24 Grinding and Other Abrasive Processes

Chapter Contents

Abrasive machining involves material removal by the action of hard, abrasive particles that are usually in the form of a bonded wheel. Grinding is the most important abrasive process. In terms of number of machine tools in use, grinding is the most common of all metalworking operations [11]. Other traditional abrasive processes include honing, lapping, superfinishing, polishing, and buffing. The abrasive machining processes are generally used as finishing operations, although some abrasive processes are capable of high material removal rates rivaling those of conventional machining operations.

The use of abrasives to shape parts is probably the oldest material removal process (Historical Note 24.1). Abrasive processes are important commercially and technologically for the following reasons:

- They can be used on all types of materials ranging from soft metals to hardened steels and hard nonmetallic materials such as ceramics and silicon.
- Some of these processes can produce extremely fine surface finishes, to 0.025 μm (1 μ-in).
- For certain abrasive processes, dimensions can be held to extremely close tolerances.

Abrasive water jet cutting and ultrasonic machining are also abrasive processes, because material removal is accomplished by means of abrasives. However, they are commonly classified as nontraditional processes and are covered in the Chapter 25.

24.1 Grinding

Grinding is a material removal process accomplished by abrasive particles that are contained in a bonded grinding wheel rotating at very high surface speeds. The grinding wheel is usually disk shaped, and is precisely balanced for high rotational speeds.

Historical Note 24.1 *Development of abrasive processes*

Use of abrasives predates any of the other machining operations. There is archaeological evidence that ancient people used abrasive stones such as sandstone found in nature to sharpen tools and weapons and scrape away unwanted portions of softer materials to make domestic implements.

Grinding became an important technical trade in ancient Egypt. The large stones used to build the Egyptian pyramids were cut to size by a rudimentary grinding process. The grinding of metals dates to around 2000 B.C.E. and was a highly valued skill at that time.

Early abrasive materials were those found in nature, such as sandstone, which consists primarily of quartz (SiO_2); emery, consisting of corundum (Al_2O_3) plus equal or lesser amounts of the iron minerals hematite (Fe_2O_3) and magnetite (Fe_3O_4); and diamond. The first grinding wheels were likely cut out of sandstone and were no doubt rotated under manual power. However, grinding wheels made in this way were not consistent in quality.

In the early 1800s, the first solid bonded grinding wheels were produced in India. They were used to grind gems, an important trade in India at the time. The abrasives were corundum, emery, or diamond. The bonding material was natural gum-resin shellac. The technology was exported to Europe and the United States, and other bonding materials were subsequently introduced: rubber bond in the mid-1800s, vitrified bond around 1870, shellac bond around 1880, and resinoid bond in the 1920s with the development of the first thermosetting plastics (phenol-formaldehyde).

In the late 1800s, synthetic abrasives were first produced: silicon carbide (SiC) and aluminum oxide (Al_2O_3). By manufacturing the abrasives, chemistry and size of the individual abrasive grains could be controlled more closely, resulting in higher quality grinding wheels.

The first real grinding machines were made by the U.S. firm Brown & Sharpe in the 1860s for grinding parts for sewing machines, an important industry during the period. Grinding machines also contributed to the development of the bicycle industry in the 1890s and later the U.S. automobile industry. The grinding process was used to size and finish heat-treated (hardened) parts in these products.

The superabrasives diamond and cubic boron nitride are products of the twentieth century. Synthetic diamonds were first produced by the General Electric Company in 1955. These abrasives were used to grind cemented carbide cutting tools, and today this remains one of the important applications of diamond abrasives. Cubic boron nitride (cBN), second only to diamond in hardness, was first synthesized in 1957 by GE using a similar process to that for making artificial diamonds. Cubic BN has become an important abrasive for grinding hardened steels.

Grinding can be likened to the milling process. Cutting occurs on either the periphery or the face of the grinding wheel, similar to peripheral and face milling. Peripheral grinding is much more common than face grinding. The rotating grinding wheel consists of many cutting teeth (the abrasive particles), and the work is fed relative to the wheel to accomplish material removal. Despite these similarities, there are significant differences between grinding and milling: (1) the abrasive grains in the wheel are much smaller and more numerous than the teeth on a milling cutter; (2) cutting speeds in grinding are much higher than in milling; (3) the abrasive grits in a grinding wheel are randomly oriented and possess on average a very high negative rake angle; and (4) a grinding wheel is self-sharpening—as the wheel wears, the abrasive particles become dull and either fracture to create fresh cutting edges or are pulled out of the surface of the wheel to expose new grains.

24.1.1 THE GRINDING WHEEL

A grinding wheel consists of abrasive particles and bonding material. The bonding material holds the particles in place and establishes the shape and structure of the wheel. These two ingredients and the way they are fabricated determine the five basic parameters of a grinding wheel: (1) abrasive material, (2) grain size, (3) bonding material, (4) wheel grade, and (5) wheel structure. To achieve the desired performance in a given application, each parameter must be carefully selected.

Abrasive Material Different abrasive materials are appropriate for grinding different work materials. General properties of an abrasive material used in grinding wheels include high hardness, wear resistance, toughness, and friability. Hardness, wear resistance, and toughness are desirable properties of any cutting-tool material. ***Friability*** refers to the capacity of the abrasive material to fracture when the cutting edge of the grain becomes dull, thereby exposing a new sharp edge.

The development of grinding abrasives is described in Historical Note 24.1. Today, the abrasive materials of greatest commercial importance are aluminum oxide, silicon carbide, cubic boron nitride, and diamond. They are briefly described in Table 24.1, together with their relative hardness values.

Grain Size The grain size of the abrasive particle is important in determining surface finish and material removal rate. Small grit sizes produce better finishes, whereas larger grain sizes permit larger material removal rates. Thus, a choice must be made between these two objectives when selecting abrasive grain size. The selection of grit size also depends to some extent on the hardness of the work material. Harder work materials require smaller grain sizes to cut effectively, whereas softer materials require larger grit sizes.

The grit size is measured using a screen mesh procedure, as explained in Section 15.1. In this procedure, smaller grit sizes have larger numbers and vice versa. Grain sizes used in grinding wheels typically range between 8 and 250. Grit size 8 is very coarse and size 250 is very fine. Even finer grit sizes are used for lapping and superfinishing (Section 24.2).

Bonding Materials The bonding material holds the abrasive grains and establishes the shape and structural integrity of the grinding wheel. Desirable properties of the bond material include strength, toughness, hardness, and temperature resistance.

TABLE • 24.1 Abrasives of greatest importance in grinding.

Abrasive	Description	Knoop Hardness
Aluminum oxide (Al_2O_3)	Most common abrasive material (Section 7.3.1), used to grind steel and other ferrous, high-strength alloys.	2100
Silicon carbide (SiC)	Harder than Al_2O_3, but not as tough (Section 7.2.2). Applications include ductile metals such as aluminum, brass, and stainless steel, as well as brittle materials such as some cast irons and certain ceramics. Cannot be used effectively for grinding steel because of the strong chemical affinity between the carbon in SiC and the iron in steel.	2500
Cubic boron nitride (cBN)	When used as an abrasive, cBN (Section 7.3.3) is produced under the trade name Borazon by the General Electric Company. cBN grinding wheels are used for hard materials such as hardened tool steels and aerospace alloys.	5000
Diamond	Diamond abrasives occur naturally and are also made synthetically (Section 7.5.1). Diamond wheels are generally used in grinding applications on hard, abrasive materials such as ceramics, cemented carbides, and glass.	7000

TABLE • 24.2 Bonding materials used in grinding wheels.

Bonding Material	Description
Vitrified bond	Consists chiefly of baked clay and ceramic materials. Most grinding wheels in common use are vitrified bonded wheels. They are strong and rigid, resistant to elevated temperatures, and relatively unaffected by water and oil that might be used in grinding fluids.
Silicate bond	Consists of sodium silicate (Na_2SO_3). Applications are generally limited to situations in which heat generation must be minimized, such as grinding cutting tools.
Rubber bond	Most flexible of the bonding materials and used as a bonding material in cutoff wheels.
Resinoid bond	Consists of various thermosetting resin materials, such as phenol-formaldehyde. It has very high strength and is used for rough grinding and cutoff operations.
Shellac bond	Relatively strong but not rigid; often used in applications requiring a good finish.
Metallic bond	Metal, usually bronze, is the common bond material for diamond and cBN grinding wheels. Particulate processing (Chapters 15 and 16) is used to bond the metal matrix and abrasive grains to the outside periphery of the wheel, thus conserving the costly abrasive materials.

The bonding material must be able to withstand the centrifugal forces and high temperatures experienced by the grinding wheel, resist shattering in shock loading of the wheel, and hold the abrasive grains rigidly in place to accomplish the cutting action while allowing those grains that are worn to be dislodged so that new grains can be exposed. Bonding materials commonly used in grinding wheels are identified and briefly described in Table 24.2.

