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

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

where d = depth of cut and D = distance (diameter).

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

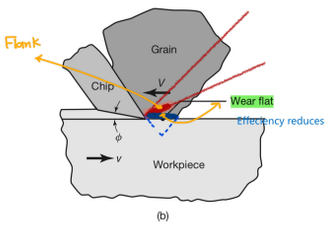
The **specific energy** consumed in producing a grinding chip consists of three components:

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

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.



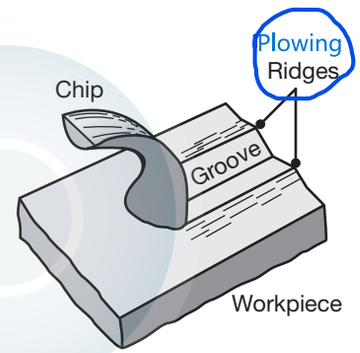
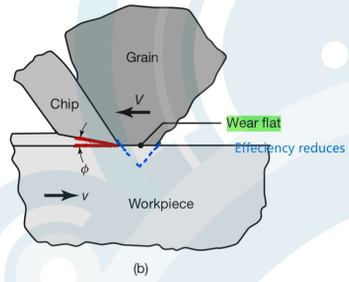


FIGURE 9.10 Chip formation and plowing (plastic deformation without chip removal) of the workpiece surface by an abrasive grain.

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

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

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,

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.

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.

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.

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.
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.

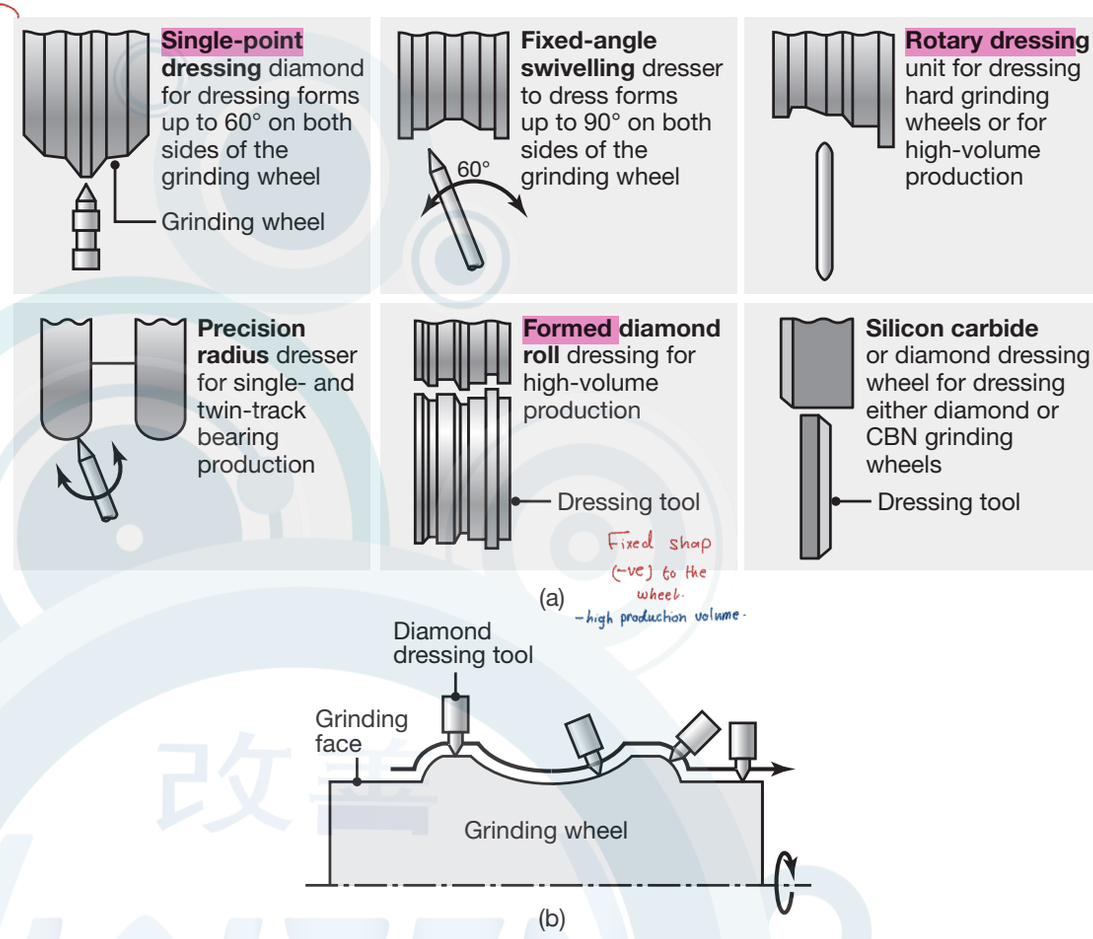


FIGURE 9.12 (a) Methods of grinding wheel dressing. (b) Shaping the grinding face of a wheel by dressing it with computer-controlled shaping features. Note that the diamond dressing tool is normal to the wheel surface at point of contact. *Source:* OKUMA America Corporation.

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.

Removed

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

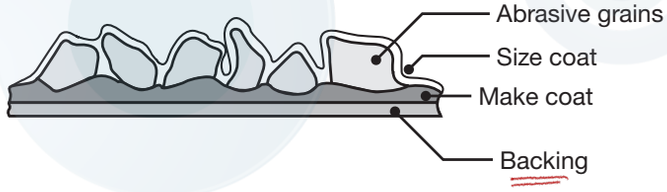


FIGURE 9.19 Schematic illustration of the structure of a coated abrasive. Sandpaper, developed in the 16th century, and emery cloth are common examples of coated abrasives.

