Manu 2

Jana Househ



8.7.1 Types of Cutting Fluids and Methods of Application

There are four basic types of cutting fluids commonly used in machining operations: **oils**, **emulsions**, **semisynthetics**, and **synthetics** (see Section 4.4.4). Cutting-fluid recommendations for specific machining operations are given throughout the rest of this chapter. In selecting an appropriate

cutting fluid, considerations should be given to its possible detrimental effects on the workpiece material (such as corrosion, stress-corrosion cracking, staining), machine tool components, biological and environmental effects, and recycling and disposal of chips.

The most common method of applying cutting fluids is **flood cooling**. Flow rates typically range from 10 L/min for single-point tools, to 225 L/min per cutter for multiple-tooth cutters, as in milling. In such operations as gun drilling and end milling (see Section 8.10.1), fluid pressures in the range of 700–14,000 kPa are used to flush away the chips.

Mist cooling involves delivery of fluid as small droplets suspended in air, and is generally used with water-base fluids. Although it requires venting (to prevent inhalation of fluid particles by the machine operator and others nearby) and has limited cooling capacity, mist cooling supplies fluid to otherwise inaccessible areas and provides better visibility of the workpiece being machined. It is particularly effective in grinding operations (see Chapter 9), using air pressures in the range of 70–600 kPa.

High-pressure refrigerated coolant systems can be used to improve the rate of heat removal from the cutting zone. Pressures on the order of 35 MPa are used to deliver the fluid, via specially-designed nozzles that aim a powerful jet of fluid to the zone. This action breaks up the chips (thus the fluid also acts as a chip breaker) in situations where the chips produced would otherwise be too long and continuous, and thus interfere with the machining operation.

Through the cutting-tool system. One method to overcome the difficulty of supplying cutting fluids into the cutting zone and flushing away the chips is to provide them through the cutting tool. Narrow passages are produced in the cutting tool and the toolholder, through which the cutting fluid is applied under high pressure.

8.7.2 Near-Dry and Dry Machining

For economic and environmental reasons, there is a continuing trend to minimize or eliminate the use of metalworking fluids. This trend has lead to the practice of *near-dry machining* (NDM), where coolant use is eliminated or reduced significantly. The significance of this approach is apparent when the global metalworking fluids market was expected to grow from USD 9.95 billion in 2020 to USD 10.71 billion in 2021 and is expected to reach USD 13.06 billion in 2025. Moreover, it has been estimated that metalworking fluids constitute about 7 to 17% of the total machining costs. The major benefits of NDM include:

1. Reducing the environmental impact of using cutting fluids, improving air quality in manufacturing plants, and reducing health hazards.
2. Reducing the cost of machining operations, including the cost of maintaining, recycling, and disposing of cutting fluids.

The principle behind near-dry machining is the application of a fine mist of air and fluid mixture, containing a very small amount of cutting

fluid. The mixture is delivered to the cutting zone, through the spindle of the machine tool, typically through a 1-mm diameter nozzle and under a pressure of 600 kPa. The fluid is applied at rates of 1 to 100 cc/hr, which is estimated to be, at most, one ten-thousandth of that used in flood cooling; consequently, the process is also known as *minimum quantity lubrication* (MQL).

With continued advances in cutting-tool materials, *dry machining* has been shown to be effective, especially in turning, milling, and gear cutting of steels, alloys steels, and cast irons, although generally not for aluminum alloys.

Recall that one of the functions of a cutting fluid is to flush chips away from the cutting zone. Although it first appears that this may present difficulties in dry machining, tools have been designed to allow the application of *pressurized air*, often through holes in the tool shank (See Fig. 8.46). The compressed air provides limited cooling of the cutting zone, but it is very effective at clearing chips away from the cutting zone.

8.7.3 Cryogenic Machining

In the interest of reducing or eliminating the adverse environmental impact of using metalworking fluids, *liquid nitrogen* can be used as a coolant in machining, as well as in grinding (see Section 9.6.9). With appropriate small-diameter nozzles, liquid nitrogen is injected at a temperature of about −200°C into the tool-workpiece interface, reducing its temperature. As a result, tool hardness is maintained, and tool life is enhanced, thus allowing for higher cutting speeds. Moreover, the chips become more brittle and easier to flush from the cutting zone. Because no fluids are involved and the liquid nitrogen simply evaporates, the chips can be recycled more easily.

8.8 High-Speed Machining

With continuing demands for higher productivity and lower manufacturing costs, much effort has been expended in increasing the cutting speed. Although *high-speed machining* (HSM) is a relative term, an approximate range of cutting speeds are:

1. **High speed:** 600–1800 m/min;
2. **Very high speed:** 1800–18,000 m/min; and
3. **Ultrahigh speed:** >18,000 m/min.

Spindle rotational speeds in machine tools range up to 60,000 rpm. The *spindle power* required is generally on the order of 0.004 W/rpm, which is much lower than in traditional machining which is typically in the range of 0.2 to 0.4 W/rpm. The maximum workpiece speed in high-speed machining is on the order of 1 m/s, and the acceleration of machine-tool components is very high.

Spindles for high rotational speeds require *high stiffness and accuracy*, and generally involve an integral electric motor. The armature is built

onto the shaft and the stator is placed in the wall of the spindle housing. The bearings may be rolling element or hydrostatic; the latter is more desirable because it requires less space than the former. Because of *inertial effects* during acceleration and deceleration of machine-tool components, the use of lightweight materials, including ceramics and composite materials, is important. Selection of appropriate cutting-tool materials also is a major consideration. Depending on the workpiece material, multiphase coated carbides, ceramics, cubic boron nitride, and diamond are typical tool materials for high-speed machining.

High-speed machining should be considered primarily for operations where **cutting time** is a significant portion of the time in the overall machining operation. As described in Section 8.15, **non-cutting time** and various other factors (e.g. tool material costs, capital equipment costs, labor costs, etc.) are important considerations in the overall assessment of the benefits of high-speed machining for a particular application. It has, for example, been implemented in machining (a) aluminum structural components for aircraft; (b) submarine propellers of 6 m diameter, made of nickel-aluminum-bronze alloy and weighing 55,000 kg; and (c) automotive engines, with five to ten times the productivity of traditional machining.

Another major factor in the adoption of high-speed machining has been the requirement to further improve dimensional tolerances. As can be seen in Fig. 8.18, as the cutting speed increases, more and more of the heat generated is removed by the chip; thus the tool and, more importantly, the workpiece remain close to ambient temperature. The machine-tool characteristics and special requirements that are important in high-speed machining may be summarized as follows:

1. Spindle design for high stiffness, accuracy, and balance at very high rotational speeds, and workholding devices that can withstand high centrifugal forces;
2. Fast feed drives, bearing characteristics, and effects of inertia of the machine-tool components;
3. Selection of appropriate cutting tools, processing parameters, and their computer control; and
4. effective chip removal systems at very high rates.

based on the geometry produced. ←

8.9 Cutting Processes and Machine Tools for Producing Round Shapes

Round cross section

This section describes the processes that produce parts that are *round in shape*, as outlined in Table 8.7. Typical products machined include parts as small as miniature screws for eyeglass hinges and as large as cylinders, gun barrels, and turbine shafts for hydroelectric power plants. These processes are generally performed by turning the workpiece on a lathe. *Turning* means that the part is rotating while it is being machined using a cutting tool. The starting material is typically a workpiece that has been produced by other processes, such as casting, forging, extrusion, and

Linearly

TABLE 8.7 General characteristics of machining processes.

Process	Characteristics	Commercial tolerances (±mm)
Turning	Turning and facing operations are performed on all types of materials; requires skilled labor; low production rate, but medium to high rates can be achieved with turret lathes and automatic machines, requiring less skilled labor	Fine: 0.025–0.13 Rough: 0.13 Skiving: 0.025–0.05
Boring	Internal surfaces or profiles, with characteristics similar to those produced by turning; stiffness of boring bar is important to avoid chatter	0.025
Drilling	Round holes of various sizes and depths; requires boring and reaming for improved accuracy; high production rate, labor skill required depends on hole location and accuracy specified	0.075
Milling	Variety of shapes involving contours, flat surfaces, and slots; wide variety of tooling; versatile; low to medium production rate; requires skilled labor	0.13–0.25
Planing	Flat surfaces and straight contour profiles on large surfaces; suitable for low-quantity production; labor skill required depends on part shape	0.08–0.13
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; suitable for low-quantity production; labor skill required depends on part shape	0.05–0.13
Broaching	External and internal flat surfaces, slots, and contours with good surface finish; costly tooling; high production rate; labor skill required depends on part shape	0.025–0.15
Sawing	Straight and contour cuts on flats or structural shapes; not suitable for hard materials unless the saw has carbide teeth or is coated with diamond; low production rate; requires only low skilled labor	0.8

drawing. Turning processes are very versatile and capable of producing a wide variety of shapes, as outlined in Fig. 8.37.

- **Turning** straight, conical, curved, or grooved workpieces, such as shafts, spindles, pins, handles, and various machine components;
- **Facing**, to produce a flat surface at the end of a part, such as for those that are attached to other components, or to produce grooves for O-ring seats;
- Producing various shapes by **form tools**, for functional purposes and for appearance;
- **Boring**, to enlarge a hole made by a previous process or in a tubular workpiece, or to produce internal grooves;
- **Drilling**, to produce a hole, which may be followed by tapping or by boring to improve the accuracy of the hole and its surface finish;
- **Parting**, also called **cutting off**, to cut a piece from the end of a part, as in making slugs or blanks for subsequent processing into discrete parts;
- **Threading**, to produce external or internal threads in workpieces; and
- **Knurling**, to produce surface characteristics on cylindrical surfaces, as in making knurled knobs.

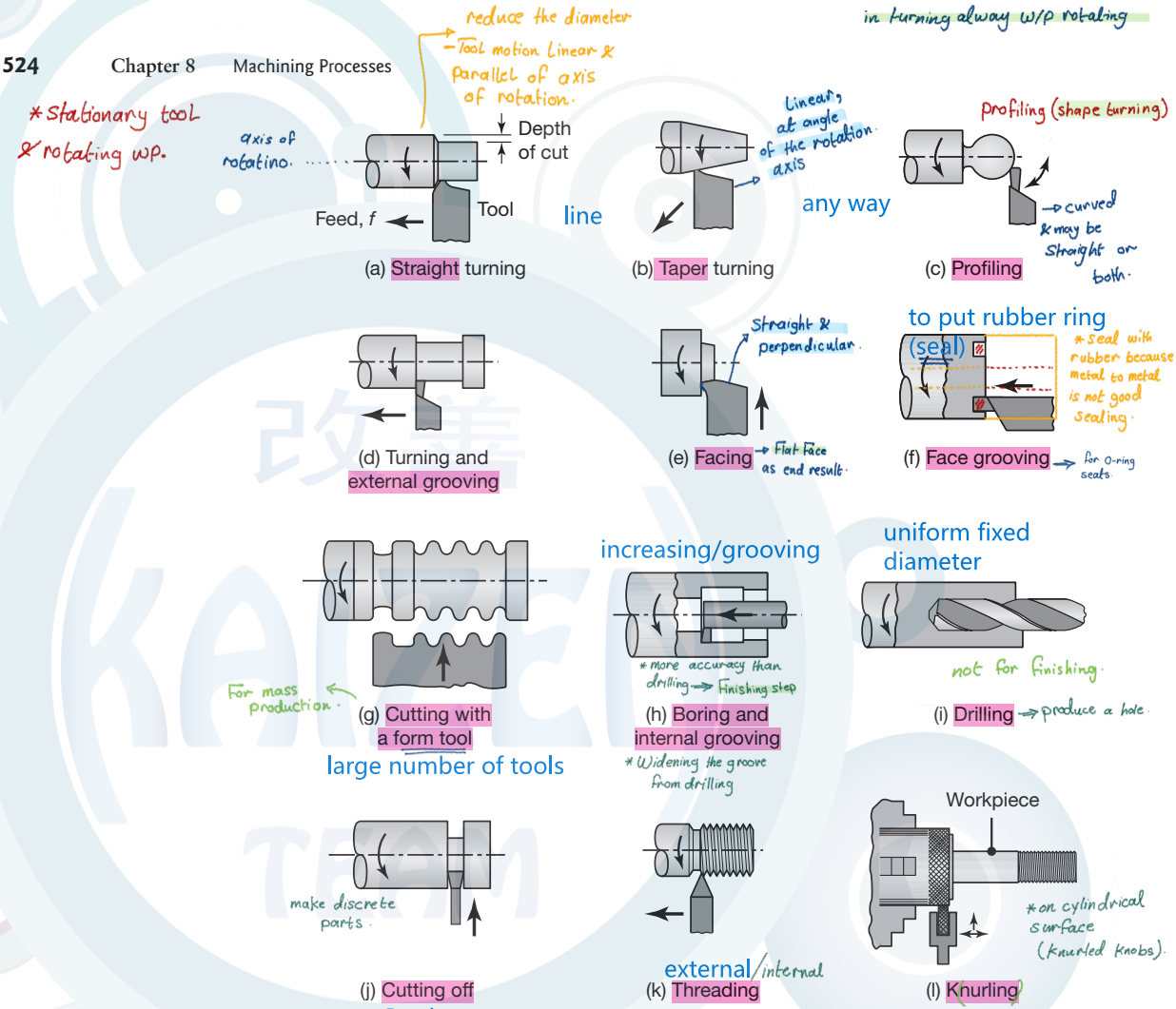


FIGURE 8.37 Examples of the wide variety of machining operations that can be performed on a lathe and similar machine tools.

These machining operations may be performed at various rotational speeds of the workpiece, depths of cut, d, and feed, f (See Fig. 8.19), depending on the workpiece and tool materials, the surface finish and dimensional accuracy required, and the capacity of the machine tool.

Roughing cuts are performed for large-scale material removal, and typically involve depths of cut greater than 0.5 mm and feeds on the order of 0.2–2 mm/rev. **Finishing cuts** usually involve smaller depths of cut and feed. Most machining operations consist of roughing cuts to define the part shape, followed by a finishing cut to meet specific dimensional tolerances and surface finish requirements.

8.9.1 Turning Parameters

Parameters that affect machinability:
- Tool Geometry → Faces & Angles
- Material removing rate → depth of cut & feed rate
- Forces in turning
- Tool material, feeds, cutting speeds

The majority of turning operations involve the use of *single-point* cutting tools. Figure 8.38 shows the geometry of a typical right-hand cutting tool for turning; such tools are identified by a standardized nomenclature. Each group of tool and workpiece materials has an optimum set of tool angles, that have been developed through many years of industrial experience. Some data on tool geometry can be found in Table 8.8.