Wheel Structure and Wheel Grade ***Wheel structure*** refers to the relative spacing of the abrasive grains in the wheel. In addition to the abrasive grains and bond material, grinding wheels contain air gaps or pores, as illustrated in Figure 24.1. The volumetric proportions of grains, bond material, and pores can be expressed as

$$P_g + P_b + P_p = 1.0 \tag{24.1}$$

where P_g = proportion of abrasive grains in the total wheel volume, P_b = proportion of bond material, and P_p = proportion of pores (air gaps).

Wheel structure is measured on a scale that ranges between "open" and "dense." An open structure is one in which P_p is relatively large, and P_g is relatively small. That is, there are more pores and fewer grains per unit volume in a wheel of open structure. By contrast, a dense structure is one in which P_p is relatively small, and P_g is larger. Generally, open structures are recommended in situations in which clearance for chips must be provided. Dense structures are used to obtain better surface finish and dimensional control.

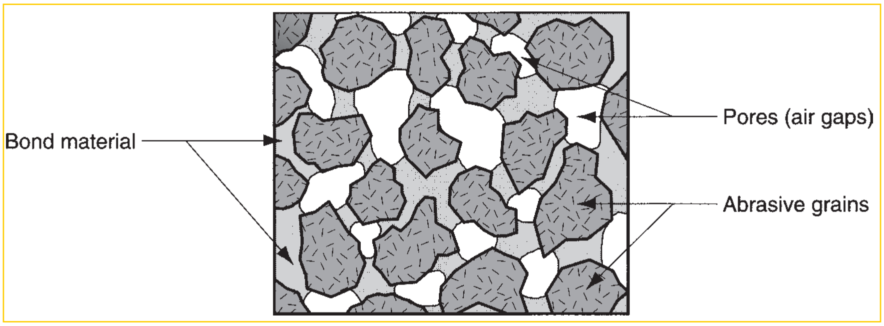

FIGURE 24.1 Typical structure of a grinding wheel.

TABLE • 24.3 Marking system for conventional grinding wheels as defined by ANSI Standard B74.13-1977 [2].

30 A 46 H 6 V XX

- ***Manufacturer's private marking*** for wheel (optional)
- ***Bond type***: B = Resinoid, BF = resinoid reinforced, E = Shellac, R = Rubber, RF = rubber reinforced, S = Silicate, V = Vitrified.
- ***Structure***: Scale ranges from 1 to 15: 1 = very dense structure, 15 = very open structure
- ***Grade***: Scale ranges from A to Z: A = soft, M = medium, Z = hard
- ***Grain size***: Coarse = grit sizes 8 to 24, Medium = grit sizes 30 to 60, Fine = grit sizes 70 to 180, Very fine = grit sizes 220 to 600.
- ***Abrasive type***: A = aluminum oxide, C = silicon carbide.
- ***Prefix***: Manufacturer's symbol for abrasive (optional)

Wheel grade indicates the grinding wheel's bond strength in retaining the abrasive grits during cutting. This is largely dependent on the amount of bonding material present in the wheel structure—P_b in Equation (24.1). Grade is measured on a scale that ranges between soft and hard. "Soft" wheels lose grains readily, whereas "hard" wheels retain their abrasive grains. Soft wheels are generally used for applications requiring low material removal rates and grinding of hard work materials. Hard wheels are typically used to achieve high stock removal rates and for grinding of relative soft work materials.

Grinding Wheel Specification The preceding parameters can be concisely designated in a standard grinding wheel marking system defined by the American National Standards Institute (ANSI) [2]. This marking system uses numbers and letters to specify abrasive type, grit size, grade, structure, and bond material. Table 24.3 presents an abbreviated version of the ANSI Standard, indicating how the numbers and letters are interpreted. The standard also provides for additional identifications that might be used by the grinding wheel manufacturers. The ANSI Standard for diamond and cubic boron nitride grinding wheels is slightly different than for conventional wheels. The marking system for these newer grinding wheels is presented in Table 24.4.

TABLE • 24.4 Marking system for diamond and cubic boron nitride grinding wheels as defined by ANSI Standard B74.13-1977 [2].

XX D 150 P YY M ZZ 3

- ***Depth of abrasive*** = working depth of abrasive section in mm (shown) or inches, as in Figure 24.2(c).
- ***Bond modification*** = manufacturer's notation of special bond type or modification.
- ***Bond type***: B = Resin, M = metal, V = Vitrified
- ***Concentration***: Manufacturer's designation. May be number or symbol.
- ***Grade***: Scale ranges from A to Z: A = soft, M = medium, Z = hard
- ***Grain size***: Coarse = grit sizes 8 to 24, Medium = grit sizes 30 to 60, Fine = grit sizes 70 to 180, Very fine = grit sizes 220 to 600.
- ***Abrasive type***: D = diamond, B = cubic boron nitride.
- ***Prefix***: Manufacturer's symbol for abrasive (optional)

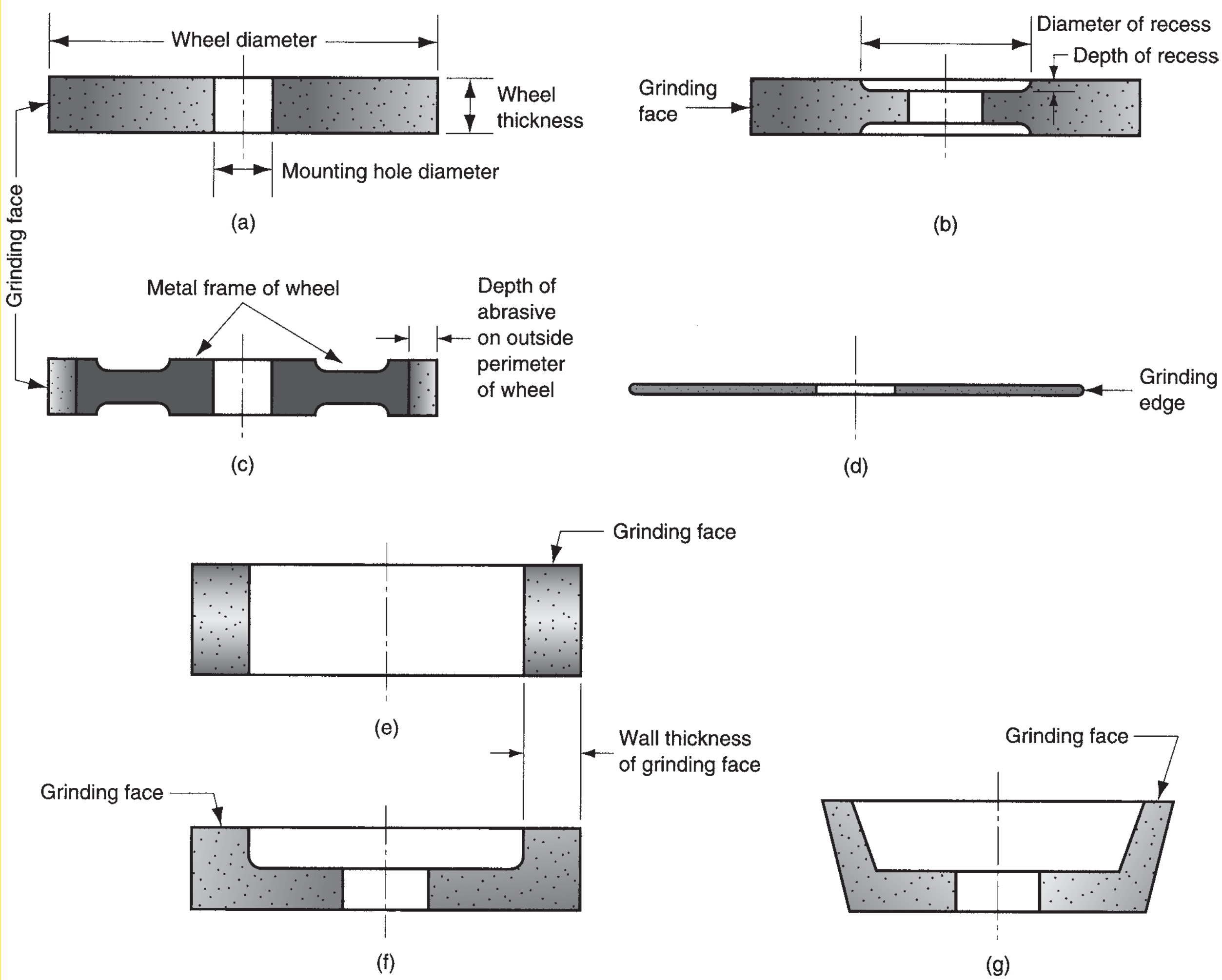

FIGURE 24.2 Some standard grinding wheel shapes: (a) straight, (b) recessed two sides, (c) metal wheel frame with abrasive bonded to outside circumference, (d) abrasive cutoff wheel, (e) cylinder wheel, (f) straight cup wheel, and (g) flaring cup wheel.

