IE 309 Manufacturing Processes I
Grinding and Advanced Machining

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Abrasive Machining and Finishing Operations
Introduction

- An abrasive is a small, hard particle having sharp edges and an irregular shape
- Abrasives are capable of removing small amounts of material from a surface through a cutting process
- Most of us are familiar with using grinding wheels (bonded abrasives), as shown
The types of workpieces and operations typical of grinding:

- (a) cylindrical surfaces
- (b) conical surfaces
- (c) fillets on a shaft
- (d) helical profiles
- (e) concave shape
- (f) cutting off or slotting with thin wheels
- (g) internal grinding
Abrasives and Bonded Abrasives

Abrasives that are used most commonly in abrasive-machining operations are

• Conventional abrasives
  - Aluminum oxide
  - Silicon carbide (SiC)

• Superabrasives
  - Cubic boron nitride (cBN)
  - Diamond
Abrasives and Bonded Abrasives

These abrasives are much harder than conventional cutting-tool materials

Cubic boron nitride and diamond are the two hardest materials known, they are referred to as superabrasives

Another important characteristic is friability, the ability of abrasive grains to fracture (break down) into smaller pieces
The abrasives commonly found in nature are:

- Emery
- Corundum (alumina)
- Quartz
- Garnet
- Diamond

### Ranges of Knoop Hardness for Various Materials and Abrasives

<table>
<thead>
<tr>
<th>Material</th>
<th>Range (Knoop Hardness)</th>
<th>Material</th>
<th>Range (Knoop Hardness)</th>
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<tbody>
<tr>
<td>Common glass</td>
<td>350–500</td>
<td>Titanium nitride</td>
<td>2000</td>
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<tr>
<td>Flint, quartz</td>
<td>800–1100</td>
<td>Titanium carbide</td>
<td>1800–3200</td>
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<tr>
<td>Zirconium oxide</td>
<td>1000</td>
<td>Silicon carbide</td>
<td>2100–3000</td>
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<tr>
<td>Hardened steels</td>
<td>700–1300</td>
<td>Boron carbide</td>
<td>2800</td>
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<tr>
<td>Tungsten carbide</td>
<td>1800–2400</td>
<td>Cubic boron nitride</td>
<td>4000–5000</td>
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<tr>
<td>Aluminum oxide</td>
<td>2000–3000</td>
<td>Diamond</td>
<td>7000–8000</td>
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</table>
Abrasives generally are very small when compared to the size of cutting tools.

The size of an abrasive grain is identified by a grit number, which is a function of sieve size: the smaller the grain size, the larger the grit number.

Grit number 10 is typically regarded as very coarse, 100 as fine, and 500 as very fine.
As shown schematically, the abrasive grains in a grinding wheel are held together by a bonding material.
Grinding Wheels

Common types of grinding wheels made with conventional abrasives

(a) Type 1—straight
(b) Type 2—cylinder
(c) Type 6—straight cup
(d) Type 11—flaring cup
(e) Type 27—depressed center
(f) Type 28—depressed center
(g) Mounted
Grinding Wheels

Examples of superabrasive wheel configurations

The bonding materials for the superabrasives are (a), (d), and (e) resinoid, metal, or vitrified; (b) metal; (c) vitrified; and (f) resinoid.
Marking System

Marking system for aluminum-oxide and silicon-carbide

Example: 51 - A - 36 - L - 5 - V - 23

Prefix | Abrasive type | Abrasive grain size | Grade | Structure | Bond type | Manufacturer’s record

Manufacturer’s symbol (indicating exact kind of abrasive) (use optional)

A Aluminium oxide
C Silicon carbide

Grade scale:

Soft: A B C D E F G H I J K L
Medium: M N O P Q R S T U V
Hard: W X Y Z

Bond type:

Open: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 etc. (Use optional)

Manufacturer’s private marking (to identify wheel) (use optional)

Bond type:

B Resinoid
BF Resinoid reinforced
E Shellac
O Oxychloride
R Rubber
RF Rubber reinforced
S Silicate
V Vitrified
# Marking System