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,

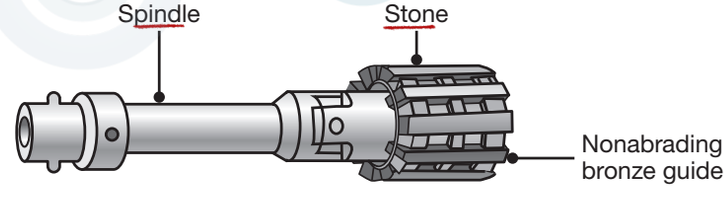


FIGURE 9.20 Schematic illustration of a honing tool to improve the surface finish of bored or ground holes.

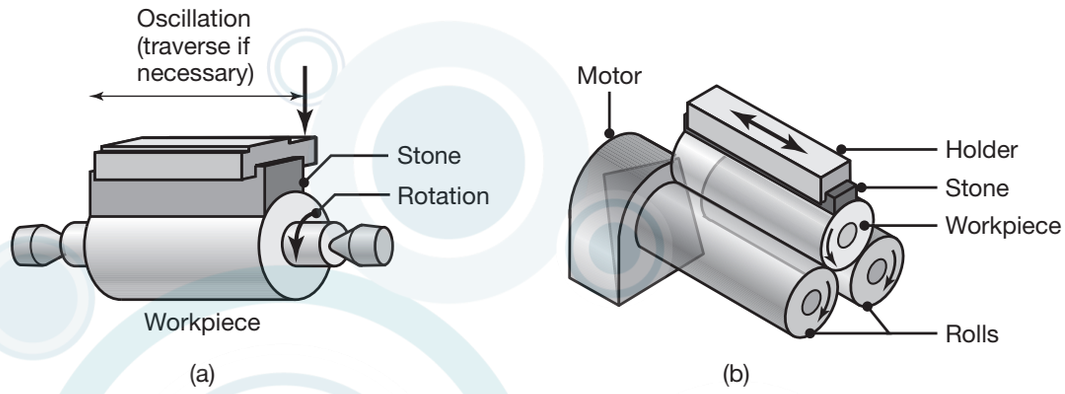


FIGURE 9.21 Schematic illustration of the superfinishing process for a cylindrical part: (a) cylindrical microhoning; and (b) centerless microhoning.

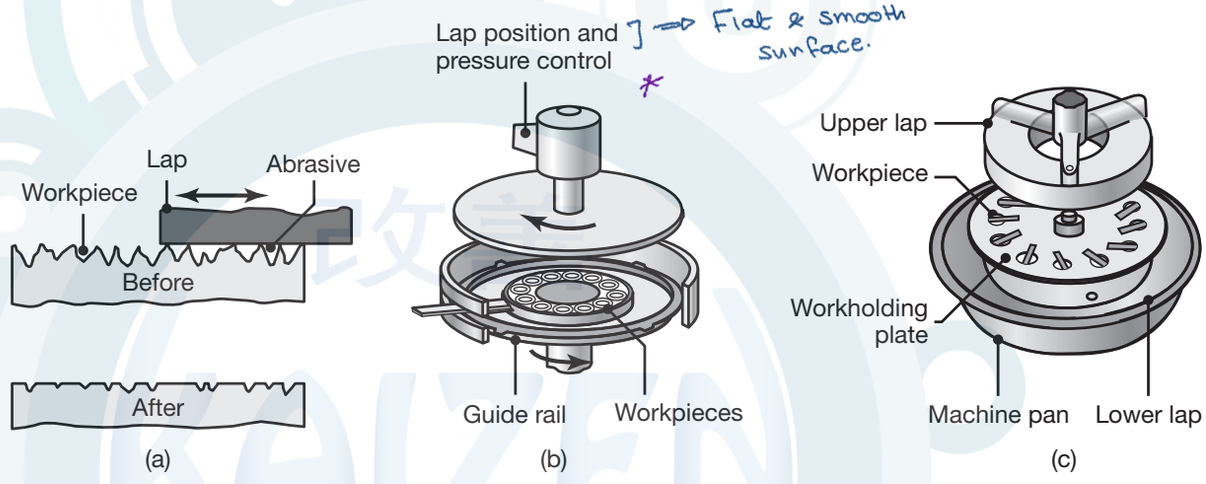


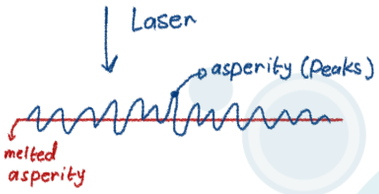
FIGURE 9.22 (a) Schematic illustration of the lapping process. (b) Production lapping on flat surfaces. (c) Production lapping on cylindrical surfaces.

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,

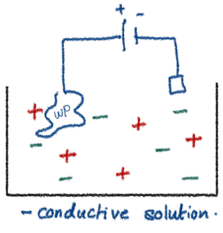
made of fabric, leather, or felt, that are coated with fine powders of aluminum oxide or diamond. Parts with irregular shapes, sharp corners, deep recesses, and sharp projections are difficult to polish.