Grinding wheels come in a variety of shapes and sizes, as shown in Figure 24.2. Configurations (a), (b), and (c) are peripheral grinding wheels, in which material removal is accomplished by the outside circumference of the wheel. A typical abrasive cutoff wheel is shown in (d), which also involves peripheral cutting. Wheels (e), (f), and (g) are face grinding wheels, in which the flat face of the wheel removes material from the work surface.

24.1.2 ANALYSIS OF THE GRINDING PROCESS

The cutting conditions in grinding are characterized by very high speeds and very small cut size, compared to milling and other traditional machining operations. Using surface grinding to illustrate, Figure 24.3(a) shows the principal features of the

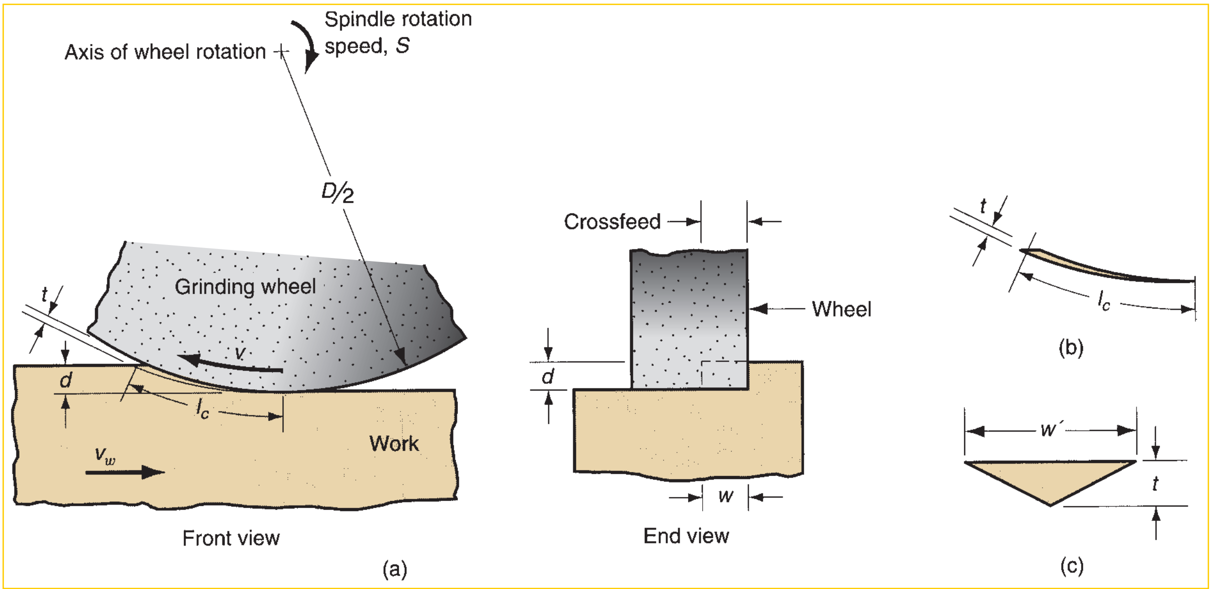

FIGURE 24.3 (a) The geometry of surface grinding, showing the cutting conditions; (b) assumed longitudinal shape and (c) cross section of a single chip.

process. The peripheral speed of the grinding wheel is determined by the rotational speed of the wheel:

$$v = \pi DN \tag{24.2}$$

where $v =$ surface speed of wheel, m/min (ft/min); $N =$ spindle speed, rev/min; and $D =$ wheel diameter, m (ft).

Depth of cut d, called the ***infeed***, is the penetration of the wheel below the original work surface. As the operation proceeds, the grinding wheel is fed laterally across the surface on each pass by the work. This is called the ***crossfeed***, and it determines the width of the grinding path w in Figure 24.3(a). This width, multiplied by depth d determines the cross-sectional area of the cut. In most grinding operations, the work moves past the wheel at a certain speed v_w, so that the material removal rate is

$$R_{MR} = v_w wd \tag{24.3}$$

Each grain in the grinding wheel cuts an individual chip whose longitudinal shape before cutting is shown in Figure 24.3(b) and whose assumed cross-sectional shape is triangular, as in Figure 24.3(c). At the exit point of the grit from the work, where the chip cross section is largest, this triangle has height t and width w'.

In a grinding operation, one is interested in how the cutting conditions combine with the grinding wheel parameters to affect (1) surface finish, (2) forces and energy, (3) temperature of the work surface, and (4) wheel wear.

Surface Finish Most commercial grinding is performed to achieve a surface finish that is superior to that which can be accomplished with conventional machining. The surface finish of the work part is affected by the size of the individual chips formed during grinding. One obvious factor in determining chip size is grit size—smaller grit sizes yield better finishes.

Consider the dimensions of an individual chip. From the geometry of the grinding process in Figure 24.3, it can be shown that the average length of a chip is given by

$$l_c = \sqrt{Dd} \tag{24.4}$$

where l_c is the length of the chip, mm (in); $D =$ wheel diameter, mm (in); and $d =$ depth of cut, or infeed, mm (in). This assumes the chip is formed by a grit that acts throughout the entire sweep arc shown in the diagram.

Figure 24.3(c) shows the assumed cross section of a chip in grinding. The cross-sectional shape is triangular with width w' being greater than the thickness t by a factor called the grain aspect ratio r_g, defined by

$$r_g = \frac{w'}{t} \tag{24.5}$$

Typical values of grain aspect ratio are between 10 and 20.

The number of active grits (cutting teeth) per square inch on the outside periphery of the grinding wheel is denoted by C. In general, smaller grain sizes give larger C values. C is also related to the wheel structure. A denser structure means more grits per area. Based on the value of C, the number of chips formed per time n_c is given by

$$n_c = vwC \tag{24.6}$$

where $v =$ wheel speed, mm/min (in/min); $w =$ crossfeed, mm (in); and $C =$ grits per area on the grinding wheel surface, grits/mm^2 (grits/in^2). It stands to reason that surface finish will be improved by increasing the number of chips formed per unit time on the work surface for a given width w. Therefore, according to Equation (24.6), increasing v and/or C will improve finish.

Forces and Energy If the force required to drive the work past the grinding wheel were known, the specific energy in grinding could be determined as

$$U = \frac{F_c v}{v_w w d} \tag{24.7}$$

where $U =$ specific energy, J/mm^3 (in-lb/in^3); $F_c =$ cutting force, which is the force to drive the work past the wheel, N (lb); $v =$ wheel speed, m/min (ft/min); $v_w =$ work speed, mm/min (in/min); $w =$ width of cut, mm (in); and $d =$ depth of cut, mm (in).

In grinding, the specific energy is much greater than in conventional machining. There are several reasons for this. First is the ***size effect*** in machining. The chip thickness in grinding is much smaller than for other machining operations, such as milling. According to the size effect (Section 20.4), the small chip sizes in grinding cause the energy required to remove each unit volume of material to be significantly higher than in conventional machining—roughly 10 times higher.

Second, the individual grains in a grinding wheel possess extremely negative rake angles. The average rake angle is about $-30°$, with values on some individual grains believed to be as low as $-60°$. These very low rake angles result in low values of shear plane angle and high shear strains, both of which mean higher energy levels in grinding.

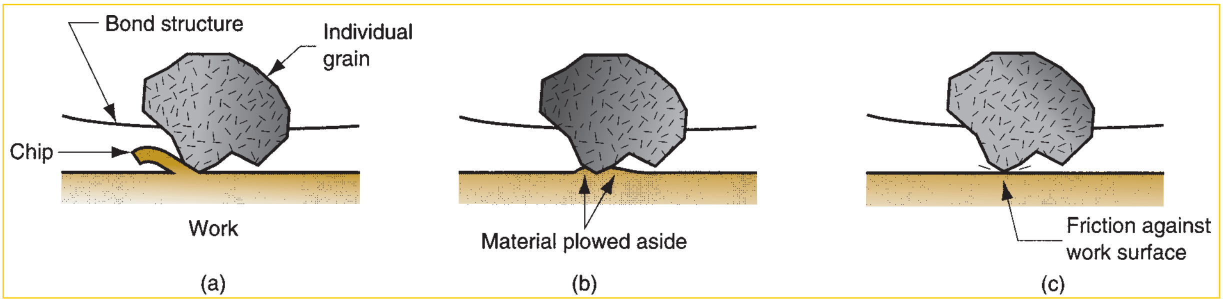

FIGURE 24.4 Three types of grain action in grinding: (a) cutting, (b) plowing, and (c) rubbing.

Third, specific energy is higher in grinding because not all of the individual grits are engaged in actual cutting. Because of the random positions and orientations of the grains in the wheel, some grains do not project far enough into the work surface to accomplish cutting. Three types of grain actions can be recognized, as illustrated in Figure 24.4: (a) ***cutting***, in which the grit projects far enough into the work surface to form a chip and remove material; (b) ***plowing***, in which the grit projects into the work, but not far enough to cause cutting; instead, the work surface is deformed and energy is consumed without any material removal; and (c) ***rubbing***, in which the grit contacts the surface during its sweep, but only rubbing friction occurs, thus consuming energy without removing any material.

