool and the smaller the diameter of stock, the smaller the feed. On multiple-spindle machines, where many tools are working simultaneously, the feeds should be such as to reduce the actual cutting time to a minimum. Often only one or two tools in a set are working up to capacity, as far as actual speed and feed are concerned.

BORING

Boring is a machining process for producing internal straight cylindrical surfaces or profiles, with process characteristics and tooling similar to those for turning operations.

Boring machines are of two general types, horizontal and vertical, and are frequently referred to as horizontal boring machines and vertical boring and turning mills. A classification of boring machines comprises horizontal boring, drilling, and milling machines; vertical boring and turning mills; vertical multispindle cylinder boring mills; vertical cylinder boring mills; vertical turret boring mills (vertical turret lathes); car-wheel boring mills; diamond or precision boring machines (vertical and horizontal); and jig borers.

The **horizontal type** is made for both precision work and general manufacturing. It is particularly adapted for work not conveniently revolved, for milling, slotting, drilling, tapping, boring, and reaming long holes, and for making interchangeable parts that must be produced without jigs and fixtures. The machine is universal and has a wide range of speeds and feeds, for a face-mill operation may be followed by one with a small-diameter drill or end mill.

Vertical boring mills are adapted to a wide range of faceplate work that can be revolved. The advantage lies in the ease of fastening a workpiece to the horizontal table, which resembles a four-jaw independent chuck with extra radial T slots, and in the lessened effect of centrifugal forces arising from unsymmetrically balanced workpieces.

A **jig-boring machine** has a single-spindle sliding head mounted over a table adjustable longitudinally and transversely by lead screws which roughly locate the work under the spindle. Precision setting of the table may be obtained with end measuring rods, or it may depend only on the accuracy of the lead screw. These machines, made in various sizes, are used for accurately finishing holes and surfaces in definite relation to one another. They may use drills, rose or fluted reamers, or single-point boring tools. The latter are held in an adjustable **boring head** by which the tool can be moved eccentrically to change the diameter of the hole.

Precision-boring machines may have one or more spindles operating at high speeds for the purpose of boring to accurate dimensions such surfaces as wrist-pin holes in pistons and connecting-rod bushings.

Boring Recommendations   Boring recommendations for tool materials, depth of cut, feed, and cutting speed are generally the same as those for turning operations (see Table 13.4.4). However, tool deflec-

tions, chatter, and dimensional accuracy can be significant problems because the boring bar has to reach the full length to be machined and space within the workpiece may be limited. Boring bars have been designed to dampen vibrations and reduce chatter during machining.

DRILLING

Drilling is a commonly employed hole-making process that uses a **drill** as a cutting tool for producing round holes of various sizes and depths. Drilled holes may be subjected to additional operations for better surface finish and dimensional accuracy, such as reaming and honing, described later in this section.

Drilling machines are intended for drilling holes, tapping, counterboring, reaming, and general boring operations. They may be classified into a large variety of types.

Sizes of Drilling Machines   **Vertical drilling machines** are usually designated by a dimension which roughly indicates the diameter of the largest circle that can be drilled at its center under the machine. This dimensioning, however, does not hold for all makes of machines. The sizes begin with about 6 and continue to 50 in. Heavy-duty drill presses of the vertical type, with all-geared speed and feed drive, are constructed with a box-type column instead of the older cylindrical column.

The size of a **radial drill** is designated by the length of the arm. This represents the radius of a piece which can be drilled in the center.

Twist drills (Fig. 13.4.12) are the most common tools used in drilling and are made in many sizes and lengths. For years they have been grouped according to numbered sizes, 1 to 80, inclusive, corresponding approximately to Stub's steel wire gage; some by lettered sizes A to Z, inclusive; some by fractional inches from ¹⁄₆₄ up, and the group of millimeter sizes.

Straight-shank twist drills of fractional size and various lengths range from ¹⁄₆₄ in diam to 1¼ in by ¹⁄₆₄ in increments; to 1½ in by ¹⁄₃₂ in; and to 2 in by ¹⁄₁₆ in. **Taper-shank drills** range from ⅛ in diam to 1¾ in by ¹⁄₆₄ increments; to 2¼ in by ¹⁄₃₂ in; and to 3½ in by ¹⁄₁₆ in. Larger drills are made by various drill manufacturers. Drills are also available in metric dimensions.

Tolerances have been set on the various features of all drills so that the products of different manufacturers will be interchangeable in the user's plants.

Twist drills are decreased in diameter from point to shank (back taper) to prevent binding. If the web is increased gradually in thickness from point to shank to increase the strength, it is customary to reduce the helix angle as it approaches the shank. The shape of the groove is important, the one that gives a straight cutting edge and allows
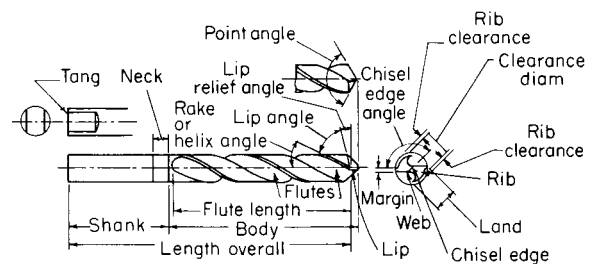
Fig. 13.4.12   Straight shank twist drill.

a full curl to the chip being the best. The **helix angles** of the flutes vary from 10 to 45°. The standard **point angle** is 118°. There are a number of **drill grinders** on the market designed to give the proper angles. The point may be ground either in the **standard** or the **crankshaft** geometry. The drill geometry for high-speed steel twist drills for a variety of workpiece materials is given in Table 13.4.6.

Among the common **types of drills** (Fig. 13.4.13) are the combined drill and countersink or **center drill,** a short drill used to center shafts before squaring and turning: the **step drill,** with two or more diameters; the **spade drill** which has a removable tip or bit clamped in a holder on the drill shank, used for large and deep holes; the **trepanning tool** used to

Table 13.4.6   Recommended Drill Geometry for High-Speed Steel Twist Drills

| Material	Point angle, deg	Lip relief angle, deg	Chisel edge angle, deg	Helix angle, deg	Point grind
Aluminum alloys	90–118	12–15	125–135	24–48	Standard
Magnesium alloys	70–118	12–15	120–135	30–45	Standard
Copper alloys	118	12–15	125–135	10–30	Standard
Steels	118	10–15	125–135	24–32	Standard
High strength steels	118–135	7–10	125–135	24–32	Crankshaft
Stainless steels, low-strength	118	10–12	125–135	24–32	Standard
Stainless steels, high-strength	118–135	7–10	120–130	24–32	Crankshaft
High-temperature alloys	118–135	9–12	125–135	15–30	Crankshaft
Refractory alloys	118	7–10	125–135	24–32	Standard
Titanium alloys	118–135	7–10	125–135	15–32	Crankshaft
Cast irons	118	8–12	125–135	24–32	Standard
Plastics	60–90	7	120–135	29	Standard

SOURCE: ''Machining Data Handbook,'' published by the Machinability Data Center, Metcut Research Associates Inc.

cut a core from a piece of metal instead of reducing all the metal removed to chips; the **gun drill,** run at a high speed under a light feed, and used to drill small long holes; the **core drill** used to bore out cored holes; the **oil-hole drill,** having holes or tubes in its body through which oil is forced to the cutting lips; **three- and four-fluted drills,** used to enlarge holes after a leader hole has been cored, punched, or drilled with a
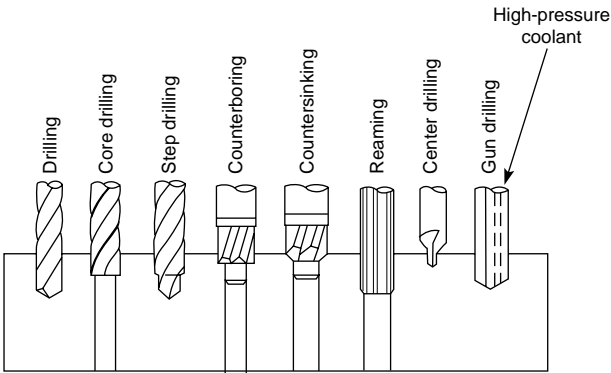
Fig. 13.4.13   Various types of drills, and drilling and reaming operations.

two-fluted drill; **twisted drills** made from flat high-speed steel or drop-forged to desired shape and then twisted. Drills are also made of solid carbide or of high-speed steel with an insert of carbide to form the chisel edge and both cutting edges. They are used primarily for drilling abrasive or very hard materials.

Drilling Recommendations   The most common tool material for drills is high-speed steel M1, M7, and M10. General recommendations for speeds and feeds in drilling a variety of materials are given in Table

13.4.7. Hole depth is also a factor in selecting drilling parameters. A general **troubleshooting guide** for drilling is given in Table 13.4.8.

Table 13.4.8   General Troubleshooting Guide for Drilling Operations

Problem	Probable causes
Drill breakage	Dull drill; drill seizing in hole because of chips clogging flutes; feed too high; lip relief angle too small
Excessive drill wear	Cutting speed too high; ineffective cutting fluid; rake angle too high; drill burned and strength lost when sharpened
Tapered hole	Drill misaligned or bent; lips not equal; web not central
Oversize hole	Same as above; machine spindle loose; chisel edge not central; side pressure on workpiece
Poor hole surface finish	Dull drill; ineffective cutting fluid; welding of workpiece material on drill margin; improperly ground drill; improper alignment

REAMING

A **reamer** is a multiple-cutting edge tool used to enlarge or finish holes, and to provide accurate dimensions as well as good finish. Reamers are of two types: (1) rose and (2) fluted.

The **rose reamer** is a heavy-bodied tool with end cutting edges. It is used to remove considerable metal and to true up a hole preparatory to flute reaming. It is similar to the three- and four-fluted drills. Wide cylindrical lands are provided back of the flute edges.

Fluted reamers cut principally on the periphery and remove only 0.004 to 0.008 in (0.1 to 0.2 mm) on the bore. Very narrow cylindrical margins are provided back of the flute edges, 0.012 to 0.015 in (0.3 to

Table 13.4.7   General Recommendations for Drilling

Workpiece material	Surface speed		Feed, mm/r (in/r)		r/min	
			Drill diameter			
	m/min	ft/min	1.5 mm (0.060 in)	12.5 mm (0.5 in)	1.5 mm	12.5 mm
Aluminum alloys	30–120	100–400	0.025 (0.001)	0.30 (0.012)	6,400–25,000	800–3,000
Magnesium alloys	45–120	150–400	0.025 (0.001)	0.30 (0.012)	9,600–25,000	1,100–3,000
Copper alloys	15–60	50–200	0.025 (0.001)	0.25 (0.010)	3,200–12,000	400–1,500
Steels	20–30	60–100	0.025 (0.001)	0.30 (0.012)	4,300–6,400	500–800
Stainless steels	10–20	40–60	0.025 (0.001)	0.18 (0.007)	2,100–4,300	250–500
Titanium alloys	6–20	20–60	0.010 (0.0004)	0.15 (0.006)	1,300–4,300	150–500
Cast irons	20–60	60–200	0.025 (0.001)	0.30 (0.012)	4,300–12,000	500–1,500
Thermoplastics	30–60	100–200	0.025 (0.001)	0.13 (0.005)	6,400–12,000	800–1,500
Thermosets	20–60	60–200	0.025 (0.001)	0.10 (0.004)	4,300–12,000	500–1,500

NOTE: As hole depth increases, speeds and feeds should be reduced. Selection of speeds and feeds also depends on the specific surface finish required.

0.4 mm) wide for machine-finish reaming and 0.004 to 0.006 in (0.1 to 0.15 mm) for hand reaming, to provide free cutting of the edges due to the slight body taper and also to pilot the reamer in the hole. The hole to be flute- or finish-reamed should be true. A rake of 5° is recommended for most reaming operations. A reamer may be straight or helically fluted. The latter provides much smoother cutting and gives a better finish.

Expansion reamers permit a slight expansion by a wedge so that the reamer may be resharpened to its normal size or for job shop use; they provide slight variations in size. **Adjustable reamers** have means of adjusting inserted blades so that a definite size can be maintained through numerous grindings and fully worn blades can be replaced with new ones. **Shell reamers** constitute the cutting portion of the tool which fits interchangeably on arbors to make many sizes available or to make replacement of worn-out shells less costly. Reamers float in their holding fixtures to ensure alignment, or they should be piloted in guide bushings above and below the work. They may also be held rigidly, such as in the tailstock of a lathe.

The **speed** of high-speed steel reamers should be two-thirds to three-quarters and **feeds** usually are two or three times that of the corresponding drill size. The most common tool materials for reamers are M1, M2, and M7 high-speed steels and C-2 carbide.

THREADING

Threads may be formed on the outside or inside of a cylinder or cone (1) with single-point threading tools, (2) with threading chasers, (3) with taps, (4) with dies, (5) by thread milling, (6) by thread rolling, and (7) by grinding. There are numerous types of taps, such as hand, machine screw, pipe, and combined pipe tap and drill. Small taps usually have no radial relief. They may be made in two, three, or four flutes. Large taps may have still more flutes.

The **feed** of a tap depends upon the lead of the screw thread. The **cutting speed** depends upon numerous factors: Hard tough materials, great length of hole, taper taps, and full-depth thread reduce the speed; long chamfer, fine pitches, and a cutting fluid applied in quantity increase the speed. Taps are cut or formed by grinding. The ground-thread taps may operate at much higher speeds than the cut taps. Speeds may range from 3 ft/min (1 m/min) for high-strength steels to 150 ft/min (45 m/min) for aluminum and magnesium alloys. Common high-speed steel tool materials for taps are M1, M7, and M10.

Threading dies, used to produce external threads, may be solid, adjustable, spring-adjustable, or self-opening die heads. Replacement chasers are used in die heads and may be of the fixed or self-opening type. These chasers may be of the radial type, hobbed or milled; of the tangenital type; or of the circular type. Emulsions and oils are satisfactory for most threading operations.

MILLING

Milling is one of the most versatile machining processes and is capable of producing a variety of shapes involving flat surfaces, slots, and contours (Fig. 13.4.14).

Milling machines use cutters with multiple teeth in contrast with the single-point tools of the lathe and planer. The workpiece is generally fed past the cutter perpendicular to the cutter axis. Milling usually is face or peripheral cutting.

Standard spindle noses and arbors for milling machines provide interchangeability of arbors and face-milling cutters, regardless of make or size of machine. The taper of the spindle end and arbor is 3½ in/ft, to make them **self-releasing**. The retention of the shank is dependent upon a positive locking device, such as screws or draw-in bolt. When unlocked, these tapers release themselves.

Milling-machine classification is based on design, operation, or purpose. **Knee-and-column** type milling machines have the table and saddle supported on the vertically adjustable knee gibbed to the face of the column. The table is fed longitudinally on the saddle, and the latter transversely on the knee to give three feeding motions.

Knee-type machines are made with horizontal or vertical spindles. The **horizontal** universal machines have a swiveling table for cutting helices. The plain machines are used for jobbing or production work, the universal for toolroom work. **Vertical** milling machines with fixed or sliding heads are otherwise similar to the horizontal type. They are used for face or end milling and are frequently provided with a rotary table for making cylindrical surfaces.

The **fixed-bed** machines have a spindle mounted in a head dovetailed to and sliding on the face of the column. The table rests directly on the bed. They are simple and rigidly built and are used primarily for high-production work. These machines are usually provided with work-holding fixtures and may be constructed as plain or multiple-spindle machines, simple or duplex.

Rotary-type millers usually have a rotating table on which fixtures carrying the workpiece are mounted. The cutter spindles are mounted over the edge of the table past which the workpiece is fed.

