# Manufacturing 2
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CHAPTER

# 8 Machining Processes

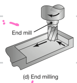
**Machining is a general term describing a group of processes that remove material from a workpiece after it has been produced by the methods described in the preceding chapters. Machining processes are very versatile, and capable of producing almost any shape with good dimensional tolerances and surface finish. The topics covered in this chapter include:**

*The cutting process is an interaction between three elements: (1) workpiece (2) machine (3) cutting tool

* the goal from the workpiece → final geometry with acceptable dimensions accuracy & tolerances
* the goal from the cutting tool → longest useful tool life

* Machining operations:

(1) Cutting:




- the major source of energy → Mechanical energy
- involves single point (edge) or multi point cutting tools & processes

- **Cutting**, which generally involves single-point or multipoint cutting tools and processes, such as turning, boring, drilling, tapping, milling, broaching, and sawing. Cutting is the focus of this chapter.

(2) Abrasive processes:

- **Abrasive processes,** such as grinding, honing, lapping, and ultrasonic machining (Sections 9.6 through 9.9).

(3) Advanced machining processes:

- **Advanced machining processes,** sometimes referred to as *nontraditional machining processes*, that use electrical, chemical, thermal, hydrodynamic, and optical sources of energy, as well as combinations of these sources, to remove material from the workpiece (Sections 9.10 through 9.15).

*Why we use machining processes:

1. Closer **dimensional accuracy** may be required than can be achieved by metalworking or casting processes alone. For example, in a crankshaft, the bearing surfaces cannot be produced with good dimensional accuracy and smooth enough surface finish through forging or sand casting alone.
2. Parts may require external and/or internal geometric **features**, such as sharp corners and internal threads, that cannot be produced by other processes.
3. Some parts are heat treated for improved hardness and wear resistance, but because heat-treated parts may undergo distortion and surface discoloration, they may require additional **finishing operations.**
4. Special surface characteristics or textures may be required on surfaces of the part that cannot be produced by other means. As an example, copper mirrors with very high reflectivity are typically made by machining with a diamond cutting tool.
5. It may be more **economical** to machine the part than to make it by other processes, particularly if the number of parts required is relatively small. Recall that metalworking processes typically require expensive dies and tooling; the cost of these can only be justified if the number of parts made is sufficiently high.

Against these major advantages, machining has certain limitations:

1. Machining processes inevitably **waste material** and generally require more energy and labor than other metalworking operations.
2. Removing a volume of material from a workpiece generally takes **more time** than other processes.
3. Material-removal processes can have **adverse effects** on the surface integrity of the product, including its fatigue life.

In spite of these limitations, machining operations continue to be indispensable in manufacturing.

As in all manufacturing operations, machining should be viewed as a **system**, consisting of the *workpiece, cutting tool, tool holder, workholding devices, machine tool, and operating personnel*. Machining operations cannot be carried out efficiently and economically without a fundamental knowledge of the often complex interactions among these critical factors, as will be evident throughout this chapter.

## 8.2 Mechanics of Chip Formation

Machining processes remove material from the surface of a workpiece by producing chips, as shown in Fig. 8.1. The basic mechanics of chip formation are represented by the model shown in Fig. 8.2. A cutting tool moves along the workpiece at a certain velocity (**cutting speed**), *V*, and a **depth of**