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)

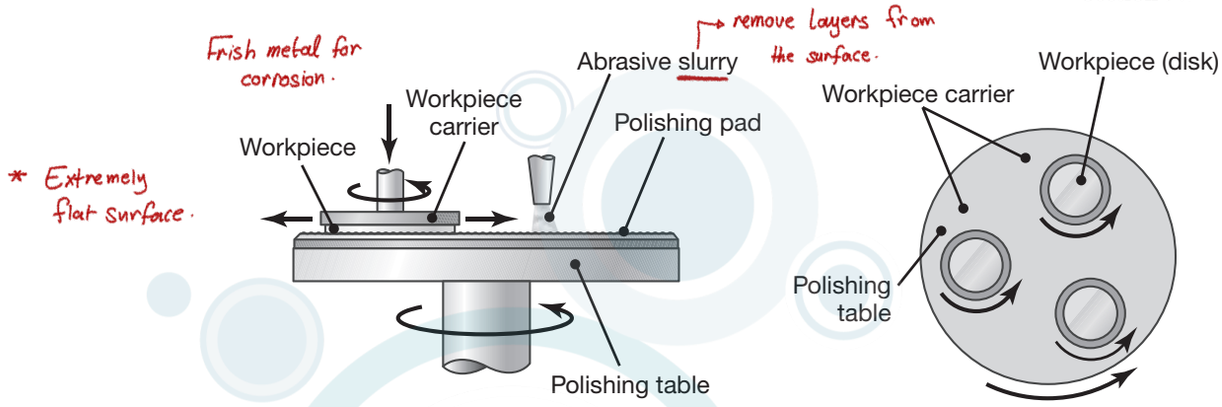


FIGURE 9.23 Schematic illustration of the chemical-mechanical polishing process. This process is widely used in the manufacture of silicon wafers and integrated circuits, where it is known as *chemical-mechanical planarization*. Additional carriers and more disks per carrier also are possible.

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

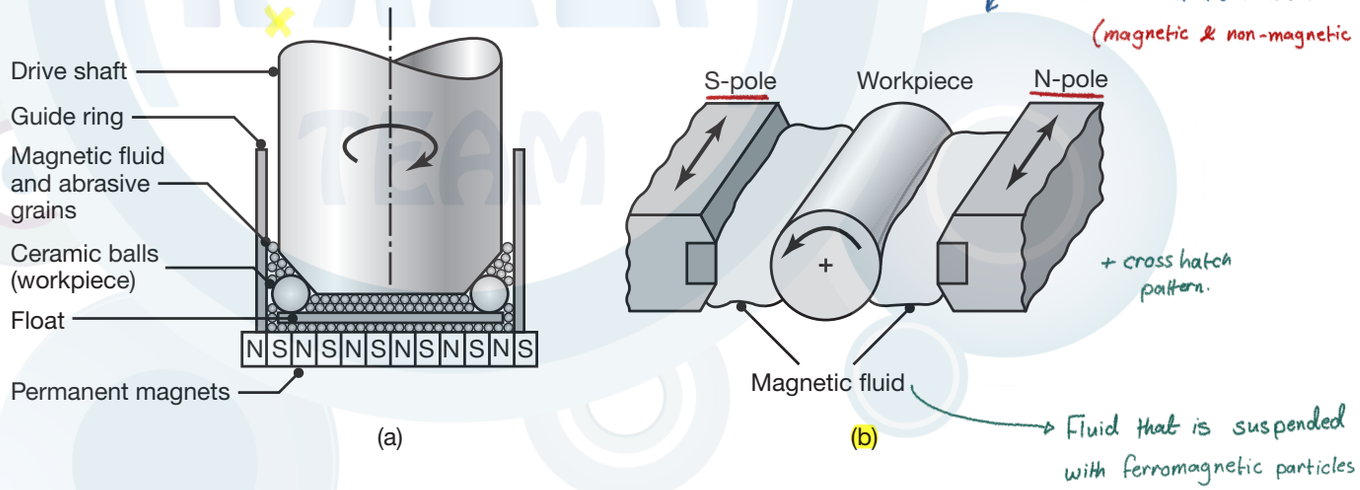


FIGURE 9.24 Schematic illustration of the use of magnetic fields to polish balls and rollers: (a) magnetic float polishing of ceramic balls and (b) magnetic-field-assisted polishing of rollers. *Source:* After R. Komanduri, M. Doc, and M. Fox.

magnetic forces. The balls are pressed against the rotating drive shaft and are polished by abrasive action. The forces applied by the abrasive particles on the balls are extremely small and controllable, hence the polishing action is very fine. Polishing times are much lower than those for other polishing methods, thus the process is very economical and the surfaces produced have little or no defects.

b. **Magnetic abrasive finishing** (MAF) involves fine (1 μm – 2 mm) ferromagnetic particles suspended in a fluid. A workpiece, such as the ceramic roller in Fig. 9.24b, is clamped and rotated on a spindle. The magnetic poles are oscillated, introducing a vibratory motion to the magnetic-abrasive conglomerate. This produces a so-called *magnetic brush* because of the similarities to the response from a wire brush. However, the magnetic brush is more compliant than wire brushes, and geometrically complex surfaces can be accommodated. Bearing steels of 63 HRC have been mirror finished in 30 s by this process.

c. **Magnetorheological finishing** (MRF) is similar to MAF, but involves the use of a fluid whose viscosity increases in the presence of a magnetic field. The fluid, referred to as a *ribbon*, is very viscous next to the workpiece, so that the abrasive particles are pushed against the surface with higher force.