1. **Tool geometry.** The various angles on a cutting tool have important functions in machining operations. (a) **Rake angles** are important in controlling the direction of chip flow and in the strength of the tool

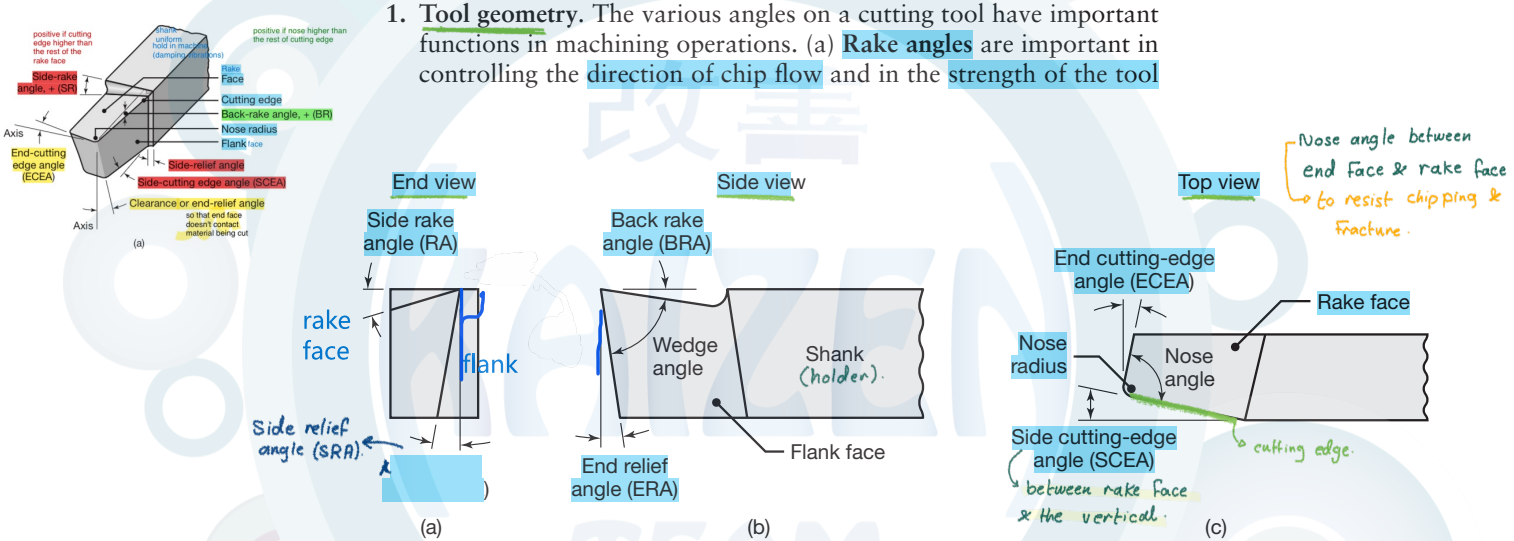


FIGURE 8.38 Designations and symbols for a right-hand cutting tool. The designation "right hand" means that the tool travels from right to left, as shown in Fig. 8.19.

Large (+ve) rake angle ⇒ small included angle, less strength.
or large Relief angle.

TABLE 8.8 General recommendations for tool angles (in degrees) in turning.

	High-speed steel					Carbide 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 and 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	5	8–10	5	5	15	−5–0	−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	0	0	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
Thermosets	0	0	20–30	15–20	10	0	15	5	5	15

tip. Positive-rake angles improve the cutting operation by reducing forces and temperatures; however, positive angles also have a small included angle of the tool tip (See Fig. 8.2). Depending on the toughness of the tool material, a small included angle may cause premature tool chipping and failure. (b) **Side-rake angle** is more important than **back-rake angle**, although the latter usually controls the direction of chip flow. (c) **Relief angles** control interference and rubbing at the tool-workpiece interface. If the relief angle is too large, the tool tip may chip off, and if it is too small, flank wear may be excessive. (d) **Cutting-edge angles** affect chip formation, tool strength, and cutting forces. (e) **Nose radius** affects surface finish and tool-tip strength. The smaller the radius, the rougher the surface finish of the workpiece, and the lower the strength of the tool; on the other hand, large nose radii can lead to tool chatter (see Section 8.12).

2. **Material-removal rate**. The *material-removal rate* (MRR) is the volume of material removed per unit time, such as mm^3/min. Referring to Fig. 8.39a, note that for each revolution of the workpiece, a ring-shaped layer of material is removed; its cross-sectional area is the product of the axial distance the tool travels in one revolution (known as the feed, f) and the depth of cut, d. The volume of this ring is the product of the cross-sectional area (fd) and the average circumference of the ring (πD_{avg}), where $D_{avg} = (D_o + D_f)/2$. For light cuts on large-diameter workpieces, the average diameter can be replaced by D_o.

The material-removal rate per revolution is $\pi D_{avg} df$. Since the rotational speed of the workpiece is N revolutions per minute, the removal rate is

$$\text{MRR} = \pi D_{avg} df N. \tag{8.38}$$

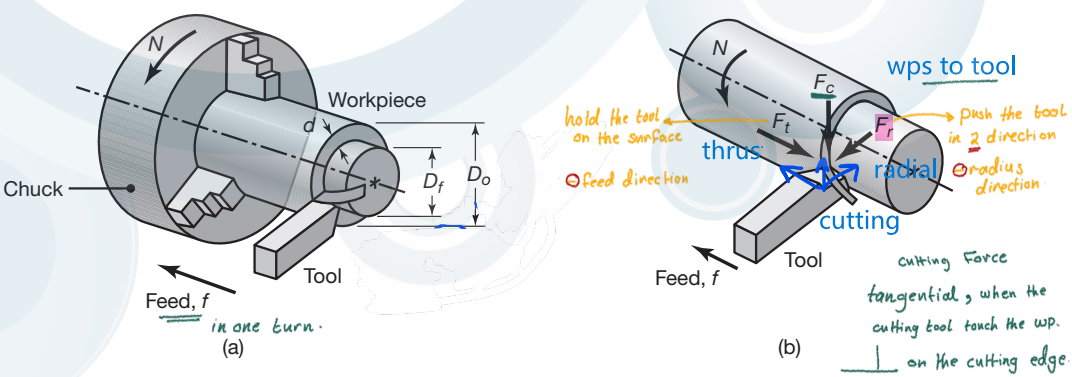


FIGURE 8.39 (a) Schematic illustration of a turning operation, showing depth of cut, d, and feed, f. Cutting speed is the surface speed of the workpiece at the tool tip. (b) Forces acting on a cutting tool in turning. F_c is the cutting force; F_t is the thrust or feed force (in the direction of feed); and F_r is the radial force that tends to push the tool away from the workpiece being machined. Compare this figure with Fig. 8.11 for a two-dimensional cutting operation.

Similarly, the cutting time, t, for a workpiece of length l can be calculated by noting that the tool travels at a *feed rate* of fN = (mm/rev)(rev/min) = mm/min. Since the distance traveled is l mm, the cutting time is

$$t = \frac{\text{Distance}}{\text{Velocity}} = \frac{(\text{length of cut})}{(\text{linear speed})} = t = \frac{l}{fN}. \quad (8.39)$$

The cutting time does not include (a) the time required for *tool approach*; and (b) *retraction* during the overall machining operation. Using computer controls, modern machine tools are designed and constructed to minimize the *nonproductive time*. A typical method employed in practice is to first quickly move the tool and then to slow it down as the tool engages with the workpiece.

3. **Forces in turning.** The three principal forces acting on a cutting tool in turning are illustrated in Fig. 8.39b. These forces are important in the design of machine tools and in determining the tool deflection, which is especially important in precision machining operations. The *cutting force*, F_c, acts downward on the tool and thus tends to deflect the tool downward; note that the cutting force is the force that supplies the energy required for the cutting operation. As can be seen in Example 8.4, the cutting force can be calculated (a) from the energy per unit volume of material machined, described in Section 8.2.5; and (b) by using the data given in Table 8.3.

   The *thrust force*, F_t, acts in the longitudinal direction; this force is also called the *feed force* because it is in the feed direction. The *radial force*, F_r, is in the radial direction; it tends to push the tool away from the workpiece.

4. **Tool materials, feeds, and cutting speeds.** The general characteristics of cutting-tool materials are described in Section 8.6. Figure 8.40

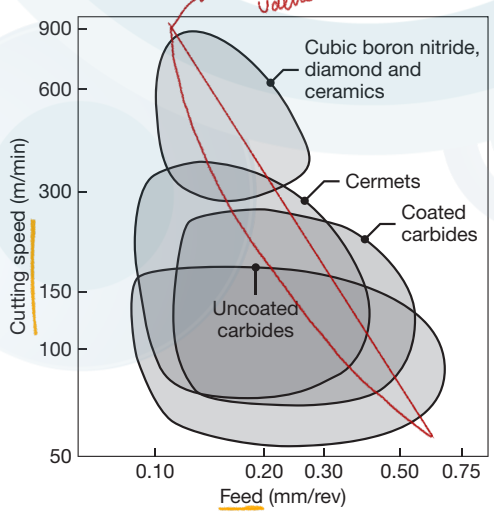


FIGURE 8.40 The range of applicable cutting speeds and feeds for a variety of cutting-tool materials.

Workpiece material	Cutting speed m/min
Aluminum alloys	200–1000
Cast iron, gray	60–900
Copper alloys	50–700
High-temperature alloys	20–400
Steels	50–500
Stainless steels	50–300
Thermoplastics and thermosets	90–240
Titanium alloys	10–100
Tungsten alloys	60–150

Note: (a) The speeds given in this table are for carbides and ceramic cutting tools. Speeds for high-speed steel tools are lower than indicated. The higher ranges are for coated carbides and cermets. Speeds for diamond tools are significantly higher than any of the values indicated in the table.

Tangential speed $V = \pi D N$ (m/min) ← max D_o, min D_f.

time = (L) / axial speed) min.

$MRR = \left(\frac{\text{axial speed}}{N}\right)\left(\frac{D_o - D_f}{2}\right).\pi\left(\frac{D_o + D_f}{2}\right).N.$

$= f.d.\pi.D_{avg}.N \quad (mm^3/min)$

$\text{Power} = \frac{(\text{specific energy})(MRR)}{60\,(s)} = \frac{(\frac{J}{mm^3})(\frac{mm^3}{min})}{60(\frac{s}{min})} = \frac{J}{s} = W$

$T = \frac{\text{Power}}{N\left(\frac{2\pi}{60s}\right)} = Nm.$, $P = VF$

$F_c = \frac{P\,(\frac{N.m}{s})}{V(\frac{m}{s})} = N = \frac{T\,(2)}{(D_{avg})} = kN$

* EXAMPLE 8.4 Material-Removal Rate and Cutting Force in Turning

Given: A 150-mm-long, 10-mm-diameter, 304 stainless-steel rod is being reduced in diameter to 8 mm by turning on a lathe. The spindle rotates at $N = 400$ rpm, and the tool is traveling at an axial speed of 200 mm/min.

so feed :

$200\frac{mm}{min} = (\text{feed})(400\frac{rev}{min})$

$\text{feed} = 0.5\frac{mm}{rev}$.

Find: Calculate the cutting speed, material-removal rate, cutting time, power dissipated, and cutting force.

Solution: The cutting speed is the tangential speed of the workpiece. The maximum cutting speed is at the outer diameter, D_o, and is obtained from the expression

$$V = \pi D_o N.$$

Thus,

$$V = (\pi)(0.010)(400) = 12.57 \text{ m/min}.$$

The cutting speed at the machined diameter is

$$V = (\pi)(0.008)(400) = 10.05 \text{ m/min}.$$

From the information given, note that the depth of cut is

$$d = \frac{10 - 8}{2} = 1 \text{ mm} = 0.001 \text{ m},$$

and the feed is

$$f = \frac{200}{400} = 0.5 \text{ mm/rev} = 0.0005 \text{ m/rev}.$$

H.W :

$P = VF \longrightarrow V = \frac{m}{s}$, $F.N \rightarrow P = \frac{N.m}{s}$

$F = \frac{P}{V} \longrightarrow \frac{(386\ N.m/s)}{(10.05\ m/min)(\frac{1\ min}{60\ s})} = 2.3\ kN.$

Thus, according to Eq. (8.38), the material-removal rate is

$$\text{MRR} = (\pi)(9)(1)(0.5)(400) = 5655 \text{ mm}^3/\text{min}.$$

The actual time to cut, according to Eq. (8.39), is

$$t = \frac{150}{(0.5)(400)} = 0.75 \text{ min}.$$

length of the cut. (not always length of the wp).

The power required can be calculated by referring to Table 8.3 and taking an average value for stainless steel as 4.1 W-s/mm^3. Therefore, the power dissipated is

$\frac{W\text{-}s}{mm^3} = \frac{J}{mm^3}$ → specific energy.

$$\text{Power} = \frac{(4.1)(5655)}{60} = 386 \text{ W}.$$

$\frac{J}{s} = W$

The cutting force, F_c, is the tangential force exerted by the tool. Since power is the product of torque, T, and rotational speed in radians per unit time, we have

same magnitude as exerted by wp. but opposite direction.

power = T.ω

$\omega = N * (\frac{\text{radial}}{s})$

$$T = \frac{(386)}{(400)(2\pi/60)} = 9.2 \text{ Nm}.$$

Since $T = (F_c)(D_{avg}/2)$,

Distance = from the center of rotation to the point of action of the force (radius).

D_{avg} → R_{avg}.

$$F_c = \frac{(9.2)(2)}{(0.009)} = 2.0 \text{ kN}.$$

components, using polycrystalline cubic-boron-nitride (PcBN) tools. Called *hard turning*, this process produces machined parts with good dimensional accuracy, surface finish, and surface integrity. It has been shown that it can compete successfully with grinding the same components, from both technical and economic aspects. A comparative example of hard turning vs. grinding is given in Example 9.4.

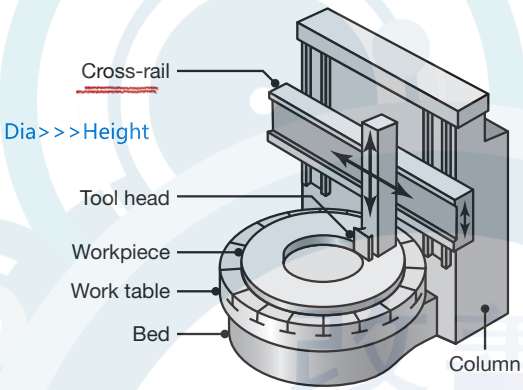
6. **Cutting screw threads.** External threads are produced primarily by (a) *thread rolling* (See Fig. 6.42), but also by (b) cutting, as shown in Fig. 8.37k. When threads are produced externally or internally by cutting, the process is called *thread cutting* or *threading*. When the threads are cut internally with a special threaded tool (*tap*), the process is called *tapping*. External threads may also be cut with a die or by milling. Although it adds considerably to the cost of the operation, threads also may be ground for high accuracy and surface finish.

Automatic screw machines are designed for machining of screws and similar threaded parts at high production-rates. Because these machines are also capable of producing other components, they are generally called *automatic bar machines*. All operations are performed automatically, with tools clamped to a special turret. The bar stock is automatically fed forward through an opening in the headstock, after each screw or part is machined to finished dimensions and then cut off. The machines may be equipped with single or multiple spindles, and capacities range from 3–150-mm diameter bar stock.

8.9.3 Boring and Boring Machines

The basic *boring* operation, shown in Fig. 8.37h, consists of producing circular internal profiles in hollow workpieces and enlarging or finishing a hole made by another process, such as drilling. It is carried out using cutting tools that are similar to those used in turning. Note that the boring bar has to reach the full length of the bore, thus tool deflection and maintaining dimensional accuracy can be a concern. The boring bar must also be sufficiently stiff, and is made of a material with high elastic modulus (such as carbides) to minimize deflection and avoid vibration and chatter. Boring bars have been designed with capabilities for damping vibrations (see Section 8.12).

Although boring operations on relatively small workpieces can be carried out on a lathe, **boring mills** are used for large workpieces. These machines are either vertical or horizontal in design and are also capable of performing such operations as turning, facing, grooving, and chamfering. A *vertical boring machine* (Fig. 8.44) is similar to a lathe, but with a vertical axis of workpiece rotation. In *horizontal boring machines*, the workpiece is mounted on a table that can move horizontally, in both axial and radial directions. The cutting tool is mounted on a spindle that rotates in the headstock, and is capable of both vertical and longitudinal movements. Drills, reamers, taps, and milling cutters can also be mounted on the spindle.