The size effect, negative rake angles, and ineffective grain actions combine to make the grinding process inefficient in terms of energy consumption per volume of material removed.

Using the specific energy relationship in Equation (24.7), and assuming that the cutting force acting on a single grain in the grinding wheel is proportional to $r_g t$, it can be shown [10] that

$$F_c' = K_1 \left(\frac{r_g v_w}{vC}\right)^{0.5} \left(\frac{d}{D}\right)^{0.25} \tag{24.8}$$

where F_c' is the cutting force acting on an individual grain, K_1 is a constant of proportionality that depends on the strength of the material being cut and the sharpness of the individual grain, and the other terms have been previously defined. The practical significance of this relationship is that F_c' affects whether an individual grain will be pulled out of the grinding wheel, an important factor in the wheel's capacity to "resharpen" itself. Referring back to the discussion on wheel grade, a hard wheel can be made to appear softer by increasing the cutting force acting on an individual grain through appropriate adjustments in v_w, v, and d, according to Equation (24.8).

Temperatures at the Work Surface Because of the size effect, high negative rake angles, and plowing and rubbing of the abrasive grits against the work surface, the grinding process is characterized by high temperatures. Unlike conventional machining operations in which most of the heat energy generated in the process is carried off in the chip, much of the energy in grinding remains in the ground surface [11], resulting in high work surface temperatures. The high surface temperatures have several possible damaging effects, primarily surface burns and cracks. The burn marks show themselves as discolorations on the surface caused by oxidation. Grinding burns are often a sign of metallurgical damage immediately beneath the surface.

The surface cracks are perpendicular to the wheel speed direction. They indicate an extreme case of thermal damage to the work surface.

A second harmful thermal effect is softening of the work surface. Many grinding operations are carried out on parts that have been heat-treated to obtain high hardness. High grinding temperatures can cause the surface to lose some of its hardness. Third, thermal effects in grinding can cause residual stresses in the work surface, possibly decreasing the fatigue strength of the part.

It is important to understand what factors influence work surface temperatures in grinding. Experimentally, it has been observed that surface temperature is dependent on energy per surface area ground (closely related to specific energy U). Because this varies inversely with chip thickness, it can be shown that surface temperature T_s is related to grinding parameters as follows [10]:

$$T_s = K_2 d^{0.75}\left(\frac{r_g C v}{v_w}\right)^{0.5} D^{0.25} \tag{24.9}$$

where $K_2 =$ a constant of proportionality. The practical implication of this relationship is that surface damage caused by high work temperatures can be mitigated by decreasing depth of cut d, wheel speed v, and number of active grits per square inch on the grinding wheel C, or by increasing work speed v_w. In addition, dull grinding wheels and wheels that have a hard grade and dense structure tend to cause thermal problems. Of course, using a cutting fluid can also reduce grinding temperatures.

Wheel Wear Grinding wheels wear, just as conventional cutting tools wear. Three mechanisms are recognized as the principal causes of wear in grinding wheels: (1) grain fracture, (2) attritious wear, and (3) bond fracture. ***Grain fracture*** occurs when a portion of the grain breaks off, but the rest of the grain remains bonded in the wheel. The edges of the fractured area become new cutting edges on the grinding wheel. The tendency of the grain to fracture is called ***friability***. High friability means that the grains fracture more readily because of the cutting forces on the grains F_c'.

Attritious wear involves dulling of the individual grains, resulting in flat spots and rounded edges. Attritious wear is analogous to tool wear in a conventional cutting tool. It is caused by similar physical mechanisms including friction and diffusion, as well as chemical reactions between the abrasive material and the work material in the presence of very high temperatures.

Bond fracture occurs when the individual grains are pulled out of the bonding material. The tendency toward this mechanism depends on wheel grade, among other factors. Bond fracture usually occurs because the grain has become dull from attritious wear, and the resulting cutting force is excessive. Sharp grains cut more efficiently with lower cutting forces; hence, they remain attached in the bond structure.

The three mechanisms combine to cause the grinding wheel to wear as depicted in Figure 24.5. Three wear regions can be identified. In the first region, the grains are initially sharp, and wear is accelerated because of grain fracture. This corresponds to the "break-in" period in conventional tool wear. In the second region, the wear rate is fairly constant, resulting in a linear relationship between wheel wear and volume of metal removed. This region is characterized by attritious wear, with some grain and bond fracture. In the third region of the wheel wear curve, the grains become dull, and the amount of plowing and rubbing increases relative to cutting. In addition, some of the chips become clogged in the pores of the wheel. This is called ***wheel loading***, and it impairs the cutting action and leads to higher heat and work surface

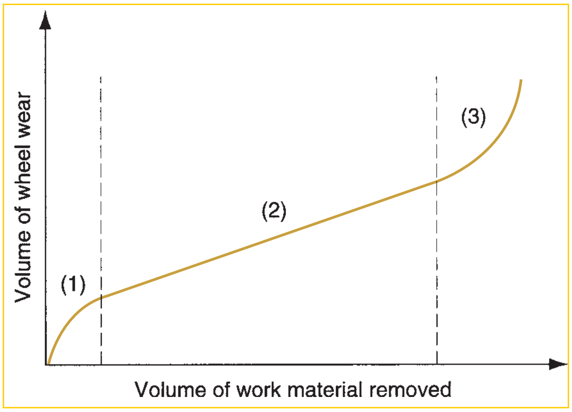

FIGURE 24.5 Typical wear curve of a grinding wheel. Wear is conveniently plotted as a function of volume of material removed, rather than as a function of time. (Based on [16].)

temperatures. As a consequence, grinding efficiency decreases, and the volume of wheel removed increases relative to the volume of metal removed.

The ***grinding ratio*** is a term used to indicate the slope of the wheel wear curve. Specifically,

$$GR = \frac{V_w}{V_g} \tag{24.10}$$

where $GR =$ the grinding ratio, $V_w =$ the volume of work material removed, and $V_g =$ the corresponding volume of the grinding wheel that is worn in the process. The grinding ratio has the most significance in the linear wear region of Figure 24.5. Typical values of GR range between 95 and 125 [5], which is about five orders of magnitude less than the analogous ratio in conventional machining. Grinding ratio is generally increased by increasing wheel speed v. The reason for this is that the size of the chip formed by each grit is smaller with higher speeds, so the amount of grain fracture is reduced. Because higher wheel speeds also improve surface finish, there is a general advantage in operating at high grinding speeds. However, when speeds become too high, attritious wear and surface temperatures increase. As a result, the grinding ratio is reduced and the surface finish is impaired. This effect was originally reported by Krabacher [14], as in Figure 24.6.

When the wheel is in the third region of the wear curve, it must be resharpened by a procedure called ***dressing***, which consists of (1) breaking off the dulled grits on

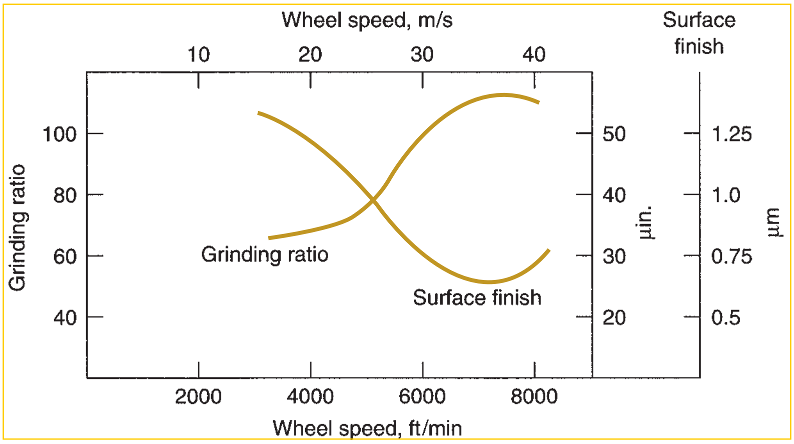

FIGURE 24.6 Grinding ratio and surface finish as a function of wheel speed. (Based on data in Krabacher [14].)

the outside periphery of the grinding wheel in order to expose fresh sharp grains and (2) removing chips that have become clogged in the wheel. It is accomplished by a rotating disk, an abrasive stick, or another grinding wheel operating at high speed, held against the wheel being dressed as it rotates. Although dressing sharpens the wheel, it does not guarantee the shape of the wheel. ***Truing*** is an alternative procedure that not only sharpens the wheel, but also restores its cylindrical shape and insures that it is straight across its outside perimeter. The procedure uses a diamond-pointed tool (other types of truing tools are also used) that is fed slowly and precisely across the wheel as it rotates. A very light depth is taken (0.025 mm or less) against the wheel.

24.1.3 APPLICATION CONSIDERATIONS IN GRINDING

This section attempts to bring together the previous discussion of wheel parameters and theoretical analysis of grinding and consider their practical application. Also considered are grinding fluids, which are commonly used in grinding operations.

Application Guidelines There are many variables in grinding that affect the performance and success of the operation. The guidelines listed in Table 24.5 are helpful in sorting out the many complexities and selecting the proper wheel parameters and grinding conditions.