Drum-type millers consist of a drum carrying the work and rotating on a horizontal axis. Both rotary and drum types are mass-production machines, there being no idle time, for the drums rotate continuously while the parts, loaded on one side of the machine, pass first the roughing and then the finishing cutters and are replaced when they return to the loading position.

In **planetary** milling machines the workpiece is stationary on the bed or clamped to the tailstock while the cutter rotates. Plain and formed internal or external surfaces and threads are produced by inserting the cutter into the bore to be milled, feeding it to depth radially, making a sweeping cut about the bore, and withdrawing first radially and then axially.

Planer-type millers are used only on the heaviest work. They are used to machine a number of surfaces on a particular part or group of parts arranged in series in fixtures on the table.

Thread millers are used to cut threads and worms. A single formed cutter may be used or all the threads may be cut at one time by a multiple-thread cutter.

Milling Cutters

Milling cutters are made in a wide variety of shapes and sizes. The nomenclature of tooth parts and angles is standardized as in
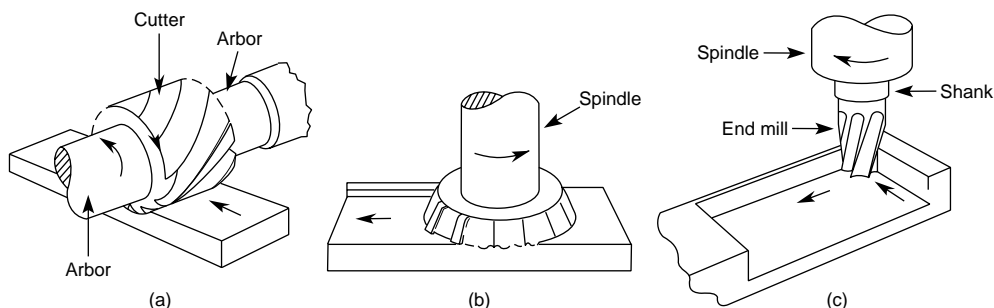

Fig. 13.4.14   Basic types of milling cutters and operations. (*a*) Slab (peripheral) milling; (*b*) face milling; (*c*) end milling.
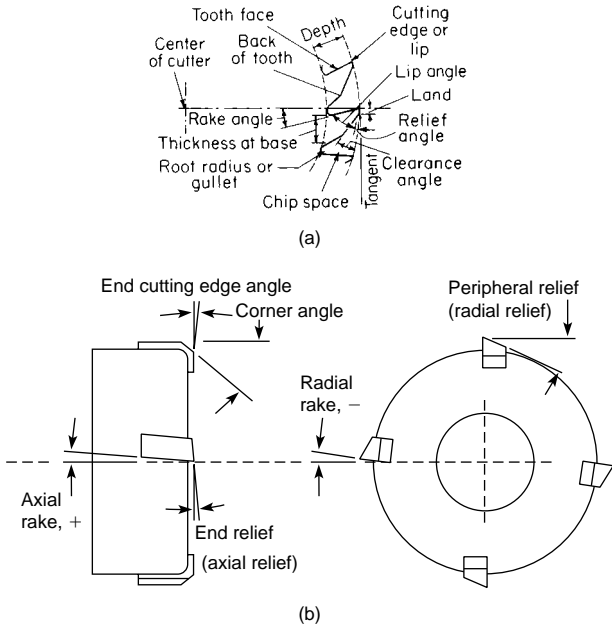
Fig. 13.4.15   (a) Plain milling cutter teeth; (b) face milling cutter.

Table 13.4.10   General Troubleshooting Guide for Milling Operations

Problem	Probable causes
Tool breakage	Tool material lacks toughness; improper tool angles; cutting parameters too high
Tool wear excessive	Cutting parameters too high; improper tool material; improper tool angles; improper cutting fluid
Rough surface finish	Feed too high; spindle speed too low; too few teeth on cutter; tool chipped or worn; built-up edge; vibration and chatter
Tolerances too broad	Lack of spindle stiffness; excessive temperature rise; dull tool; chips clogging cutter
Workpiece surface burnished	Dull tool; depth of cut too low; radial relief angle too small
Back striking	Dull cutting tools; cutter spindle tilt; negative tool angles
Chatter marks	Insufficient stiffness of system; external vibrations; feed, depth, and width of cut too large
Burr formation	Dull cutting edges or too much honing; incorrect angle of entry or exit; feed and depth of cut too high; incorrect insert geometry
Breakout	Lead angle too low; incorrect cutting edge geometry; incorrect angle of entry or exit; feed and depth of cut too high

Table 13.4.9   General Recommendations for Milling Operations

Workpiece material	Cutting tool	General-purpose starting conditions Feed, mm/tooth (in/tooth)	Speed, m/min (ft/min)	Range of conditions Feed, mm/tooth (in/tooth)	Speed, m/min (ft/min)
Low-C and free-machining steels	Uncoated carbide, coated carbide, cermets	0.13–0.20 (0.005–0.008)	120–180 (400–600)	0.085–0.38 (0.003–0.015)	90–425 (300–1,400)
Alloy steels					
Soft	Uncoated, coated, cermets	0.10–0.18 (0.004–0.007)	90–170 (300–550)	0.08–0.30 (0.003–0.012)	60–370 (200–1,200)
Hard	Cermets, PCBN	0.10–0.15 (0.004–0.006)	180–210 (600–700)	0.08–0.25 (0.003–0.010)	75–460 (250–1,500)
Cast iron, gray					
Soft	Uncoated, coated, cermets, SiN	0.10–0.20 (0.004–0.008)	120–760 (400–2,500)	0.08–0.38 (0.003–0.015)	90–1,370 (300–4,500)
Hard	Cermets, SiN, PCBN	0.10–0.20 (0.004–0.008)	120–210 (400–700)	0.08–0.38 (0.003–0.015)	90–460 (300–1,500)
Stainless steel, austenitic	Uncoated, coated, cermets	0.13–0.18 (0.005–0.007)	120–370 (400–1,200)	0.08–0.38 (0.003–0.015)	90–500 (300–1,800)
High-temperature alloys, nickel base	Uncoated, coated, cermets, SiN, PCBN	0.10–0.18 (0.004–0.007)	30–370 (100–1,200)	0.08–0.38 (0.003–0.015)	30–550 (90–1,800)
Titanium alloys	Uncoated, coated, cermets	0.13–0.15 (0.005–0.006)	50–60 (175–200)	0.08–0.38 (0.003–0.015)	40–140 (125–450)
Aluminum alloys					
Free-machining	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	610–900 (2,000–3,000)	0.08–0.46 (0.003–0.018)	300–3,000 (1,000–10,000)
High-silicon	PCD	0.13 (0.005)	610 (2,000)	0.08–0.38 (0.003–0.015)	370–910 (1,200–3,000)
Copper alloys	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	300–760 (1,000–2,500)	0.08–0.46 (0.003–0.018)	90–1,070 (300–3,500)
Thermoplastics and thermosets	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	270–460 (900–1,500)	0.08–0.46 (0.003–0.018)	90–1,370 (300–4,500)

NOTE: Depths of cut, d, usually are in the range of 1–8 mm (0.04–0.3 in). PCBN: polycrystalline cubic boron nitride; PCD: polycrystalline diamond.
SOURCE: Based on data from Kennametal Inc.

Fig. 13.4.15. Milling cutters may be classified in various ways, such as purpose or use of the cutters (Woodruff keyseat cutters, T-slot cutters, gear cutters, etc.); construction characteristics (solid cutters, carbide-tipped cutters, etc.); method of mounting (arbor type, shank type, etc.); and relief of teeth. The latter has two categories: profile cutters which produce flat, curved, or irregular surfaces, with the cutter teeth sharpened on the land; and formed cutters which are sharpened on the face to retain true cross-sectional form of the cutter.

Two kinds of milling are generally considered to represent all forms of milling processes: **peripheral (slab)** and **face** milling. In the peripheral-milling process the axis of the cutter is parallel to the surface milled, whereas in face milling, the cutter axis is generally at a right angle to the surface. The peripheral-milling process is also divided into two types: **conventional (up) milling** and **climb (down) milling**. Each has its advantages, and the choice depends on a number of factors such as the type and condition of the equipment, tool life, surface finish, and machining parameters.

Milling Recommendations   Recommendations for tool materials, feed per tooth, and cutting speed for milling a variety of materials are given in Table 13.4.9. The cutting speeds for high-speed steels for turning, which are generally M2 and M7, are about one-half those for uncoated carbides. A general **troubleshooting guide** for milling operations is given in Table 13.4.10.

GEAR MANUFACTURING

(See also Sec. 8)

Gear Cutting   Most gear-cutting processes can be classified as either **forming** or **generating**. In a forming process, the shape of the tool is reproduced on the workpiece; in a generating process, the shape produced on the workpiece depends on both the shape of the tool and the relative motion between the tool and the workpiece during the cutting operation. A soft live center on a lathe can be formed by means of a broad, flat-form tool fed at right angles to the lathe spindle, or generated by a single-point tool fed at the point angle in the compound rest. In general, a generating process is more accurate than a forming process.

In the **form cutting** of gears, the tool has the shape of the space between the teeth. For this reason, form cutting will produce precise tooth profiles only when the cutter is accurately made and the tooth space is of constant width, such as on spur and helical gears. A form cutter may cut or finish one of or all the spaces in one pass. Single-space cutters may be disk-type or end-mill-type milling cutters. In all single-space operations, the gear blank must be retracted and indexed, i.e., rotated one tooth space, between each pass.

Single-space form milling with disk-type cutters is particularly suitable for gears with large teeth, because, as far as metal removal is concerned, the cutting action of a milling cutter is more efficient than that of the tools used for generating. Form milling of spur gears is done on machines that retract and index the gear blank automatically.

For the same tooth size (pitch), the shape (profile) of the teeth on an involute gear depends on the number of teeth on the gear. Most gears have active profiles that are wholly, partially, or approximately involute, and, consequently, accurate form cutting would require a different cutter for each number of teeth. In most cases, satisfactory results can be obtained by using the eight cutters for each pitch that are commercially available. Each cutter is designed to cut a range of tooth numbers; the

no. 1 cutter, for example, cuts from 135 teeth to a rack, and the no. 8 cuts 12 and 13 teeth. (See Table 13.4.11.)

Multiple-space form cutting is done with a broach or with a patented Shear Speed toolhead. The broach is pushed down into or over the gear blank, usually on a hydraulic press, and all the spaces can be cut in one pass.

The Shear-Speed toolhead contains three main parts: a housing, a member with radial slots in which a tool for each of the tooth spaces on the gear being cut can slide, and a movable, double cone-shaped guiding unit that controls the radial movement (feed) of the tools. With the toolhead stationary, the part is reciprocated past the cutting tools; each tool is fed radially a predetermined amount each stroke until the full tooth depth is cut. To avoid drag, the tools are retracted on each return (noncutting) stroke of the gear.

Gears always operate in pairs and are usually required to have contacting profiles of such a shape that the ratio of the speeds of the pair remains constant at all times; such gears are said to be **conjugate** to one another.

In a **gear generating machine**, the generating tool can be considered as one of the gears in a conjugate pair and the gear blank as the other gear. The correct relative motion between the tool arbor and the blank arbor is obtained by means of a train of indexing gears within the machine.

One of the most valuable properties of the involute as a gear-tooth profile is that if a cutter is made in the form of an involute gear of a given pitch and any number of teeth, it can generate all gears of all tooth numbers of the same pitch and they will all be conjugate to one another. The generating tool may be a pinion-shaped cutter, a rack-shaped (straight) cutter, or a hob, which is essentially a series of racks wrapped around a cylinder in a helical, screwlike form.

On a **gear shaper**, the generating tool is a pinion-shaped cutter that rotates slowly at the proper speed as if in mesh with the blank; the cutting action is produced by a reciprocation of the cutter parallel to the work axis. These machines can cut spur and helical gears, both internal and external; they can also cut continuous-tooth helical (herringbone) gears and are particularly suitable for cluster gears, or gears that are close to a shoulder.

On a **rack shaper** the generating tool is a segment of a rack that moves perpendicular to the axis of the blank while the blank rotates about a fixed axis at the speed corresponding to conjugate action between the rack and the blank; the cutting action is produced by a reciprocation of the cutter parallel to the axis of the blank. Since it is impracticable to have more than 6 to 12 teeth on a rack cutter, the cutter must be disengaged from the blank at suitable intervals and returned to the starting point, the blank meanwhile remaining fixed. These machines can cut both spur and helical external gears.

A gear-cutting **hob** is basically a worm, or screw, made into a generating tool by cutting a series of longitudinal slots or ''gashes'' to form teeth; to form cutting edges, the teeth are ''backed off,'' or relieved, in a lathe equipped with a backing-off attachment. A hob may have one, two, or three threads; on involute hobs with a single thread, the generating portion of the hob-tooth profile usually has straight sides (like an involute rack tooth) in a section taken at right angles to the thread.

In addition to the conjugate rotary motions of the hob and workpiece, the hob must be fed parallel to the workpiece axis for a distance greater than the face width of the gear. The feed, per revolution of the work-

Table 13.4.11

No. of cutter	1	2	3	4	5	6	7	8
No. of teeth	$135-\infty$	$55-134$	$35-54$	$27-34$	$21-26$	$17-20$	$14-16$	12 and 13

For more accurate gears, 15 cutters are available

No. of cutter	1	1½	2	2½	3	3½	4	4½
No. of teeth	$135-\infty$	$80-134$	$55-79$	$42-54$	$35-41$	$30-34$	$26-29$	$23-25$

No. of cutter	5	5½	6	6½	7	7½	8
No. of teeth	21 and 22	19 and 20	17 and 18	15 and 16	14	13	12

piece, is produced by the feed gears, and its magnitude depends on the material, pitch, and finish desired; the feed gears are independent of the indexing gears. The hobbing process is continuous until all the teeth are cut.

The same machines and the same hobs that are used for cutting spur gears can be used for helical gears; it is only necessary to tip the hob axis so that the hob and gear pitch helices are tangent to one another and to correlate the indexing and feed gears so that the blank and the hob are advanced or retarded with respect to each other by the amount required to produce the helical teeth. Some hobbing machines have a differential gear mechanism that permits the indexing gears to be selected as for spur gears and the feed gearing to be chosen independently.

The threads of worms are usually cut with a disk-type milling cutter on a thread-milling machine and finished, after hardening, by grinding. Worm gears are usually cut with a hob on the machines used for hobbing spur and helical gears. Except for the gashes, the relief on the teeth, and an allowance for grinding, the hob is a counterpart of the worm. The hob and workpiece axes are inclined to one another at the shaft angle of the worm and gear set, usually 90°. The hob may be fed in to full depth in a radial (to the blank) direction or parallel to the hob axis.

Although it is possible to approximate the true shape of the teeth on a straight bevel gear by taking two or three cuts with a form cutter on a milling machine, this method, because of the taper of the teeth, is obviously unsuited for the rapid production of accurate teeth. Most straight bevel gears are roughed out in one cut with a form cutter on machines that index automatically and then finished to the proper shape on a generator.

The generating method used for straight bevel gears is analogous to the rack-generating method used for spur gears. Instead of using a rack with several complete teeth, however, the cutter has only one straight cutting edge that moves, during generation, in the plane of the tooth of a basic crown gear conjugate to the gear being generated. A crown gear is the rack among bevel gears; its pitch surface is a plane, and its teeth have straight sides.

The generating cutter moves back and forth across the face of the bevel gear like the tool on a shaper; the ''generating roll'' is obtained by rotating the gear slowly relative to the tool. In practice two tools are used, one for each side of a tooth; after each tooth has been generated, the gear must be retracted and indexed to the next tooth.