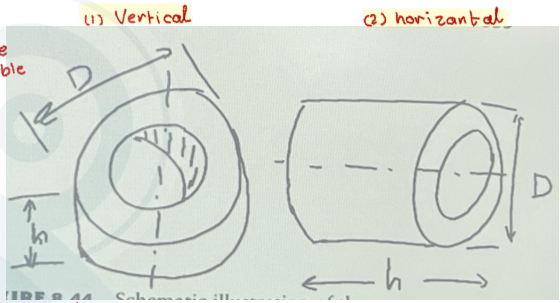


FIGURE 8.44 Schematic illustration of the components of a vertical boring mill.

8.9.4 Drilling, Reaming, and Tapping

One of the most common machining processes is *drilling*. **Drills** typically have a high length-to-diameter ratio (Fig. 8.45) and are capable of producing deep holes. They are, however, somewhat flexible, depending on their length and diameter. Moreover, note that chips produced move through the flutes in a direction opposite to the axial movement of the drill; consequently, chip disposal in drilling and selecting an effective cutting fluid are important.

The most common drill is the standard-point twist drill (Fig. 8.45). The main features of the drill point are the *point angle*, the *lip-relief angle*, the *chisel-edge angle*, and the *helix angle*. The geometry of the drill tip is such that the normal rake angle and the velocity of the cutting edge vary with the distance from the center of the drill. Other types of drills include the *step drill*, *core drill*, *counterboring* and *countersinking drills*, *center drill*, and *spade drill* (See Fig. 8.46).

Crankshaft drills have good centering ability, and because the chips they produce tend to break up easily, they are suitable for drilling deep holes. In *gun drilling*, a special drill is used for drilling deep holes; depth-to-diameter ratios produced can be 300 or higher. In the *trepanning* technique, a cutting tool produces a hole by removing a disk-shaped piece of material (*core*), usually from flat plates; the hole is produced without reducing all the material to be removed to chips. The trepanning process can be used to make disks up to 150 mm in diameter from flat sheet or plate.

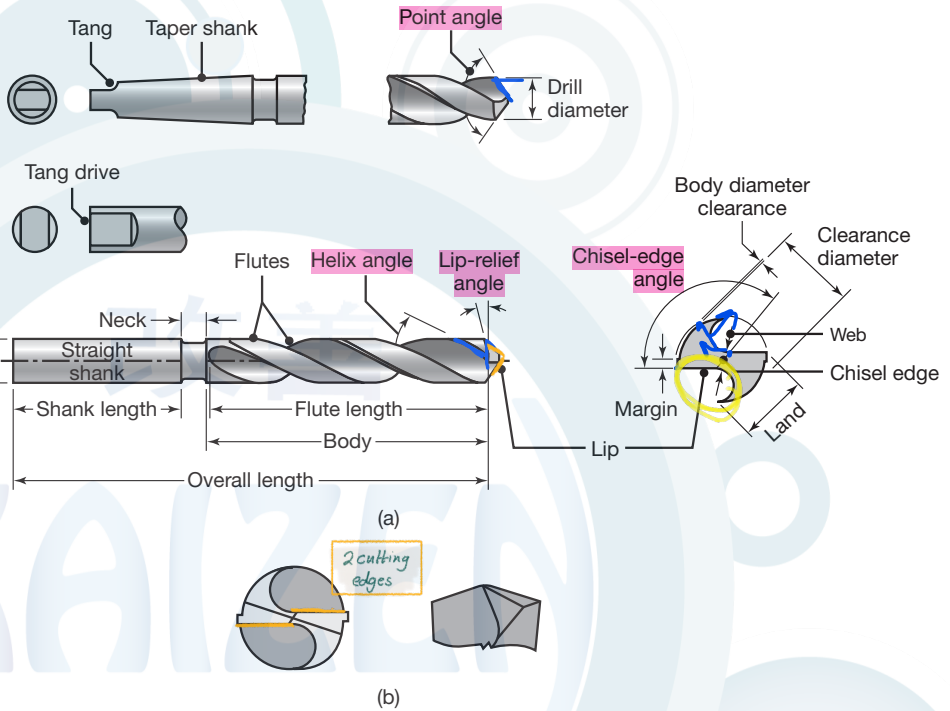
The *material-removal rate* in drilling can be expressed as

$$\text{MRR} = \frac{\pi D^2}{4} f N, \qquad (8.40)$$

where D is the drill diameter, f is the feed (in mm/revolution), and N is the rpm of the drill. Recommendations for speed and feed in drilling are given in Table 8.11.

The *thrust force* in drilling is the force that acts in the drilling direction; if excessive, this force can cause the drill to bend and break. The thrust

rake angle and velocity **



$V_c = \pi (D) N$

not constant
change with changing the distance.

N: constant.
D: vary with distance from the center. (Not constant).

FIGURE 8.45 Two common types of drills: (a) Chisel-point drill. The function of the pair of margins is to provide a bearing surface for the drill against walls of the hole as it penetrates into the workpiece. Drills with four margins (double-margin) are available for improved drill guidance and accuracy. Drills with chip-breaker features are also available. (b) Crankshaft drill. These drills have good centering ability, and because chips tend to break up easily, they are suitable for producing deep holes.

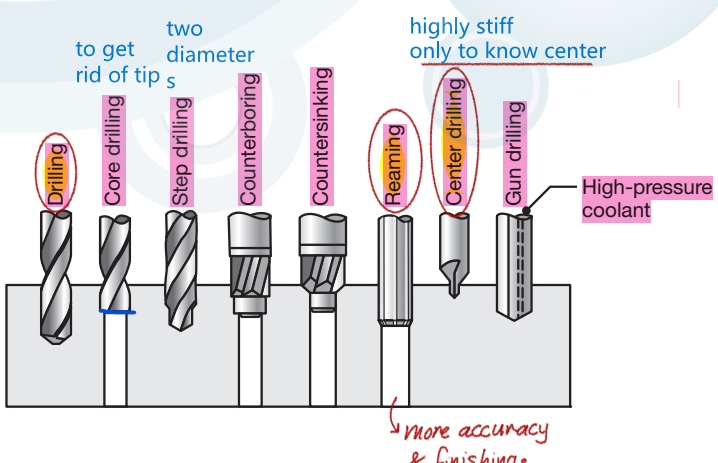
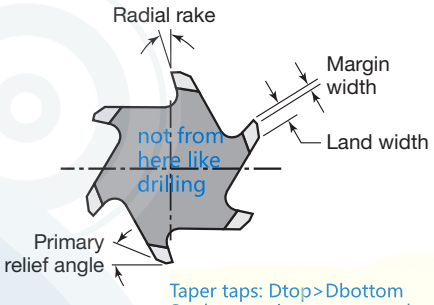


FIGURE 8.46 Various types of drills and drilling operations.

Reaming and reamers. *Reaming* is an operation that makes an existing hole dimensionally more accurate than can be achieved by drilling alone; it also improves the surface finish of the hole. The most accurate holes are produced by the following sequence of operations: centering, drilling, [1] [2]

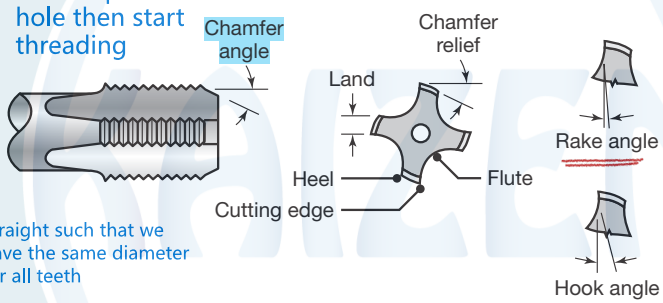


not from here like drilling

FIGURE 8.47 Terminology for a helical reamer.

Taper taps: Dtop>Dbottom
So that tapping occurs gradually reducing th torque.
so friction and contact between the tap and wps is not through the hole length of tap

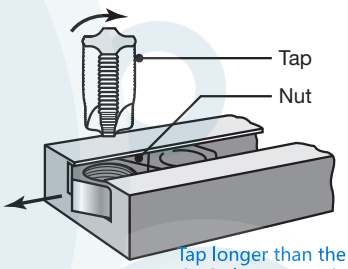
To take place in the hole then start threading



Straight such that we have the same diameter for all teeth

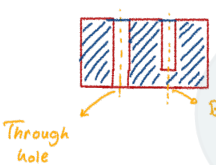
(a)

4 flutes



Tap longer than the depth of the hole so even though it has diff diameters we will get a uniform diameter of threads

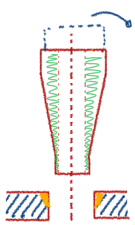
(b)



* tapping should always be used with lubrication, because of the high friction.

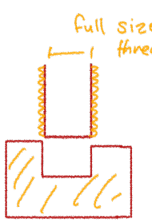
FIGURE 8.48 (a) Terminology for a tap; (b) illustration of tapping of steel nuts in high production.

[3] [4]
boring, and reaming. For even better dimensional accuracy and surface finish, holes may be internally *ground* and *honed* (see Section 9.7). A *reamer* (Fig. 8.47) is a multiple-cutting-edge tool with straight or helically fluted edges that removes very little material. The shanks may be straight or tapered, as they are in drills. The basic types of reamers are *hand* and *machine (chucking)* reamers; other types include *rose* reamers, with cutting edges that have wide margins and no relief angle, and *fluted, shell, expansion,* and *adjustable* reamers.



* use the tapered taps, → in the first the amount of material removed is small so will use less torque, less force than starting with the full-size.

Tapping and taps. Internal threads can be produced by *tapping*; a **tap** is basically a threading tool with multiple cutting teeth (Fig. 8.48). Taps are typically available with three or four flutes; three-fluted taps are stronger because their flute is wider. *Tapered taps* are designed to reduce the torque required for tapping through-holes, and *bottoming taps* are designed for tapping blind holes to their full depth. *Collapsible taps* are used for large-diameter holes; after tapping is completed, the tap is mechanically collapsed and removed from the hole, without having to be rotated. Tap sizes range up to 100 mm.



* bottoming tap, straight, true size high force & torque



much easier to set up & remove. — less torque.

8.10 Cutting Processes and Machine Tools for Producing Various Shapes

Several machining processes and machine tools are used for producing complex shapes, typically with the use of multitooth cutting tools (Fig. 8.49 and Table 8.7).

8.10.1 Milling Operations

Milling includes a number of versatile machining operations that use a **milling cutter**, a multitooth tool that produces a number of chips per revolution, to machine a wide variety of part geometries. Parts such as the ones shown in Fig. 8.49 can be machined efficiently and repetitively using various milling cutters.

The basic types of milling operations are described as follows.

1. **Slab milling.** In *slab milling*, also called **peripheral milling**, the axis of cutter rotation is parallel to the surface of the workpiece to be machined, as shown in Fig. 8.50a. The cutter, called a *plain mill*, has a number of teeth along its periphery, each tooth acting as a single-point cutting tool. Cutters used in slab milling may have *straight* or *helical* teeth, producing an orthogonal or an oblique cutting action, respectively. Figure 8.1c shows the helical teeth on a milling cutter.

   In **conventional milling**, also called *up milling*, the maximum chip thickness is at the end of the cut (Fig. 8.50b). The advantages of conventional milling are that tooth engagement is not a function of workpiece geometry, and contamination or scale on the surface does not affect tool life. The machining process is smooth, provided that

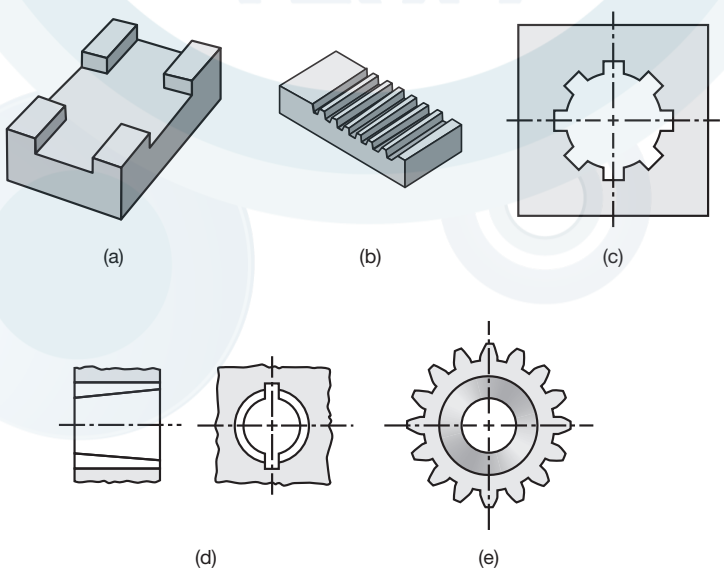


FIGURE 8.49 Typical parts and shapes produced by the machining processes described in Section 8.10.

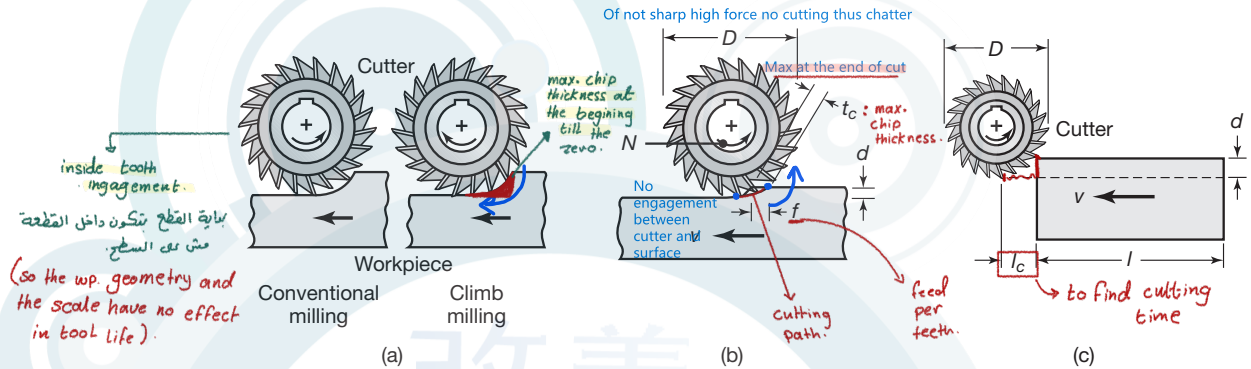


FIGURE 8.50 (a) Illustration showing the difference between conventional milling and climb milling. (b) Slab-milling operation, showing depth of cut, d; feed per tooth, f; chip depth of cut, t_c and workpiece speed, v. (c) Schematic illustration of cutter travel distance, l_c, to reach full depth of cut.

the cutter teeth are sharp. There is, however, a tendency for the tool to chatter, and for the workpiece to be pulled away from the surface, and thus proper clamping is important.

In **climb milling**, also called *down milling*, cutting starts at the thickest location of the chip. The advantage of climb milling is that the downward component of cutting forces holds the workpiece in place, particularly for slender parts. However, because of the resulting high-impact forces when the teeth first engage the workpiece, this operation requires a rigid setup, and backlash in the table feed mechanism must be eliminated. Climb milling is not suitable for machining workpieces that have surface scale, such as hot-worked metals, forgings, and castings; the scale is hard and abrasive, and causes excessive wear and damage to the cutter teeth. In general, climb milling is recommended for applications such as finishing cuts on aluminum workpieces.