Grinding Fluids The proper application of cutting fluids has been found to be effective in reducing the thermal effects and high work surface temperatures described previously. When used in grinding operations, cutting fluids are called grinding fluids. The functions performed by grinding fluids are similar to those performed by cutting

TABLE • 24.5 Application guidelines for grinding.

Application Problem or Objective	Recommendation or Guideline
Grinding steel and most cast irons	Select aluminum oxide as the abrasive.
Grinding most nonferrous metals	Select silicon carbide as the abrasive.
Grinding hardened tool steels and certain aerospace alloys	Select cubic boron nitride as the abrasive.
Grinding hard abrasive materials such as ceramics, cemented carbides, and glass	Select diamond as the abrasive.
Grinding soft metals	Select a large grit size and harder grade wheel.
Grinding hard metals	Select a small grit size and softer grade wheel.
Optimize surface finish	Select a small grit size and dense wheel structure. Use high wheel speeds (v), lower work speeds (v_w).
Maximize material removal rate	Select a large grit size, more open wheel structure, and vitrified bond.
To minimize heat damage, cracking, and warping of the work surface	Maintain sharpness of the wheel. Dress the wheel frequently. Use lighter depths of cut (d), lower wheel speeds (v), and faster work speeds (v_w).
If the grinding wheel glazes and burns	Select wheel with a soft grade and open structure.
If the grinding wheel breaks down too rapidly	Select wheel with a hard grade and dense structure.

Compiled from [8], [11], and [16].

fluids (Section 22.4). Reducing friction and removing heat from the process are the two common functions. In addition, washing away chips and reducing temperature of the work surface are very important in grinding.

Types of grinding fluids by chemistry include grinding oils and emulsified oils. The grinding oils are derived from petroleum and other sources. These products are attractive because friction is such an important factor in grinding. However, they pose hazards in terms of fire and operator health, and their cost is high relative to emulsified oils. In addition, their capacity to carry away heat is less than fluids based on water. Accordingly, mixtures of oil in water are most commonly recommended as grinding fluids. These are usually mixed with higher concentrations than emulsified oils used as conventional cutting fluids. In this way, the friction reduction mechanism is emphasized.

24.1.4 GRINDING OPERATIONS AND GRINDING MACHINES

Grinding is traditionally used to finish parts whose geometries have already been created by other operations. Accordingly, grinding machines have been developed to grind plain flat surfaces, external and internal cylinders, and contour shapes such as threads. The contour shapes are often created by special formed wheels that have the opposite of the desired contour to be imparted to the work. Grinding is also used in tool rooms to form the geometries on cutting tools. In addition to these traditional uses, applications of grinding are expanding to include more high speed, high material removal operations. The discussion of operations and machines in this section includes the following types: (1) surface grinding, (2) cylindrical grinding, (3) centerless grinding, (4) creep feed grinding, and (5) other grinding operations.

Surface Grinding Surface grinding is normally used to grind plain flat surfaces. It is performed using either the periphery of the grinding wheel or the flat face of the wheel. Because the work is normally held in a horizontal orientation, peripheral grinding is performed by rotating the wheel about a horizontal axis, and face grinding is performed by rotating the wheel about a vertical axis. In either case, the relative motion of the work part is achieved by reciprocating the work past the wheel or by rotating it. These possible combinations of wheel orientations and work part motions provide the four types of surface grinding machines illustrated in Figure 24.7.

Of the four types, the horizontal spindle machine with reciprocating worktable is the most common, shown in Figure 24.8. Grinding is accomplished by reciprocating the work longitudinally under the wheel at a very small depth (infeed) and by feeding the wheel transversely into the work a certain distance between strokes. In these operations, the width of the wheel is usually less than that of the workpiece.

In addition to its conventional application, a grinding machine with horizontal spindle and reciprocating table can be used to form special contoured surfaces by employing a formed grinding wheel. Instead of feeding the wheel transversely across the work as it reciprocates, the wheel is ***plunge-fed*** vertically into the work. The shape of the formed wheel is therefore imparted to the work surface.

Grinding machines with vertical spindles and reciprocating tables are set up so that the wheel diameter is greater than the work width. Accordingly, these operations can be performed without using a transverse feed motion. Instead, grinding is accomplished by reciprocating the work past the wheel, and feeding the wheel

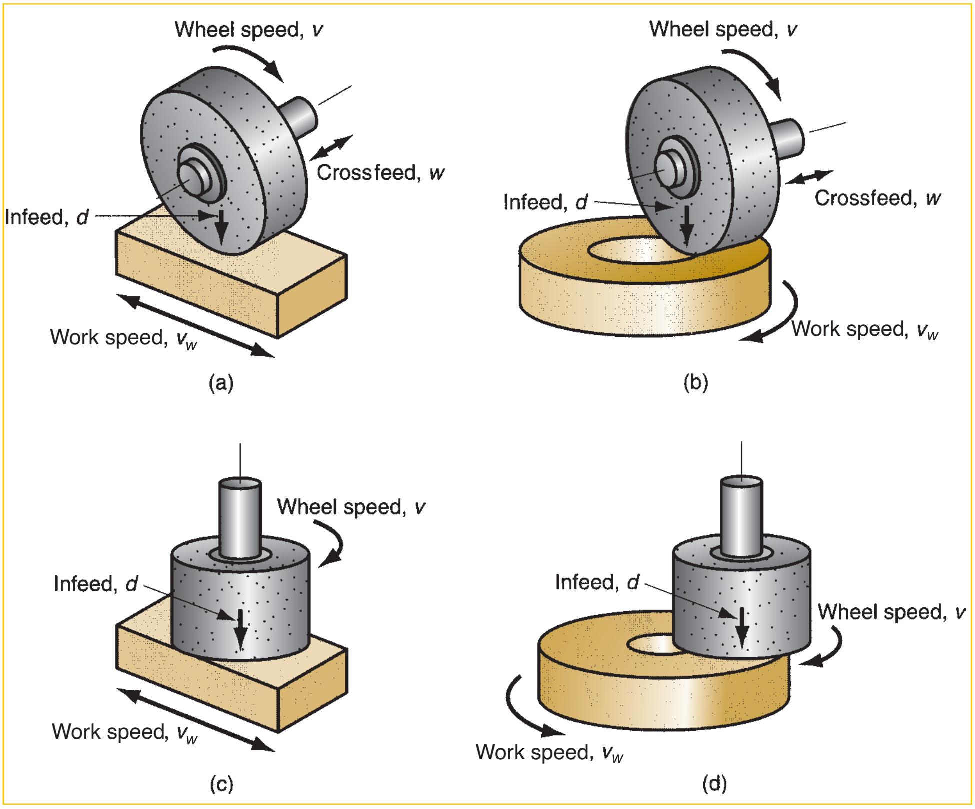

FIGURE 24.7 Four types of surface grinding: (a) horizontal spindle with reciprocating worktable, (b) horizontal spindle with rotating worktable, (c) vertical spindle with reciprocating worktable, and (d) vertical spindle with rotating worktable.

vertically into the work to the desired dimension. This configuration is capable of achieving a very flat surface on the work.

Of the two types of rotary table grinding in Figure 24.7(b) and (d), the vertical spindle machines are more common. Owing to the relatively large surface contact area between wheel and work part, vertical spindle-rotary table grinding machines are capable of high metal removal rates when equipped with appropriate grinding wheels.

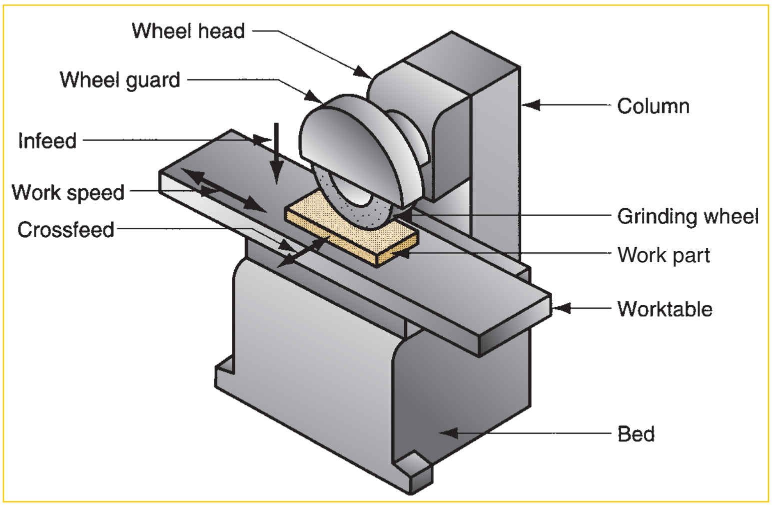

FIGURE 24.8 Surface grinder with horizontal spindle and reciprocating worktable.