The machines used for cutting spiral bevel gears operate on essentially the same principle as those used for straight bevel gears; only the cutter is different. The spiral cutter is basically a disk that has a number of straight-sided cutting blades protruding from its periphery on one side to form the rim of a cup. The machines have means for indexing, retracting, and producing a generating roll; by disconnecting the roll gears, spiral bevel gears can be form cut.

Gear Shaving   For improving the surface finish and profile accuracy of cut spur and helical gears (internal and external), gear shaving, a free-cutting gear finishing operation that removes small amounts of metal from the working surfaces of the teeth, is employed. The teeth on the shaving cutter, which may be in the form of a pinion (spur or helical) or a rack, have a series of sharp-edged rectangular grooves running from tip to root. The intersection of the grooves with the tooth profiles creates cutting edges; when the cutter and the workpiece, in tight mesh, are caused to move relative to one another along the teeth, the cutting edges remove metal from the teeth of the work gear. Usually the cutter drives the workpiece, which is free to rotate and is traversed past the cutter parallel to the workpiece axis. Shaving requires less time than grinding, but ordinarily it cannot be used on gears harder than approximately 400 HB (42 HRC).

Gear Grinding   Machines for the grinding of spur and helical gears utilize either a forming or a generating process. For form grinding, a disk-type grinding wheel is dressed to the proper shape by a diamond held on a special dressing attachment; for each number of teeth a special index plate, with V-type notches on its periphery, is required. When grinding helical gears, means for producing a helical motion of the blank must be provided.

For grinding-generating, the grinding wheel may be a disk-type, double-conical wheel with an axial section equivalent to the basic

rack of the gear system. A master gear, similar to the gear being ground, is attached to the workpiece arbor and meshes with a master rack; the generating roll is created by rolling the master gear in the stationary rack.

Spiral bevel and hypoid gears can be ground on the machines on which they are generated. The grinding wheel has the shape of a flaring cup with a double-conical rim having a cross section equivalent to the surface that is the envelope of the rotary cutter blades.

Gear Rolling   The cold-rolling process is used for the finishing of spur and helical gears for automatic transmissions and power tools; in some cases it has replaced gear shaving. It differs from cutting in that the metal is not removed in the form of chips but is displaced under heavy pressure.

There are two main types of cold-rolling machines, namely, those employing dies in the form of racks or gears that operate in a parallel-axis relationship with the blank and those employing worm-type dies that operate on axes at approximately 90° to the workpiece axis. The dies, under pressure, create the tooth profiles by the plastic deformation of the blank.

When racks are used, the process resembles thread rolling; with gear-type dies the blank can turn freely on a shaft between two dies, one mounted on a fixed head and the other on a movable head. The dies have the same number of teeth and are connected by gears to run in the same direction at the same speed. In operation, the movable die presses the blank into contact with the fixed die, and a conjugate profile is generated on the blank. On some of these machines the blank can be fed axially, and gears can be rolled in bar form to any convenient length.

On machines employing worm-type dies, the two dies are diametrically opposed on the blank and rotate in opposite directions. The speeds of the blank and the dies are synchronized by change gears, like the blank and the hob on a hobbing machine; the blank is fed axially between the dies.

Although gears have been cold-rolled from solid blanks, most commercial rolling is done as a finishing operation on fine-pitch, precut gears.

PLANING AND SHAPING

Planers are used to rough and finish large flat surfaces, although arcs and special forms can be made with proper tools and attachments. Surfaces to be finished by scraping, such as ways and long dovetails and, particularly, parts of machine tools, are, with few exceptions, planed. With fixtures to arrange parts in parallel and series, quantities of small parts can be produced economically on planers.

Shapers are used for miscellaneous planing, surfacing, notching, key seating, and production of flat surfaces on flat parts. They are virtually obsolete, but some are still in use. The tool is held in a holder supported on a clapper on the end of a ram which is reciprocated hydraulically or by crank and rocker arm, in a straight line. A table carrying the vise and the workpiece feeds transversely on each return stroke.

BROACHING

Broaching is a production process whereby a cutter, called a **broach,** is used to finish internal or external surfaces such as holes of circular, square, or irregular section, keyways, the teeth of internal gears, multiple spline holes, and flat surfaces. In broaching, the action of the broach itself serves as a clamping medium so that in many cases the operation may be completed in the time ordinarily taken to chuck the piece. The expense of making a broach may be large. However, the cost of maintaining its size is usually not excessive, and very little scrap work results. Broaching round holes gives greater accuracy and better finish than reaming, but since the broach may be guided only by the workpiece it is cutting, the hole may not be accurate with respect to previously machined surfaces. Where such accuracy is required, it is better practice to broach first and then turn other surfaces with the workpiece mounted on a mandrel. The broach is usually long and is provided with many teeth so graded in size that each takes a small chip when the tool is

pulled or pushed through the previously prepared leader hole or past the surface.

The main features of the broach are the pitch, degree of taper or increase in height of each successive tooth, relief, tooth depth, and rake.

The **pitch** of the teeth, i.e., the distance from one tooth to the next, depends upon tooth strength, length of cut, shape and size of chips, etc. The pitch should be as coarse as possible to provide ample chip clearance, but at least two teeth should be in contact with the workpiece at all times. The formula $p = 0.35 \sqrt{l}$ may be used, where p is pitch of the roughing teeth and l the length of hole or surface, in. An average pitch for small broaches is ⅛ to ¼ in (3.175 to 6.35 mm) and for large ones ½ to 1 in (12.7 to 25.4 mm). Where the hole or other surface to be broached is short, the teeth are often cut on an angle or helix, so as to give more continuous cutting action by having at least two teeth cutting simultaneously.

The degree of **taper,** or increase in size per tooth, depends largely on the hardness or toughness of the material to be broached and the finish desired. The degree of taper or feed for broaching cast iron is approximately double that for steel. Usually the first few teeth coming in contact with the workpiece are undersize but of uniform taper to take the greatest feeds per tooth, but as the finished size is approached, the teeth take smaller and smaller feeds with several teeth at the finishing end of nearly zero taper. In some cases, for soft metals and even cast iron, the large end is left plain or with rounded lands a trifle larger than the last cutting tooth so as to burnish the surface. For medium-sized broaches, the taper per tooth is 0.001 to 0.003 in (0.025 to 0.076 mm). Large broaches remove 0.005 to 0.010 in (0.127 to 0.254 mm) per tooth or even more. The teeth are given a **front rake** angle of 5 to 15° to give a curl to the chip, provide a cleaner cut surface, and reduce the power consumption. The **land** back of the cutting edge, which may be ¹⁄₆₄ to ¹⁄₁₆ in (0.4 to 1.6 mm) wide, usually is provided with a land relief varying from 1 to 3° with a clearance of 30 to 45°.

The heavier the feed per tooth or the longer the surface being broached, the greater must be the **chip clearance** or space between successive teeth for the chips to accumulate. The root should be a smooth curve.

Broaches are generally made of M2 or M7 high-speed steel; carbide is also used for the teeth of large broaches. Broaches of complicated shape are likely to warp during the heat-treating process. For this reason, in hardening, they are often heated in a vertical cylindrical furnace and quenched by being hung in an air blast furnished from small holes along the side of pipes placed vertically about the broach.

Push broaches are usually shorter than pull broaches, being 6 to 14 in (150 to 350 mm) long, depending on their diameter and the amount of metal to be removed. In many cases, for accuracy, four to six broaches of the push type constitute a set used in sequence to finish the surface being broached. Push broaches usually have a large cross-sectional area so as to be sufficiently rigid. With **pull broaches,** pulling tends to straighten the hole, whereas pushing permits the broaches to follow any irregularity of the leader hole. Pull broaches are attached to the cross-head of the broaching machine by means of a key slot and key, by a threaded connection, or by a head that fits into an automatic broach puller. The threaded connection is used where the broach is not removed from the drawing head while the workpiece is placed over the cutter, as in cutting a keyway. In enlarging holes, however, the small end of the pull broach must first be extended through the reamed, drilled, or cored hole and then fixed in the drawing head before being pulled through the workpiece.

Broaching Machines   Push broaching is done on machines of the press type with a sort of fixture for holding the workpiece and broach or on presses operated by power. They are usually vertical and may be driven hydraulically or by screw, rack, or crank. The pull type of broach may be either vertical or horizontal. The ram may be driven hydraulically or by screw, rack, or crank. Both are made in the duplex- and multiple-head type.

Processing Parameters for Broaching   Cutting speeds for broaching may range from 5 ft/min (1.5 m/min) for high-strength materials to as high as 30 to 50 ft/min (9 to 15 m/min) for aluminum and magnesium

alloys. The most common tool materials are M2 and M7 high-speed steels. An emulsion is often used for broaching for general work, but oils may also be used.

CUTTING OFF

Cutting off involves parting or slotting bars, tubes, plate, or sheet by various means. The machines come in various types such as a lathe (using a single-point cutting tool), hacksaws, band saws, circular saws, friction saws, and thin abrasive wheels. Cutting off may also be carried out by shearing and cropping, as well as using flames and laser beams.

In **power hacksaws,** the frame in which the blade is strained is reciprocated above the workpiece which is held in a vise on the bed. The cutting feed is effected by weighting the frame, with 12 to 50 lb (55 to 225 N) of force from small to large machines; adding weights or spring tension giving up to 180 lb (800 N); providing a positive screw feed or a friction screw feed; and by a hydraulic feed mechanism giving forces up to 300 lb (1.34 kN) between the blade and workpiece. With high-speed steel blades, cutting speeds range from about 30 strokes per minute for high-strength materials to 180 strokes per minute for carbon steels.

Hacksaw **blades** for hand frames are made 8, 10, and 12 in long, ⁷⁄₁₆ to ⁹⁄₁₆ in wide, and 0.025 in thick. Number of teeth per inch for cutting soft steel or cast iron, 14; tool steel and angle iron, 18; brass, copper, and heavy tubing, 24; sheet metal and thin tube, 32.

Blades for power hacksaws are made of alloy steels and of high-speed steels. Each length is made in two or more widths. The coarsest teeth should be used on large workpieces and with heavy feeds.

Band saws, vertical, horizontal, and universal, are used for cutting off. The kerf or width of cut is small with a consequently small loss in expensive material. The teeth of band saws, like those of hacksaws, are set with the regular alternate type, one bent to the right and the next to the left; or with the alternate and center set, in which one tooth is bent to the right, the second to the left, and the third straight in the center. With high-speed steel saw blades, band speeds range from about 30 ft/min (10 m/min) for high-temperature alloys to about 400 (120) for carbon steels. For aluminum and magnesium alloys the speed ranges up to about 1,300 ft/min (400 m/min) with high-carbon blades. The band speed should be decreased as the workpiece thickness increases.

Friction sawing machines are used largely for cutting off structural shapes. Peripheral speeds of about 20,000 ft/min (6,000 m/min) are used. The wheels may be plain on the periphery, V-notched, or with milled square notches.

Abrasive cutoff wheels are made of thin resinoid or rubber bonded abrasives. The wheels operate at surface speeds of 12,000 to 16,000 ft/min (3,600 to 4,800 m/min). These wheels are used for cutting off tubes, shapes, and hardened high-speed steel.

Circular saws are made in a wide variety of styles and sizes. Circular saws may have teeth of several shapes, as radial face teeth for small fine-tooth saws; radial face teeth with a land for fine-tooth saws; alternate bevel-edged teeth to break up the chips, with every other tooth beveled 45° on each side with the next tooth plain; alternate side-beveled teeth; and one tooth beveled on the right, the next on the left, and the third beveled on both sides, each leaving slightly overlapping flats on the periphery of the teeth. The most common high-speed steels for circular saws are M2 and M7; some saws have inserted carbide teeth.

ABRASIVE PROCESSES
(See also Sec. 6)

Abrasive processes consist of a variety of operations in which the tool is made of an abrasive material, the most common examples of which are grinding (using wheels, known as **bonded abrasives**), honing, and lapping. An abrasive is a small, nonmetallic hard particle having sharp cutting edges and an irregular shape. Abrasive processes, which can be performed on a wide variety of metallic and nonmetallic materials, remove material in the form of tiny chips and produce surface finishes

51 — A — 36 — L — 5 — V — 23

Prefix	Abrasive type	Grain size				Grade			Structure		Bond type	Manufacturer's record
		Coarse	Medium	Fine	Very fine	Soft	Medium	Hard	Dense to Open			
Manufacturer's symbol indicating exact kind of abrasive (use optional)	A – Aluminum oxide	10	36	70	220	A E	I M	Q V	1	9	V –Vitrified	Manufacturer's private marking to identify wheel (use optional)
		12	46	80	240				2	10	S –Silicate	
		14	54	90	280	B F	J N	R W	3	11	B –Resinoid	
		16	60	100	320				4	12	BF–Resinoid reinforced	
		20		120	400	C G	K O	S X	5	13	R –Rubber	
	C – Silicon carbide	24		150	500	D H	L P	T Y	6	14	RF–Rubber reinforced	
				180	600			U Z	7	15	E –Shellac	
									8	etc.	O –Oxychloride	
									(use optional)			

Fig. 13.4.16   Standard marking system chart for aluminum oxide and silicon carbide bonded abrasives.

and dimensional accuracies that are generally not obtainable through other machining or manufacturing processes.

Grinding wheels have characteristics influenced by (1) type of abrasive; (2) grain size; (3) grade; (4) structure; and (5) type of bond. (See Figs. 13.4.16 and 13.4.17.)

Selection of Abrasive   Although a number of natural abrasives are available, such as emery, corundum, quartz, garnet, and diamond, the most commonly used abrasives in grinding wheels are **aluminum oxide** and **silicon carbide,** the former being more commonly used than the latter. Aluminum oxide is softer than silicon carbide, and because of its friability and low attritious wear it is suitable for most applications. Silicon carbide is used for grinding aluminum, magnesium, titanium, copper, tungsten, and rubber. It is also used for grinding very hard and brittle materials such as carbides, ceramics, and stones. **Diamond** and **cubic boron nitride** grains are used to grind very hard materials and are known as **superabrasives**.

Selection of **grain size** depends on the rate of material removal desired and the surface finish. Coarse grains are used for fast removal of stock;

fine grain for low removal rates and for fine finish. Coarse grains are also used for ductile materials and a finer grain for hard and brittle materials.

The **grade** of a grinding wheel is a measure of the strength of its bond. The force that acts on the grain in grinding depends on process variables (such as speeds, depth of cut, etc.) and the strength of the work material. Thus a greater force on the grain will increase the possibility of dislodging the grain; if the bond is too strong, the grain will tend to get dull, and if it is too weak then wheel wear will be high. If glazing occurs, the wheel is **acting hard;** reducing the wheel speed or increasing the work speed or the depth of cut causes the wheel to **act softer**. If the wheel breaks down too rapidly, reversing this procedure will make the wheel act harder. Harder wheels are generally recommended for soft work materials, and vice versa.

A variety of **bond** types are used in grinding wheels; these are generally categorized as **organic** and **inorganic**. Organic bonds are materials such as resin, rubber, shellac, and other similar bonding agents. Inorganic materials are glass, clay, porcelain. sodium silicate, magnesium

M   D   100–P   100–B   1/8

| | | Sequence 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | | | | | | | Diamond depth (in) |
Prefix	Abrasive type	Grit size	Grade	Diamond concentration	Bond	Bond modification	
	B Cubic boron nitride	20 24 30 36	A – Soft	25 (Low)			1/16
		46 54	To	50	B – Resinoid M – Metal		1/8
	D Diamond	60 80 90 100	Z – Hard	75 100 (High)	V – Vitrified		1/4
		120 150 180 220 240 280					Absence of depth symbol indicates solid diamond.
Manufacturer's symbol to indicate type of diamond.		320 400 500 600 800 1000				A letter or numeral or combination used here will indicate a variation from standard bond.	