Marking system for cubic boron nitride and diamond

<table>
<thead>
<tr>
<th>Example: M</th>
<th>D</th>
<th>100</th>
<th>P</th>
<th>100</th>
<th>B</th>
<th>1/8</th>
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<tbody>
<tr>
<td>Prefix</td>
<td>Abrasive type</td>
<td>Grit size</td>
<td>Grade</td>
<td>Diamond concentration</td>
<td>Bond</td>
<td>Bond modification</td>
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<tr>
<td>Manufacturer’s symbol (to indicate type of diamond)</td>
<td>B Cubic boron nitride</td>
<td>D Diamond</td>
<td>20</td>
<td>A (soft) to Z (hard)</td>
<td>25 (low) to 100 (high)</td>
<td>B Resinoid</td>
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A letter or numeral or combination (used here will indicate a variation from standard bond)
Bond Types

The common types of bonds used in bonded abrasives are

• Vitrified
• Resinoid
• Reinforced Wheels
• Thermoplastic
• Rubber
• Metal
The Grinding Process

Chip-removal process that uses an individual abrasive grain as the cutting tool.

The grinding process and its parameters can be observed best in the surface grinding operation shown schematically.

A straight grinding wheel with a diameter $D$ removes a layer of metal at a depth $d$ (wheel depth of cut).
The major differences between abrasive grain action and that of a single-point cutting tool can be summarized as follows:

- Abrasive grains have irregular shapes and are spaced randomly.
- The average rake angle of the grains is highly negative, typically or even less. Consequently, grinding chips undergo much larger plastic deformation.
- The radial positions of the grains vary; thus, not all grains are active during grinding.
- Surface speeds (i.e., cutting speeds) in grinding are very high, typically 20 to 30 m/s and may be as high as 150 m/s in high-speed grinding using specially designed and manufactured wheels.
The Grinding Process

From geometric relationships, undeformed chip length, $l$, in surface grinding is approximated by the equation

$$l = \sqrt{Dd}$$

and the undeformed chip thickness, $t$, by the equation

$$t = \sqrt{\left(\frac{4\nu}{VCr}\right)\sqrt{\left(\frac{d}{D}\right)}}$$

where $C$ is the number of cutting points per unit area.

$r$ is the ratio of chip width to average undeformed chip thickness and has an estimated value typically between 10 and 20.
A knowledge of grinding forces is essential for:

- Estimating power requirements.
- Designing grinding machines and work-holding fixtures and devices.
- Determining the deflections that the workpiece, as well as the grinding machine itself, may undergo.

### Approximate Specific-energy Requirements for Surface Grinding

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>Hardness</th>
<th>Specific energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W · s/mm³</td>
</tr>
<tr>
<td>Aluminum</td>
<td>150 HB</td>
<td>7–27</td>
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<tr>
<td>Cast iron (class 40)</td>
<td>215 HB</td>
<td>12–60</td>
</tr>
<tr>
<td>Low-carbon steel (1020)</td>
<td>110 HB</td>
<td>14–68</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>300 HB</td>
<td>16–55</td>
</tr>
<tr>
<td>Tool steel (T15)</td>
<td>67 HRC</td>
<td>18–82</td>
</tr>
</tbody>
</table>
Grinding Forces

If it is assumed that the cutting force on the grain is proportional to the cross-sectional area of the undeformed chip, **grain force**:

\[
\text{Grain force } \propto \left( \frac{v}{V\sqrt{d/D}} \right) \text{(UTS)}
\]

Grinding forces should be kept low in order to avoid distortion and to maintain the high dimensional accuracy of the workpiece.
Grinding Forces

Specific Energy

The energy dissipated in producing a grinding chip consists of the energy required for the following actions:

- Chip formation
- Plowing (shown in figure)
- Friction

Chip formation and plowing of the workpiece surface by an abrasive grain
Example

A surface-grinding operation is being performed on low-carbon steel with a wheel of diameter $D = 10$ in. that is rotating at $N = 4000$ rpm and a width of cut the feed rate of the workpiece, $v$, is 60 in./min. Calculate the cutting force (the force tangential to the wheel), $F_c$, and the thrust force (the force normal to the workpiece surface), $F_n$.