The cutting speed in milling, V, is the peripheral speed of the cutter, that is,

$$V = \pi DN, \tag{8.41}$$

where D is the cutter diameter and N is the rotational speed of the cutter (Fig. 8.50b). Note that the thickness of the chip in slab milling varies along its length, because of the relative longitudinal movement between the cutter and the workpiece. For a straight-tooth cutter, the approximate *undeformed chip thickness*, t_c (called *chip depth of cut*), can be determined from the equation

$$t_c = 2f\sqrt{\frac{d}{D}}, \tag{8.42}$$

where f is the feed per tooth of the cutter (measured along the workpiece surface, that is, the distance the workpiece travels per tooth of

the cutter, in mm/tooth), and d is the depth of cut. With increasing t_c, the force on the cutter tooth also increases.

Feed per tooth is determined from the equation

$$f = \frac{v}{Nn}, \tag{8.43}$$

where v is the linear speed (feed rate) of the workpiece and n is the number of teeth on the cutter periphery. The dimensional accuracy of this equation can be checked by substituting appropriate units for the individual terms; thus, (mm/tooth) = (m/min)(10^3 mm/m)/(rev/min)(number of teeth/rev), which is correct. The cutting time, t, is given by the expression

$$t = \frac{l + 2l_c}{v}, \tag{8.44}$$

where l is the length of the workpiece (Fig. 8.50c) and l_c is the extent of the cutter's first contact with the workpiece. Based on the assumption that $l_c \ll l$ (although this may not be always reasonable), the *material-removal rate* is

$$\text{MRR} = \frac{lwd}{t} = wdv, \tag{8.45}$$

where w is the width of the cut, which is the same as the workpiece width if it is narrower than the cutter. The distance that the cutter travels in the noncutting-cycle of the operation is an important economic consideration and should be minimized.

2. **Face milling.** In this operation, the cutter is mounted on a spindle with an axis of rotation perpendicular to the workpiece surface, and removes material in the manner shown in Fig. 8.51a. The cutter rotates at a speed of N, and the workpiece moves along a straight path and at a linear speed of v. When the cutter rotates in the direction shown in Fig. 8.51b, the operation is called *climb milling*; when it rotates in the opposite direction (Fig. 8.51c), it is *conventional milling*.

Because of the relative movement between the cutting teeth and the workpiece, a face-milling cutter leaves *feed marks* on the machined surface, much as in turning operations (See Fig. 8.19). Surface roughness depends on insert corner geometry and feed per tooth [see also Eqs. (8.35) to (8.37)].

The terminology for a face-milling cutter and its various angles is given in Fig. 8.52; the side view of the cutter is shown in Fig. 8.53. Note that, (a) as in turning operations, the *lead angle* of the insert has a direct influence on the *undeformed chip thickness*; (b) as the lead angle (positive, as shown in the figure) increases, the undeformed chip thickness (thus also the thickness of the actual chip) decreases; (c) the length of contact increases; and (d) the cross-sectional area of the undeformed chip remains constant. The range of lead angles

climb milling → thickness decrease.
conventional milling → thickness increases.

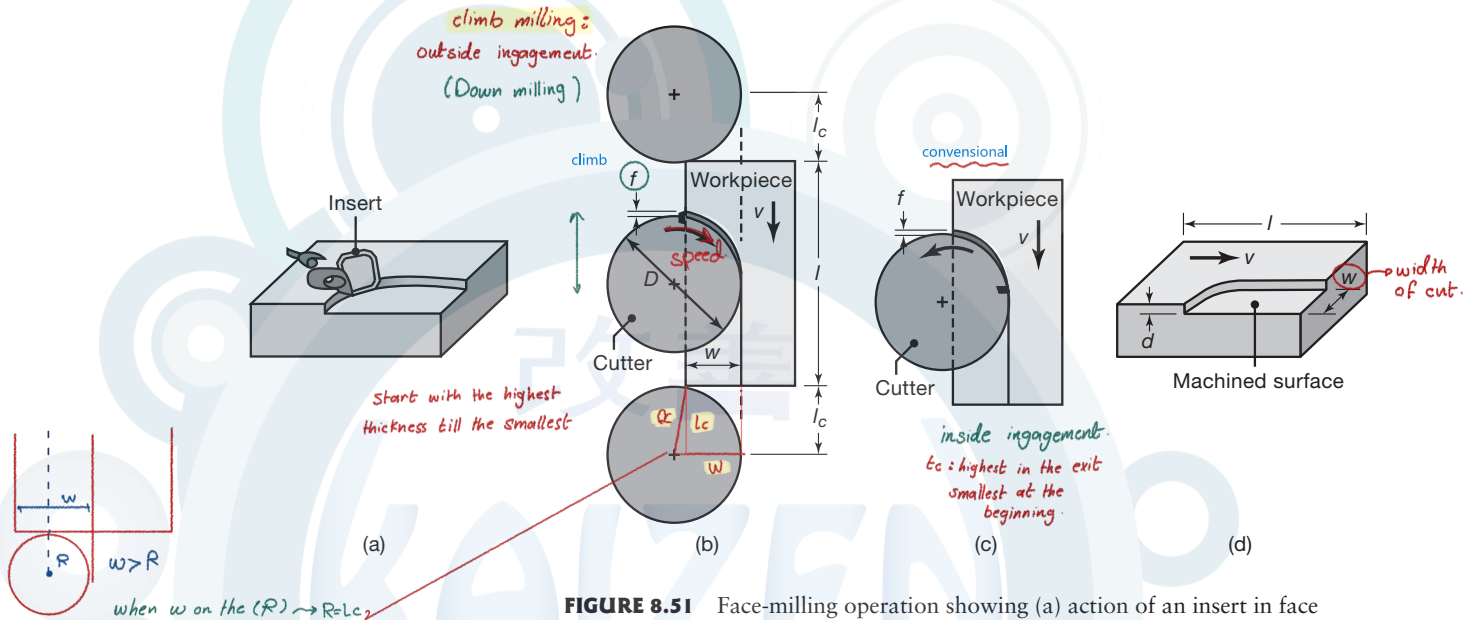


FIGURE 8.51 Face-milling operation showing (a) action of an insert in face milling with the cutter removed for clarity; (b) climb milling; (c) conventional milling; and (d) dimensions in face milling.

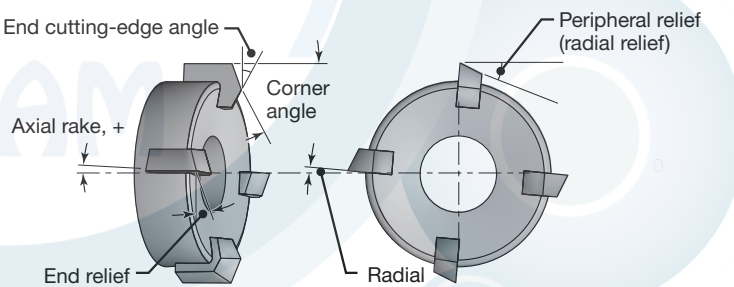
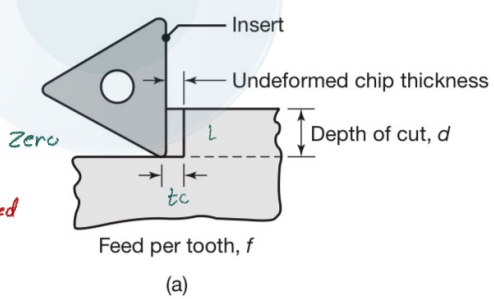


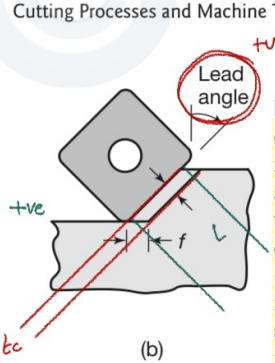
FIGURE 8.52 Terminology for a

MRR = Dipth, width, linear speed.
→ no effect from lead angle on the volume of material removed
effect just on the shape; the cross-sectional area.

*MRR = (depth of cut)(width of cut)·(Length/time)
↳ linear speed $\bar{v} = \frac{m}{min}$
m^3/min

2.





higher length but with smaller undeformed chip thickness (t_c). → the cross-section area constant.

FIGURE 8.53 The effect of lead angle on the undeformed chip thickness in face milling. Note that as the lead angle increases, the undeformed chip thickness (and hence chip thickness) decreases, and the length of contact (and hence the width of the chip) increases. Note that the insert must be sufficiently large to accommodate the increase in contact length.

3. **End milling.** The cutter in *end milling*, shown in Fig. 8.1d, has either a straight or a tapered shank for smaller and larger cutter sizes, respectively. The cutter usually rotates on an axis perpendicular to the workpiece, but it can be tilted to produce inclined surfaces. Some end mills have cutting teeth on their end faces, allowing the end mill to be used as a drill to start a cavity. End mills are also available with hemispherical ends (called *ball-nose end mills*), for producing curved surfaces, as in making molds and dies. *Hollow end mills* have *internal* cutting teeth and are used for machining the cylindrical surface of solid round workpieces, as in preparing stock with accurate diameters for automatic bar machines.

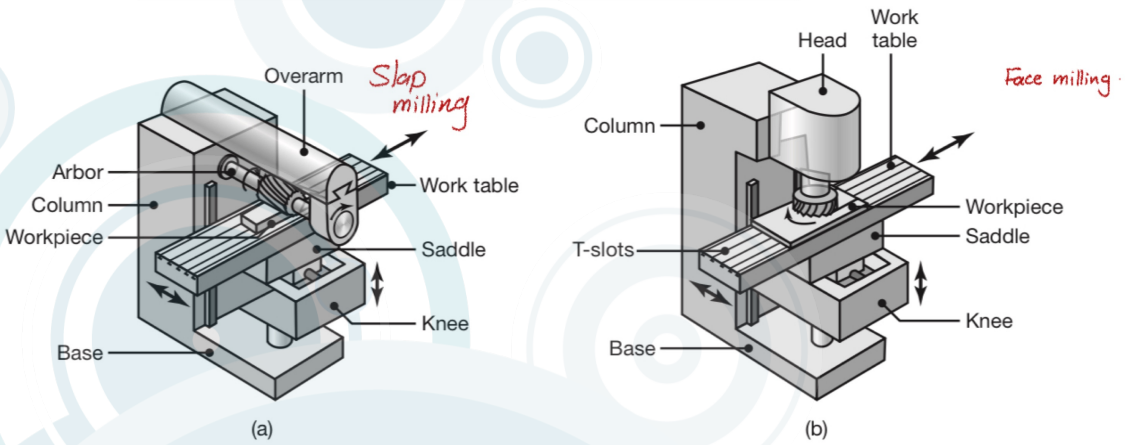


FIGURE 8.56 (a) Schematic illustration of a horizontal-spindle column-and-knee-type milling machine. (b) Schematic illustration of a vertical-spindle column-and-knee-type milling machine.

8.10.4 Broaching and Broaching Machines

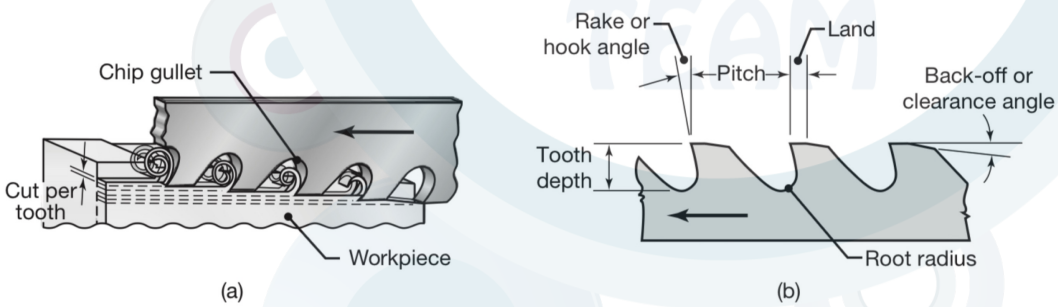


FIGURE 8.58 (a) Cutting action of a broach, showing various features. (b) Terminology for a broach.

Abrasive and Other Material Removal Processes

CHAPTER 9

9.1 Introduction

In all the machining operations described in detail in Chapter 8, the cutting tool is made of a certain material and has a clearly defined geometry. Moreover, the machining process involves chip removal, the mechanics of which can be fairly complicated. There are, however, many situations in manufacturing where the workpiece material is either *too hard* or *too brittle*, or its *shape* is difficult to produce with sufficient dimensional accuracy and surface finish by any of the machining methods described previously. One of the best methods for producing such parts is by using **abrasives**. An abrasive is a small, hard particle that has sharp edges and an irregular shape. Abrasives are capable of removing small amounts of material from a surface by a cutting process that produces tiny chips.

Abrasive machining processes are generally among the last operations performed on manufactured products, although they are not necessarily confined to fine or small-scale material removal from workpieces, and they can indeed compete economically with some of the machining processes described in Chapter 8. Because they are hard, abrasives are also suitable for (a) finishing very hard or heat-treated parts; (b) shaping hard nonmetallic materials, such as ceramics and glasses; (c) cutting off lengths of bars, structural shapes, masonry, and concrete; (d) cleaning surfaces, using jets of air or water containing abrasive particles; and (e) removing unwanted weld beads.

In addition to abrasive machining, several **advanced machining processes** have been developed, starting in the 1940s. Also called *nontraditional* or *unconventional* machining, these processes are based on electrical, chemical, fluid, and thermal principles, and are advantageous when:

1. The hardness and strength of the workpiece material is very high, typically above 400 HB.
2. The part is too flexible or slender to support the machining or grinding forces, or it is difficult to clamp in workholding devices.
3. The shape of the part is complex, such as internal and external features or deep small-diameter holes.
4. Surface finish and dimensional accuracy requirements are better than those obtainable by other processes.
5. Temperature rise or residual stresses developed in the workpiece is undesirable or unacceptable.

When selected and applied properly, advanced machining processes offer significant technological and economic advantages over the traditional machining methods.

9.2 Abrasives

The abrasives commonly used in manufacturing are:

1. **Conventional abrasives:**
   - *Aluminum oxide* (Al_2O_3);
   - *Silicon carbide* (SiC).
2. **Superabrasives:**
   - *Cubic boron nitride* (cBN);
   - *Diamond*.

The last two of the four abrasives listed above are the two hardest materials known, hence the term *superabrasives*. Abrasives are significantly harder than conventional cutting-tool materials, as can be seen by comparing Table 8.6 with Table 9.1. In addition to hardness, an important characteristic of an abrasive is **friability**, that is, the ability of an abrasive grain to fracture (break down) into smaller fragments. Friability gives abrasives *self-sharpening characteristics*, important in maintaining the cutting efficiency of the abrasives during use. High friability indicates low strength or low fracture resistance of the abrasive; thus, under the grinding forces, a highly friable abrasive grain fragments more rapidly than an abrasive grain with low friability. Aluminum oxide, for example, has lower friability than silicon carbide.

The shape and size of an abrasive grain also affect its friability. For example, blocky grains, which are analogous to negative-rake-angle cutting tools (Fig. 8.26), are less friable than plate-like grains. As for grain



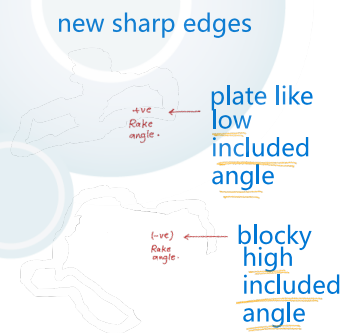




TABLE 9.1 Knoop hardness range for various materials and abrasives.