Fig. 13.4.17   Standard marking system chart for diamond tool and cubic boron nitride (CBN) bonded abrasives.

oxychloride, and metal. The most common bond type is the vitrified bond which is composed of clay, glass, porcelain, or related ceramic materials. This type of bond is brittle and produces wheels that are rigid, porous, and resistant to oil and water. The most flexible bond is rubber which is used in making very thin, flexible wheels. Wheels subjected to bending strains should be made with organic bonds. In selecting a bonding agent, attention should be paid to its sensitivity to temperature, stresses, and grinding fluids, particularly over a period of time. The term **reinforced** as applied to grinding wheels indicates a class of organic wheels which contain one or more layers of strengthening fabric or filament, such as fiberglass. This term does not cover wheels with reinforcing elements such as steel rings, steel cup backs, or wire or tape winding. Fiberglass and filament reinforcing increases the ability of wheels to withstand operational forces when cracked.

The **structure** of a wheel is important in two aspects: It supplies a clearance for the chip, and it determines the number of cutting points on the wheel.

In addition to wheel characteristics, grinding wheels come in a very large variety of shapes and dimensions. They are classified as **types**, such as type 1-straight wheels, type 4-taper side wheels, type 12-dish wheels, etc.

The **grinding ratio** is defined as the ratio of the volume of material removed to the volume of wheel wear. The grinding ratio depends on parameters such as the type of wheel, workpiece speed, wheel speed, cross-feed, down-feed, and the grinding fluid used. Values ranging from a low of 2 to over 200 have been observed in practice. A high grinding ratio, however, may not necessarily result in the best surface integrity of the part.

Wheel Speeds Depending on the type of wheel and the type and strength of bond, wheel speeds for standard applications range between 4,500 and 16,000 surface ft/min (1,400 and 4,800 m/min). The lowest speeds are for low-strength, inorganic bonds whereas the highest speeds are for high-strength organic bonds. The majority of surface grinding operations are carried out at speeds from 5,500 to 6,500 ft/min (1,750 to 2,000 m/min). A recent trend is toward high-efficiency grinding where wheel speeds from 12,000 to 18,000 ft/min (3,600 to 5,500 m/min) are employed.

It has been found that, by increasing the wheel speed, the rate of material removal can be increased, thus making the process more economical. This, of course, requires special grinding wheels to withstand the high stresses. Design changes or improvements involve items such as a composite wheel with a vitrified bond on the outside and a resinoid bond toward the center of the wheel; elimination of the central hole of the wheel by providing small bolt holes; and clamping of wheel segments instead of using a one-piece wheel. Grinding machines for such high-speed applications have requirements such as rigidity, high work and wheel speeds, high power, and special provisions for safety.

Workpiece speeds depend on the size and type of workpiece material and on whether it is rigid enough to hold its shape. In surface grinding, table speeds generally range from 50 to 100 ft/min (15 to 30 m/min); for cylindrical grinding, work speeds from 70 to 100 ft/min (20 to 30 m/min), and for internal grinding they generally range from 75 to 200 ft/min (20 to 60 m/min).

Cross-feed depends on the width of the wheel. In roughing, the workpiece should travel past the wheel ¾ to ⅞ of the width of the wheel for each revolution of the work. As the workpiece travels past the wheel with a helical motion, the preceding rule allows a slight overlap. In finishing, a finer feed is used, generally ¹⁄₁₀ to ¼ of the width of the wheel for each revolution of the workpiece.

Depth of Cut In the roughing operation, the depth of cut should be all the wheel will stand. This varies with the hardness of the material and the diameter of the workpiece. In the finishing operation, the depth of cut is always small: 0.0005 to 0.001 in (0.013 to 0.025 mm). Good results as regards finish are obtained by letting the wheel run over the workpiece several times without cross-feeding.

Grinding Allowances From 0.005 to 0.040 in (0.13 to 1 mm) is generally removed from the diameter in rough grinding in a cylindrical machine. For finishing, 0.002 to 0.010 in (0.05 to 0.25 mm) is common.

Workpieces can be finished by grinding to a tolerance of 0.0002 in (0.005 mm) and a surface roughness of $50+ \mu$in R_q (1.2 μm).

In situations where grinding leaves unfavorable surface **residual stresses,** the technique of **gentle** or **low-stress** grinding may be employed. This generally consists of removing a layer of about 0.010 in (0.25 mm) at depths of cut of 0.0002 to 0.0005 in (0.005 to 0.013 mm) with wheel speeds that are lower than the conventional 5,500 to 6,500 ft/min.

Truing and Dressing In **truing,** a diamond supported in the end of a soft steel rod held rigidly in the machine is passed over the face of the wheel two or three times to remove just enough material to give the wheel its true geometric shape. **Dressing** is a more severe operation of removing the dull or loaded surface of the wheel. Abrasive sticks or wheels or steel star wheels are pressed against and moved over the wheel face.

Safety If not stored, handled, and used properly, a grinding wheel can be a very dangerous tool. Because of its mass and high rotational speed, a grinding wheel has considerable energy and, if it fractures, it can cause serious injury and even death to the operator or to personnel nearby. A safety code B7.1 entitled ''The Use, Care, and Protection of Abrasive Wheels'' is available from ANSI; other safety literature is available from the Grinding Wheel Institute and from the National Safety Council.

The salient features of safety in the use of grinding wheels may be listed as follows: Wheels should be stored and handled carefully; a wheel that has been dropped should not be used. Before it is mounted on the machine, a wheel should be visually inspected for possible cracks; a simple ''ring'' test may be employed whereby the wheel is tapped gently with a light nonmetallic implement and if it sounds cracked, it should not be used. The wheel should be mounted properly with the required blotters and flanges, and the mounting nut tightened not excessively. The label on the wheel should be read carefully for maximum operating speed and other instructions. An appropriate guard should always be used with the machine, whether portable or stationary.

Newly mounted wheels should be allowed to run idle at the operating speed for at least 1 min before grinding. The operator should always wear safety glasses and should not stand directly in front of a grinding wheel when a grinder is started. If a grinding fluid is used, it should be turned off first before stopping the wheel to avoid creating an out-of-balance condition. Because for each type of operation and workpiece material there usually is a specific type of wheel recommended, the operator must make sure that the appropriate wheel has been selected.

Finishing Operations

Polishing is an operation by which scratches or tool marks or, in some instances, rough surfaces left after forging, rolling, or similar operations are removed. It is not a precision operation. The nature of the polishing process has been debated for a long time. Two mechanisms appear to play a role: One is fine-scale abrasion, and the other is softening of surface layers. In addition to removal of material by the abrasive particles, the high temperatures generated because of friction soften the asperities of the surface of the workpiece, resulting in a smeared surface layer. Furthermore, chemical reactions may also take place in polishing whereby surface irregularities are removed by chemical attack.

Polishing is usually done in stages. The first stage is rough polishing, using abrasive grain sizes of about 36 to 80, followed by a second stage, using an abrasive size range of 80 to 120, a third stage of size 150 and finer, etc., with a final stage of buffing. For the first two steps the polishing wheels are used dry. For finishing, the wheels are first worn down a little and then coated with tallow, oil, beeswax, or similar substances. This step is partly polishing and partly buffing, as additional abrasive is often added in cake form with the grease. The cutting action is freer, and the life of the wheel is prolonged by making the wheel surface flexible. Buffing wheels are also used for the finishing step when tallow, etc., containing coarse or fine abrasive grains is periodically rubbed against the wheel.

Polishing wheels consisting of wooden disks faced with leather, turned to fit the form of the piece to be polished, are used for flat surfaces or on work where it is necessary to maintain square edges. A large variety of

other types of wheels are in common use. Compress wheels are used extensively and are strong, durable, and easily kept in balance. They consist of a steel center the rim of which holds a laminated surface of leather, canvas, linen, felt, rubber, etc., of various degrees of pliability. Wheels of solid leather disks of walrus hide, buffalo hide, sheepskin, or bull's neck hide, or of soft materials such as felt, canvas, and muslin, built up of disks either loose, stitched, or glued, depending on the resiliency or pliability required, are used extensively for polishing as well as buffing. **Belts** of cloth or leather are often charged with abrasive for polishing flat or other workpieces. Wire brushes may be used with no abrasive for a final operation to give a satin finish to nonferrous metals.

For most polishing operations speeds range from 5,000 to 7,500 surface ft/min (1,500 to 2,250 m/min). The higher range is for high-strength steels and stainless steels. Excessively high speeds may cause burning of the workpiece and glazing.

Buffing is a form of finish polishing in which the surface finish is improved; very little material is removed. The powdered abrasives are applied to the surface of the wheel by pressing a mixture of abrasive and tallow or wax against the face for a few seconds. The abrasive is replenished periodically. The wheels are made of a soft pliable material, such as soft leather, felt, linen, or muslin, and rotated at high speed.

Buffing generally comprises two stages: **cutting down** and **coloring**. Cutting down makes a surface smoother by removing scratches and other marks from previous operations. Coloring further refines the surface and brings out maximum luster. A variety of buffing compounds are available: Tripoli (an amorphous silica), aluminum oxide, chromium oxide, soft silica, rouge (iron oxide), pumice, lime compounds, emery, and crocus. In cutting down nonferrous metals, Tripoli is used; and for steels and stainless steels, aluminum oxide is the common abrasive. For coloring, soft silica, rouge, and chromium oxide are the more common compounds used. Buffing speeds range from 6,000 to 10,000 surface ft/min (1,800 to 3,000 m/min); the higher speeds are for steels, although the speed may be as high at 12,000 surface ft/min (3,600 m/min) for coloring brass and copper.

Lapping is a process of producing extremely smooth and accurate surfaces by rubbing the surface which is to be lapped against a mating form which is called a **lap**. The lap may either be charged with a fine abrasive and moistened with oil or grease, or the fine abrasive may be introduced with the oil. If a part is to be lapped to a final accurate dimension, a mating form of a softer material such as soft close-grained cast iron, copper, brass, or lead is made up. Aluminum oxide, silicon carbide, and diamond grits are used for lapping. Lapping requires considerable time. No more than 0.0002 to 0.0005 in (0.005 to 0.013 mm) should be left for removal by this method. Surface plates, rings, and plugs are common forms of laps. For most applications grit sizes range between 100 and 800, depending on the finish desired. For most efficient lapping, speeds generally range from 300 to 800 surface ft/min (150 to 240 m/min) with pressures of 1 to 3 lb/in^2 (7 to 21 kPa) for soft materials and up to 10 lb/in^2 (70 kPa) for harder materials.

Honing is an operation similar to lapping. Instead of a metal lap charged with fine abrasive grains, a honing stone made of fine abrasives is used. Small stones of various cross-sectional shapes and lengths are manufactured for honing the edges of cutting tools. Automobile cylinders are honed for fine finish and accurate dimensions. This honing usually follows a light-finish reaming operation or a precision-boring operation using diamonds or carbide tools. The tool consists of several honing stones adjustable at a given radius or forced outward by springs or a wedge forced mechanically or hydraulically and is given a reciprocating (25 to 40 per min) and a rotating motion (about 300 r/min) in the cylinder which is flooded with kerosine.

Hones operate at speeds of 50 to 200 surface ft/min (15 to 60 m/min) and use universal joints to allow the tool to center itself in the workpiece. The automatic pressure-cycle control of hone expansion, in which the pressure is reduced in steps as the final finish is reached, removes metal 10 times as fast as with the spring-expanded hone. Rotational and reciprocating movements are provided to give an uneven ratio and thus prevent an abrasive grain from ever traversing its own path twice.

Superfinishing is a honing process. Formed honing stones bear against the workpiece previously finished to 0.0005 in (0.013 mm) or at the most to 0.001 in (0.025 mm) by a very light pressure which gradually increases to several pounds per square inch (1 lb/in^2 = 0.0069 MPa) of stone area in proportion to the development of the increased area of contact between the workpiece and stone. The workpiece or tool rotates and where possible is reciprocated slowly over the surface which may be finished in a matter of 20 s to a surface quality of 1 to 3 μin (0.025 to 0.075 μm). Superfinishing is applied to many types of workpieces such as crankshaft pins and bearings, cylinder bores, pistons, valve stems, cams, and other metallic moving parts.

Sand blasting consists of particles of sand, powdered quartz, chilled-iron shot, emery, or other hard granular material blown by a jet of compressed air or of steam against a hard surface which it is desired to abrade. It is commonly used for cleaning metal castings, frosting smooth surfaces, etc. Portions of the surface which are not to be abraded can be protected by coating with a soft material such as wax, lead, or rubber.

Grinders

Grinding machines may be classified as to purpose and type as follows: for **rough removal of stock,** the swinging-frame, portable, flexible shaft, two-wheel stand, and disk; **cutting off** or parting, the cutting-off machine; **surface finishing,** band polisher, two-wheel combination, two-wheel polishing machine, two-wheel buffing machine, and semiautomatic polishing and buffing machine; **precision grinding,** tool post, cylindrical (plain and universal), crankshaft, centerless, internal, and surface (reciprocating table with horizontal or vertical wheel spindle, and rotary table with horizontal or vertical wheel spindle); **special form** grinders, gear or worm, ball-bearing balls, cams, and threads; and **tool and cutter** grinders for single-point tools, drills, and milling cutters, reamers, taps, dies, knives, etc.

Grinding equipment of all types (many with computer controls) has been improved during the past few years so as to be more rigid, provide more power to the grinding wheel, and provide automatic cycling, loading, clamping, wheel dressing, and automatic feedback.

Centerless grinders are used to good advantage where large numbers of relatively small pieces must be ground and where the ground surface has no exact relation to any other surface except as a whole; the work is carried on a support between two abrasive wheels, one a normal grinding wheel, the second a rubber-bonded wheel, rotating at about ½₀th the grinding speed, and is tilted 3 to 8° to cause the work to rotate and feed past the grinding wheel (see also Sec. 6).

Cylinder grinders are a special type for grinding the inside of cylinders of engines; one form has a planetary motion for the grinding spindle. The **cylindrical grinder** is a companion machine to the engine lathe; shafts, cylinders, rods, studs, and a wide variety of other cylindrical parts are first roughed out on the lathe, then finished accurately to size by the cylindrical grinder. The work is carried on centers, rotated slowly, and traversed past the face of a grinding wheel.

Universal grinders are cylindrical machines arranged with a swiveling table so that both straight and taper internal and external work can be ground. **Drill grinders** are provided with rests so mounted that by a simple swinging motion, correct cutting angles are produced automatically on the lips of drills; a cupped wheel is usually employed. **Internal grinders** are used for finishing the holes in bushings, rolls, sleeves, cutters, and the like; spindle speeds from 15,000 to 30,000 r/min are common.

Horizontal surface grinders range from small capacity, used mainly in tool making or small production work, to large sizes used for production work.

Vertical surface grinders are used for producing flat surfaces on production work. **Vertical** and **horizontal disk grinders** are used for surfacing. Grinding machines are used for **cutting off** steel, especially tubes, structural shapes, and hard metals. A thin resinoid or rubber-bonded wheel is used, with aluminum oxide abrasive for all types of steel, aluminum, brass, bronze, nickel, Monel, and Stellite; silicon carbide for cast iron, copper, carbon, glass, stone, plastics, and other nonmetallic materials; and diamond for cemented carbides and ceramics.

Belt grinders use a coated abrasive belt running between pulleys. Belt grinding is generally considered to be a roughing process, but finer finishes may be obtained by using finer grain size. Belt speeds generally range from 2,000 to 10,000 ft/min (600 to 3,000 m/min) with grain sizes ranging between 24 and 320, depending on the workpiece material and the surface finish desired. The process has the advantage of high-speed material removal and is applied to flat as well as irregular surfaces.