9.8 Deburring

Burrs are thin ridges, usually triangular in shape, that develop along the edges of a workpiece from processes such as shearing of sheet materials (Fig. 7.5), trimming of forgings and castings, and machining operations. Burrs may interfere with the assembly of parts and can cause jamming, misalignment, and short circuiting of electrical components, and may reduce the fatigue life of a part (Section 7.3). Because they are usually sharp, burrs can also be a safety hazard to personnel. The need for deburring may be reduced by adding chamfers to sharp edges on parts.

Several *deburring processes* are available: (a) manually, using files (Section 8.10.6); (b) mechanically, by cutting; (c) wire brushing (Section 9.7); (d) abrasive finishing, using rotary nylon brushes, with the nylon filaments embedded with abrasive grits; (e) abrasive belts (Section 9.7); (f) ultrasonic machining (Section 9.9); (g) electropolishing (Section 9.7); (h) electrochemical machining (Section 9.11); (i) vibratory finishing; (j) shot blasting; (k) abrasive-flow machining; and (l) thermal energy. The last four processes are described below.

1. **Vibratory** and **barrel-finishing** processes are used to improve the surface finish and remove burrs from large numbers of relatively small parts. This is a batch-type operation in which specially-shaped *abrasive pellets* or *media* are placed in a container along with the parts to be deburred. The container is either vibrated or tumbled. The impact of individual abrasives removes sharp edges and burrs from the parts.

Depending on the application, this process is performed dry or wet, and liquid compounds may be added for other requirements, such as degreasing and providing resistance to corrosion.

2. In **shot blasting**, also called *grit blasting*, abrasive particles (usually sand) are propelled by a high-velocity jet of air, or by a rotating wheel, onto the surface of the workpiece. Shot blasting is particularly useful in deburring both metallic and nonmetallic materials and in stripping, cleaning, and removing surface oxides from workpieces. The surface produced by shot blasting has a matte finish. Small-scale polishing and etching also can be done by this process on bench-type units (*microabrasive blasting*).
3. In **abrasive-flow machining**, abrasive grains, such as silicon carbide or diamond, are mixed in a puttylike matrix, which is then forced back and forth through the openings and passageways in the workpiece. The movement of the abrasive matrix under pressure removes burrs and sharp corners and polishes the part. The process is particularly suitable for workpieces with internal cavities that are inaccessible by other means. Pressures applied range from 0.7 to 22 MPa. External surfaces also can be deburred using this process by containing the workpiece within a fixture that directs the abrasive media to the edges and areas to be deburred.
4. The **thermal-energy method** of deburring consists of placing the part in a chamber that is then injected with a mixture of natural gas and oxygen. This mixture is ignited, producing a heat wave with a temperature of 3300°C. The burrs instantly heat up and are melted away, while the temperature of the part itself rises only to about 150°C. The thermal energy method is effective on a wide range of materials including zinc, aluminum, brass, steel, stainless steel, cast iron, and thermoplastics. However, larger burrs or flash from forgings and castings tend to form beads after melting, and the process can distort thin and slender parts. This method does not polish or buff the workpiece surfaces as do many of the other deburring processes.
5. **Robotic deburring.** Deburring and flash removal are now being performed increasingly by programmable robots (Section 14.7), using a force-feedback system for controlling the process. The main advantage of robotic deburring is flexibility, both in terms of the geometries that can be deburred as well as the media that can be applied. This method eliminates tedious and costly manual labor and results in more consistent deburring. The main drawback is the capital equipment cost involved – robotic deburring systems with multiple spindles can cost over $250,000.

9.9 Ultrasonic Machining

In *ultrasonic machining* (UM), material is removed from a workpiece surface by the mechanism of microchipping or erosion with abrasive particles. The tip of the tool (Fig. 9.25a), called a *sonotrode*, vibrates at amplitudes

include Liquid.

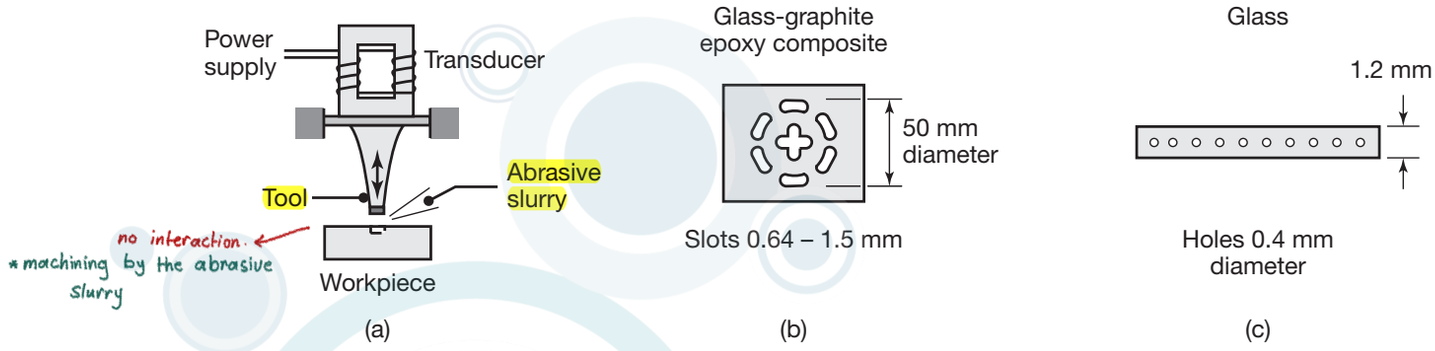


FIGURE 9.25 (a) Schematic illustration of the ultrasonic-machining process; material is removed through microchipping and erosion. (b) and (c) Typical examples of cavities produced by ultrasonic machining. Note the dimensions of cut and the types of workpiece materials.