Material	Knoop hardness	Material	Knoop hardness
Common glass	350–500	Titanium nitride	2000
Flint, quartz	800–1100	Titanium carbide	1800–3200
Zirconium oxide	1000	Silicon carbide	2100–3000
Hardened steels	700–1300	Boron carbide	2800
Tungsten carbide	1800–2400	Cubic boron nitride	4000–5000
Aluminum oxide	2000–3000	Diamond	7000–8000

size, because the probability of defects existing in smaller grains is lower (due to the *size effect*; Section 3.8.3), they are stronger and less friable than larger grains. The importance of friability in abrasive machining is described further in Section 9.5.

Types of abrasives. Abrasives found in nature include *emery*, *corundum (alumina)*, *quartz*, *garnet*, and *diamond*. However, because natural abrasives contain unknown amounts of impurities and typically have nonuniform properties, their performance is inconsistent and unreliable. Consequently, aluminum oxides and silicon carbides abrasives are made synthetically, in order to produce high-performance abrasives with consistent behavior.

1. Synthetic **aluminum oxide** (Al_2O_3), first made in 1893, is made by fusing bauxite, iron filings, and coke. Aluminum oxide is divided into two groups: fused and unfused. **Fused aluminum oxide** is categorized as *white* (very friable), *dark* (less friable), and *monocrystalline* (single crystal). **Unfused alumina**, also known as *ceramic aluminum oxide*, can be harder than fused alumina. The purest form of fused alumina is seeded gel. First introduced in 1987, seeded gel has a particle size on the order of 0.2 μm, which is much smaller than abrasive grains commonly used in industry. Seeded gels are sintered (Section 11.4) to form larger sizes. Because of their hardness and relatively high friability, seeded gels maintain their sharpness and thus are used for difficult-to-grind materials.
2. **Silicon carbide** (SiC), first discovered in 1891, is made with silica sand, petroleum coke, and small amounts of sodium chloride. Silicon carbides are available in *green* (more friable) and in *black* (less friable) types. Silicon carbide generally has higher friability than aluminum oxide, hence a higher tendency to fracture and thus remain sharp longer.
3. **Cubic boron nitride** (cBN) was first produced in the 1970s. Its properties and characteristics are described in Section 11.8.1.
4. **Diamond** was first used as an abrasive in 1955. When produced synthetically, it is called *synthetic* or *industrial diamond*. Its properties and characteristics are described in Sections 8.6.9 and 11.13.2.

Grain size. As used in manufacturing operations, abrasives are generally very small compared with the size of typical cutting tools and inserts described in Section 8.6. Also, abrasives have sharp edges, thus allowing the removal of very small amounts of material from workpiece surfaces, resulting in very fine surface finish and dimensional accuracy (See Figs. 8.24 and 9.28). The size of an abrasive grain is identified by a grit number, which is a function of sieve size. The smaller the sieve size, the larger the grit number; for example, grit number 10 is rated as very coarse, 100 as fine, and 500 as very fine. As commonly observed, sandpaper and emery cloth also are identified in this manner, with the grit number printed on the back of the abrasive paper or cloth.

9.3 Bonded Abrasives

cutoff wheel

Bonded abrasives are typically in the form of a grinding wheel (Fig. 9.1). The abrasive grains are held together by a bonding material, various types of which are described in Section 9.3.1; the bonding material acts as supporting posts or braces between the grains. Some porosity is essential in bonded abrasives to provide cooling and clearance for the chips being produced, as otherwise the chips would interfere with the grinding operation. Porosity can easily be observed by looking at the surface of any grinding wheel with a magnifying glass or microscope. Other features of the grinding wheel shown in Fig. 9.1 are described in Sections 9.4 and 9.5.

Some of the more commonly used types of grinding wheels are shown in Fig. 9.2 for conventional abrasives, and in Fig. 9.3 for superabrasives. Note that, because of their associated high cost, superabrasives make up only a small portion of the periphery of the wheels. Bonded abrasives are marked with a standardized system of letters and numbers, indicating the type of abrasive, grain size, grade, structure, and bond type. Figure 9.4 shows the marking system for aluminum-oxide and silicon-carbide bonded abrasives, and Fig. 9.5 for diamond and cubic-boron-nitride bonded abrasives.

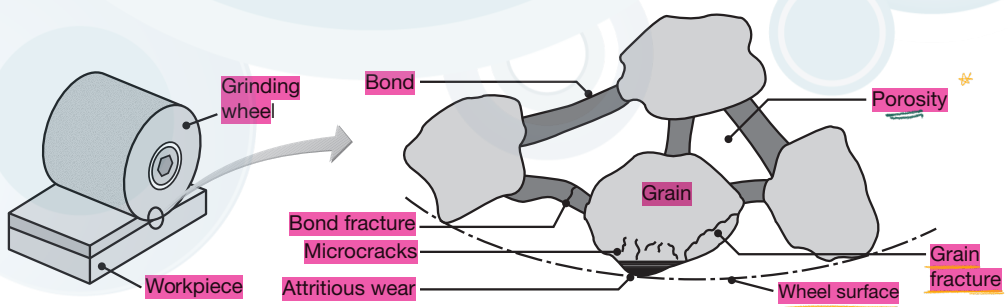


FIGURE 9.1 Schematic illustration of a physical model of a grinding wheel, showing its structure and grain wear and fracture patterns.

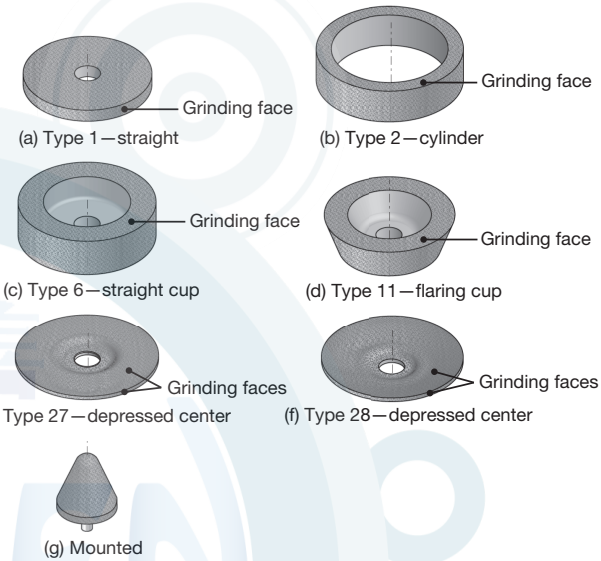


FIGURE 9.2 Some common types of grinding wheels made with conventional abrasives (aluminum oxide and silicon carbide). Note that each wheel has a specific grinding face; grinding on other surfaces is improper and unsafe.

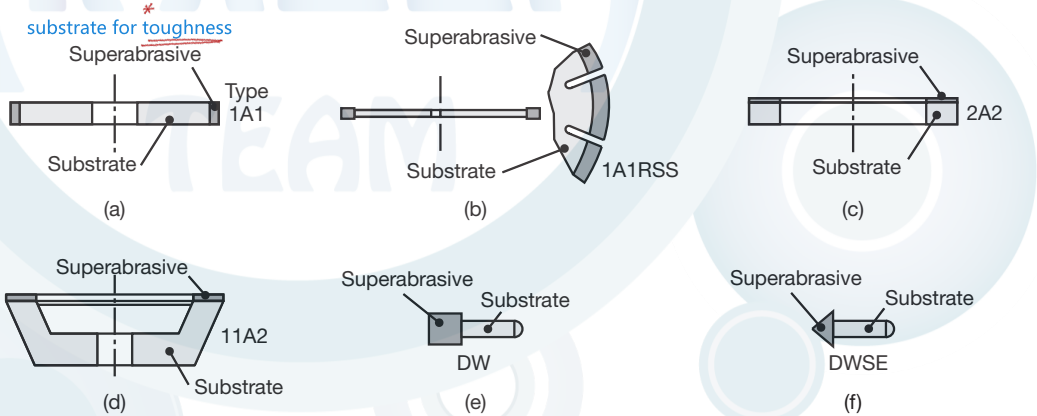


FIGURE 9.3 Examples of superabrasive wheel configurations. The rim consists of superabrasives and the wheel itself (core) is generally made of metal or composites. Note that the basic numbering of wheel types (such as 1, 2, and 11) is the same as that shown in Fig. 9.2. The bonding materials for the superabrasives are: (a), (d), and (e) resinoid, metal, or vitrified; (b) metal; (c) vitrified; and (f) resinoid.

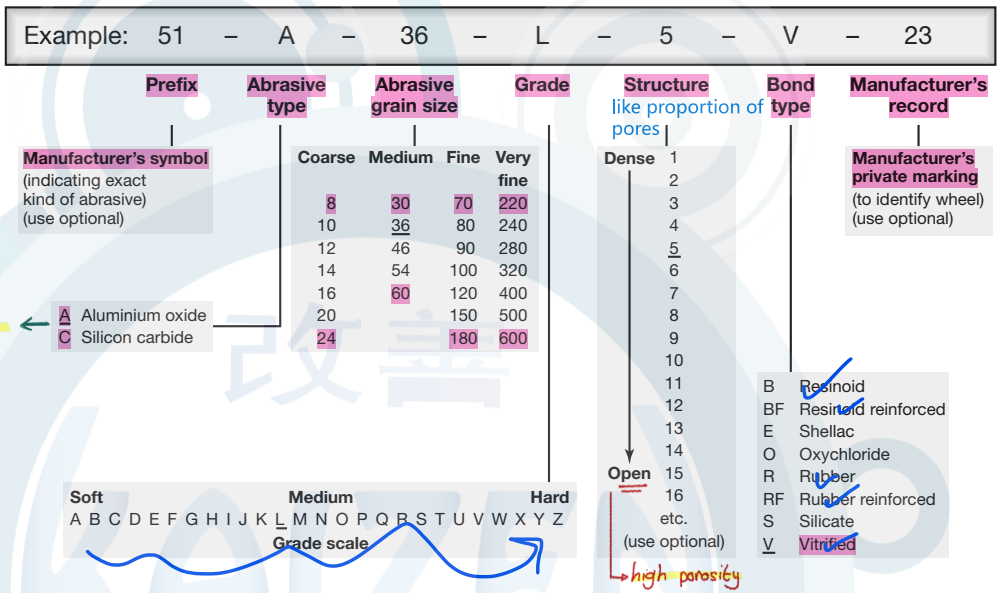


FIGURE 9.4 Standard marking system for aluminum-oxide and silicon-carbide bonded abrasives.

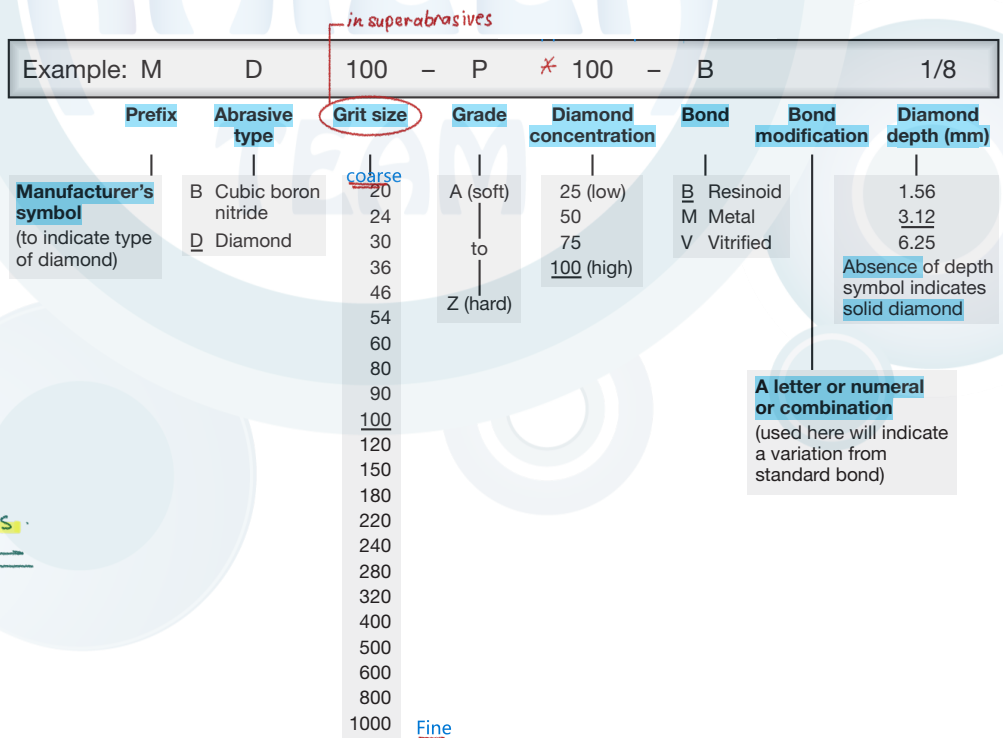


FIGURE 9.5 Standard marking system for diamond and cubic-boron-nitride bonded abrasives.

9.3.1 Bond Types

The common bond types for bonded abrasives are vitrified, resinoid, rubber, and metal, and are used for conventional abrasives as well as for superabrasives.

1. **Vitrified.** Essentially a glass, a *vitrified bond* is also called a *ceramic bond*, particularly outside the United States; it is the most common and widely used bond. The bond consists of feldspar (a crystalline mineral) and various clays. These materials are first mixed with the abrasives, moistened, and then molded under pressure into the shape of grinding wheels. These "green" products, similar to powder-metallurgy parts (Section 11.3), are then slowly fired, up to a temperature of about 1250°C, to fuse the glass and develop structural strength. The wheels are then cooled slowly, to prevent thermal cracking, then finished to size, inspected for quality and dimensional accuracy, and tested for defects.

   Vitrified bonds produce wheels that are strong, stiff, porous, and resistant to oils, acids, and water; however, because the wheels are brittle, they lack resistance to mechanical and thermal shock. Vitrified wheels are also available with steel backing plates or cups for better structural support during their use.

2. **Resinoid.** *Resinoid* bonding materials are *thermosets* (Section 10.4), and are available in a wide range of compositions and properties. Because the bond is an organic compound, these wheels are also called organic wheels. The basic manufacturing procedure consists of (a) mixing the abrasive with liquid or powdered phenolic resins and additives; (b) pressing the mixture into the shape of a grinding wheel; and (c) curing it at temperatures of about 175°C. Because the elastic modulus of thermosetting resins is lower than that of glasses, resinoid wheels are more flexible than vitrified wheels. *Polyimide* (Section 10.6) can be a substitute for the phenolic in resinoid wheels; the polymer is tough and has good resistance to high temperatures.

   Reinforced resinoid wheels consist of one or more layers of fiberglass mats of various mesh sizes, providing reinforcement. The main purpose of the reinforcement is to provide strength and prevent catastrophic failure of the wheel. Large-diameter wheels can additionally be supported with one or more internal rings (made of round steel bar) that are inserted during wheel production.

3. **Rubber.** The most flexible bond used in abrasive wheels is *rubber*. The wheels are made by (a) mixing crude rubber, sulfur, and abrasive grains together; (b) rolling the mixture into sheets; (c) cutting out circles; and (d) heating them under pressure to vulcanize the rubber. Thin wheels (called *cut-off blades*) are made in this manner, and are used like saws for cutting-off operations.

4. **Metal bonds.** Abrasive grains, usually diamond or cubic boron nitride, are bonded in a metal matrix to the periphery of a metal disc, typically to depths of 6 mm or less (See Fig. 9.3). Bonding is carried out under high pressure and temperature. The wheel itself (core)

may be made of aluminum, bronze, steel, ceramic, or composite material, depending on special requirements for the wheel, such as strength, stiffness, and dimensional stability. Superabrasive wheels may be layered so that a single abrasive layer is plated or brazed to a metal disc.