Solution The material-removal rate (MRR) is determined as

$$\text{MRR} = \frac{dwv}{dt} = 0.002(1)(60) = 0.12 \text{ in}^3/\text{min}.$$ 

The power consumed is given by

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

$$\text{Power} = (15)(0.12) = 1.8 \text{ hp}.$$ 

Because $1 \text{ hp} = 33,000 \text{ ft\cdot lb/min} = 396,000 \text{ in\cdot lb/min},$

$$\text{Power} = (1.8)(396,000) = 712,800 \text{ in\cdot lb/min}.$$ 

Since power is defined as

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

where the torque $T = \frac{F_c D}{2}$ and $\omega$ is the rotational speed of the wheel in radians per minute ($\omega = 2\pi N$). It follows that

$$712,800 = (\frac{10}{2})(2\pi)(4000),$$

and therefore, $F_c = 5.7 \text{ lb}$. The thrust force, $F_n$, can be calculated directly; however, it also can be estimated by noting from experimental data in the technical literature that it is about 30% higher than the cutting force, $F_c$. Consequently,

$$F_n = (1.3)(5.7) = 7.4 \text{ lb}.$$
Temperature

The temperature rise in grinding is an important consideration because

- It can adversely affect the surface properties of the workpiece
- Can cause residual stresses on the workpiece
- Cause distortions due to thermal expansion and contraction of the workpiece surface, thus making it difficult to control dimensional accuracy

The surface-temperature rise ($\Delta T$) in grinding is related to process variables by the following expression:

$$\Delta T \propto D^{1/4} d^{3/4} \left(\frac{V}{v}\right)^{1/2}$$
Temperature

Burning

• A burn is characterized by a bluish color on ground steel surfaces

• Can be detected by etching and metallurgical techniques

• May not be objectionable in itself, unless surface layers have undergone phase transformations

Heat Checking

• High temperatures in grinding may cause the workpiece surface to develop cracks; this condition is known as heat checking

• As expected, such a surface lacks toughness and has low fatigue and corrosion resistance
Temperature gradients within the workpiece during grinding are primarily responsible for residual stresses.

Grinding fluids and their method of application, as well as process parameters such as depth of cut and speeds, significantly influence the magnitude and type of residual stresses developed.

Residual stresses usually can be reduced by lowering wheel speed and increasing workpiece speed (called low-stress grinding or gentle grinding).
Grinding-wear is generally correlated with the amount of workpiece material ground by a parameter called the grinding ratio, $G$, defined as

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

In practice, grinding ratios vary widely, ranging from 2 to 200 and even higher, depending on the type of wheel, workpiece material, grinding fluid, and process parameters.

It has been shown that effective grinding fluids can increase the grinding ratio by a factor of 10 or more, thus greatly improving wheel life.
The selection of a grinding process and machine for a particular application depends on the workpiece shape and features, size, ease of fixturing, and production rate required.

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
<th>Typical maximum dimensions, length and diameter (m)*</th>
</tr>
</thead>
</table>
| Surface grinding     | Flat surfaces on most materials; production rate depends on table size and level of automation; labor skill depends on part complexity; production rate is high on vertical-spindle rotary-table machines | Reciprocating table $L: 6$  
Rotary table $D: 3$ |
| Cylindrical grinding | Round workpieces with stepped diameters; low production rate unless automated; low to medium labor skill | Workpiece $D: 0.8$,  
roll grinders $D: 1.8$,  
universal grinders $D: 2.5$  
Workpiece $D: 0.8$ |
| Centerless           | Round and slender workpieces; high production rate; low to medium labor skill | Hole $D: 2$,  
Spindle $D: 1.2$,  
Table $D: 3.7$ |
| Internal             | Holes in workpiece; low production rate; low to medium labor skill            |                                                       |
| Honing               | Holes in workpiece; low production rate; low labor skill                     |                                                       |
| Lapping              | Flat, cylindrical, or curved workpieces; high production rate; low labor skill |                                                       |
| Ultrasonic machining | Holes and cavities with various shapes; suitable for hard and brittle materials; medium labor skill | —                                                     |
Surface Grinding

Schematic illustrations of various surface-grinding operations.