Although grinding is generally regarded as a finishing operation, it is possible to increase the rate of stock removal whereby the process becomes, in certain instances, competitive with milling. This type of grinding operation is usually called **creep-feed grinding**. It uses equipment such as reciprocating table or vertical-spindle rotary table surface grinders with capacities up to 300 hp (220 kW). The normal stock removal may range up to ¼ in (6.4 mm) with wheel speeds between 3,400 and 5,000 surface ft/min (1,000 and 1,500 m/min).

A good ground surface with **surface roughness** of 50 to 200 μin (1 to 5 μm) is sufficient for many purposes and is a basic requirement for further finishing operations, such as lapping, honing, and superfinishing. The size and depth of the scratches can be varied considerably by the selection of the wheel.

MACHINING AND GRINDING OF PLASTICS

The low strength of thermoplastics permits high cutting speeds and feeds, but the low heat conductivity and greater resilience require increased reliefs and less rake in order to avoid undersize cutting. Hard and sharp tools should be used. Plastics are usually abrasive and cause the tools to wear or become dull rapidly. Dull tools generate heat and cause the tools to cut to shallow depths. The depth of cut should be small. When high production justifies the cost, diamond turning and boring tools are used. Diamond tools maintain sharp cutting edges and produce an excellent machined surface. They are particularly advantageous when a more abrasive plastic such as reinforced plastic is machined.

A cutting fluid, such as a small blast of air, a stream of water, or a cutting fluid, improves the **turning** and cutting of plastics as it prevents the heating of the tool and causes the chips to remain brittle and to break rather than become sticky and gummy. A zero or slightly negative back rake and a relief angle of 8 to 12° should be used. For thermoplastics cutting speeds generally range from 250 to 400 ft/min (75 to 120 m/min) and for thermosetting plastics from 400 to 1,000 ft/min (120 to 300 m/min). Recommended tool materials are M2 and T5 high-speed steels and C-2 carbide.

In **milling** plastics, speeds of 400 to 1,000 ft/min (120 to 300 m/min) should be used, with angles similar to those on a single-point tool. From 0 to 10° negative rake may be used. Good results have been obtained by hobbing plastic gears with carbide-tipped hobs. Recommended tool materials are M2 and M7 high-speed steels and C-2 carbide.

In **drilling,** speeds range from 150 to 400 ft/min (45 to 120 m/min), and the recommended drill geometry is given in Table 13.4.6. Tool materials are M1, M7, and M10 high-speed steel. Usually the drill cuts undersize; drills 0.002 to 0.003 in (0.05 to 0.075 mm) oversize should be used.

In **sawing** plastics, either precision or buttress tooth forms may be used, with a pitch ranging from 3 to 14 teeth/in (1.2 to 5.5 teeth/cm), the thicker the material the lower the number of teeth per unit length of saw. Cutting speeds for thermoplastics range from 1,000 to 4,000 ft/min (300 to 1,200 m/min) and for thermosetting plastics from about 3,000 to 5,500 ft/min (900 to 1,700 m/min), with the higher speeds for thinner stock. High-carbon-steel blades are recommended. An air blast is helpful in preventing the chips from sticking to the saw. Abrasive saws operating at 3,500 to 6,000 ft/min (1,000 to 1,800 m/min) are also used for cutting off bars and forms.

Plastics are tapped and threaded with standard tools. Ground M1, M7, or M10 high-speed steel **taps** with large polished flutes are recommended. **Tapping speeds** are usually from 25 to 50 ft/min (8 to 15 m/min); water serves as a good cutting fluid as it keeps the material brittle and prevents sticking in the flutes. **Thread cutting** is generally accomplished with tools similar to those used on brass.

Reaming is best accomplished in production by using tools of the expansion or adjustable type with relatively low speeds but high feeds. Less material should be removed in reaming plastics than in reaming other materials.

Polishing and **buffing** are done on many types of plastics. Polishing is done with special compounds containing wax or a fine abrasive. Buffing wheels for plastics should have loose stitching. Vinyl plastics can be buffed and polished with fabric wheels of standard types, using light pressures.

Thermoplastics and thermosets can be **ground** with relative ease, usually by using silicon carbide wheels. As in machining, temperature rise should be minimized.

MACHINING AND GRINDING OF CERAMICS

The technology of machining and grinding of ceramics, as well as composite materials, has advanced rapidly, resulting in good surface characteristics and product integrity. Ceramics can be machined with carbide, high-speed steel, or diamond tools, although care should be exercised because of the brittle nature of ceramics and the resulting possible surface damage. **Machinable ceramics** have been developed which minimize machining problems. Grinding of ceramics is usually done with diamond wheels.

OTHER MATERIAL REMOVAL PROCESSES

In addition to the mechanical methods of material removal described above, there are a number of other important processes which may be preferred over conventional methods. Among the important factors to be considered are the hardness of the workpiece material, the shape of the part, its sensitivity to thermal damage, residual stresses, tolerances, and economics. Some of these processes produce a heat-affected layer on the surface; improvements in surface integrity may be obtained by postprocessing techniques such as polishing or peening. Almost all machines are now computer-controlled.

Electric-discharge machining (EDM) is based on the principle of erosion of metals by spark discharges. Figure 13.4.18 gives a schematic diagram of this process. The spark is a transient electric discharge through the space between two charged electrodes, which are the tool and the workpiece. The discharge occurs when the potential difference between the tool and the workpiece is large enough to cause a breakdown in the medium (which is called the **dielectric fluid** and is usually a hydrocarbon) and to procure an electrically conductive spark channel. The breakdown potential is usually established by connecting the electrodes to the terminals of a capacitor charged from a power source. The spacing between the tool and workpiece is critical; therefore, the feed is controlled by servomechanisms. The dielectric fluid has the additional functions of providing a cooling medium and carrying away particles produced by the electric discharge. The discharge is repeated rapidly, and each time a minute amount of workpiece material is removed.

The rate of metal removal depends mostly on the average current in the discharge circuit; it is also a function of the electrode characteristics, the electrical parameters, and the nature of the dielectric fluid. In practice, this rate is normally varied by changing the number of discharges per second or the energy per discharge. Rates of metal removal may range from 0.01 to 25 in³/h (0.17 to 410 cm³/h), depending on surface
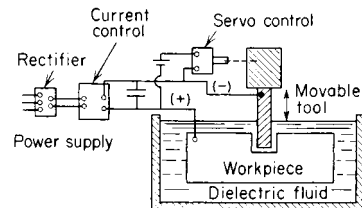

Fig. 13.4.18   Schematic diagram of the electric-discharge machining process.

finish and tolerance requirements. In general, higher rates produce rougher surfaces. Surface finishes may range from 1,000 μin R_q (25 μm) in roughing cuts to less than 25 μin (0.6 μm) in finishing cuts.

The response of materials to this process depends mostly on their thermal properties. Thermal capacity and conductivity, latent heats of melting and vaporization are important. Hardness and strength do not necessarily have significant effect on metal removal rates. The process is applicable to all materials which are sufficiently good conductors of electricity. The tool has great influence on permissible removal rates. It is usually made of graphite, copper-tungsten, or copper alloys. Tools have been made by casting, extruding, machining, powder metallurgy, and other techniques and are made in any desired shape. Tool wear is an important consideration, and in order to control tolerances and minimize cost, the ratio of tool material removed to workpiece material removed should be low. This ratio varies with different tool and workpiece material combinations and with operating conditions. Therefore, a particular tool material may not be best for all workpieces. Tolerances as low as 0.0001 to 0.0005 in (0.0025 to 0.0127 mm) can be held with slow metal removal rates. In machining some steels, tool wear can be minimized by reversing the polarity and using copper tools. This is known as ''no-wear EDM.''

The electric-discharge machining process has numerous applications, such as machining cavities and dies, cutting small-diameter holes, blanking parts from sheets, cutting off rods of materials with poor machinability, and flat or form grinding. It is also applied to sharpening tools, cutters, and broaches. The process can be used to generate almost any geometry if a suitable tool can be fabricated and brought into close proximity to the workpiece.

Thick plates may be cut with **wire EDM**. A slowly moving wire travels a prescribed path along the workpiece and cuts the metal with the sparks acting like saw teeth. The wire, usually about 0.01 in (0.25 mm) in diameter, is made of brass, copper, or tungsten and is generally used only once. The process is also used in making tools and dies from hard materials, provided that they are electrically conducting.

Electric-discharge grinding (EDG) is similar to the electric-discharge machining process with the exception that the electrode is in the form of a grinding wheel. Removal rates are up to 1.5 in^3/h (25 cm^3/h) with practical tolerances on the order of 0.001 in (0.025 mm). A graphite or brass electrode wheel is operated around 100 to 600 surface ft/min (30 to 180 m/min) to minimize splashing of the dielectric fluid. Typical applications of this process are in grinding of carbide tools and dies, thin slots in hard materials, and production grinding of intricate forms.

The **electrochemical machining (ECM)** process (Fig. 13.4.19) uses electrolytes which dissolve the reaction products formed on the workpiece by electrochemical action; it is similar to a reverse electroplating process. The electrolyte is pumped at high velocities through the tool. A gap of 0.005 to 0.020 in (0.13 to 0.5 mm) is maintained. A dc power supply maintains very high current densities between the tool and the workpiece. In most applications, a current density of 1,000 to 5,000 A is required per in^2 of active cutting area. The rate of metal removal is proportional to the amount of current passing between the tool and the workpiece. Removal rates up to 1 in^3/min (16 cm^3/min) can be obtained
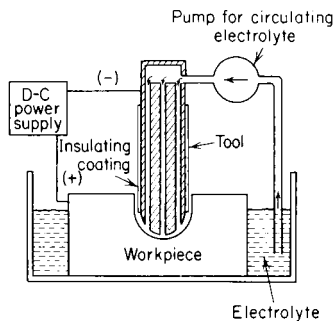

Fig. 13.4.19 Schematic diagram of the electrochemical machining process.

with a 10,000-A power supply. The penetration rate is proportional to the current density for a given workpiece material.

The process leaves a burr-free surface. It is also a cold machining process and does no thermal damage to the surface of the workpiece. Electrodes are normally made of brass or copper; stainless steel, titanium, sintered copper-tungsten, aluminum, and graphite have also been used. The electrolyte is usually a sodium chloride solution up to 2.5 lb/gal (300 g/L); other solutions and proprietary mixtures are also available. The amount of overcut, defined as the difference between hole diameter and tool diameter, depends upon cutting conditions. For production applications, the average overcut is around 0.015 in (0.4 mm). The rate of penetration is up to 0.750 in/min (20 mm/min).

Very good surface finishes may be obtained with this process. However, sharp square corners or sharp corners and flat bottoms cannot be machined to high accuracies. The process is applied mainly to round or odd-shaped holes with straight parallel sides. It is also applied to cases where conventional methods produce burrs which are costly to remove. The process is particularly economical for materials with a hardness above 400 HB.

The **electrochemical grinding (ECG)** process (Fig. 13.4.20) is a combination of electrochemical machining and abrasive cutting where most of the metal removal results from the electrolytic action. The process consists of a rotating cathode, a neutral electrolyte, and abrasive particles in contact with the workpiece. The equipment is similar to a conventional grinding machine except for the electrical accessories. The cath-
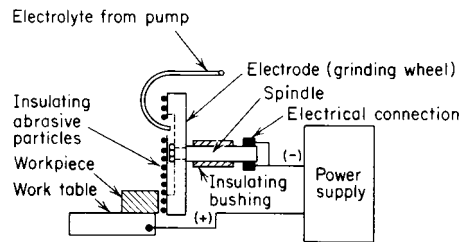

Fig. 13.4.20 Schematic diagram of the electrochemical grinding process.

ode usually consists of a metal-bonded diamond or aluminum oxide wheel. An important function of the abrasive grains is to maintain a space for the electrolyte between the wheel and workpiece.

Surface finish, precision, and metal-removal rate are influenced by the composition of the electrolyte. Aqueous solutions of sodium silicate, borax, sodium nitrate, and sodium nitrite are commonly used as electrolytes. The process is primarily used for tool and cutter sharpening and for machining of high-strength materials.

A combination of the electric-discharge and electrochemical methods of material removal is known as **electrochemical discharge grinding (ECDG)**. The electrode is a pure graphite rotating wheel which electrochemically grinds the workpiece. The intermittent spark discharges remove oxide films that form as a result of electrolytic action. The equipment is similar to that for electrochemical grinding. Typical applications include machining of fragile parts and resharpening or form grinding of carbides and tools such as milling cutters.

In **chemical machining (CM)** material is removed by chemical or electrochemical dissolution of preferentially exposed surfaces of the workpiece. Selective attack on different areas is controlled by masking or by partial immersion. There are two processes involved: chemical **milling** and chemical **blanking**. Milling applications produce shallow cavities for overall weight reduction, and are also used to make tapered sheets, plates, or extrusions. Masking with paint or tapes is common. Masking materials may be elastomers (such as butyl rubber, neoprene, and styrene-butadiene) or plastics (such as polyvinyl chloride, polystyrene, and polyethylene). Typical blanking applications are decorative panels, printed-circuit etching, and thin stampings. Etchants are solutions of sodium hydroxide for aluminum, and solutions of hydrochloric and nitric acids for steel.

Ultrasonic machining (USM) is a process in which a tool is given a high-frequency, low-amplitude oscillation, which, in turn, transmits a high velocity to fine abrasive particles that are present between the tool and the workpiece. Minute particles of the workpiece are chipped away on each stroke. Aluminum oxide, boron carbide, or silicone carbide grains are used in a water slurry (usually 50 percent by volume), which also carries away the debris. Grain size ranges from 200 to 1,000 (see Sec. 6 and Figs. 13.4.16 and 13.4.17).

The equipment consists of an electronic oscillator, a transducer (Fig. 13.4.21), a connecting cone or toolholder, and the tool. The oscillatory motion is obtained most conveniently by magnetostriction, at approximately 20,000 Hz and a stroke of 0.002 to 0.005 in (0.05 to 0.13 mm). The tool material is normally cold-rolled steel or stainless steel and is brazed, soldered, or fastened mechanically to the transducer through a
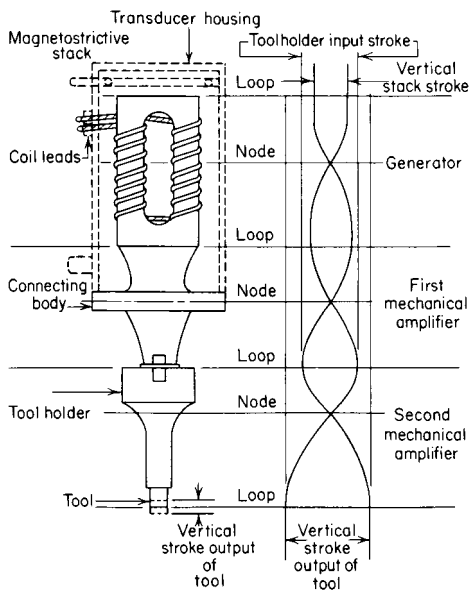

Fig. 13.4.21   Schematic diagram of a transducer used in the ultrasonic machining (USM) process.

toolholder. The tool is ordinarily 0.003 to 0.004 in (0.075 to 0.1 mm) smaller than the cavity it produces. Tolerances of 0.0005 in (0.013 mm) or better can be obtained with fine abrasives. For best results, roughing cuts should be followed with one or more finishing operations with finer grits. The ultrasonic machining process is used in drilling holes, engraving, cavity sinking, slicing, broaching, etc. It is best suited to materials which are hard and brittle, such as ceramics, carbides, borides, ferrites, glass, precious stones, and hardened steels.