5. **Other types of bonds.** In addition to those described above, other types of bonds include *silicate*, *shellac*, and *oxychloride* bonds. These bonds are far less common, but use the same abrasives as other wheels.

9.3.2 Wheel Grade and Structure

The *grade* of a bonded abrasive is a measure of the strength of the bond, and it includes both the *type* and the *amount of bond* in the wheel. Because strength and hardness are directly related, the grade is also referred to as the *hardness* of a bonded abrasive; thus, a hard wheel has a stronger bond and/or a larger amount of bonding material than a soft wheel. The *structure* is a measure of the *porosity*, the spacing between the grains (Fig. 9.1) of the bonded abrasive. Some porosity is essential to provide space for the grinding chips as otherwise they would interfere with the grinding operation. The structure of bonded abrasives ranges from dense to open (Fig. 9.6).

9.4 Mechanics of Grinding

Grinding is a *chip removal process* in which the cutting tool is an individual abrasive grain. The following are major factors that differentiate the action of a single grain from that of a single-point cutting tool (See Fig. 8.2):

1. Conventional abrasive grains have an irregular geometry and are spaced randomly along the periphery of the wheel (Fig. 9.6). Newly developed shaped abrasives are available that provide less random and more aggressive machining surfaces.
2. The average rake angle of the grains is highly negative, typically −60° and lower, thus the shear angles are very low (Section 8.2.4).

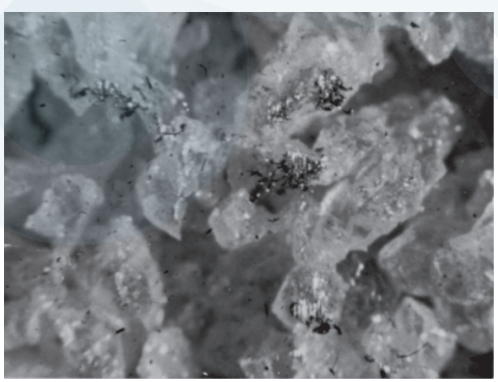


FIGURE 9.6 The grinding surface of an abrasive wheel (A46-J8V), showing grains, porosity, wear flats on grains (See also Fig. 9.7b), and metal chips from the workpiece adhering to the grains. Note the random distribution and shape of the abrasive grains. Magnification: 50×. *Source:* After S. Kalpakjian.

3. Depths of cut are very shallow, and chips are small and always discontinuous.
4. Temperatures are much higher in grinding than in metal cutting; the temperatures can be high enough for some chips to react with oxygen in air, often leading to 'sparks' (see Section 9.4.2).
5. The grains in the periphery of a grinding wheel have different radial positions from the center of the wheel.
6. The cutting speeds of grinding wheels are very high (Table 9.2), typically on the order of 30 m/s.

An example of chip formation by an abrasive grain is shown in Fig. 9.7. Note the negative rake angle, the low shear angle, and the very small size of the chip (see also Example 9.1). Grinding chips can easily be collected on an adhesive tape, which is held against the sparks of a grinding wheel; from direct observation of the tape, it will be noted that a variety of metal chips are produced in grinding.

The mechanics of grinding chip formation and the variables involved can best be studied by analyzing the *surface-grinding* operation shown in Fig. 9.9. In this figure, a grinding wheel, with a diameter of D, is removing a layer of material at a depth d, known as the **wheel depth of cut**.

TABLE 9.2 Typical ranges of speeds and feeds for abrasive processes.

Process variable	Conventional grinding	Creep-feed grinding	Buffing	Polishing
Wheel speed (m/min)	1500–3000	1500–3000	1800–3600	1500–2400
Work speed (m/min)	10–60	0.1–1	–	–
Feed (mm/pass)	0.01–0.05	1–6	–	–

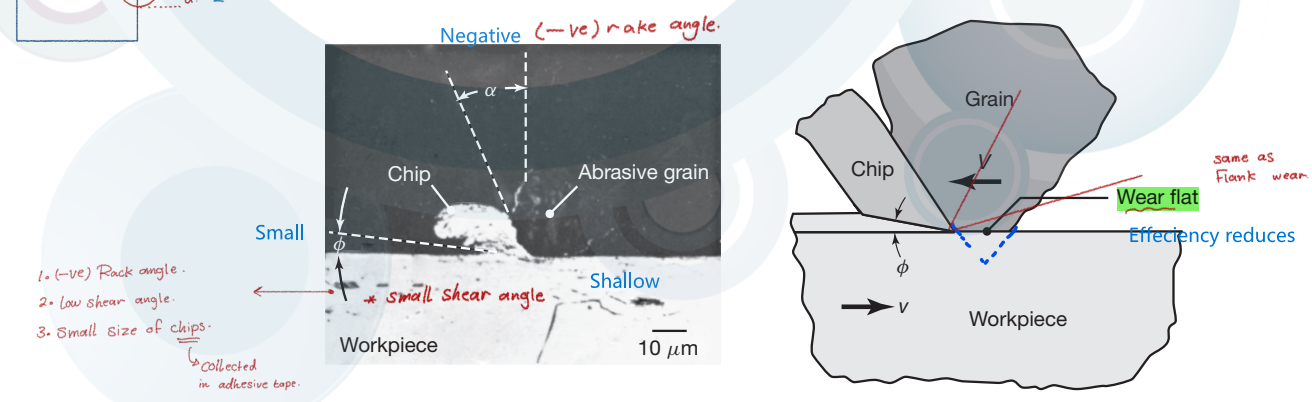
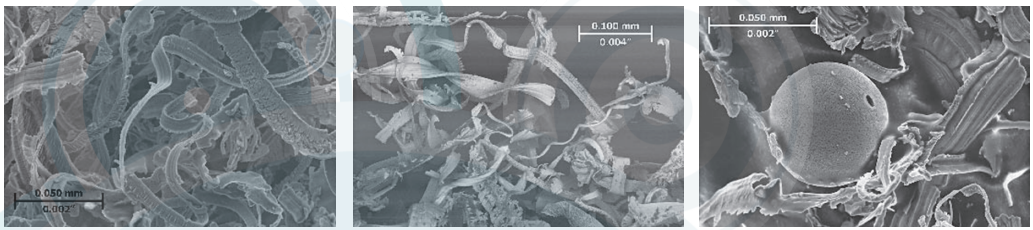


FIGURE 9.7 (a) Grinding chip being produced by a single abrasive grain. Note the large negative rake angle of the grain. *Source:* After M.E. Merchant. (b) Schematic illustration of chip formation by an abrasive grain. Note the negative rake angle, the small shear angle, and the wear flat on the grain.



(a) (b) (c)

melted chip Globule

high temp. with O_2

FIGURE 9.8 Typical chips, or swarf, from grinding operations. (a) Swarf from grinding a conventional HSS drill bit; (b) swarf from a tungsten carbide workpiece using a diamond wheel; and (c) swarf of cast iron, showing a melted globule among the chips. *Source:* Courtesy of J. Badger.

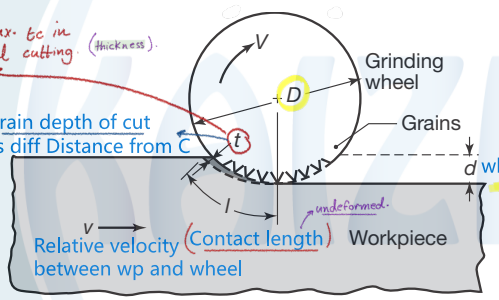


FIGURE 9.9 Basic variables in surface grinding. In actual grinding operations, the wheel depth of cut, d, and contact length, l, are much smaller than the wheel diameter, D. The dimension t is called the *grain depth of cut*.

An individual grain on the periphery of the wheel is rotating at a tangential velocity V; the workpiece is moving at a velocity v. As shown, it is called *up* or *conventional grinding* (see also *milling*, Section 8.10.1). The abrasive grain is removing a chip with an *undeformed thickness* (**grain depth of cut**), t, and an undeformed length, l.

Typical chips from grinding operations are shown in Fig. 9.8. Note that the chips, just as in machining, are thin and long. From geometric relationships, it can be shown that for the condition of $v \ll V$, the *undeformed-chip length*, l, is approximately

$$l \simeq \sqrt{Dd}. \tag{9.1}$$

For *external (cylindrical) grinding* (see Section 9.6),

$$l = \sqrt{\frac{Dd}{1 + (D/D_w)}}, \tag{9.2}$$

and for *internal grinding*,

$$l = \sqrt{\frac{Dd}{1 - (D/D_w)}}, \tag{9.3}$$

where D_w is the diameter of the workpiece.

The relationship between t and other process variables can be derived as follows: Let C be the number of cutting points per unit area of wheel surface, and v and V the surface speeds of the workpiece and the wheel, respectively (Fig. 9.9). Assuming the width of the workpiece to be unity, the number of grinding chips produced per unit time is VC, and the volume of material removed per unit time is vd.

Assume the chip shown in Fig. 9.9 has a triangular cross section with a base of t and a constant width of w. The volume of such a chip can be expressed as

$$\text{Vol}_{\text{chip}} = \frac{wtl}{2} = \frac{rt^2 l}{4}, \tag{9.4}$$

where r is the ratio of the chip width, w, to the average chip thickness. The volume of material removed per unit time is the product of the volume of each chip and the number of chips produced per unit time; thus,

$$VC\frac{rt^2 l}{4} = vd,$$

and because $l = \sqrt{Dd}$, the undeformed chip thickness in surface grinding will be

$$t = \sqrt{\frac{4v}{VCr}}\sqrt{\frac{d}{D}}. \tag{9.5}$$

Experimental observations have indicated that C is on the order of 0.1 to 10 per mm^2. Note that the finer the grain size of the wheel, the larger is this quantity. The magnitude of r is between 10 and 20 for most grinding operations. Substituting typical values into Eqs. (9.1) through (9.5), it will be found that l and t are very small quantities; typical values of t are in the range of 0.3–0.4 μm.

EXAMPLE 9.1 Chip Dimensions in Grinding

Given: A typical surface grinding operation is being performed with $D = 200$ mm, $d = 0.05$ mm, $C = 2$ per mm^2, and $r = 15$.

Find: Estimate the undeformed-chip length and the undeformed chip thickness.

Solution: The formulas for undeformed length and thickness, respectively, are given by Eqs. (9.1) and (9.5) as

$$l = \sqrt{Dd} \qquad \text{and} \qquad t = \sqrt{\frac{4v}{VCr}}\sqrt{\frac{d}{D}}.$$

From Table 9.2 the following values are selected:

$$v = 30 \text{ m/min} = 0.5 \text{ m/s} \qquad \text{and} \qquad V = 1800 \text{ m/min} = 30 \text{ m/s}.$$

9.4.1 Grinding Forces

As in machining operations, knowledge of forces is essential not only in the design of grinding machines and workholding devices, but also in determining the deflections that the workpiece and the machine will undergo. Deflections, in turn, adversely affect dimensional accuracy of the workpiece, which is especially critical in precision grinding.

Based on the discussion of cutting force, F_c, in Section 8.2.3 and assuming that the *force* on the grain is proportional to the cross-sectional area of the undeformed grinding chip, it can be shown that the **grain force** is

$$\text{Grain force} \propto \frac{v}{VC}\sqrt{\frac{d}{D}}, \tag{9.6}$$

where d = depth of cut, D = workpiece diameter, v = linear velocity, V = workpiece velocity, and C = number of cutting points per unit area of the wheel surface.

The grain force is then the product of the expression in Eq. (9.6) and the strength of the metal being ground.

The specific energy consumed in producing a grinding chip consists of three components:

$$u = u_{\text{chip}} + u_{\text{plowing}} + u_{\text{sliding}}, \tag{9.7}$$

where the quantity u_{chip} is the specific energy required for chip formation by plastic deformation; u_{plowing} is the specific energy required for plowing, which is plastic deformation without chip removal (Fig. 9.10); and the last term, u_{sliding}, can best be understood by observing the grain in Fig. 9.7b. Note that the grain develops a wear flat, similar to flank wear in cutting tools (see Section 8.3).

Typical specific-energy requirements in grinding are given in Table 9.3. Note that these energy levels are much higher than those in machining operations with single-point tools, as given in Table 8.3. This difference has been attributed to the following three factors:

1. **Size effect.** Recall that the size of grinding chips is very small, as compared with chips produced in machining operations, by about two orders of magnitude. As described in Section 3.8.3, the smaller the size of a metal specimen, the higher is its strength; for this reason, grinding involves higher specific energy than machining operations.

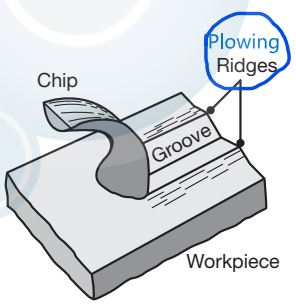
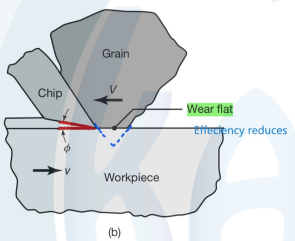


FIGURE 9.10 Chip formation and plowing (plastic deformation without chip removal) of the workpiece surface by an abrasive grain.

TABLE 9.3 Approximate specific-energy requirements for surface grinding.

Workpiece material	Hardness	Specific energy W-s/mm^3
Aluminum	150 HB	7–27
Cast iron (class 40)	215 HB	12–60
Low-carbon steel (1020)	110 HB	14–68
Titanium alloy	300 HB	16–55
Tool steel (T15)	67 HRC	18–82



2. **Wear flat.** The wear flat (Fig. 9.7b) dissipates frictional energy, which contributes significantly to the total energy consumed. The size of the wear flat in grinding is much larger than the grinding chip, unlike in metal cutting by a single-point tool, where flank wear land is small compared with the size of the chip (Section 8.3).
3. **Chip morphology.** Recall that the average rake angle of a grain is highly negative (Fig. 9.7), thus the shear strains in grinding are very large. This indicates that the energy required for plastic deformation to produce a grinding chip is higher than in machining processes. Moreover, plowing consumes energy without contributing to grinding chip formation (Fig. 9.10).

EXAMPLE 9.2 Forces in Surface Grinding

Given: Assume that you are performing a surface-grinding operation on a low-carbon steel workpiece using a wheel of diameter $D = 250$ mm that rotates at $N = 4000$ rpm. The width of cut is $w = 25$ mm, depth of cut is $d = 0.05$ mm, and the feed rate of the workpiece is $v = 1.5$ m/s.

Find: Calculate the cutting force, F_c (the force tangential to the wheel), and the thrust force, F_n (the force normal to the workpiece), noting that in general F_n is around 30% higher than F_c.