(a) Traverse grinding with a horizontal-spindle surface grinder.

(b) Plunge grinding with a horizontal-spindle surface grinder.

(c) A vertical-spindle rotary table grinder.
Surface Grinding

Typically, the workpiece is secured on a magnetic chuck

A straight wheel is mounted on the horizontal spindle of the surface grinder

In addition to the surface grinder shown, other types include vertical spindles and rotary tables

(a) Rough grinding of steel balls on a vertical-spindle grinder. The balls are guided by a special rotary fixture. (b) Finish grinding of balls in a multiple-groove fixture
Examples of various cylindrical-grinding operations:

- (a) traverse grinding
- (b) plunge grinding
- (c) profile grinding
Cylindrical Grinding

The external cylindrical surfaces and shoulders of workpieces such as crankshaft bearings, spindles, pins, and bearing rings are ground.

The rotating cylindrical workpiece reciprocates laterally along its axis to cover the width to be ground.

Figure: Plunge grinding of a workpiece on a cylindrical grinder.
Centerless Grinding

High-production process for continuously grinding cylindrical surfaces in which the workpiece is supported not by centers

Schematic illustrations of centerless grinding operations:
(a) through-feed grinding
(b) plunge grinding
(c) and internal grinding
(d) a computer numerical-control cylindrical-grinding machine
Creep-feed Grinding

Used for large-scale metal-removal operations

In creep-feed grinding, the wheel depth of cut, $d$, is as much as 6 mm (0.25 in.) and the workpiece speed is low.

To keep workpiece temperatures low and improve surface finish, the wheels are softer grade resin bonded and have an open structure.

(a) Schematic illustration of the creep-feed grinding process.
(b) A shaped groove produced on a flat surface by creep-feed grinding in one pass.
(c) An example of creep-feed grinding with a shaped wheel.
Ultrasonic Machining

Material is removed from a surface by microchipping and erosion with loose, fine abrasive grains in a water slurry

Best suited for materials that are hard and brittle, such as ceramics, carbides, precious stones, and hardened steels

(a) Schematic illustration of the ultrasonic machining process.
(b) and (c) Types of parts made by this process. Note the small size of the holes produced
Finishing Operations

Coated Abrasives

Common examples of coated abrasives are sandpaper and emery cloth.

The majority of coated abrasives are made of aluminum oxide, with silicon carbide and zirconia alumina.

Schematic illustration of the structure of a coated abrasive. Sandpaper and emery cloth are common examples of coated abrasives.
Finishing Operations

Belt Grinding

• Coated abrasives also are used as belts for high-rate material removal with good surface finish

• Machines for abrasive-belt operations require proper belt support and have rigid construction to minimize vibrations

Honing

• used primarily to improve the surface finish of holes produced by boring, drilling, and internal grinding

Schematic illustration of a honing tool used to improve the surface finish of bored or ground holes
Superfinishing

- The pressure applied is very light and the motion of the honing stone has a short stroke.
- The motion of the stone is controlled so that the grains do not travel along the same path on the surface of the workpiece.

Schematic illustrations of the superfinishing process. (a) Cylindrical microhoning. (b) Centerless microhoning.
Finishing Operations

Lapping

Used for finishing flat, cylindrical, or curved surfaces.

The lap is relatively soft and porous and usually is made of cast iron, copper, leather, or cloth.

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

Produces a smooth, lustrous surface finish

The softening and smearing of surface layers by frictional heating developed

Very fine scale abrasive removal from the workpiece surface

Schematic illustration of the chemical–mechanical polishing process. This process is used widely in the manufacture of silicon wafers and integrated circuits.
Increase in the cost of machining and finishing a part as a function of the surface finish required. This is the main reason that the surface finish specified on parts should not be any finer than is necessary for the part to function properly.
Difficulties led to the development of chemical, electrical, laser, and high-energy beams as energy sources for removing material from metallic or nonmetallic workpieces.