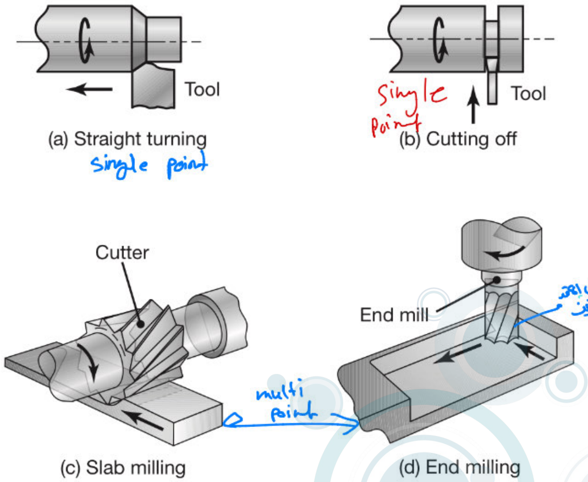



**FIGURE 8.1** Some examples of common machining operations.

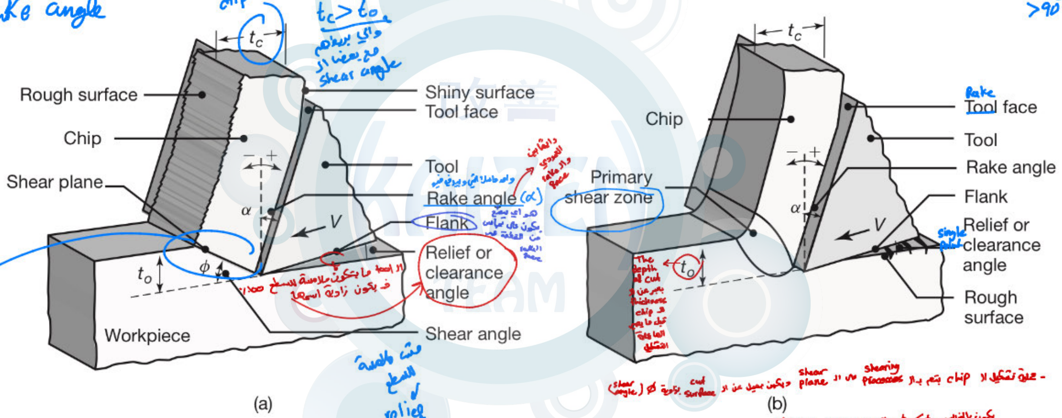



**FIGURE 8.2** Schematic illustration of a two-dimensional cutting process, or orthogonal cutting. (a) Orthogonal cutting with a well-defined shear plane, also known as the Merchant model; and (b) Orthogonal cutting without a well-defined shear plane.

**cut**, $t_o$. A **chip** is produced just ahead of the tool by *shearing* the material continuously along the **shear plane**.

In this process, the major *independent variables* are:

- Type of cutting tool and its properties;
- The shape of the tool, its surface finish and sharpness;
- Workpiece material, its properties, and the temperature at which it is machined;
- Cutting conditions, such as speed, feed, and depth of cut;

- Type of cutting fluid, if used;
- Characteristics of the machine tool, particularly its stiffness and damping; and
- Tool holder and workholding devices.

The *dependent variables* are:

- Type of chip produced;
- Force required and energy dissipated in the cutting process;
- Temperature rise in the workpiece, the chip, and the cutting tool;
- Wear, chipping, and failure of the tool; and
- Surface finish and integrity of the workpiece after it is machined.

In order to appreciate the importance of the complex interrelationships among these variables, consider the following commonly encountered situations:

1. If the surface finish of the machined workpiece is unacceptable, which of the independent variables should be modified first?
2. If the workpiece becomes too hot, thus possibly affecting its properties and dimensional accuracy, what modifications should be made to the process parameters?
3. If the cutting tool wears rapidly and becomes dull, what should be changed: the cutting speed, the depth of cut, the tool material, or some other variable?
4. If the dimensional tolerance of the machined part is over the specified limits, what modification should be made?
5. If the cutting tool begins to vibrate and chatter, what should be changed to eliminate or reduce this problem?

Although almost all machining operations are three dimensional in nature, the two-dimensional model shown in Fig. 8.2 is appropriate and useful in studying the basic mechanics of the metal cutting process. This model is known as **orthogonal cutting**, meaning that the cutting edge of the tool is perpendicular (orthogonal) to the cutting direction. The tool has a **rake angle**, $\alpha$, (positive as shown in the figure) and a **relief**, or **clearance, angle.** Note that the sum of the rake, the relief, and the included angles of the tool is 90°.

Microscopic examinations reveal that metal chips are produced by a **shearing** mechanism, shown in Fig. 8.3a. Shearing takes place along the **shear plane**, which makes an angle $\phi$ with the workpiece surface, called the *shear angle*. Below the shear plane, the workpiece is deformed elastically, and above the shear plane, the chip is already formed and is moving up the face of the tool as cutting progresses. Because of the relative movement, there is friction involved between the chip and the rake face of the tool.