of 0.05 to 0.125 mm and at a frequency of 20 kHz. The vibration, in turn, transmits a high velocity to fine abrasive grains between the tool and the surface of the workpiece. The grains are in a water slurry with concentrations ranging from 20 to 60% by volume; the slurry also carries away the debris from the cutting area. Although the grains are usually boron carbide, aluminum oxide and silicon carbide are also used, with grain sizes ranging from 100 (for roughing) to 1000 (for finishing).

Ultrasonic machining is best suited for hard and brittle materials, such as ceramics, carbides, glass, precious stones, and hardened steels. The tip of the tool is usually made of low-carbon steel and is attached to a transducer through the toolholder. With fine abrasives, dimensional tolerances of 0.0125 mm or better can be held in this process. Figures 9.25b and c show two applications of ultrasonic machining.

Microchipping in ultrasonic machining is possible because of the high stresses produced by particles striking a solid surface. The contact time between the particle and the surface is very short (10 to 100 μs) and the area of contact is very small. The contact time, t_o, can be expressed as

$$t_o \simeq \frac{5r}{c_o}\left(\frac{c_o}{v}\right)^{1/5}, \tag{9.11}$$

where r is the radius of a spherical particle, c_o is the elastic wave velocity in the workpiece $\left(c_o = \sqrt{E/\rho}\right)$, and v is the velocity with which the particle strikes the surface. The force, F, of the particle on the surface is obtained from the rate of change of momentum; that is,

$$F = \frac{d(mv)}{dt}, \tag{9.12}$$

where m is the mass of the particle. The *average force*, F_{ave}, of a particle striking the surface and rebounding is

$$F_{\text{ave}} = \frac{2mv}{t_o}. \tag{9.13}$$

Substitution of numerical values into Eq. (9.13) indicates that even small particles can exert significant forces and, because of the very small contact area, the contact stresses are very high. In brittle materials, these stresses are sufficiently high to cause microchipping and surface erosion (see also the discussion of *abrasive-jet machining* in Section 9.15).

Rotary ultrasonic machining (RUM). In this process, the abrasive slurry is replaced by a tool with metal-bonded diamond abrasives that have been either impregnated or electroplated on the tool surface. The tool is rotated and ultrasonically vibrated, and the workpiece is pressed against it at a constant pressure; the operation is thus similar to a face milling operation (Section 8.10.1). The rotary ultrasonic machining process is particularly effective in producing deep holes in ceramics at high material removal rates.

9.10 Chemical Machining

The *chemical machining* (CM) process was developed based on the fact that certain chemicals attack metals and etch them, thereby removing small amounts of material from the surface (Table 9.4). The material is removed from a surface by chemical dissolution, using **reagents**, or **etchants**, such as acids and alkaline solutions. Chemical machining is the oldest of the nontraditional machining processes, and has been used for many years for engraving metals and hard stones and in the production of printed-circuit boards and microprocessor chips. Parts can also be deburred by chemical means.

9.10.1 Chemical Milling

In *chemical milling*, shallow cavities are produced on sheets, plates, forgings, and extrusions, either for design requirements or for weight reduction in parts (Fig. 9.26). Chemical milling has been used on a wide variety of metals, with depths of material removal to as much as 12 mm. Selective attack by the chemical reagent on different areas of the workpiece surfaces is controlled by removable layers of a **maskant** (Fig. 9.27) or by partial immersion in the reagent.

Chemical milling is used in the aerospace industry, particularly for removing shallow layers of material from large aircraft, missile skin panels, and extruded parts for airframes. The process is also used to fabricate microelectronic devices (Sections 13.8 and 13.14), often referred to as **wet etching**. Tank capacities for reagents are as large as 3.7 m × 15 m. Figure 9.28 shows the range of surface finish and dimensional tolerances obtained by chemical machining and other machining processes. Some surface damage may result from chemical milling, because of preferential etching and intergranular attack by the reagents (see Section 3.4), which adversely affect surface properties. Chemical milling of welded and brazed structures may produce uneven material removal because the filler metal or the structure material may machine preferentially.

TABLE 9.4 General characteristics of advanced machining processes.