In **abrasive-jet machining (AJM),** material is removed by fine abrasive particles (aluminum oxide or silicon carbide) carried in a high-velocity stream of air, nitrogen, or carbon dioxide. The gas pressure ranges up to 120 lb/in^2 (800 kPa), providing a nozzle velocity of up to 1,000 ft/s (300 m/s). Nozzles are made of tungsten carbide or sapphire. Typical applications are in drilling, sawing, slotting, and deburring of hard, brittle materials such as glass.

In **water jet machining (WJM),** water is ejected from a nozzle at pressures as high as 200,000 lb/in^2 (1,400 MPa) and acts as a saw. The process is suitable for cutting and deburring of a variety of materials such as polymers, paper, and brick in thicknesses ranging from 0.03 to 1 in (0.8 to 25 mm) or more. The cut can be started at any location, wetting is minimal, and no deformation of the rest of the piece takes place. Abrasives can be added to the water stream to increase material removal rate, and this is known as **abrasive water jet machining (AWJM).**

In **laser-beam machining (LBM),** material is removed by converting electric energy into a narrow beam of light and focusing it on the workpiece. The high energy density of the beam is capable of melting and vaporizing all materials, and consequently, there is a thin heat-affected zone. The most commonly used laser types are CO_2 (pulsed or continuous-wave) and Nd : YAG. Typical applications include cutting a variety of metallic and nonmetallic materials, drilling (as small as 0.0002 in or 0.005 mm in diameter), and marking. The efficiency of cutting increases with decreasing thermal conductivity and reflectivity of the material. Because of the inherent flexibility of the process, programmable and computer-controlled laser cutting is now becoming important, particularly in cutting profiles and multiple holes of various shapes and sizes on large sheets. Cutting speeds may range up to 25 ft/min (7.5 m/min).

The **electron-beam machining (EBM)** process removes material by focusing high-velocity electrons on the workpiece. Unlike lasers, this process is carried out in a vacuum chamber and is used for drilling small holes in all materials including ceramics, scribing, and cutting slots.

13.5   SURFACE TEXTURE DESIGNATION, PRODUCTION, AND CONTROL
by Thomas W. Wolff

Rapid changes in the complexity and precision requirements of mechanical products since 1945 have created a need for improved methods of determining, designating, producing, and controlling the surface texture of manufactured parts. Although standards are aimed at standardizing methods for measuring by using stylus probes and electronic transducers for surface quality control, other descriptive specifications are sometimes required, i.e., interferometric light bands, peak-to-valley by optical sectioning, light reflectance by commercial glossmeters, etc. Other parameters are used by highly industrialized foreign countries to solve their surface specification problems. These include the high-spot counter and bearing area meter of England (Talysurf); the total peak-to-

valley, or R_1, of Germany (Perthen); and the R or average amplitude of surface deviations of France. In the United States, peak counting is used in the sheet-steel industry, instrumentation is available (Bendix), and a standard for specification, SAE J-911, exists.

Surface texture control should be considered for many reasons, among them being the following:

1. Advancements in the technology of metal-cutting tools and machinery have made the production of higher-quality surfaces possible.

2. Products are now being designed that depend upon proper quality control of critical surfaces for their successful operation as well as for long, troublefree performance in service.

3. Artisans who knew the function and finish requirements for all the parts they made have been replaced, in most cases, by machine operators who are not qualified to determine the proper texture requirements for critical surfaces. The latter must depend, instead, on drawing specifications.

4. Remote manufacture and the necessity for controlling costs have made it preferable that finish requirements for all the critical surfaces of a part be specified on the drawing.

5. The design engineer, who best understands the overall function of a part and all its surfaces, should be able to determine the requirement for surface texture control where applicable and to use a satisfactory standardized method for providing this information on the drawing for use by manufacturing departments.

6. Manufacturing personnel should know what processes are able to produce surfaces within specifications and should be able to verify that the production techniques in use are under control.

7. Quality control personnel should be able to check conformance to surface texture specifications if product quality is to be maintained and product performance and reputation ensured.

8. Too much control may be worse than too little; hence, overuse of available techniques may hinder rather than assist, there being no payoff in producing surfaces that are more expensive than required to ensure product performance to establish standards.

DESIGN CRITERIA

Surfaces produced by various processes exhibit distinct differences in texture. These differences make it possible for honed, lapped, polished, turned, milled, or ground surfaces to be easily identified. As a result of its unique character, the surface texture produced by any given process can be readily compared with other surfaces produced by the same process through the simple means of comparing the average size of its irregularities, using applicable standards and modern measurement methods. It is then possible to predict and control its performance with considerable certainty by limiting the range of the average size of its characteristic surface irregularities. Surface texture standards make this control possible.

Variations in the texture of a critical surface of a part influence its ability to resist wear and fatigue; to assist or destroy effective lubrication; to increase or decrease its friction and/or abrasive action on other parts, and to resist corrosion, as well as affect many other properties that may be critical under certain conditions.

Clay has shown that the load-carrying capacity of nitrided shafts of varying degrees of roughness, all running at 1,500 r/min in diamond-turned lead-bronze bushings finished to 20 μin (0.50 μm), varies as shown in Fig. 13.5.1. The effects of roughness values on the friction between a flat slider on a well-lubricated rotating disk are shown in Fig. 13.5.2.

Surface texture control should be a normal design consideration under the following conditions:

1. For those parts whose roughness must be held within closely controlled limits for optimum performance. In such cases, even the process may have to be specified. Automobile engine cylinder walls, which should be finished to about 13 μin (0.32 μm) and have a circumferential (ground) or an angular (honed) lay, are an example. If too rough, excessive wear occurs, if too smooth, piston rings will not seat properly, lubrication is poor, and surfaces will seize or gall.

2. Some parts, such as antifriction bearings, cannot be made too smooth for their function. In these cases, the designer must optimize the tradeoff between the added costs of production and various benefits derived from added performance, such as higher reliability and market value.

3. There are some parts where surfaces must be made as smooth as possible for optimum performance regardless of cost, such as gages, gage blocks, lenses, and carbon pressure seals.

4. In some cases, the nature of the most satisfactory finishing process may dictate the surface texture requirements to attain production efficiency, uniformity, and control even though the individual performance of the part itself may not be dependent on the quality of the controlled surface. Hardened steel bushings, e.g., which must be ground to close tolerance for press fit into housings, could have outside surfaces well beyond the roughness range specified and still perform their function satisfactorily.

5. For parts which the shop, with unjustified pride, has traditionally finished to greater perfection than is necessary, the use of proper surface texture designations will encourage rougher surfaces on exterior and other surfaces that do not need to be finely finished. Significant cost reductions will accrue thereby.
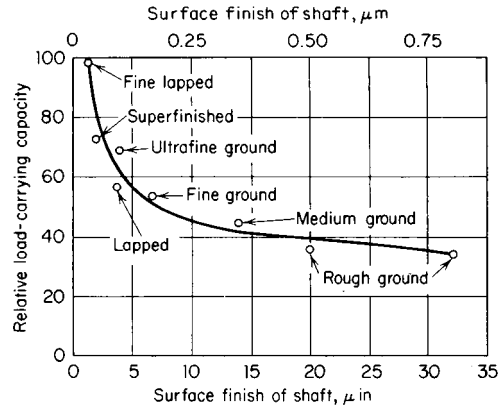

Fig. 13.5.1 Load-carrying capacity of journal bearings related to the surface roughness of a shaft. *(Clay, ASM Metal Progress, Aug. 15, 1955.)*
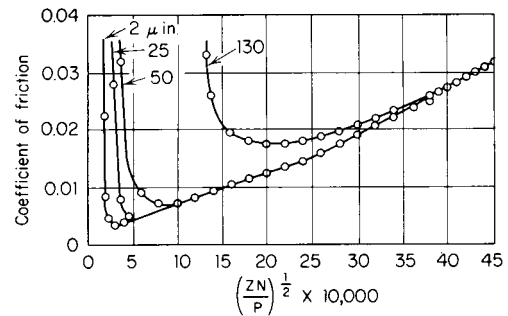

Fig. 13.5.2 Effect of surface texture on friction with hydrodynamic lubrication using a flat slider on a rotating disk. Z = oil viscosity, cP; N = rubbing speed, ft/min; P = load, lb/in^2.

It is the designer's responsibility to decide which surfaces of a given part are critical to its design function and which are not. This decision should be based upon a full knowledge of the part's function as well as of the performance of various surface textures that might be specified. From both a design and an economic standpoint, it may be just as unsound to specify too smooth a surface as to make it too rough—or to control it at all if not necessary. Wherever normal shop practice will produce acceptable surfaces, as in drilling, tapping, and threading, or in keyways, slots, and other purely functional surfaces, unnecessary surface texture control will add costs which should be avoided.

Whereas each specialized field of endeavor has its own traditional criteria for determining which surface finishes are optimum for adequate performance, Table 13.5.1 provides some common examples for design review, and Table 13.5.6 provides data on the surface texture ranges that can be obtained from normal production processes.

DESIGNATION STANDARDS, SYMBOLS, AND CONVENTIONS

The precise definition and measurement of surface texture irregularities of machined surfaces are almost impossible because the irregularities are very complex in shape and character and, being so small, do not lend themselves to direct measurement. Although both their shape and length may affect their properties, control of their average height and direction usually provides sufficient control of their performance. The standards

Table 13.5.1   Typical Surface Texture Design Requirements

(250 μin)	6.3 ∕	Clearance surfaces Rough machine parts	(16 μin)	0.40 ∕	Motor shafts Gear teeth (heavy loads)
(125 μin)	3.2 ∕	Mating surfaces (static) Chased and cut threads Clutch-disk faces Surfaces for soft gaskets			Spline shafts O-ring grooves (static) Antifriction bearing bores and faces Camshaft lobes Compressor-blade airfoils Journals for elastomer lip seals
(63 μin)	1.60 ∕	Piston-pin bores Brake drums Cylinder block, top Gear locating faces Gear shafts and bores Ratchet and pawl teeth Milled threads Rolling surfaces Gearbox faces Piston crowns Turbine-blade dovetails	(13 μin)	0.32 ∕	Engine cylinder bores Piston outside diameters Crankshaft bearings
			(8 μin)	0.20 ∕	Jet-engine stator blades Valve-tappet cam faces Hydraulic-cylinder bores Lapped antifriction bearings
			(4 μin)	0.10 ∕	Ball-bearing races Piston pins
(32 μin)	0.80 ∕	Broached holes Bronze journal bearings Gear teeth Slideways and gibs Press-fit parts Piston-rod bushings Antifriction bearing seats Sealing surfaces for hydraulic tube fittings			Hydraulic piston rods Carbon-seal mating surfaces
			(2 μin)	0.050 ∕	Shop-gage faces Comparator anvils
			(1 μin)	0.025 ∕	Bearing balls Gages and mirrors Micrometer anvils

do not specify the surface texture suitable for any particular application, nor the means by which it may be produced or measured. Neither are the standards concerned with other surface qualities such as appearance, luster, color, hardness, microstructure, or corrosion and wear resistance, any of which may be a governing design consideration.

The standards provide definitions of the terms used in delineating critical surface-texture qualities and a series of symbols and conventions suitable for their designation and control. In the discussion which follows, the reference standards used are ''Surface Texture'' (ANSI/ASME B46.1-1985) and ''Surface Texture Symbols'' (ANSI Y14.36-1978).

The basic ANSI symbol for designating surface texture is the checkmark with horizontal extension shown in Fig. 13.5.3. The symbol with the triangle at the base indicates a requirement for a machining allowance, in preference to the old *f* symbol. Another, with the small circle in the base, prohibits machining; hence surfaces must be produced without the removal of material by processes such as cast, forged, hot- or cold-finished, die-cast, sintered- or injection-molded, to name a few. The surface-texture requirement may be shown at A; the machining allowance at B; the process may be indicated above the line at C; the roughness width cutoff (sampling length) at D, and the lay at E. The ANSI symbol provides places for the insertion of numbers to specify a wide variety of texture characteristics, as shown in Table 13.5.2.

Control of **roughness,** the finely spaced surface texture irregularities resulting from the manufacturing process or the cutting action of tools or abrasive grains, is the most important function accomplished through the use of these standards, because roughness, in general, has a greater effect on performance than any other surface quality. The roughness-height index value is a number which equals the arithmetic average deviation of the minute surface irregularities from a hypothetical perfect surface, expressed in either millionths of an inch (microinches, μin, 0.000001 in) or in micrometres, μm, if drawing dimensions are in metric, SI units. For control purposes, roughness-height values are taken from Table 13.5.1, with those in boldface type given preference.

The term *roughness cutoff,* a characteristic of tracer-point measuring instruments, is used to limit the length of trace within which the asperities of the surface must lie for consideration as roughness. Asperity spacings greater than roughness cutoff are then considered as waviness.

Waviness refers to the secondary irregularities upon which roughness is superimposed, which are of significantly longer wavelength and are usually caused by machine or work deflections, tool or workpiece vibration, heat treatment, or warping. Waviness can be measured by a dial indicator or a profile recording instrument from which roughness has been filtered out. It is rated as maximum peak-to-valley distance and is indicated by the preferred values of Table 13.5.4. For fine waviness control, techniques involving contact-area determination in percent (90, 75, 50 percent preferred) may be required. Waviness control by interferometric methods is also common, where notes, such as ''Flat within XX helium light bands,'' may be used. Dimensions may be determined from the precision length table (see Sec. 1).
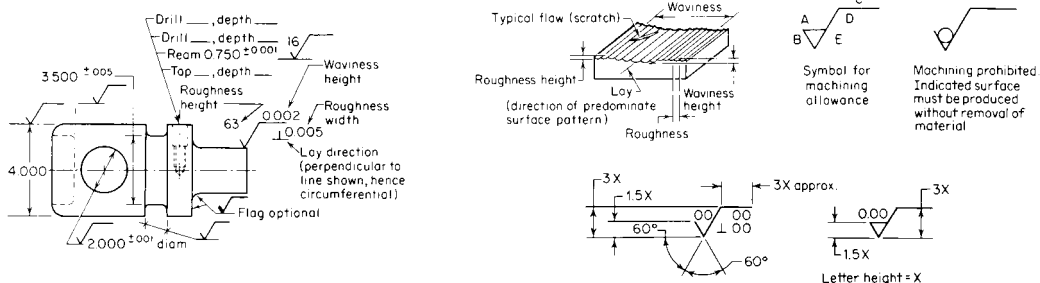

Fig. 13.5.3   Application and use of surface texture symbols.

Table 13.5.2   Application of Surface Texture Values to Surface Symbols

(63) 1.6 ∨	Roughness average rating is placed at the left of the long leg. The specification of only one rating shall indicate the maximum value and any lesser value shall be acceptable. Specify in micrometres (microinches).	(63) 1.6 / 3.5 ∨ Machining is required to produce the surface. The basic amount of stock provided for machining is specified at the left of the short leg of the symbol. Specify in millimetres (inches).
(63) 1.6 (32) 0.8 ∨	The specification of maximum value and minimum value roughness average ratings indicates permissible range of value rating. Specify in micrometres (microinches).	(63) 1.6 ∅ Removal of material by machining is prohibited. (32) 0.8 / ⊥ Lay designation is indicated by the lay symbol placed at the right of the long leg.
(32) 0.8 / 0.05 ∨	Maximum waviness height rating is placed above the horizontal extension. Any lesser rating shall be acceptable. Specify in millimetres (inches).	(32) 0.8 / 2.5 (0.100) Roughness sampling length or cutoff rating is placed below the horizontal extension. When no value is shown, 0.80 mm is assumed. Specify in millimetres (inches).
(32) 0.8 / 0.05 − 100 ∨	Maximum waviness spacing rating is placed above the horizontal extension and to the right of the waviness height rating. Any lesser rating shall be acceptable. Specify in millimetres (inches).	(32) 0.8 / ⊥0.5 Where required, maximum roughness spacing shall be placed at the right of the lay symbol. Any lesser rating shall be acceptable. Specify in millimetres (inches).