Note that the thickness of the chip, $t_c$, can be determined if $t_o$, $\alpha$, and $\phi$ are known. The ratio of $t_o$ to $t_c$ is known as the **cutting ratio**, $r$, which can be expressed as

$$r = \frac{t_o}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)}. \tag{8.1}$$

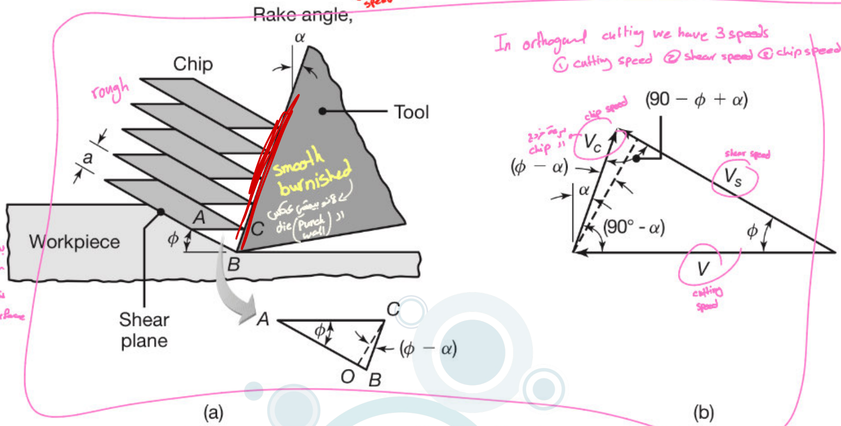



**FIGURE 8.3** (a) Schematic illustration of the basic mechanism of chip formation in cutting. (b) Velocity diagram in the cutting zone.

Note that the chip thickness is always greater than the depth of cut (also known as the **undeformed chip thickness**), so that $r$ is always less than unity. The reciprocal of $r$ is known as the **chip compression ratio**, and is a measure of how thick the chip has become compared with the depth of cut; thus the chip compression ratio is always greater than unity.

On the basis of Fig. 8.3a, the **shear strain**, $\gamma$, that the material undergoes during cutting can be expressed as

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC}, \qquad (8.2)$$

or

$$\gamma = \cot\phi + \tan(\phi - \alpha). \qquad (8.3)$$

Note from this equation that high shear strains are associated with low shear angles and low or negative rake angles. Shear strains of 5 or higher have been observed in actual cutting operations. Thus, the chip undergoes greater deformation during cutting than it does in other operations such as forging and shaping operations (Chapter 6), as can also be seen in Table 2.3.

From Fig. 8.2, it can be noted that the undeformed chip thickness and the depth of cut are the same parameter, $t_o$, in orthogonal cutting. Because the chip thickness, $t_c$, is greater than the undeformed chip thickness, $t_o$, the *velocity of the chip*, $V_c$, must be lower than the cutting speed, $V$. Since mass continuity has to be maintained,

$$Vt_o = V_c t_c \quad \text{or} \quad V_c = Vr, \qquad (8.4)$$

and therefore,

$$V_c = V\frac{\sin\phi}{\cos(\phi - \alpha)}. \qquad (8.5)$$

A velocity diagram can be constructed, such as that shown in Fig. 8.3b. From trigonometric relationships, the following equations can be written:

$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos\alpha} = \frac{V_c}{\sin\alpha}, \tag{8.6}$$

where $V_s$ is the velocity at which shearing takes place in the shear plane. The **shear-strain rate** is the ratio of $V_s$ to the thickness, $a$, of the *shear zone* (Fig. 8.3a), or