These advanced methods, which in the past have been called nontraditional or unconventional machining.

Examples of parts made by advanced machining processes.
Chemical Machining

Developed from the observation that chemicals attack and etch most metals, stones, and some ceramics, thereby removing small amounts of material from the surface.

Chemical Milling

Shallow cavities are produced on plates, sheets, forgings, and extrusions, generally for the overall reduction of weight.

(a) Missile skin-panel section contoured by chemical milling.
(b) Weight reduction of space-launch vehicles by the chemical milling of aluminum-alloy plates.
Chemical Machining

(a) Schematic illustration of the chemical-machining process. Note that no forces or machine tools are involved in this process.

(b) Stages in producing a profiled cavity by chemical machining; note the undercut.
Chemical Machining

Chemical Blanking

Similar to the blanking of sheet metals in that it is used to produce features which penetrate through the thickness of the material with the exception that the material is removed by chemical dissolution rather than by shearing.

Various parts made by chemical blanking. Note the fine detail.
Electrochemical Machining

An electrolyte acts as current carrier, and the high rate of electrolyte movement in the tool–workpiece gap washes metal ions away from the workpiece (anode)

Schematic illustration of the electrochemical machining process.
Electrochemical Machining

Typical parts made by electrochemical machining. 
(a) Turbine blade made of a nickel alloy of 360 HB. 
(b) Thin slots on a 4340- steel roller-bearing cage. 
(c) Integral airfoils on a compressor disk.
Electrical-discharge wire cutting, which is similar to contour cutting with a band saw, a slowly moving wire travels along a prescribed path, cutting the workpiece.

The wire is usually made of brass, copper, tungsten, or molybdenum; zinc- or brass-coated and multicoated wires also are used.
Laser-beam Machining

The source of energy is a laser which focuses optical energy on the surface of the workpiece.

High-density energy source melts and evaporates portions of the workpiece in a controlled manner.

(a) Schematic illustration of the laser-beam machining process.
(b) and (c) Examples of holes produced in nonmetallic parts by LBM.
(d) Cutting sheet metal with a laser beam.
The energy source in electron-beam machining (EBM) is high-velocity electrons, which strike the workpiece surface and generate heat.

The machines utilize voltages in the range from 50 to 200 kV to accelerate the electrons to speeds of 50 to 80% of the speed of light.

Schematic illustration of the electron-beam machining process. Unlike LBM, this process requires a vacuum, so the workpiece size is limited to the size of the vacuum chamber.
**Water-jet Machining**

Force results from the momentum change of the stream and, in fact, is the principle on which the operation of water or gas turbines is based.

In water-jet machining (WJM) this force is utilized in cutting and deburring operations.

A water-jet cutting machine and its operation are shown.
The advantages of this process are

- Cuts can be started at any location
- No heat is produced
- No deflection of the rest of the workpiece takes place
- Little wetting of the workpiece takes place
- The burr produced is minimal
- It is an environmentally safe manufacturing process
In abrasive-jet machining (AJM), a high-velocity jet of dry air, nitrogen, or carbon dioxide containing abrasive particles.

(a) Schematic illustration of the abrasive-jet machining process.
(b) Examples of parts made by abrasive-jet machining, produced in 50-mm (2-in.) thick 304 stainless steel.
Hybrid Machining Systems

Two or more machining processes are combined into one system to take advantage of the capabilities of each process, increasing production speed and thus improving the efficiency of the operation.

Examples of such systems:

- Abrasive and electrochemical machining
- Abrasive and electrical discharge machining
- Abrasive and electrochemical finishing
- Water-jet cutting and wire EDM
- High-speed milling, laser ablation, and blasting, as an example of three integrated processes
- Machining and blasting
- Electrochemical and electrical discharge machining (ECDM), also called electrochemical spark machining (ECSM)