Process	Characteristics	Process parameters and typical material removal rate or cutting speed
Chemical machining (CM)	Shallow removal (up to 12 mm) on large flat or curved surfaces; blanking of thin sheets; low tooling and equipment cost; suitable for low production runs	0.0025–0.1 mm/min
Electrochemical machining (ECM)	Complex shapes with deep cavities; highest rate of material removal; expensive tooling and equipment; high power consumption; medium to high production quantity	V: 5–25 dc; I: 1.5–8 A/mm^2; 2.5–12 mm/min, depending on current density
Electrochemical grinding (ECG)	Cutting off and sharpening hard materials, such as tungsten-carbide tools; also used as a honing process; higher material removal rate than grinding	I: 1–3 A/mm^2; typically 25 mm^3/s per 1000 A
Electrical-discharge machining (EDM)	Shaping and cutting complex parts made of hard materials; some surface damage may result; also used for grinding and cutting; versatile; expensive tooling and equipment	V: 50–380; I: 0.1–500 A; typically 300 mm^3/min
Wire EDM	Contour cutting of flat or curved surfaces; expensive equipment	Varies with workpiece material and its thickness
Laser-beam machining (LBM)	Cutting and hole making on thin materials; heat-affected zone; does not require a vacuum; expensive equipment; consumes much energy; extreme caution required in use	0.50–7.5 m/min
Electron-beam machining (EBM)	Cutting and hole making on thin materials; very small holes and slots; heat-affected zone; requires a vacuum; expensive equipment	1–2 mm^3/min
Water-jet machining (WJM)	Cutting all types of nonmetallic materials to 25 mm and greater in thickness; suitable for contour cutting of flexible materials; no thermal damage; environmentally safe process	Varies considerably with workpiece material
Abrasive water-jet machining (AWJM)	Single or multilayer cutting of metallic and nonmetallic materials	Up to 7.5 m/min
Abrasive-jet machining (AJM)	Cutting, slotting, deburring, flash removal, etching, and cleaning of metallic and nonmetallic materials; tends to round off sharp edges; some hazard because of airborne particulates	Varies considerably with workpiece material
Laser microjet	Water-jet guided laser uses a 25–100 μm diameter stream to mill or cut; large depth of field; little thermal damage from laser machining	Varies with material; up to 20 mm in silicon, 2 mm in stainless steel; up to 300 mm/s in 50-μm thick silicon

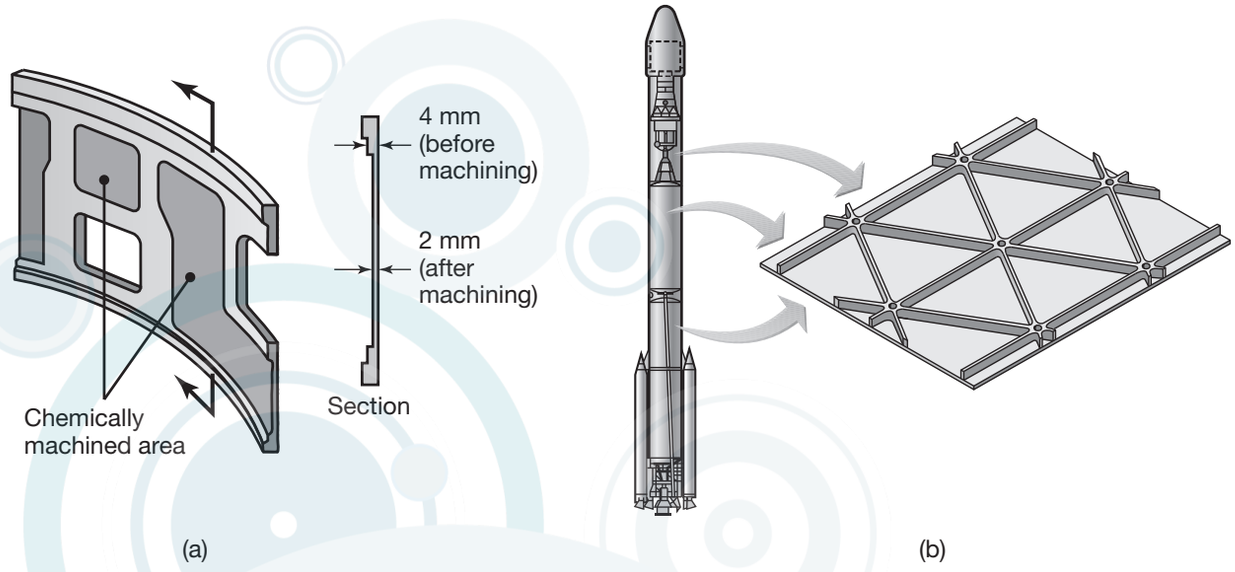


FIGURE 9.26 (a) Missile skin-panel section contoured by chemical milling to improve the stiffness-to-weight ratio of the part. (b) Weight reduction of space launch vehicles by chemical milling of aluminum-alloy plates. These panels are chemically milled after the plates have first been formed into shape, such as by roll forming or stretch forming. *Source:* After ASM International.

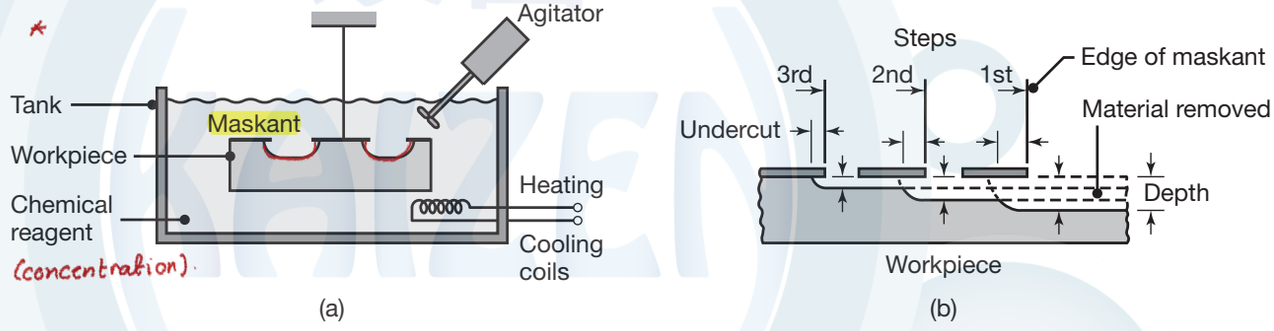
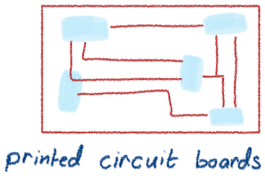


FIGURE 9.27 (a) Schematic illustration of the chemical machining process. Note that no forces are involved in this process. (b) Stages in producing a profiled cavity by chemical machining.