$$\dot{\gamma} = \frac{V_s}{a}. \tag{8.7}$$

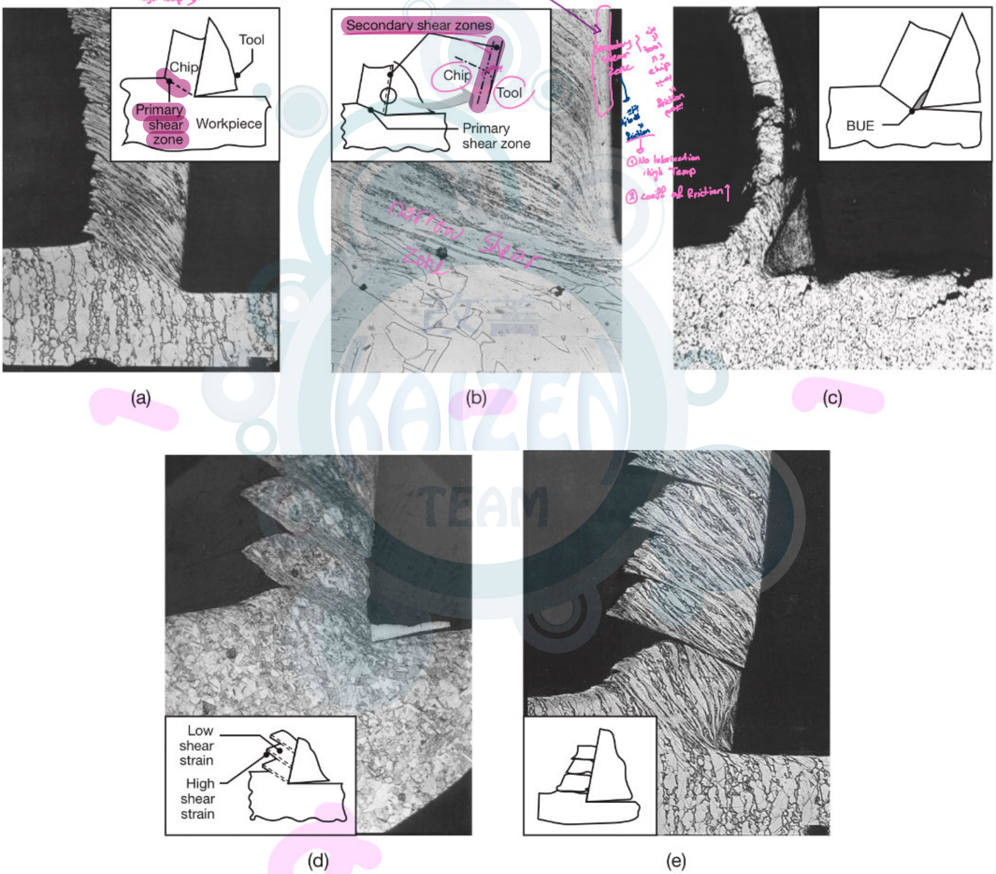



**FIGURE 8.4** Basic types of chips produced in metal cutting and their micrographs: (a) continuous chip with narrow, straight primary shear zone; (b) secondary shear zone at the tool-chip interface; (c) continuous chip with built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip. *Source:* After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

## 8.2.1 Chip Morphology

- Basic types of metal chips :

### * Continuous chips

- High rake angle , less curling , less tensile stresses , lower fracture probability
- Good surface finish
- Not always desirable
  → because the chips tend to become tangled around the tool
  → we can fix this by putting a chip breaker → ة بنضيفها على ال surface ال tool بتزيد من ال curling وبتقلل ال rake angle (بتزيد ال strain)

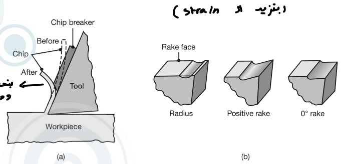
**Continuous chips.** *Continuous chips* are typically formed at high cutting speeds and/or high rake angles (Fig. 8.4a). The deformation of the metal takes place along a very narrow shear zone, called the **primary shear zone.** These type of chips also may develop a **secondary shear zone** at the tool-chip interface (Fig. 8.4b), caused by friction; as expected, the secondary zone becomes thicker as the tool-chip friction increases.

Deformation of continuous chips may also take place along a wide primary-shear zone, with *curved boundaries*, as shown in Fig. 8.2b. Note that the lower boundary of this zone is *below* the machined surface, and thus it has subjected the machined surface to distortion, possible surface damage and induced surface residual stresses. This situation occurs particularly in machining soft metals at low cutting speeds and low rake angles.