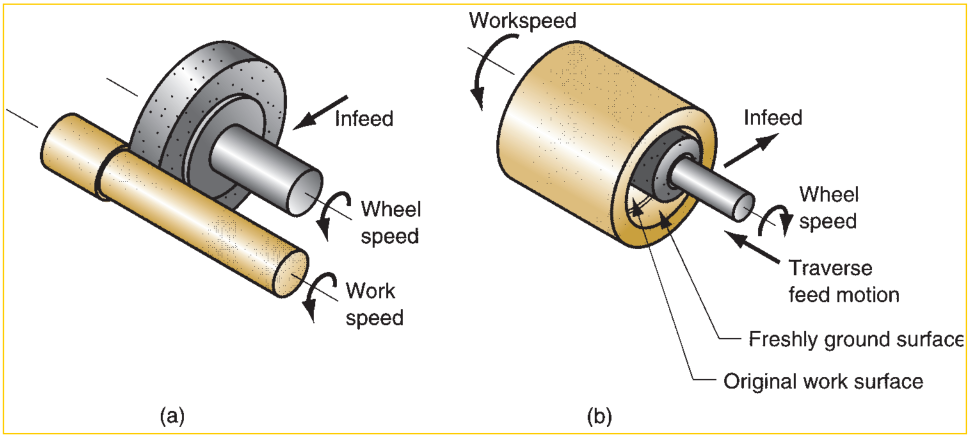

FIGURE 24.9 Two types of cylindrical grinding: (a) external, and (b) internal.

Cylindrical Grinding As its name suggests, cylindrical grinding is used for rotational parts. These grinding operations divide into two basic types, Figure 24.9: (a) external cylindrical grinding and (b) internal cylindrical grinding.

External cylindrical grinding (also called ***center-type grinding*** to distinguish it from centerless grinding) is performed much like a turning operation. The grinding machines used for these operations closely resemble a lathe in which the tool post has been replaced by a high-speed motor to rotate the grinding wheel. The cylindrical workpiece is rotated between centers to provide a surface speed of 18–30 m/min (60–100 ft/min) [16], and the grinding wheel, rotating at 1200–2000 m/min (4000–6500 ft/min), is engaged to perform the cut. There are two types of feed motion possible, traverse feed and plunge-cut, shown in Figure 24.10. In traverse feed, the grinding wheel is fed in a direction parallel to the axis of rotation of the work part. The infeed is set within a range typically from 0.0075 to 0.075 mm (0.0003–0.003 in). A longitudinal reciprocating motion is sometimes given to either the work or the wheel to improve surface finish. In plunge-cut, the grinding wheel is fed radially into the work. Formed grinding wheels use this type of feed motion.

External cylindrical grinding is used to finish parts that have been machined to approximate size and heat treated to desired hardness. The parts include axles,

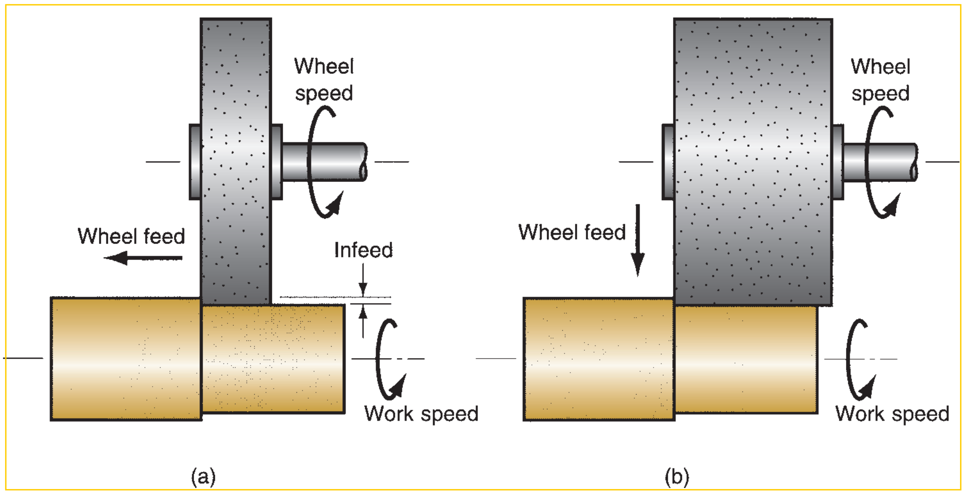

FIGURE 24.10 Two types of feed motion in external cylindrical grinding: (a) traverse feed, and (b) plunge-cut.

crankshafts, spindles, bearings and bushings, and rolls for rolling mills. The grinding operation produces the final size and required surface finish on these hardened parts.

Internal cylindrical grinding operates somewhat like a boring operation. The workpiece is usually held in a chuck and rotated to provide surface speeds of 20 to 60 m/min (75–200 ft/min) [16]. Wheel surface speeds similar to external cylindrical grinding are used. The wheel is fed in either of two ways: traverse feed, Figure 24.9(b), or plunge feed. Obviously, the wheel diameter in internal cylindrical grinding must be smaller than the original bore hole. This often means that the wheel diameter is quite small, necessitating very high rotational speeds in order to achieve the desired surface speed. Internal cylindrical grinding is used to finish the hardened inside surfaces of bearing races and bushing surfaces.

Centerless Grinding Centerless grinding is an alternative process for grinding external and internal cylindrical surfaces. As its name suggests, the workpiece is not held between centers. This results in a reduction in work handling time; hence, centerless grinding is often used for high-production work. The setup for ***external centerless grinding*** (Figure 24.11), consists of two wheels: the grinding wheel and a regulating wheel. The work parts, which may be many individual short pieces or long rods (e.g., 3–4 m long), are supported by a rest blade and fed through between the two wheels. The grinding wheel does the cutting, rotating at surface speeds of 1200 to 1800 m/min (4000–6000 ft/min). The regulating wheel rotates at much lower speeds and is inclined at a slight angle I to control throughfeed of the work. The following equation can be used to predict throughfeed rate, based on inclination angle and other parameters of the process [16]:

$$f_r = \pi D_r N_r \sin I \tag{24.11}$$

where f_r = throughfeed rate, mm/min (in/min); D_r = diameter of the regulating wheel, mm (in); N_r = rotational speed of the regulating wheel, rev/min; and I = inclination angle of the regulating wheel.

The typical setup in ***internal centerless grinding*** is shown in Figure 24.12. In place of the rest blade, two support rolls are used to maintain the position of the work. The regulating wheel is tilted at a small inclination angle to control the feed of the work past the grinding wheel. Because of the need to support the grinding wheel, throughfeed of the work as in external centerless grinding is not possible. Therefore this grinding operation cannot achieve the same high-production rates as in the external centerless process. Its advantage is that it is capable of providing very close

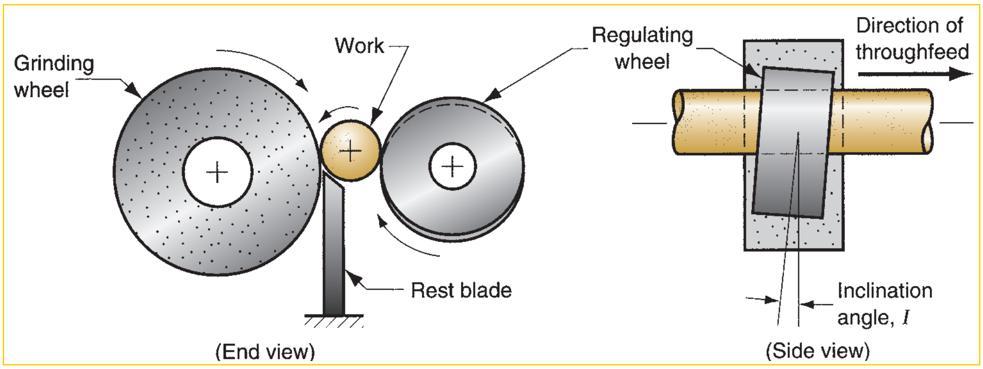

FIGURE 24.11 External centerless grinding.

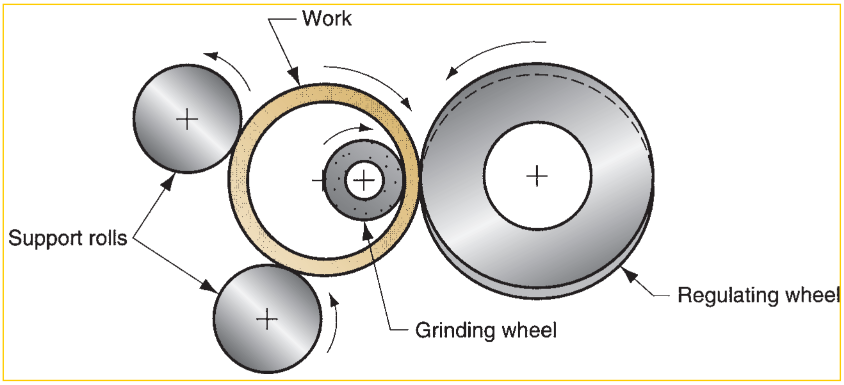

FIGURE 24.12 Internal centerless grinding.

concentricity between internal and external diameters on a tubular part such as a roller bearing race.