Solution: We first determine the material removal rate as follows:

$$\text{MRR} = dwv = (0.05)(25)(1500) = 1875 \text{ mm}^3/\text{s}.$$

The power consumed is given by

$$\text{Power} = (u)(\text{MRR}),$$

where u is the specific energy, as obtained from Table 9.3. For low-carbon steel, use an average value of 41 W-s/mm^3. Hence,

$$\text{Power} = (41)(1875) = 76.875 \text{ kW}.$$

Also note that the angular velocity is

$$\omega = (4000)\left(\frac{2\pi}{60}\right) = 418.9 \text{ deg/s}.$$

Since power is defined as

$$\text{Power} = T\omega,$$

9.4.2 Temperature

Temperature rise in grinding is an important consideration, because it can (a) adversely affect workpiece surface properties; (b) cause residual stress; (c) cause distortion and difficulties in controlling dimensional accuracy; and (d) when high, it can cause burning and structural changes. The work expended in grinding is mainly converted into heat. The *surface temperature rise*, ΔT, has been found to be a function of the ratio of the total energy input to the surface area ground. In *surface grinding*, if w is the width and L is the length of the surface area that is ground, then

$$\Delta T \propto \frac{(uwLd)}{(wL)} \propto ud.$$

Including the size effect and assuming that u varies inversely with the undeformed-chip thickness, t, the temperature rise is

$$\text{Temperature rise} \propto D^{1/4} d^{3/4} \left(\frac{V}{\nu}\right)^{1/2}. \qquad (9.9)$$

The *peak temperatures* in chip generation during grinding can be as high as 1650°C; however, because the time involved in producing a chip is extremely short (on the order of microseconds), melting of the chip may or may not occur. Because, as in machining, the chips carry away much of the heat generated (See also Fig. 8.18), only a small fraction of the heat generated is conducted into the workpiece (see Section 8.2).

Sparks. The sparks observed in grinding metals are actually glowing chips. The glowing occurs because of the *exothermic reaction* of the hot chips with oxygen in the atmosphere; sparks have not been observed with any metal ground in an oxygen-free environment. The color, intensity, and shape of the sparks depend on the composition of the metal being ground. If the heat generated by exothermic reaction is sufficiently high, the chip may melt and, because of surface tension, solidify as a shiny spherical particle. Scanning electron microscopy has shown that these particles are hollow and have a fine dendritic structure (Fig. 5.8), indicating that they were once molten and have resolidified rapidly. Moreover, some of the spherical particles may also have been formed by plastic deformation and rolling of chips at the grain-workpiece interface during grinding.

9.4.3 Effects of Temperature

The major effects of temperature in grinding are:

Any structural change (Softning)

1. **Tempering.** Excessive temperature rise caused by grinding can temper (Section 5.11.5) and soften the surfaces of steel components; they are often ground in the heat-treated and hardened state. Tempering can be eliminated by avoiding excessive temperature rise; grinding fluids (Section 9.6.9) also can effectively control temperatures.
2. **Burning.** If the temperature rise is excessive, the workpiece surface may burn, such as a bluish color on steels, which indicates oxidation at high temperatures. A burn may not be objectionable in itself; however, the surface layers may undergo metallurgical transformations, with martensite formation in high-carbon steels from reaustenization, followed by rapid cooling (Section 5.11). This phenomenon is known as *metallurgical burn*, which is especially serious with nickel-base alloys.
3. **Heat checking.** High temperatures in grinding lead to thermal stresses which may cause thermal cracking of the workpiece surface, known as *heat checking* (see also Section 5.10.3). The cracks are usually perpendicular to the grinding direction; under severe grinding conditions, however, parallel cracks may also develop.
4. **Residual stresses.** Temperature gradients within the workpiece are mainly responsible for residual stresses in grinding. Other contributing factors are the physical interactions of the abrasive grain in chip formation and the sliding of the wear flat along the workpiece surface. Two examples of residual stresses in grinding are given in Fig. 9.11, demonstrating the effects of wheel speed and the type of grinding fluid used. The method and direction of the application of grinding fluid also can have a significant effect on the residual stresses developed. Because of the deleterious effect of tensile residual stresses on fatigue strength (see Section 3.8.2), process parameters should be chosen properly. Residual stresses can usually be lowered by (a) using softer grade wheels (called *free-cutting wheels*); (b) lower wheel speeds; and (c) higher work speeds, a procedure known as **low-stress** or **gentle grinding**.

9.5 Grinding-Wheel Wear

Wheel wear is an important consideration because it adversely affects the shape and dimensional accuracy of ground surfaces, a situation similar to the wear of cutting tools (Section 8.3). Grinding wheels wear by three different mechanisms:

1. **Attritious wear.** The cutting edges of a sharp grain become dull by attrition (known as *attritious wear*), developing a *wear flat* (Fig. 9.7b) that is similar to flank wear in cutting tools. This type of wear is caused by the interaction of the grain with the workpiece material,



تكسير degradation & decomposition : تحليل
degrad into carbon & silicon under high temp. in the steel

* plastic deformation of the WP. not the tool.

Solubility

resulting in complex physical and chemical reactions between the two. These reactions involve (a) diffusion; (b) chemical degradation or decomposition of the grains; (c) fracture at a microscopic scale; (d) plastic deformation; and (e) melting.

A and B won't happen

Attritious wear is low when the two materials are chemically inert with respect to each other, much like in cutting tools; the more inert the two materials, the lower the tendency for adhesion to occur between the grain and the workpiece being ground. For example, because aluminum oxide is relatively inert to iron, its rate of attritious wear in grinding steels is much lower than that for silicon carbide and diamond grains. On the other hand, carbon can dissolve in iron, and thus diamond is not suitable for grinding steels. Cubic boron nitride has a higher inertness to steels, and hence it is suitable for use as an abrasive. The selection of the type of abrasive for low attritious wear should thus be based on the reactivity of the grain and the workpiece materials and their relative mechanical properties, especially hardness and toughness. The environment and the type of grinding fluid used also have an influence on grain-workpiece interactions.

* melting ⇒ the bond itself. not the abrasive grains. — abrasive grains have high melting point.

* Diamond is bad in machining & Grinding the steels.

Friability ←

2. Grain fracture. Because abrasive grains are brittle, their fracture characteristics in grinding are important. If the wear flat caused by attritious wear is excessive, the grain becomes dull and the grinding operation becomes inefficient and produces high temperatures.

* one of the properties of good abrasives : ← certain amount of friability ↘ the grain fractures and produce new sharp-edges

Surface area ↑ ⇒ Friction ↑ ⇒ temp ↑

Ideally, the grain should fracture or fragment at a moderate rate, so that new and sharp cutting edges are produced continuously during the grinding operation. Note that the fracturing process is equivalent to breaking a piece of rounded and dull chalk into two or more pieces in order to expose new sharp edges. Recall that Section 9.2 has described *friability* of abrasive grains, giving them their *self-sharpening* characteristics, an important consideration in effective grinding.

The selection of grain type and size for a particular application also depends on the attritious-wear rate. Note that a grain-workpiece material combination with high attritious wear and low friability causes dulling of grains and the development of a large wear flat. Grinding then becomes inefficient and surface damage is likely to occur.

The following workpiece material and abrasive combinations are generally recommended:

a. *Aluminum oxide*: steels, ferrous alloys, and alloy steels.
b. *Silicon carbide*: cast iron, nonferrous metals, and hard and brittle materials (such as carbides, ceramics, marble, and glass).
c. *Diamond*: composite materials, ceramics, cemented-carbide ceramics, and some hardened steels.
d. *Cubic boron nitride*: composite materials, steels and cast irons that are hard at 50 HRC (such as hardened tool steels) or above, and for high-temperature superalloys.

3. **Bond fracture.** The strength of the bond (*grade*) is a significant parameter in grinding. If the bond is too strong, dull grains cannot be easily dislodged so that other sharp grains, along the circumference of the grinding wheel, can begin to contact the workpiece and remove chips; thus the grinding process then becomes inefficient. On the other hand, if the bond is too weak, the grains can easily be dislodged and wheel wear increases, thus controlling the dimensional accuracy of the workpiece becomes difficult. In general, softer bonds are recommended for harder materials, and for reducing residual stresses and thermal damage to the workpiece. Hard-grade wheels are recommended for softer materials, and for removing large amounts of material at high rates (see also Section 9.5.3).

9.5.1 Dressing, Truing, and Shaping of Grinding Wheels

Dressing is the process of conditioning worn grains on the surface of a grinding wheel in order to produce sharp new grains, but also will true an out-of-round wheel (see below). Dressing is necessary when excessive attritious wear dulls the wheel, called **glazing** because of the shiny appearance of the wheel surface, or when the wheel becomes loaded. **Loading** occurs when the porosities on the grinding surfaces of the wheel (Fig. 9.6) become filled or clogged with grinding chips. Loading can occur (a) when grinding soft workpiece materials; (b) by improper selection of the grinding wheel; and (c) by improper selection of grinding parameters. A loaded

* wheel grinds very inefficiently, generating much frictional heat and causing surface damage and loss of dimensional accuracy.

Sharpening Dressing is done by the following techniques:

1. A specially shaped diamond-point tool or a diamond *cluster* is moved across the width of the grinding face of a rotating wheel, removing a very small layer from the wheel surface with each pass across the wheel. This method can be used either dry or wet (using grinding fluids), depending on whether the wheel is to be used dry or wet, respectively, during the grinding operation.
2. A set of star-shaped steel disks is pressed against the rotating grinding wheel, and material is removed from the wheel surface by crushing the grains. This method produces a coarse grinding surface on the wheel and is used only for rough grinding operations on bench or pedestal grinders (Section 9.6.5).
3. *Abrasive sticks* may be held against the grinding surface of the wheel. This is a common method for softer wheels but is not appropriate for precision grinding operations.
4. For metal-bonded diamond wheels, electrical-discharge and electrochemical machining techniques (see Sections 9.11 and 9.13) can be used to erode very small layers of the metal bond, thus exposing new diamond cutting edges. For a specific profile
5. Dressing for *form grinding* involves **crush dressing**, or *crush forming*; the method consists of pressing a metal roll on the surface of the (usually vitrified) grinding wheel. The roll is made of high-speed steel, tungsten carbide, or boron carbide, and has a machined or ground profile, thus reproducing this profile on the surface of the grinding wheel being dressed (Fig. 9.12). Dressing is also done to generate a specific shape on the grinding surface of a wheel for the purpose of grinding profiles on workpieces (see Section 9.6.2).

Dressing techniques and the frequency at which the wheel surface is dressed are significant factors, affecting grinding forces and workpiece surface finish. Modern computer-controlled grinders (Section 9.6) are equipped with automatic dressing features that dress the wheel during the grinding operation. For a typical aluminum-oxide wheel, the depth removed during dressing is on the order of 5 to 15 μm, but for a cBN wheel, it is 2 to 10 μm. Modern dressing systems have a resolution as low as 0.25 to 1 μm.

* *Truing* is an operation by which a wheel is restored to its original shape. A round wheel is *shaped* to make its circumference a true circle, hence the word *truing*. Truing can also produce a desired workpiece shape. The grinding face on the Type 1 straight wheel shown in Fig. 9.2a is cylindrical and thus produces a flat surface; however, modern grinders are equipped with computer-controlled shaping features, whereby the diamond dressing tool automatically traverses the wheel face along a certain prescribed path (Fig. 9.12). Note in this figure that the axis of the diamond dressing tool remains normal to the wheel face at the point of contact. The result of the operation is a profile that can be produced in a workpiece.

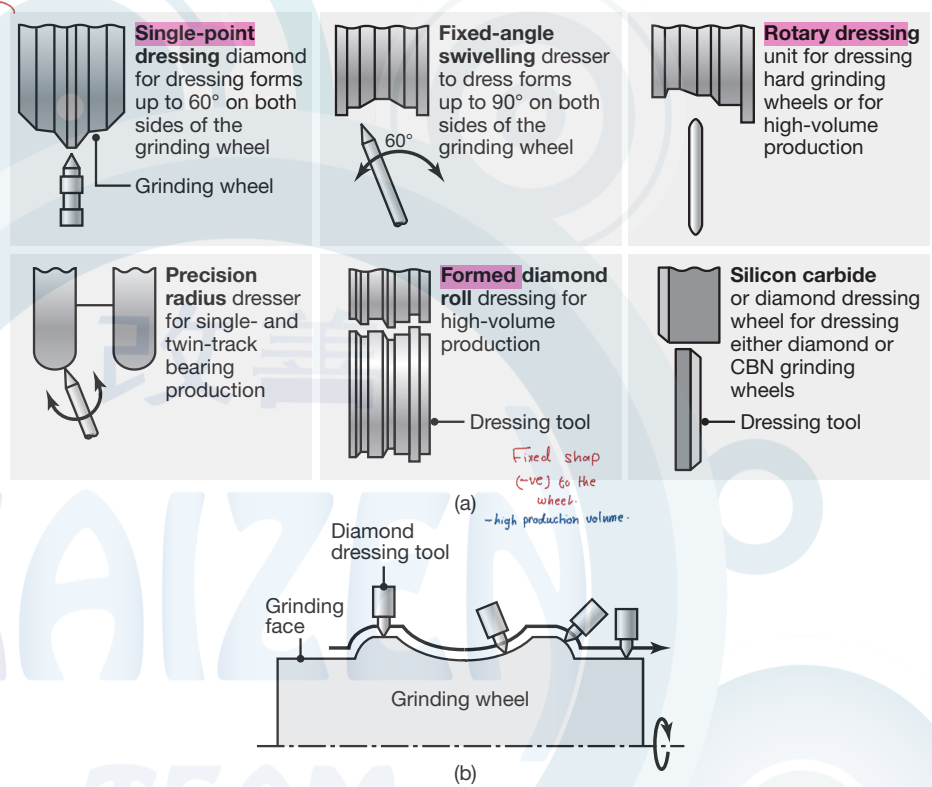


FIGURE 9.12 (a) Methods of grinding wheel dressing. (b) Shaping the grinding face of a wheel by dressing it with computer-controlled shaping features. Note that the diamond dressing tool is normal to the wheel surface at point of contact. *Source:* OKUMA America Corporation.

9.5.2 Grinding Ratio

Grinding-wheel wear is generally correlated to the amount of material ground; it is expressed by the *grinding ratio*, G, which is defined as

$$G = \frac{\text{Volume of material removed}}{\text{Volume of wheel wear}}. \tag{9.10}$$

In practice, grinding ratios vary widely, ranging from 2 to 200 and higher, depending on (a) the type of wheel; (b) workpiece material; (c) grinding fluid; and (d) process parameters, such as depth of cut and speeds of the wheel and the workpiece. Attempting to obtain a high grinding ratio in practice is not necessarily desirable because high ratios may indicate grain dulling, leading to possible surface damage. A lower ratio may well be acceptable if an overall economic analysis justifies it.

Soft-acting or hard-acting wheels. During a grinding operation, a particular wheel may *act soft* (meaning its wear rate is high) or *hard* (wear rate is low), regardless of its grade. This behavior is a function of the force on the grain. The higher the force, the greater the tendency for the grains to undergo fracture or to be dislodged from the wheel surface, hence the higher the wheel wear and the lower the grinding ratio. Equation (9.6) indicates that the grain force increases with the (a) strength of the workpiece material; (b) work speed; and (c) depth of cut, and decreases with increasing (a) wheel speed and (b) wheel diameter.

EXAMPLE 9.3 Action of a Grinding Wheel

Given: A surface-grinding operation is being carried out with the wheel rotating at a constant spindle speed.

Find: Will the wheel act soft or act hard as it wears down over a period of time?

Solution: Referring to Eq. (9.6), it will be noted that the parameters that change with time in this operation are the wheel surface speed, V, and the wheel diameter, D. As both become smaller with time, the relative grain force increases, and therefore the wheel acts softer. Some grinding machines are equipped with variable-speed spindle motors to accommodate these changes and to make provisions for wheels of different diameter.

9.5.3 Wheel Selection and Grindability of Materials

Proper selection of a grinding wheel for a given application greatly influences the quality of surfaces produced and the economics of the operation. Selection involves not only the shape of the wheel with respect to the shape of the part, but also the characteristics of the workpiece material. The *grindability* of materials, like machinability (Section 8.5) or forgeability (Section 6.2.5), is difficult to define precisely. It is a general indication of how easy it is to grind a particular material; it includes such considerations as surface finish, surface integrity, wheel wear, cycle time, and overall economics of the operation.