Although they generally produce good surface finish, continuous chips are not always desirable, particularly in computer-controlled machine tools (see Section 8.11), because the chips tend to become tangled around the tool. This situation can be avoided with *chip breaker* features on cutting tools (see below).

As a result of strain hardening (caused by the shear strain to which it is subjected), a chip generally becomes harder, stronger, and less ductile than the original workpiece material. As the rake angle decreases, the shear strain increases, as can be seen from Eq. (8.3).

بنحطها لما تفتل تلف وما تكسر ←




### * Built up edge chips

→ (on the cutting edge) هي chip بتكون متراكمة على الحافة
تتراكم عند بداية ال cutting zone وبداية ال shear zone

- عبارة عن layers بتتكون من المعدن على سطح ال tool وكل ما كبرت بتصير unstable اكثر
  وبتكون ال hardness الها اعلى من ال material اي عم تنقطع (مع انهم من نفس ال material)
- عادة بتكون في ال soft metals والي الها affinity انو تلتصق بال tool material
- تتراكم هذه ال edge على ال tool وبتوصل لحجم بتكون فيه unstable
- و بصير unstable بسبب شغلتين : ① large volume (size)
  ② high plastic deformation
- واخر اشي بكون في sharp edge بتكسر ال built up edge لجزئين جزء ممكن يطلع مع ال chip (upper portion)
  وجزء بضل على ال surface وبيمشي مع ال tool (lower portion) (ولما يمشي مع ال tool رح
  يعطيني extremely rough surface) (رح يجرحلي السطح)
- يؤثر ال Built up edge سلبيا على شغلتين : ① surface finish ② integrity (تماسك القطعة)
- بيعطيني rough surface لسببين : ① لانه ال lower portion من ال built up edge بتتكسر وبتنتثر بشكل random على ال surface
  ② المفروض يكون tip radius (sharp) صغير بس بسبب ال built up edge بصير كتير كبير
  فبيعمل ازاحة (مش cutting)
- الاشي الوحيد الي ممكن يكون منيح من ال built up edge ← (اذا كانت) (thin & stable) (extremely thin layer built up edge)
  → تعطي حماية لل tool

**Built-up-edge chips.** A *built-up edge* (BUE) may form at the tip of the tool during cutting (Fig. 8.4c); it consists of thin layers of metal from the workpiece that are gradually deposited on the tool (hence the term *built-up*). As it grows larger, the BUE becomes unstable and eventually breaks up; the upper portion of the BUE is carried away on the tool side of the chip and the lower portion is deposited randomly on the machined surface. The process of BUE formation and breakup is repeated continuously during the cutting operation.

The built-up edge is commonly observed in practice and is one of the significant factors that adversely affects surface finish and integrity in machining, as can be seen in Figs. 8.4 and 8.6. A built-up edge, in effect, changes the geometry of cutting. Note, for example, the large tip radius of the BUE and the rough surface finish it has produced. Because of work hardening and deposition of successive layers of material, BUE hardness increases significantly (Fig. 8.6a). Although BUE is generally undesirable, a thin but stable BUE is generally regarded as desirable, because it protects the tool surface.

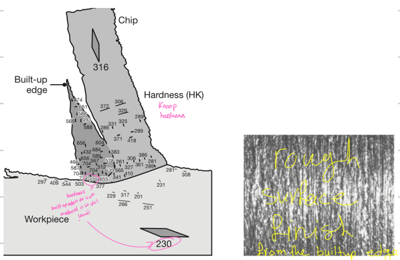



**FIGURE 8.6** (a) Hardness distribution in the cutting zone for 3115 steel. Note that some regions in the built-up edge are as much as three times harder than the bulk workpiece. (b) Surface finish in turning 5130 steel with a built-up edge. *Source:* Courtesy of Metcut Research Associates, Inc.

- Built up edge is effected by : (factors)

① Adhesion of the workpiece material to the rake face of the tool & the strength of the interfacial bond

يعتمد على كم مادة ال tool قابلة انو يلتصق عليها المادة اي انا بقطعها

why
→ ex: ceramic cutting tools : have much lower affinity to built up edge than do tool steels ?