Creep Feed Grinding A relatively new form of grinding is creep feed grinding, developed around 1958. Creep feed grinding is performed at very high depths of cut and very low feed rates; hence, the name creep feed. The comparison with conventional surface grinding is illustrated in Figure 24.13.

Depths of cut in creep feed grinding are 1000 to 10,000 times greater than in conventional surface grinding, and the feed rates are reduced by about the same proportion. However, material removal rate and productivity are increased in creep feed grinding because the wheel is continuously cutting. This contrasts with conventional surface grinding in which the reciprocating motion of the work results in significant lost time during each stroke.

Creep feed grinding can be applied in both surface grinding and external cylindrical grinding. Surface grinding applications include grinding of slots and profiles. The process seems especially suited to those cases in which depth-to-width ratios are relatively large. The cylindrical applications include threads, formed gear shapes, and other cylindrical components. The term ***deep grinding*** is used in Europe to describe these external cylindrical creep feed grinding applications.

The introduction of grinding machines designed with special features for creep feed grinding has spurred interest in the process. The features include [11] high static

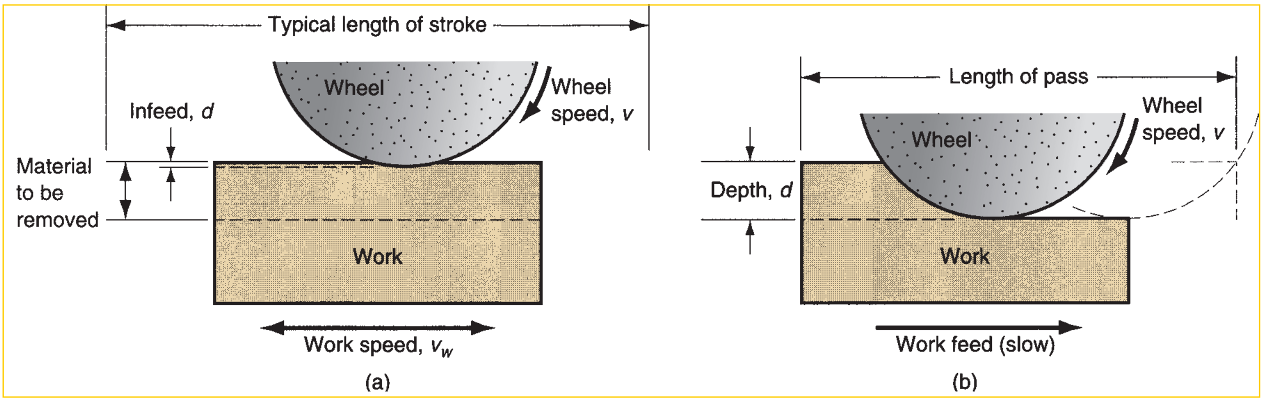

FIGURE 24.13 Comparison of (a) conventional surface grinding and (b) creep feed grinding.

and dynamic stability, highly accurate slides, two to three times the spindle power of conventional grinding machines, consistent table speeds for low feeds, high-pressure grinding fluid delivery systems, and dressing systems capable of dressing the grinding wheels during the process. Typical advantages of creep feed grinding include (1) high material removal rates, (2) improved accuracy for formed surfaces, and (3) reduced temperatures at the work surface.

Other Grinding Operations Several other grinding operations should be briefly mentioned to complete the survey. These include tool grinding, jig grinding, disk grinding, snag grinding, and abrasive belt grinding.

Cutting tools are made of hardened tool steel and other hard materials. ***Tool grinders*** are special grinding machines of various designs to sharpen and recondition cutting tools. They have devices for positioning and orienting the tools to grind the desired surfaces at specified angles and radii. Some tool grinders are general purpose while others cut the unique geometries of specific tool types. General-purpose tool and cutter grinders use special attachments and adjustments to accommodate a variety of tool geometries. Single-purpose tool grinders include gear cutter sharpeners, milling cutter grinders of various types, broach sharpeners, and drill point grinders.

Jig grinders are grinding machines traditionally used to grind holes in hardened steel parts to high accuracies. The original applications included pressworking dies and tools. Although these applications are still important, jig grinders are used today in a broader range of applications in which high accuracy and good finish are required on hardened components. Numerical control is available on modern jig grinding machines to achieve automated operation.

Disk grinders are grinding machines with large abrasive disks mounted on either end of a horizontal spindle as in Figure 24.14. The work is held (usually manually) against the flat surface of the wheel to accomplish the grinding operation. Some disk grinding machines have double opposing spindles. By setting the disks at the desired separation, the work part can be fed automatically between the two disks and ground simultaneously on opposite sides. Advantages of the disk grinder are good flatness and parallelism at high production rates.

The ***snag grinder*** is similar in configuration to a disk grinder. The difference is that the grinding is done on the outside periphery of the wheel rather than on the side flat surface. The grinding wheels are therefore different in design than those in disk grinding. Snag grinding is generally a manual operation, used for rough grinding operations such as removing the flash from castings and forgings, and smoothing weld joints.

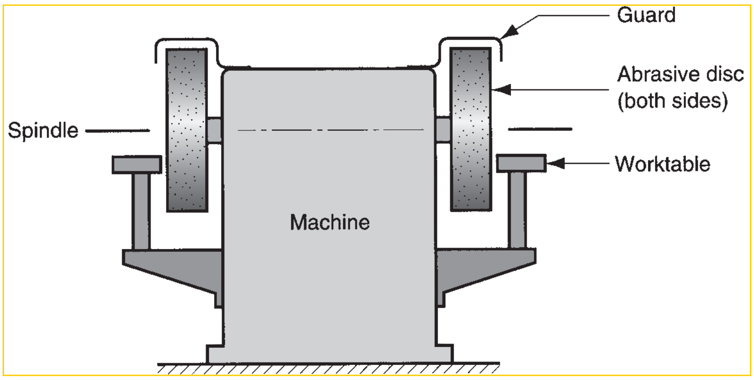

FIGURE 24.14 Typical configuration of a disc grinder.

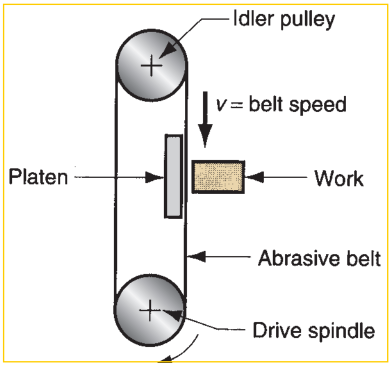

FIGURE 24.15 Abrasive belt grinding.

Abrasive belt grinding uses abrasive particles bonded to a flexible (cloth) belt. A typical setup is illustrated in Figure 24.15. Support of the belt is required when the work is pressed against it, and this support is provided by a roll or platen located behind the belt. A flat platen is used for work that will have a flat surface. A soft platen can be used if it is desirable for the abrasive belt to conform to the general contour of the part during grinding. Belt speed depends on the material being ground; a range of 750 to 1700 m/min (2500–5500 ft/min) is typical [16]. Owing to improvements in abrasives and bonding materials, abrasive belt grinding is being used increasingly for heavy stock removal rates, rather than light grinding, which was its traditional application. The term ***belt sanding*** refers to the light grinding applications in which the work part is pressed against the belt to remove burrs and high spots, and to produce an improved finish quickly by hand.

24.2 Related Abrasive Processes

Other abrasive processes include honing, lapping, superfinishing, polishing, and buffing. They are used exclusively as finishing operations. The initial part shape is created by some other process; then the part is finished by one of these operations to achieve superior surface finish. The usual part geometries and typical surface roughness values for these processes are indicated in Table 24.6. For comparison, corresponding data for grinding are also presented.

TABLE • 24.6 Usual part geometries for honing, lapping, superfinishing, polishing, and buffing.

Process	Usual Part Geometry	Surface Roughness μm	Surface Roughness μ-in
Grinding, medium grit size	Flat, external cylinders, round holes	0.4–1.6	16–63
Grinding, fine grit size	Flat, external cylinders, round holes	0.2–0.4	8–16
Honing	Round hole (e.g., engine bore)	0.1–0.8	4–32
Lapping	Flat or slightly spherical (e.g., lens)	0.025–0.4	1–16
Superfinishing	Flat surface, external cylinder	0.013–0.2	0.5–8
Polishing	Miscellaneous shapes	0.025–0.8	1–32
Buffing	Miscellaneous shapes	0.013–0.4	0.5–16

Another class of finishing operations, called mass finishing (Section 27.1.2), is used to finish parts in bulk rather than individually. These mass finishing methods are also used for cleaning and deburring.

24.2.1 HONING

Honing is an abrasive process performed by a set of bonded abrasive sticks. A common application is to finish the bores of internal combustion engines. Other applications include bearings, hydraulic cylinders, and gun barrels. Surface finishes of around 0.12 μm (5 μ-in) or slightly better are typically achieved in these applications. In addition, honing produces a characteristic cross-hatched surface that tends to retain lubrication during operation of the component, thus contributing to its function and service life.