Also, chemical milling of castings may result in uneven surfaces caused by porosity and nonuniformity of the structure.

9.10.2 Chemical Blanking



Chemical blanking is similar to blanking of sheet metal (See Fig. 7.8), in that it is used to produce features that penetrate through the thickness of the material; the material is removed by chemical dissolution. Typical applications include burr-free etching of printed-circuit boards (Fig. 13.33) and the production of decorative panels, thin sheet metal stampings, and small or complex shapes.

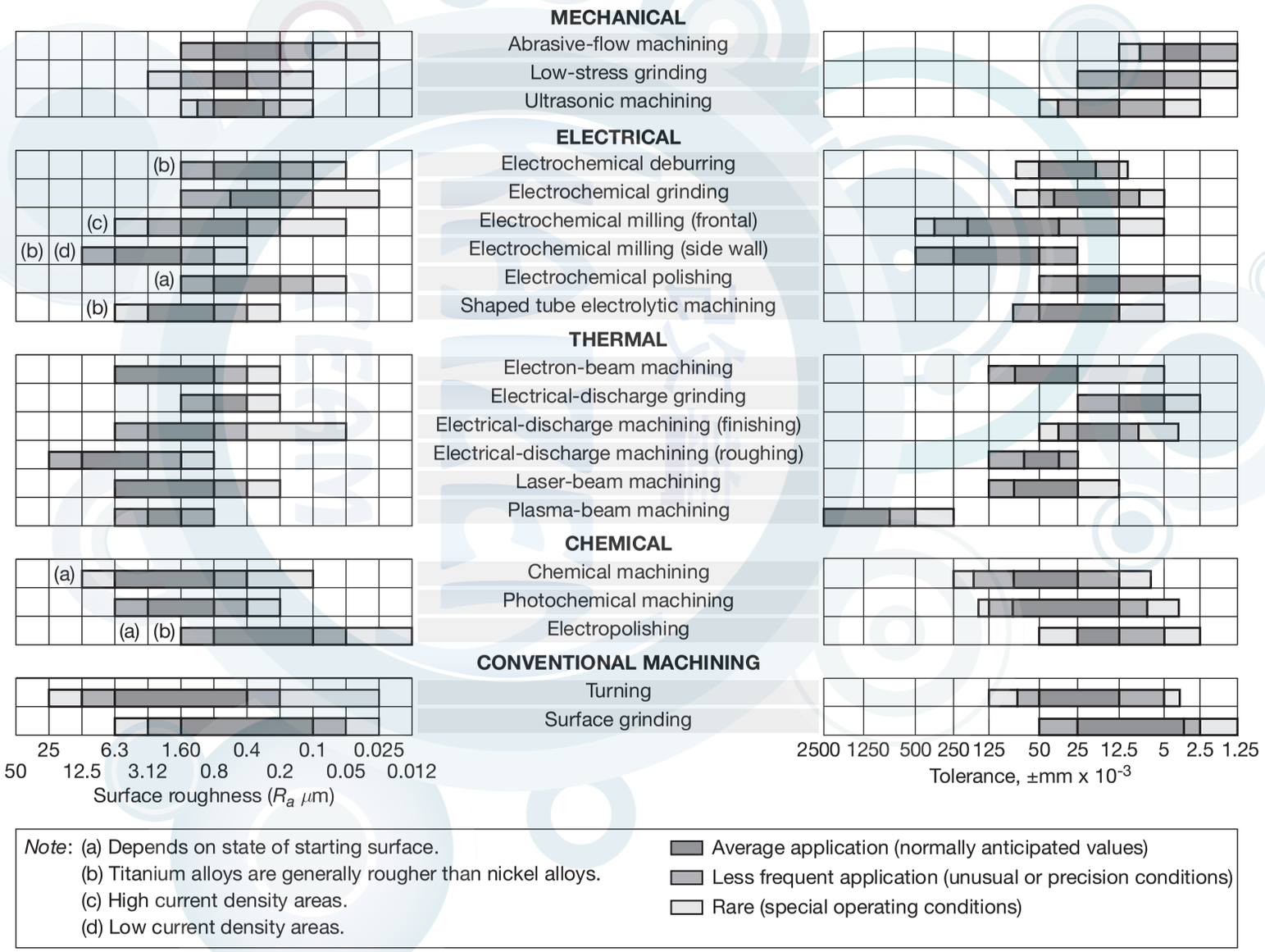


FIGURE 9.28 Surface roughness and dimensional tolerance capabilities of various machining processes. Note the wide range within each process. (See also Fig. 8.24.) *Source: After Machining Data Handbook*, 3rd ed., ©1980. Used by permission of Metcut Research Associates, Inc.