→ because the ceramics are chemically stabled

BUE formation is affected by (a) adhesion of the workpiece material to the rake face of the tool and the strength of the interfacial bond (see also Section 4.4). Ceramic cutting tools (see Section 8.6), for example, have much lower affinity to form BUE than do tool steels; (b) growth of the successive layers of adhered metal on the tool; (c) tendency of the workpiece material for strain hardening; the higher the strain-hardening exponent, $n$, the higher the probability for BUE formation.

Generally, the built-up edge decreases or is eliminated (a) as the cutting speed, $V$, increases; (b) as depth of cut, $t_o$, decreases; (c) as rake angle, $\alpha$, increases; (d) as tip radius of the tool decreases; and (e) by using an effective cutting fluid (Section 8.7).

② Growth of the successive layers of adhered metal on the tool

يعني اذا كانت ال layers قابلة انها تنمو (يعني ما تكسر بسرعة)

③ Tendency of the workpiece material for strain hardening

يعني كل ما زادت ال hardness او strength لل material بسبب ال strain hardening بكون احتمالية تكوين ال built up edge اعلى

why
(بس العكس مش صح) عشان اذا ما كانت hard رح يصير لها spreading (رح يضل ال thickness تقريبًا ثابت) (ما رح تتكون ال built up edge)(ما رح يتكون كتير layers)

when rake angle = 0° → then 100% of cutting force on the rake
(normal force نفسو cutting force)

why
# built up edge decreases , cutting speed (V) increases ? → لانه احتمالية الالتصاق بتزيد مع ال frictional forces

- كل ما كبرنا ال rake angle ال component العمودية على ال rake face رح تقل

ال chip وهي ماشية على ال tool لما ال normal force يزيد رح يزيد معه ال friction force (ممانعة لحركة ال chip) ← رح تكون ال friction force على ال tip بالذات بتكون عالية جدًا و كمان ال Temperature عالية جدًا بسبب القطع ورح تتكون ال built up edge

- كيف بإمكاني اخفضها ؟ عن طريق انو اخفف ال friction force و بستطيع اخفف ال friction force عن طريق انو اخفف ال normal force وبخفف ال normal force عن طريق انو اقلل من ال cosine الزاوية وتعطيني component اقل ومعنى ذلك انو انا لازم ازيد ال rake angle

يعني بقلل ال frictional force عن طريق زيادة ال rake angle

# built up edge decreases , Depth of cut ($t_o$) decreases

ال cutting force نفسو لما يقل ال depth of cut معنى ذلك انو رح يقل

# built up edge decreases , rake angle ($\alpha$) increases

$$\text{cutting ratio} = r = \frac{t_o}{t_c}$$

(كل ما قل $t_o$ ال $t_c$ رح يقل وبالتالي طول ال shear plane رح يقل) معنى ذلك انو ال cutting force رح تقل

لما تقل ال cutting force معنى ذلك انو تقلت ال normal & friction forces ← يا بنزلها يا بنزيد ال rake angle او بقلل ال thickness اي بالنهاية بقلل طول ال shear zone

# built up edge decreases , Tip radius of the tool decreases

ال cutting بكون more efficient واسهل انو تكسر لما يكون ال radius صغير

# built up edge decreases , by using an effective cutting fluid

لما بنستخدم effective cutting fluid بنقلل ال friction force

# built up edge decreases , cutting speed (V) increases at maximum heat dissipation

100% كل ال ideal work بتحول ل Temperature في عملية ال shearing وفي Temperature جاي من ال friction

وال Temperature غالبًا بتساعد في تكوين ال built up edge لسببين : ① ال coefficient of friction في الغالب اعلى عند درجات حرارة عالية ② ال strain rate sensitivity بتزيد مع ال Temperature (بتصير المادة اكثر قابلية لل strain hardening )

**Serrated chips.** *Serrated chips*, also called **segmented** or **nonhomogeneous** chips, are semi-continuous, with zones of low shear and high shear strain (Fig. 8.4d); the chips have the appearance of saw teeth, hence the term serrated. Metals with low thermal conductivity and strength that decreases sharply with temperature, such as titanium, exhibit this behavior.