The honing process for an internal cylindrical surface is illustrated in Figure 24.16. The honing tool consists of a set of bonded abrasive sticks. Four sticks are used on the tool shown in the figure, but the number depends on hole size. Two to four sticks would be used for small holes (e.g., gun barrels), and a dozen or more would be used for larger diameter holes. The motion of the honing tool is a combination of rotation and linear reciprocation, regulated in such a way that a given point on the abrasive stick does not trace the same path repeatedly. This rather complex motion accounts for the cross-hatched pattern on the bore surface. Honing speeds are 15 to 150 m/min (50–500 ft/min) [3]. During the process, the sticks are pressed outward against the hole surface to produce the desired abrasive cutting action. Hone pressures of 1 to 3 MPa (150–450 lb/in^2) are typical. The honing tool is supported in the hole by two universal joints, thus causing the tool to follow the previously defined hole axis. Honing enlarges and finishes the hole but cannot change its location.

Grit sizes in honing range between 30 and 600. The same trade-off between better finish and faster material removal rates exists in honing as in grinding. The amount of material removed from the work surface during a honing operation may be as much as 0.5 mm (0.020 in), but is usually much less than this. A cutting fluid must be used in honing to cool and lubricate the tool and to help remove the chips.

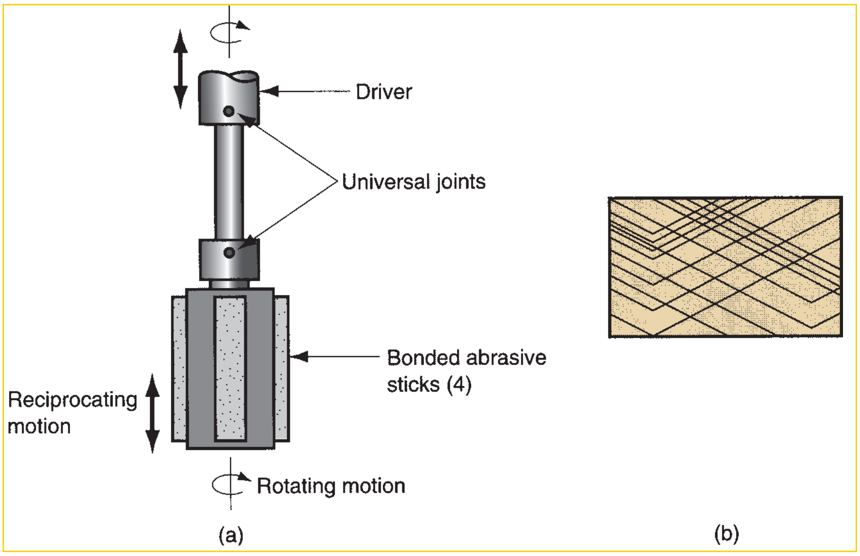

FIGURE 24.16 The honing process: (a) the honing tool used for internal bore surface, and (b) cross-hatched surface pattern created by the action of the honing tool.

24.2.2 LAPPING

Lapping is an abrasive process used to produce surface finishes of extreme accuracy and smoothness. It is used in the production of optical lenses, metallic bearing surfaces, gages, and other parts requiring very good finishes. Metal parts that are subject to fatigue loading or surfaces that must be used to establish a seal with a mating part are often lapped.

Instead of a bonded abrasive tool, lapping uses a fluid suspension of very small abrasive particles between the workpiece and the lapping tool. The process is illustrated in Figure 24.17 as applied in lens-making. The fluid with abrasives is referred to as the ***lapping compound*** and has the general appearance of a chalky paste. The fluids used to make the compound include oils and kerosene. Common abrasives are aluminum oxide and silicon carbide with typical grit sizes between 300 and 600. The lapping tool is called a ***lap***, and it has the reverse of the desired shape of the work part. To accomplish the process, the lap is pressed against the work and moved back and forth over the surface in a figure-eight or other motion pattern, subjecting all portions of the surface to the same action. Lapping is sometimes performed by hand, but lapping machines accomplish the process with greater consistency and efficiency.

Materials used to make the lap range from steel and cast iron to copper and lead. Wood laps have also been made. Because a lapping compound is used rather than a bonded abrasive tool, the mechanism by which this process works is somewhat different than grinding and honing. It is hypothesized that two alternative cutting mechanisms are at work in lapping [3]. The first mechanism is that the abrasive particles roll and slide between the lap and the work, with very small cuts occurring in both surfaces. The second mechanism is that the abrasives become imbedded in the lap surface and the cutting action is very similar to grinding. It is likely that lapping is a combination of these two mechanisms, depending on the relative hardnesses of the work and the lap. For laps made of soft materials, the embedded grit mechanism is emphasized; and for hard laps, the rolling and sliding mechanism dominates.

24.2.3 SUPERFINISHING

Superfinishing is an abrasive process similar to honing. Both processes use a bonded abrasive stick moved with a reciprocating motion and pressed against the surface to be finished. Superfinishing differs from honing in the following respects [4]: (1) the strokes are shorter, 5 mm (3/16 in); (2) higher frequencies are used, up to 1500 strokes per minute; (3) lower pressures are applied between the tool and the surface, below 0.28 MPa (40 lb/in^2); (4) workpiece speeds are lower, 15 m/min (50 ft/min) or less; and (5) grit sizes are generally smaller. The relative motion between the abrasive stick and the work surface is varied so that individual grains do not retrace the same path. A cutting fluid is used to cool the work surface and

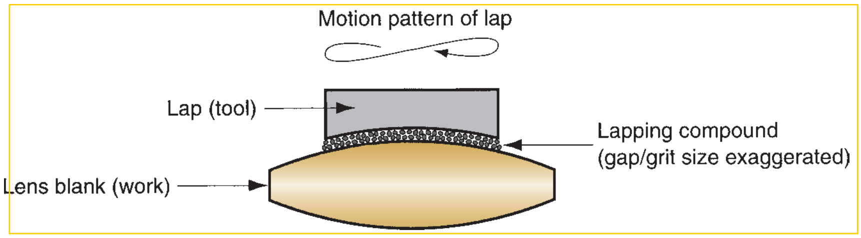

FIGURE 24.17 The lapping process in lens-making.

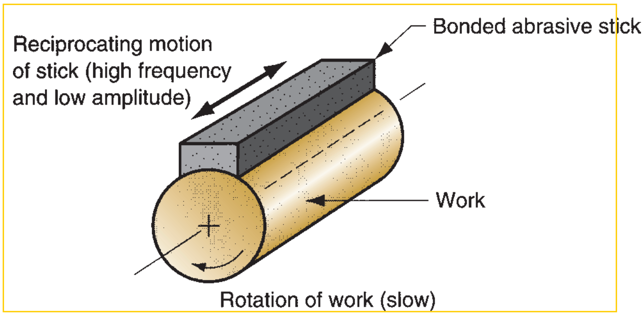

FIGURE 24.18 Superfinishing on an external cylindrical surface.

wash away chips. In addition, the fluid tends to separate the abrasive stick from the work surface after a certain level of smoothness is achieved, thus preventing further cutting action. The result of these operating conditions is mirror-like finishes with surface roughness values around 0.025 μm (1 μ-in). Superfinishing can be used to finish flat and external cylindrical surfaces. The process is illustrated in Figure 24.18 for the latter geometry.

24.2.4 POLISHING AND BUFFING

Polishing is used to remove scratches and burrs and to smooth rough surfaces by means of abrasive grains attached to a polishing wheel rotating at high speed—around 2300 m/min (7500 ft/min). The wheels are made of canvas, leather, felt, and even paper; thus, the wheels are somewhat flexible. The abrasive grains are glued to the outside periphery of the wheel. After the abrasives have been worn down and used up, the wheel is replenished with new grits. Grit sizes of 20 to 80 are used for rough polishing, 90 to 120 for finish polishing, and above 120 for fine finishing. Polishing operations are often accomplished manually.

Buffing is similar to polishing in appearance, but its function is different. Buffing is used to provide attractive surfaces with high luster. Buffing wheels are made of materials similar to those used for polishing wheels—leather, felt, cotton, etc.—but buffing wheels are generally softer. The abrasives are very fine and are contained in a buffing compound that is pressed into the outside surface of the wheel while it rotates. This contrasts with polishing in which the abrasive grits are glued to the wheel surface. As in polishing, the abrasive particles must be periodically replenished. Buffing is usually done manually, although machines have been designed to perform the process automatically. Speeds are generally 2400 to 5200 m/min (8000–17,000 ft/min).

References

[1] Andrew, C., Howes, T. D., and Pearce, T. R. A. ***Creep Feed Grinding***. Holt, Rinehart and Winston, London, 1985.

[2] ***ANSI Standard B74.13-1977***, "Markings for Identifying Grinding Wheels and Other Bonded Abrasives." American National Standards Institute, New York, 1977.

[3] Armarego, E. J. A., and Brown, R. H. ***The Machining of Metals***. Prentice-Hall, Englewood Cliffs, New Jersey, 1969.