Table 13.5.3   Preferred Series Roughness Average Values R_a, μm and μin

μm	μin	μm	μin	μm	μin	μm	μin	μm	μin
—									
—									
— —									
0.012	0.5	0.125	5	0.50	20	2.00	80	8.0	320
0.025	1	0.15	6	0.63	25	2.50	100	10.0	400
0.050	**2**	**0.20**	**8**	**0.80**	**32**	**3.20**	**125**	**12.5**	**500**
0.075	3	0.25	10	1.00	40	4.0	160	15.0	600
0.10	**4**	0.32	13	1.25	50	5.0	200	20.0	800
		0.40	**16**	**1.60**	**63**	**6.3**	**250**	**25.0**	**1,000**

Lay refers to the direction of the predominant visible surface roughness pattern. It can be controlled by use of the approved symbols given in Table 13.5.5, which indicate desired lay direction with respect to the boundary line of the surface upon which the symbol is placed.

Flaws are imperfections in a surface that occur only at infrequent intervals. They are usually caused by nonuniformity of the material, or they result from damage to the surface subsequent to processing, such as scratches, dents, pits, and cracks. Flaws should not be considered in surface texture measurements, as the standards do not consider or classify them. Acceptance or rejection of parts having flaws is strictly a matter of judgment based upon whether the flaw will compromise the intended function of the part.

To call attention to the fact that surface texture values are specified on any given drawing, a note and typical symbol may be used as follows:

√ Surface texture per ANSI B46.1

Values for nondesignated surfaces can be limited by the note

xx√ All machined surfaces except as noted

Table 13.5.4   Preferred Series Maximum Waviness Height Values

mm	in	mm	in	mm	in
0.0005	0.00002	0.008	0.0003	0.12	0.005
0.0008	0.00003	0.012	0.0005	0.20	0.008
0.0012	0.00005	0.020	0.0008	0.25	0.010
0.0020	0.00008	0.025	0.001	0.38	0.015
0.0025	0.0001	0.05	0.002	0.50	0.020
0.005	0.0002	0.08	0.003	0.80	0.030

MEASUREMENT

Two general methods exist to measure surface texture: **profile methods** and **area methods**. Profile methods measure the contour of the surface in a plane usually perpendicular to the surface. Area methods measure an area of a surface and produce results that depend on area-averaged properties.

Another categorization is by **contact methods** and **noncontact methods**. Contact methods include stylus methods (tracer-point analysis) and capacitance methods. Noncontact methods include light section microscopy, optical reflection measurements, and interferometry.

Replicas of typical standard machined surfaces provide less accurate but often adequate reference and control of rougher surfaces with R_a over 16 μin.

The United States and 25 other countries have adopted the **roughness average R_a** as the standard measure of surface roughness. (See ANSI/ASME B46.1-1985.)
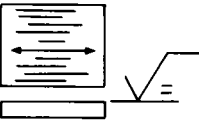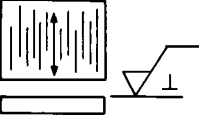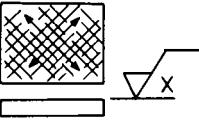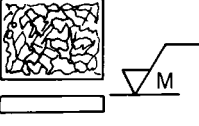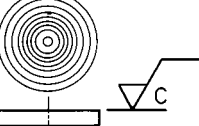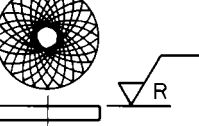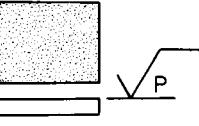
PRODUCTION

Various production processes can produce surfaces within the ranges shown in Table 13.5.6. For production efficiency, it is best that critical areas requiring surface texture control be clearly designated on drawings so that proper machining and adequate protection from damage during processing will be ensured.

SURFACE QUALITY VERSUS TOLERANCES

It should be remembered that surface quality and tolerances are distinctly different attributes that are controlled for completely separate purposes. **Tolerances** are established to limit the range of the size of a

Table 13.5.5 Lay Symbols

Lay symbol	Interpretation	Example showing direction of tool marks
—	Lay approximately parallel to the line representing the surface to which the symbol is applied	
⊥	Lay approximately perpendicular to the line representing the surface to which the symbol is applied	
X	Lay angular in both directions to line representing the surface to which symbol is applied	
M	Lay multidirectional	
C	Lay approximately circular relative to the center of the surface to which the symbol is applied	
R	Lay approximately radial relative to the center of the surface to which the symbol is applied	
P	Lay particulate, nondirectional, or protuberant	

part at the time of manufacture, as measured with gages, micrometres, or other traditional measuring devices having anvils that make contact with the part. **Surface quality** controls, on the other hand, serve to limit the minute surface irregularities or asperities that are formed by the manufacturing process. These lie under the gage anvils during measurement and **do not use up tolerances**.

Table 13.5.6   Surface-Roughness Ranges of Production Processes

Roughness height rating, μm (μin) Ra

Process	50 (2000)	25 (1000)	12.5 (500)	6.3 (250)	3.2 (125)	1.8 (63)	0.80 (32)	0.40 (16)	0.20 (8)	0.10 (4)	0.05 (2)	0.025 (1)	0.012 (0.5)
Flame cutting													
Snagging													
Sawing													
Planing, shaping													
Drilling													
Chemical milling													
Elect. discharge mach.													
Milling													
Broaching													
Reaming													
Electron beam													
Laser													
Electro-chemical													
Boring, turning													
Barrel finishing													
Electrolytic grinding													
Roller burnishing													
Grinding													
Honing													
Electro-polish													
Polishing													
Lapping													
Superfinishing													
Sand casting													
Hot rolling													
Forging													
Perm. mold casting													
Investment casting													
Extruding													
Cold rolling, drawing													
Die casting													

Smoother texture, higher cost →

← *Rougher texture, lower cost*

The ranges shown above are typical of the processes listed.
Higher or lower values may be obtained under special conditions.

■ Average application
▨ Less frequent application

13.6   WOODCUTTING TOOLS AND MACHINES
by Richard W. Perkins

REFERENCES: Davis, Machining and Related Characteristics of United States Hardwoods, *USDA Tech. Bull.* 1267. Harris, ''A Handbook of Woodcutting,'' Her Majesty's Stationery Office, London. Koch, ''Wood Machining Processes,'' Ronald Press. Kollmann, Wood Machining, in Kollmann and Côté, ''Principles of Wood Science and Technology,'' chap. 9, Springer-Verlag.

SAWING

Sawing machines are classified according to basic machine design, i.e., band saw, gang saw, chain saw, circular saw. Saws are designated as ripsaws if they are designed to cut along the grain or **crosscut** saws if they are designed to cut across the grain. A **combination** saw is designed to cut reasonably well along the grain, across the grain, or along a direction at an angle to the grain (**miter**). Sawing machines are often further classified according to the specific operation for which they are used, e.g., **headsaw** (the primary log-breakdown saw in a sawmill), **resaw** (saw for ripping cants into boards), **edger** (saw for edging boards in a sawmill), **variety saw** (general-purpose saw for use in furniture plants), **scroll saw** (general-purpose narrow-band saw for use in furniture plants).

The thickness of the saw blade is designated in terms of the Birming-

ham wire gage (BWG) (see Sec. 8.2). Large-diameter [40 to 60 in (1.02 to 1.52 mm)] circular-saw blades are tapered so that they are thicker at the center than at the rim. Typical headsaw blades range in thickness from 5 to 6 BWG [0.203 to 0.220 in (5.16 to 5.59 mm)] for use in heavy-duty applications to 8 to 9 BWG [0.148 to 0.165 in (3.76 to 4.19 mm)] for lighter operations. Small-diameter [6 to 30 in (152 to 762 mm)] circular saws are generally flat-ground and range from 10 to 18 BWG [0.049 to 0.134 in (1.24 to 3.40 mm)] in thickness. Band-saw and gang-saw blades are flat-ground and are generally thinner than circular-saw blades designed for similar applications. For example, typical wide-band-saw blades for sawmill use range in thickness from 11 to 16 BWG [0.065 to 0.120 in (1.65 to 3.05 mm)] in thickness. The thickness of a band-saw blade is determined by the cutting load and the diameter of the band wheel. Gang-saw blades are generally somewhat thicker than band-saw blades for similar operations. Narrow-band-saw blades for use on scroll band saws range in thickness from 20 to 25 BWG [0.020 to 0.035 in (0.51 to 0.89 mm)] and range in width from ⅛ to about 1¾ in (3.17 to 44.5 mm) depending upon the curvature of cuts to be made.

The considerable amount of heat generated at the cutting edge results in compressive stresses in the rim of the saw blade of sufficient magnitude to cause mechanical instability of the saw blades. Circular-saw blades and wide-band-saw blades are commonly prestressed (or **tensioned**) to reduce the possibility of buckling. Small circular-saw blades for use on power-feed rip-saws and crosscut saws are frequently provided with **expansion slots** for the same purpose.

The **shape of the cutting portion of the sawtooth** is determined by specifying the hook, face bevel, top bevel, and clearance angles. The optimum tooth shape depends primarily upon cutting direction, moisture content, and density of the workpiece material. Sawteeth are, in general, designed in such a way that the portion of the cutting edge which is required to cut across the fiber direction is provided with the maximum effective rake angle consistent with tool strength and wear considerations. Ripsaws are designed with a hook angle between some 46° for inserted-tooth circular headsaws used to cut green material and 10° for solid-tooth saws cutting dense material at low moisture content. Ripsaws generally have zero face bevel and top bevel angle; however, spring-set ripsaws sometimes are provided with a moderate top bevel angle (5 to 15°). The hook angle for crosscut saws ranges from positive 10° to negative 30°. These saws are generally designed with both top and face bevel angles of 5 to 15°; however, in some cases top and face bevel angles as high as 45° are employed. A compromise design is used for combination saws which embodies the features of both ripsaws and crosscut saws in order to provide a tool which can cut reasonably well in all directions. The clearance angle should be maintained at the smallest possible value in order to provide for maximum tooth strength. For ripsawing applications, the clearance angle should be about 12 to 15°. The minimum satisfactory clearance angle is determined by the nature of the work material, not from kinematical considerations of the motion of the tool through the work. In some cases of cutoff, combination, and narrow-band-saw designs where the tooth pitch is relatively small, much larger clearance angles are used in order to provide the necessary gullet volume.

A certain amount of clearance between the saw blade and the generated surface (**side clearance** or **set**) is necessary to prevent frictional heating of the saw blade. In the case of solid-tooth circular saws and band or gang saws, the side clearance is generally provided either by deflecting alternate teeth (**spring-setting**) or by spreading the cutting edge (**swage-setting**). The amount of side clearance depends upon density, moisture content, and size of the saw blade. In most cases, satisfactory results are obtained if the side clearance S is determined from the formula S [in (mm)] $= A/2[f(g-5) - f(g)]$, where g = gage number (BWG) of the saw blade, $f(n)$ = dimension in inches (mm) corresponding to the gage number n, and A has values from Table 13.6.1. Certain specialty circular saws such as planer, smooth-trimmer, and miter saws are hollow-ground to provide side clearance. Inserted-tooth saws, carbide-tipped saws, and chain-saw teeth are designed so that sufficient side clearance is provided for the life of the tool; consequently, the setting of such saws is unnecessary.

Table 13.6.1   Values of *A* for Computing Side Clearance

	Workpiece material			
	Specific gravity less than 0.45		Specific gravity greater than 0.55	
Saw type	Air dry	Green	Air dry	Green
Circular rip and combination	0.90	1.00	0.85	0.95
Glue-joint ripsaw	0.80	—	0.60	—
Circular crosscut	0.95	1.05	0.90	1.00
Wide-band saw	0.55	0.65	0.30	0.40
Narrow-band saw	0.65	—	0.55	—

The **tooth speed** for sawing operations ranges from 3,000 to 17,000 ft/min (15 to 86 m/s) approx. Large tooth speeds are in general desirable in order to permit maximum work rates. The upper limit of permissible tooth speed depends in most cases on machine design considerations and not on considerations of wear or surface quality as in the case of metal cutting. Exceptionally high tooth speeds may result in charring of the work material, which is machined at slow feed rates.

In many sawing applications, **surface quality** is not of prime importance since the sawed surfaces are subsequently machined, e.g., by planing, shaping, sanding; therefore, it is desirable to operate the saw at the largest feed per tooth consistent with gullet overloading. Large values of feed per tooth result in lower amounts of work required per unit volume of material cut and in lower amounts of wear per unit tool travel. Large-diameter circular saws, wide-band saws, and gang saws for ripping green material are generally designed so that the feed per tooth should be about 0.08 to 0.12 in (2.03 to 3.05 mm). Small-diameter circular saws are designed so that the feed per tooth ranges from 0.03 in (0.76 mm) for dense hardwoods to 0.05 in (1.27 mm) for low-density softwoods. Narrow-band saws are generally operated at somewhat smaller values of feed per tooth, e.g., 0.005 to 0.04 in (0.13 to 1.02 mm). Smaller values of feed per tooth are necessary for applications where surface quality is of prime importance, e.g., glue-joint ripsawing and variety-saw operations. The degree of gullet loading is measured by the **gullet-feed index (GFI),** which is computed as the feed per tooth times the depth of face divided by the gullet area. The maximum GFI depends primarily upon species, moisture content, and cutting direction. It is generally conceded that the maximum GFI for ripsawing lies between 0.3 for high-density, low-moisture-content material and 0.4 for low-density, high-moisture-content material. For specific information, see Telford, *For. Prod. Res. Soc. Proc.,* 1949.

Saws vary considerably in design of the **gullet shape**. The primary design considerations are gullet area and tooth strength; however, special design shapes are often required for certain classes of workpiece material, e.g., for ripping frozen wood.

Materials   Saw blades and the sawteeth of solid-tooth saws are generally made of a nickel tool steel. The bits for inserted-tooth saws were historically plain carbon tool steel; however, high-speed steel bits or bits with a cast-alloy inlay (e.g., Stellite) are sometimes used in applications where metal or gravel will not be encountered. Small-diameter circular saws of virtually all designs are made with cemented-carbide tips. This type is almost imperative in applications where highly abrasive material is cut, namely, in plywood and particleboard operations.

Sawing Power   References: Endersby, The Performance of Circular Plate Ripsaws, *For. Prod. Res. Bull.* 27, Her Majesty's Stationery Office, London, 1953. Johnston, Experimental Cut-off Saw, *For. Prod. Jour.,* June 1962. Oehrli, Research in Cross-cutting with Power Saw Chain Teeth, *For. Prod. Jour.,* Jan. 1960. Telford, Energy Requirements for Insert-point Circular Headsaws, *Proc. For. Prod. Res. Soc.,* 1949.