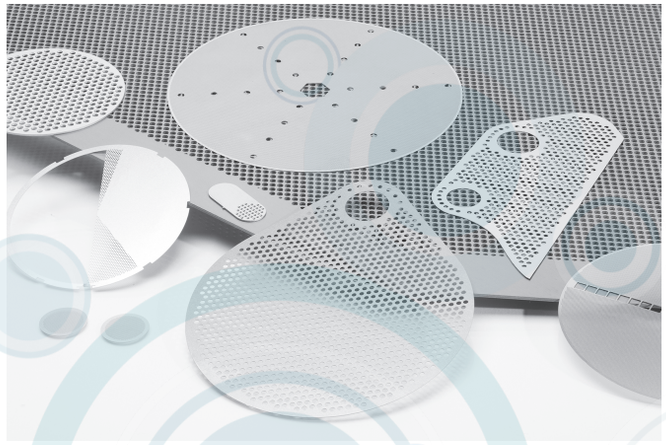


FIGURE 9.29 Typical parts made by chemical blanking; note the fine detail. *Source:* Courtesy of VACCO Industries.

9.10.3 Photochemical Blanking

Also called *photoetching*, *photochemical blanking* is a modification of chemical milling; material is removed by photographic techniques, usually from flat thin sheet. Complex burr-free shapes can be blanked (Fig. 9.29) on metals as thin as 0.0025 mm; the process is also used for etching (see Section 13.8). Typical applications for photochemical blanking include fine screens, printed-circuit boards, electric-motor laminations, and flat springs.

Photochemical blanking is capable of forming very small parts for which traditional blanking dies (Section 7.3) are difficult to make, and the process is effective for blanking fragile workpieces and materials. Handling of chemical reagents requires special safety precautions to protect personnel. Disposal of chemical by-products from this process also is a major consideration, although some by-products can be recycled. Although skilled labor is required, tooling costs are low, the process can be automated, and it is economical for medium to high production volume.

9.11 Electrochemical Machining

Electrochemical machining (ECM) is basically the reverse of electroplating. An electrolyte (Fig. 9.30) acts as a current carrier, and the high rate of electrolyte movement in the tool-workpiece gap washes metal ions away from the workpiece (*anode*) before they have a chance to plate onto the tool (*cathode*). Note that the cavity produced is the female mating image of the tool. Modifications of this process are used for operations such as turning, facing, slotting, trepanning, and profiling in which the electrode becomes the cutting tool.

The shaped tool is generally made of brass, copper, bronze, or stainless steel. The electrolyte is a highly conductive inorganic salt solution, such as sodium chloride mixed in water or sodium nitrate, and is pumped at a high rate through the passages in the tool. A dc power supply in the range of 5–25 V maintains current densities, which for most applications are 1.5–8 A/mm^2 of active machined surface. Machines that have current capacities as high as 40,000 A and as small as 5 A are available. Because

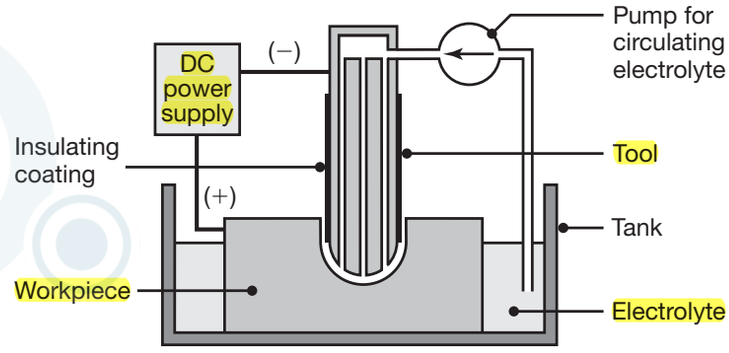


FIGURE 9.30 Schematic illustration of the electrochemical-machining process. This process is the reverse of electroplating, described in Section 4.5.1.

the metal removal rate is only a function of ion exchange rate, it is not affected by the strength, hardness, or toughness of the workpiece (which must be electrically conductive).

The material removal rate by electrochemical machining can be calculated from the equation

$$\text{MRR} = CI\eta, \tag{9.14}$$

where MRR = mm^3/min; I = current in amperes; and η = current efficiency, which typically ranges from 90 to 100%. C is a material constant in mm^3/A-min and, for pure metals, depends on valence; the higher the valence, the lower its value. For most metals, the value of C typically ranges between about 1 and 2. If a cavity of uniform cross-sectional area A_o (in mm^2) is being electrochemically machined, the feed rate, f, in mm/min would be

$$f = \frac{\text{MRR}}{A_o}. \tag{9.15}$$

Note that the feed rate is the speed at which the electrode penetrates the workpiece.

Electrochemical machining is generally used for machining complex cavities in high-strength materials, particularly in the aerospace industry for mass production of turbine blades, jet-engine parts, and nozzles (Fig. 9.31). The process is also used for machining forging-die cavities (*die sinking*) and producing small holes. The ECM process leaves a burr-free surface; in fact, it can also be used as a deburring process. It does not cause any thermal damage to the part, and the lack of tool forces prevents distortion of the part, as would be the case with typical machining operations. Furthermore, there is no tool wear, and the process is capable of producing complex shapes as well as machining hard materials. However, the mechanical properties of components made by ECM should be compared with those produced by other machining methods.

A modification of ECM is the **shaped-tube electrolytic machining** (STEM) process, typically used for drilling small-diameter deep holes, as in turbine blades. The tool is a titanium tube, coated with an electrically insulating resin to prevent removal of material from other regions. Holes as small as 0.5 mm can be drilled, at depth-to-diameter ratios of as high as 300:1.