Specific recommendations for selecting wheels and process parameters can be found in various handbooks. Examples of recommendations are: C60-L6V for cast irons, A60-M6V for steels, C60-I9V or D150-R75B for carbides, A60-K8V for titanium, and D150-N50M (diamond) for ceramics.

Ductile regime grinding. It is possible to obtain continuous chips in grinding ceramics using light passes and rigid machine tools with good damping capacity (Figs. 9.7b and 9.10). Known as *ductile regime grinding*, this technique produces good workpiece surface integrity; however, because ceramic chips are typically 1–10 μm in size, they are more difficult to remove from grinding fluids than are machining chips, requiring fine filtration.

EXAMPLE 9.4 Grinding vs. Hard Turning

It is evident that grinding and hard turning (Section 8.9.2) can be competitive in specific applications. Hard turning continues to be increasingly competitive with grinding, and the dimensional tolerances and surface finish produced are approaching those for grinding. Furthermore, (a) turning requires much less energy than grinding (See Tables 8.3 and 9.3); (b) thermal and other damage to the workpiece surface is less likely to occur; (c) cutting fluids may not be necessary; and (d) the machine tools are less expensive.

In addition, finishing the part while it is still chucked in the lathe or turning center eliminates the need for material handling and setting the part in the grinder. On the other hand, workholding devices for large and slender workpieces for hard turning can present difficulties because the machining forces are higher than those in grinding and the workpiece will tend to distort. Tool wear and its control in hard turning also can be a significant problem as compared with automatic dressing of grinding wheels.

9.7 Finishing Operations

In addition to the abrasive machining processes described thus far, several processes can be used on workpieces as the final finishing operation, using mainly abrasive grains. However, finishing operations can contribute significantly to production time and product cost, hence they should be specified with due consideration to their economic drawbacks and performance benefits.

Commonly used finishing operations are described below.

1. **Coated abrasives.** Typical examples of *coated abrasives* are sandpaper and emery cloth. The grains in coated abrasives are more pointed than those used for grinding wheels; they are electrostatically deposited on flexible backing materials, such as paper or cloth (Fig. 9.19), with their long axes perpendicular to the plane of the backing. Coated abrasives are available as sheets, belts, and disks, and usually have a much more open structure than the abrasives used in bonded wheels. They are used extensively in finishing flat or curved surfaces of metallic and nonmetallic parts, in finishing metallographic specimens, and in woodworking. The surface finish obtained depends primarily on grain size.

   Coated abrasives are also used as *belts* for high-rate material removal. **Belt grinding** is an important production process and in some cases has replaced conventional grinding operations, such as in

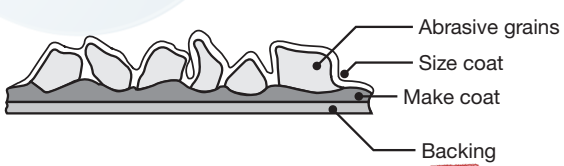


FIGURE 9.19 Schematic illustration of the structure of a coated abrasive. Sandpaper, developed in the 16th century, and emery cloth are common examples of coated abrasives.

grinding camshafts, with 8 to 16 lobes (of approximately elliptic shape) per shaft. Belt speeds are usually in the range of 700–1800 m/min. Machines for abrasive-belt operations require proper belt support and rigid construction to minimize vibrations.

In **microreplication**, aluminum-oxide abrasives in the shape of tiny pyramids are placed in a predetermined orderly arrangement on the belt surface. When used on stainless steels and superalloys, their performance is more consistent, and the temperature rise is lower than when using other coated abrasives. Typical applications include surgical implants, turbine blades, and medical and dental instruments.

2. **Wire brushing.** In this process, the workpiece is held against a circular wire brush rotating at high speed, producing longitudinal scratches on the workpiece surface. Wire brushing is used to produce a fine surface texture, but can also serve as a light material-removal process.

3. **Honing.** This is an operation used primarily to produce fine surface finish in holes. The honing tool (Fig. 9.20) consists of a set of aluminum-oxide or silicon-carbide bonded abrasives, called *stones*. The stones are mounted on a mandrel that rotates in the hole, applying a radial force, with a reciprocating axial motion, thus producing a crosshatched pattern. The stones can be adjusted radially for different hole sizes. The surface finish can be controlled by the type and size of abrasive used, the speed of rotation, and the pressure applied. A fluid is used to remove chips and to keep temperatures low. If not implemented properly, honing can produce holes that may not be straight and cylindrical, but rather bellmouthed, wavy, barrel shaped, or tapered. Honing is also used on external cylindrical or flat surfaces, and to remove sharp edges on cutting tools and inserts (See Fig. 8.31).

In **superfinishing**, the pressure applied is very low, and the motion of the honing stone has a short stroke. The operation is controlled such that the grains do not travel along the same path across the surface of the workpiece. Figure 9.21 shows examples of external superfinishing of a round part.

4. **Electrochemical honing**. This process combines the fine abrasive action of honing with electrochemical action. Although the equipment is costly, the process is as much as 5 times faster than conventional honing, and the tool lasts up to 10 times longer. Electrochemical honing is used primarily for finishing internal cylindrical surfaces.

5. **Lapping.** *Lapping* is a finishing operation on flat or cylindrical surfaces. The *lap* (Fig. 9.22a) is usually made of cast iron, copper, leather,

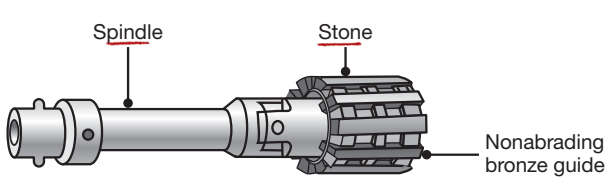


FIGURE 9.20 Schematic illustration of a honing tool to improve the surface finish of bored or ground holes.

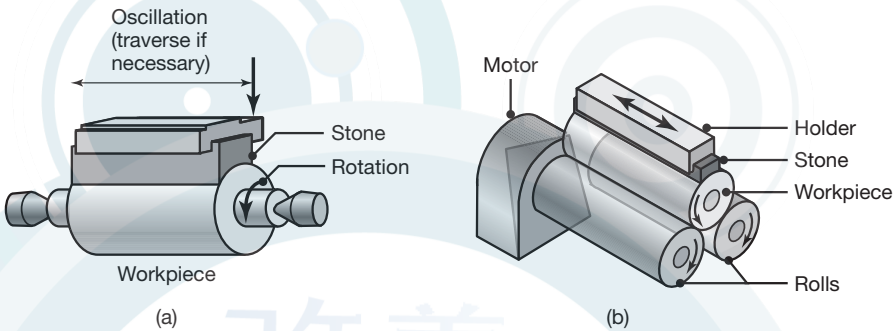


FIGURE 9.21 Schematic illustration of the superfinishing process for a cylindrical part: (a) cylindrical microhoning; and (b) centerless microhoning.

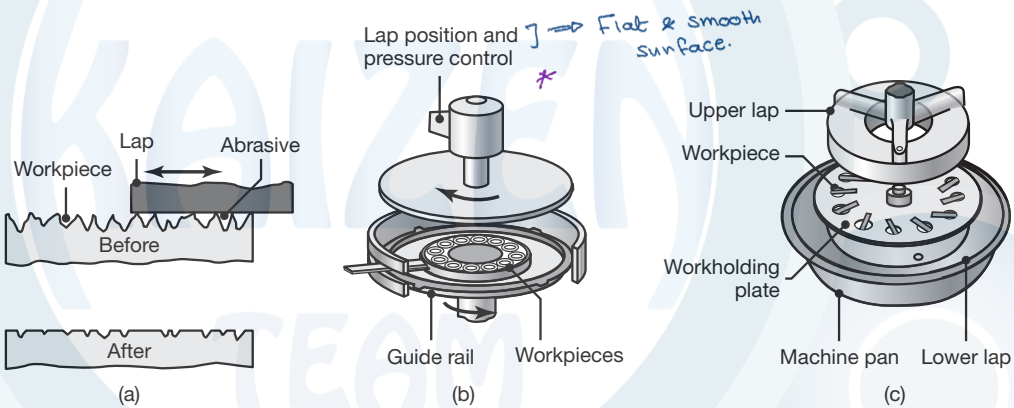


FIGURE 9.22 (a) Schematic illustration of the lapping process. (b) Production lapping on flat surfaces. (c) Production lapping on cylindrical surfaces.

or cloth. The abrasive particles are embedded in the lap or they may be carried through a slurry. Depending on workpiece hardness, lapping pressures range from 7–140 kPa. Dimensional tolerances on the order of ±0.4 μm can be obtained with the use of fine abrasives, up to size 900. Surface finish can be as smooth as 0.025–0.1 μm. Production lapping on flat or cylindrical workpieces is done on machines such as those shown in Figs. 9.22b and c. Lapping is also performed on curved surfaces, such as spherical objects and glass lenses, using specially shaped laps. *Running-in* of mating gears also can be done by lapping.

6. **Polishing.** This is a process that produces a smooth, lustrous surface finish. Two basic mechanisms are involved in the polishing process: fine-scale abrasive removal and softening and smearing of surface layers by frictional heating. The shiny appearance of polished surfaces results from the smearing action. Polishing is done with disks or belts,

made of fabric, leather, or felt, that are coated with fine powders of aluminum oxide or diamond. Parts with irregular shapes, sharp corners, deep recesses, and sharp projections are difficult to polish.

7. **Laser polishing.** This method involves rapid melting and resolidification of a surface, at depths of submicrons, using short laser pulses in the range of micro- or nanoseconds. The melting action smoothens the surface by reducing asperity heights (See Fig. 4.4), on ferrous and nonferrous metallic workpieces as well as on glass and diamond. The surface roughness developed by laser polishing can be as low as 0.05 μm and is suitable for optical use. It also has lower friction, thus making it attractive for such applications as automotive cylinder liners. Unlike traditional polishing operations, this process is much faster and also is applicable to workpieces with uneven surfaces, using programmable controls.
8. **Buffing.** This process is similar to polishing, with the exception that very fine abrasives are used on soft disks typically made of cloth. The abrasive is supplied externally from a stick of abrasive compound. Buffing may be done on polished parts to obtain an even finer surface finish.
9. **Electropolishing.** Mirrorlike finishes can be obtained on metal surfaces by *electropolishing*, a process that is the reverse of electroplating (Section 4.5.1). Because there is no mechanical contact with the workpiece, this process is particularly suitable for polishing irregular shapes. The electrolyte attacks projections and peaks on the workpiece surface and at a higher rate than for the rest of the surface, thus producing a smooth surface. Electropolishing is also used for deburring operations (Section 9.8).
10. **Chemical-mechanical polishing.** Chemical-mechanical polishing (CMP) is very important in the semiconductor industry. The process, shown in Fig. 9.23, uses a suspension of abrasive particles in a water-base solution, with a chemistry selected to cause controlled corrosion. This process removes material from the workpiece surfaces through combined actions of abrasion and corrosion. The result is exceptionally fine surface finish and a workpiece that is essentially flat (plane); for this reason, the process is often referred to as **chemical-mechanical planarization**.

A major application of this process is the polishing of silicon wafers (Section 13.4), in which the primary function of CMP is to polish a wafer at the micro-level. To evenly remove material across the whole wafer, it is held on a rotating carrier face down and is pressed against a polishing pad attached to a rotating disk (Fig. 9.23). Both the carrier and the pad rotate in order to avoid development of a linear lay (see Section 4.3). The pad contains grooves in order to supply slurry to the wafers.

Specific abrasive and solution chemistry combinations have been developed for the polishing of copper, silicon, silicon dioxide, aluminum, tungsten, and other metals. For polishing silicon dioxide or silicon, for example, an alkaline slurry of colloidal silica (SiO_2)

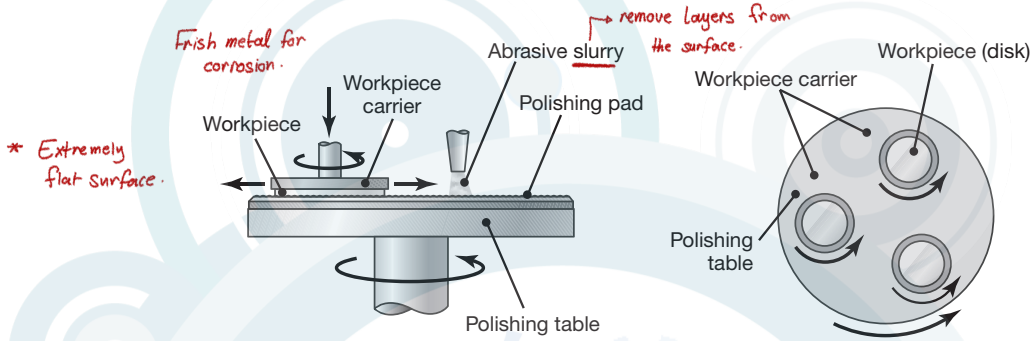


FIGURE 9.23 Schematic illustration of the chemical-mechanical polishing process. This process is widely used in the manufacture of silicon wafers and integrated circuits, where it is known as *chemical-mechanical planarization*. Additional carriers and more disks per carrier also are possible.

particles in a KOH solution or NH_4OH is continuously fed to the pad-wafer interface.

11. **Polishing processes using magnetic fields.** In this technique, an abrasive slurry is supported with and made more effective by magnetic fields. There are two basic methods:

    a. In **magnetic float polishing**, also called *magnetic fluid finishing* (Fig. 9.24a), a magnetic fluid fills the chamber within a guide ring. The magnetic fluid consists of abrasive grains and extremely fine ferromagnetic particles suspended in a carrier, such as water or kerosene. The ceramic balls are located between a drive shaft and a float. The abrasive grains, ceramic balls, and the float (made of a nonmagnetic material) are all suspended by

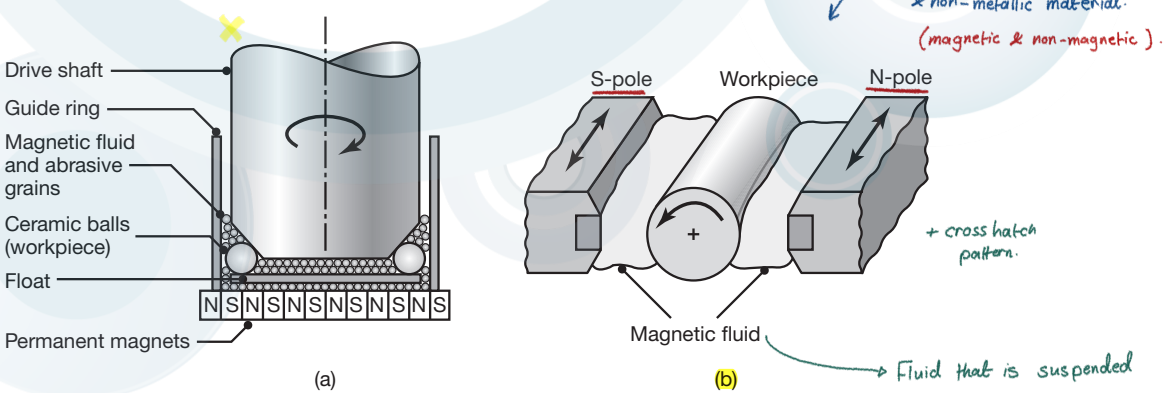


FIGURE 9.24 Schematic illustration of the use of magnetic fields to polish balls and rollers: (a) magnetic float polishing of ceramic balls and (b) magnetic-field-assisted polishing of rollers. *Source:* After R. Komanduri, M. Doc, and M. Fox.