An approximate relation for computing the power P, ft · lb/min (W), required to saw is

$$P = kvb(A + Bt_a)/p$$

where k is the kerf, in (m); v is the tooth speed, ft/min (m/s); p is the tooth pitch, in (m); A and B are constants for a given sawing operation,

Table 13.6.2   Constants for Sawing-Power Estimation

Material			Tool		Constants			
Species	Specific gravity	Moisture content, %	Angles[e]	Sawing situation	A, lb/in	A, N/m	B, lb/in² × 10⁻³	B, N/m² × 10⁻⁶
Beech, European[a]	0.72	12	20, 0, 12	SS, R	27.8	4,869	5.760	39.71
Birch, yellow[b]	0.55	FSP	− 30, 10, 10	SS, CC	19.7	3,450	4.100	28.27
Elm, wych[a]	0.67	12	20, 0, 12	SS, R	23.2	4,063	4.840	33.37
Maple, sugar[c]	0.63	FSP	41, 0, 0	IT, R	85.6	15,991	2.995	20.65
Maple, sugar[c,f]	0.63	FSP	41, 0, 0	IT, R	48.0	8,406	4.400	30.34
Pine, northern white[c]	0.34	FSP	41, 0, 0	IT, R	27.1	4,746	1.675	11.55
Pine, northern white[c,f]	0.34	FSP	41, 0, 0	IT, R	28.2	4,939	2.085	14.38
Pine, northern white[b]	0.34	FSP	− 30, 10, 10	SS, CC	0.0	0	3.300	22.75
Pine, ponderosa[d]	0.38–0.40	15–40	28, 25, 0	OFT, R	29.3	5,131	1.700	11.72
Pine, ponderosa[d]	0.38–0.40	15–40	28, 25, 0	OFT, CC	0.0	0	2.120	14.62
Poplar (*P. serotina*)[a]	0.48	12	20, 0, 12	SS, R	18.6	3,257	3.290	22.68
Redwood, California[a]	0.37	12	20, 0, 12	SS, R	15.0	2,627	2.260	15.58
Spruce, white[b]	0.32	FSP	− 30, 10, 10	SS, CC	0.0	0	4.680	32.27

[a] Endersby.
[b] Johnston.
[c] Hoyle, unpublished report, N.Y. State College of Forestry, Syracuse, NY, 1958.
[d] Oehrli.
[e] The numbers represent hook angle, face bevel angle, and top bevel in degrees.
[f] Cutting performed on frozen material.
NOTE: FSP = moisture content greater than the fiber saturation point; CC = crosscut; IT = insert-tooth; OFT = offset-tooth; R = rip; SS = spring-set.

lb/in (N/m) and lb/in² (N/m²), respectively; and t_a is the average chip thickness, in (m). The average chip thickness is computed from the relation $t_a = \gamma f_t \times d/b$, where f_t is the feed per tooth; d is the depth of face; b is the length of the tool path through the workpiece; and γ has the value 1 except for saws with spring-set or offset teeth, in which case γ has the value 2. The constants A and B depend primarily upon cutting direction (ripsawing, crosscutting), moisture content below the fiber-saturation point and specific gravity of the workpiece material, and tooth shape. The values of A and B (see Table 13.6.2) depend to some degree upon the depth of face, saw diameter, gullet shape, gullet-feed index, saw speed, and whether the tool motion is linear or rotary; however, the effect of these variables can generally be neglected for purposes of approximation.

Computers have now been utilized in sawmills where raw logs are first processed into rough-cut lumber. With suitable software, the mill operator can input key dimensions of the log and receive the cutting pattern which provides a mix of cross sections of lumber so as to maximize the yield from the log. The saving in waste is sizable, and this technique is especially attractive in view of the decreasing availability of large-caliper old stand timber, together with the cost of same.

PLANING AND MOLDING

Machinery   Planing and molding machines employ a rotating cutterhead to generate a smooth, defect-free surface by cutting in a direction approximately along the grain. A **surfacer** (or **planer**) is designed to machine boards or panels to uniform thickness. A **facer** (or **facing planer**) is designed to generate a flat (plane) surface on the wide faces of boards. The **edge jointer** is intended to perform the same task on the edges of boards in preparation for edge-gluing into panels. A **planer-matcher** is a heavy-duty machine designed to plane rough boards to uniform width and thickness in one operation. This machine is commonly used for dressing dimension lumber and producing millwork. The **molder** is a high-production machine for use in furniture plants to generate parts of uniform cross-sectional shape.

Recommended Operating Conditions   It is of prime importance to adjust the operating conditions and knife geometry so that the machining defects are reduced to a satisfactory level. The most commonly encountered defects are torn (chipped) grain, fuzzy grain, raised and loosened grain, and chip marks. **Torn grain** is caused by the wood splitting ahead of the cutting edge and below the generated surface. It is generally associated with large cutting angle, large chip thickness, low moisture content, and low workpiece material density. The **fuzzy-grain** defect is characterized by small groups of wood fibers which stand up above the generated surface. This defect is caused by incomplete sever-

ing of the wood by the cutting edge and is generally associated with small cutting angles, dull knives, low-density species, high moisture content, and (often) the presence of reaction wood. The **raised-grain** defect is characterized by an uneven surface where one portion of the annual ring is raised above the remaining part. **Loosened grain** is similar to raised grain; however, loosened grain is characterized by a separation of the early wood from the late wood which is readily discernible to the naked eye. The raised- and loosened-grain defects are attributed to the crushing of springwood cells as the knife passes over the surface. (Edge-grain material may exhibit a defect similar to the raised-grain defect if machining is performed at a markedly different moisture content from that encountered at some later time.) Raised and loosened grains are associated with dull knives, excessive jointing of knives [the jointing land should not exceed ¹⁄₃₂ in (0.79 mm)], and high moisture content of workpiece material. **Chip marks** are caused by chips which are forced by the knife into the generated surface as the knife enters the workpiece material. Chip marks are associated with inadequate exhaust, low moisture content, and species (e.g., birch, Douglas fir, and maple have a marked propensity toward the chip-mark defect).

Depth of cut is an important variable with respect to surface quality, particularly in the case of species which are quite prone to the torn-grain defect (e.g., hard maple, Douglas fir, southern yellow pine). In most cases, the depth of cut should be less than ¹⁄₁₆ in (1.59 mm). The number of **marks per inch (marks per metre)** (reciprocal of the feed per cutter) is an important variable in all cases; however, it is most important in those cases for which the torn-grain defect is highly probable. The marks per inch (marks per meter) should be between 8 and 12 (315 and 472) for rough planing operations and from 12 to 16 (472 to 630) for finishing cuts. Slightly higher values may be necessary for refractory species or for situations where knots or curly grain are present. It is seldom necessary to exceed a value of 20 marks per inch (787 marks per metre). The **clearance angle** should in all cases exceed a value of 10°. When it is desired to hone or joint the knives between sharpenings, a value of about 20° should be used. The optimum **cutting angle** lies between 20 and 30° for most planing situations; however, in the case of interlocked or wavy grain, low moisture content, or species with a marked tendency toward the torn-grain defect, it may be necessary to reduce the cutting angle to 10 or 15°.

BORING

Machinery   The typical general-purpose wood-boring machine has a single vertical spindle and is a hand-feed machine. Production machines are often of the vertical, multiple-spindle, adjustable-gang type or the

horizontal type with two adjustable, independently driven spindles. The former type is commonly employed in furniture plants for boring holes in the faces of parts, and the latter type is commonly used for boring dowel holes in the edges and ends of parts.

Tool Design A wide variety of tool designs is available for specialized boring tasks; however, the most commonly used tools are the taper-head drill, the spur machine drill, and the machine bit. The **taper-head** drill is a twist drill with a point angle of 60 to 90°, lip clearance angle of 15 to 20°, chisel-edge angle of 125 to 135°, and helix angle of 20 to 40°. Taper-head drills are used for drilling screw holes and for boring dowel holes along the grain. The **spur machine** drill is equivalent to a twist drill having a point angle of 180° with the addition of a pyramidal point (instead of a web) and spurs at the circumference. These drills are designed with a helix angle of 20 to 40° and a clearance angle of 15 to 20°. The **machine bit** has a specially formed head which determines the configuration of the spurs. It also has a point. Machine bits are designed with a helix angle of 40 to 60°, cutting angle of 20 to 40°, and clearance angle of 15 to 20°. Machine bits are designed with spurs contiguous to the cutting edges **(double-spur machine bit),** with spurs removed from the vicinity of the cutting edges **(extension-lip machine bit),** and with the outlining portion of the spurs removed **(flat-cut machine bit)**.

The purpose of the spurs is to aid in severing wood fibers across their axes, thereby increasing hole-wall smoothness when boring across the grain. Therefore, drills or bits with spurs (double-spur machine drill and bit) are intended for boring across the grain, whereas drills or bits without spurs (taper-head drill, flat-cut machine bit) are intended for boring along the grain or at an angle to the grain.

Taper-head and spur machine drills can be sharpened until they become too short for further use; however, machine bits and other bit styles which have specially formed heads can only be sharpened a limited number of times before the spur and cutting-face configuration is significantly altered. Since most wood-boring tools are sharpened by filing the clearance face, it is important to ensure that sufficient clearance is maintained. The clearance angle should be at least 5° greater than the angle whose tangent (function) is the feed per revolution divided by the circumference of the drill point.

Recommended Operating Conditions The most common defects are tearing of fibers from the end-grain portions of the hole surface and charring of hole surfaces. Rough hole surfaces are most often encountered in low-density and ring-porous species. This defect can generally be reduced to a satisfactory level by controlling the chip thickness. Charring is commonly a problem in high-density species. It can be avoided by maintaining the peripheral speed of the tool below a level which depends upon density and moisture content and by maintaining the chip thickness at a satisfactory level. Large chip thickness may result in excessive tool temperature and therefore rapid tool wear; however, large chip thickness is seldom a cause of hole charring. The following recommendations pertain to the use of spur-type drills or bits for boring material at about 6 percent moisture content across the grain. For species having a specific gravity less than 0.45, the chip thickness should be between 0.015 and 0.030 in (0.38 and 0.76 mm), and the peripheral speed of the tool should not exceed 900 ft/min (4.57 m/s). For material of specific gravity between 0.45 and 0.65, satisfactory results can be obtained with values of chip thickness between 0.015 and 0.045 in (0.38 and 1.14 mm) and with peripheral speeds less than 700 ft/min (3.56 m/s). For material of specific gravity greater than 0.65, the chip thickness should lie between 0.015 and 0.030 in (0.38 and 0.76 mm) and the peripheral speed should not exceed 500 ft/min (2.54 m/s). Somewhat higher values of chip thickness and peripheral

speed can be employed when the moisture content of the material is higher.

SANDING

(See Secs. 6.7 and 6.8)

Machinery Machines for production sanding of parts having flat surfaces are multiple-drum sanders, automatic-stroke sanders, and wide-belt sanders. **Multiple-drum** sanders are of the endless-bed or roll-feed type and have from two to six drums. The drum at the infeed end is fitted with a relatively coarse abrasive (40 to 100 grit), takes a relatively heavy cut [0.010 to 0.015 in (0.25 to 0.38 mm)], and operates at a relatively slow surface speed [3,000 to 3,500 ft/min (15.24 to 17.78 m/s)]. The drum at the outfeed end has a relatively fine abrasive paper (60 to 150 grit), takes a relatively light cut [about 0.005 in (0.13 mm)], and operates at a somewhat higher surface speed [4,000 to 5,000 ft/min (20.3 to 25.4 m/s)]. **Automatic-stroke** sanders employ a narrow abrasive belt and a reciprocating shoe which forces the abrasive belt against the work material. This machine is commonly employed in furniture plants for the final white-sanding operation prior to finish coating. The automatic-stroke sander has a relatively low rate of material removal (about one-tenth to one-third of the rate for the final drum of a multiple-drum sander) and is operated with a belt speed of 3,000 to 7,500 ft/min (15.2 to 38.1 m/s). **Wide-belt** sanders are commonly used in board plants (plywood, particle board, hardboard). They have the advantage of higher production rates and somewhat greater accuracy than multiple-drum sanders [e.g., feed rates up to 100 ft/min (0.51 m/s) as opposed to about 35 ft/min (0.18 m/s)]. Wide-belt sanders operate at surface speeds of approximately 5,000 ft/min (25.4 m/s) and are capable of operating at depths of cut of 0.006 to 0.020 in (0.15 to 0.51 mm) depending upon workpiece material density.

Abrasive Tools The abrasive tool consists of a **backing** to carry the **abrasive** and an **adhesive** coat to fix the abrasive to the backing. Backings are constructed of paper, cloth, or vulcanized fiber or consist of a cloth-paper combination. The adhesive coating (see also Sec. 6) is made up of two coatings; the first coat **(make coat)** acts to join the abrasive material to the backing, and the second coat **(size coat)** acts to provide the necessary support for the abrasive particles. Coating materials are generally animal glues, urea resins, or phenolic resins. The choice of material for the make and size coats depends upon the required flexibility of the tool and the work rate required of the tool. Abrasive materials (see also Sec. 6) for woodworking applications are garnet, aluminum oxide, and silicon carbide. **Garnet** is the most commonly used abrasive mineral because of its low cost and acceptable working qualities for low-work-rate situations. It is generally used for sheet goods, for sanding softwoods with all types of machines, and for sanding where the belt is loaded up (as opposed to worn out). **Aluminum oxide** abrasive is used extensively for sanding hardwoods, particleboard, and hardboard. **Silicon carbide** abrasive is used for sanding and polishing between coating operations and for machine sanding of particleboard and hardboard. Silicon carbide is also frequently used for the sanding of softwoods where the removal of raised fibers is a problem. The size of the abrasive particles is specified by the mesh number (the approximate number of openings per inch in the screen through which the particles will pass). (See Commercial Std.CS217-59, ''Grading of Abrasive Grain on Coated Abrasive Products,'' U.S. Government Printing Office.) Mesh numbers range from about 600 to 12. Size may also be designated by an older system of symbols which range from 10/0 (mesh no. 400) through 0 (mesh no. 80) to 4½ (mesh no. 12). Some general recommendations for common white wood sanding operations are presented in Table 13.6.3.

Table 13.6.3 Recommendations for Common Whitewood Sanding Operations

| | | Abrasive | | | | | | | | | |
| | | Backing | | Adhesive | | Mineral | | | Grit size | | |
		Material	Weight	Make coat	Size coat	1st drum	2d drum	3d drum	1st drum	2d drum	3d drum
Multiple drum	Softwood	Paper	E	Glue	Resin	G	G	G or S	50	80	100
	Hardwood	Paper	E	Glue	Resin	A	A	A	60	100	120
	Particleboard	Paper Fiber	E 0.020	Glue Resin	Resin Resin	G S	G S	G or A S	40 40	60 60	80 80
	Hardboard	Paper Fiber	E 0.020	Glue Resin	Resin Resin	S S	S S	S S	60 60	80 80	120 120
Wide-belt	Softwood	Paper Cloth	E X	Glue Resin	Resin Resin	G G	or or	S S	80–220* 80–220*		
	Hardwood	Paper Cloth	E X	Glue Resin	Resin Resin		A A		80–220* 80–220*		
	Burnishing	Paper	E	Glue	Glue		A		280–400		
	Particleboard	Cloth	X	Resin	Resin		S		24–150*		
	Hardboard	Cloth	X	Resin	Resin		S		100–150		
Stroke sanding	Softwood	Paper	E	Glue	Resin		G		80; 120†		
	Hardwood	Paper Cloth	E X	Glue Glue	Resin Resin		A A		100; 150–180† 100; 150–180†		
	Particleboard	Paper Cloth	E X	Glue Resin	Resin Resin	A A	or or	S S	80; 120† 80; 120†		
	Hardboard	Paper Cloth	E X	Glue Resin	Resin Resin	A A	or or	S S	100; 150† 100; 150†		
Edge sanding	Softwood	Cloth	X	Glue	Resin		G		60; 100†		
	Hardwood	Cloth Cloth	X X	Glue Resin	Resin Resin		A A		60–150* 60–150*		
Mold sanding	Softwood	Cloth Cloth	J J	Glue Glue	Glue Resin		G G		80–120* 80–120*		
	Hardwood	Cloth Cloth	J J	Glue Glue	Glue Resin	G G	or or	A A	80–120* 80–120*		

* May be single- or muiltiple-grit operation.
† First number for cutting-down operations, second number for finishing operations.
SOURCE: Graham, *Furniture Production,* July and Aug., 1961; and Martin, *Wood Working Digest,* Sept. 1961.
NOTE: G = garnet; A = aluminum oxide; S = silicon oxide.