مقطع

## * Serrated chips : (Semi Continuous)

→ (segmants مكونة من) (nonhomogeneous chips)

- the chips have the apperance of saw teeth

- مافي علاقة بين ال tool و metal زي ال built-up edge ، هي راجعة بشكل اساسي لل metal لوحده (لخصائص ال metal)

في high shear strains و low shear strains

اي بصير بال material بصير high shear بشكل كبير جداً بعدين فجاءة بتمشي ال material و كأنها plastic deformation

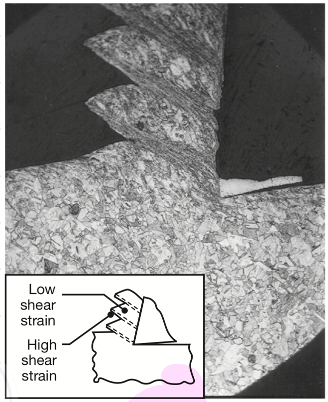
بصير تغير في ال Temperature

low Temperature بتكون مقاومة المادة عالية جداً حتى يصير قطع لازم ال material يصير لها strong shear

وال energy الي حطيناها رح تتحول على شكل heat

بتصير low strength ف بتصيرمش بحاجة ل high shear بعدين بشكلها بعدين ما عندي shear عالي يعني قلت ال Temp يعني

رجعت ال material strong & hard .




(d)

## * Discontinues chips :

→ consists of segmants that may be either firmly or loosely attached to each other

These chips usually develop under the following conditions :

a. The workpiece material is brittle, and cannot undergo the high shear strains involved in cutting.

لذلك كل شوي بطلع من ال chip بتكسر ، ما فيها اي ductility تتحمل high shear strains

b. The workpiece material contains hard inclusions and impurities (see Figs. 3.24 and 3.25) or has a structure such as that of graphite flakes in gray cast iron (Fig. 5.13a). Impurities and hard particles act as sites for internal cracks, thereby producing discontinuous chips. As the depth of cut increases, the probability of such defects being present in the cutting zone increases.

- قد لا تكون brittle ولكن فيها hard inclusions & impurities بتخليها تتصرف كأنها brittle

- " gray cast irons ← يكون " graphite فيه على شكل flakes بتعمل stress concentration

- كل ما زدت ال depth of cut ، عدد ال impurities or hard particles الي رح تلاقيها في ال shear zone رح تكون اكثر

- فيها hard inclusions & impurities ويكونو موجودين بشكل random

- بتزيد احتمالية انو يصطدم ال shear zone او ال shear plane بال hard inclusions & impurities رح تزيد لما نزيد ال sample size (كمية ال cutting) (بتزيد لما يزيد ال depth of cut) مهم

c. The cutting speed is very low or very high.

يعني انو ال heat generation قليل جداً نسبة الى ال heat dissipation (بنعمل احتكاك بس الاحتكاك بيمشي شوي شوي) ← very low cutting speed

والاحتكاكات هاد بيعطيني حرارة بس سرعان ماتروح الحرارة لأنه الوسط اي حواليها رح يمتصها ف بتصير ال material درجة حرارتها قليلة وهاد ما بساعد عل ال ductility (لأنو ال ductility بتزيد مع الحرارة)

explain : Discontinues chips formed either at very low speed or very high speed ?

→ In very low cutting speed it means that the heat generation much less than heat dissipation (the material remains brittle because of Temperature)

In very high cutting speed it means that the heat generation is very high & high strain rate sensitivity (hard brittle material)

**d.** The depth of cut (undeformed chip thickness) is large or the rake angle is low.

لما ال thickness يكون قليل ← ال radius الي بدي اثني عليه بقل

لما تزيد ال thickness , ال minimum bending radius رح يقل

- الاحسن صون انو اقلل ال rake angle مع ثبات ال thickness

- chip thickness ↑ , depth of cut ↑

**e.** The machine tool has low stiffness (ال machine مش ثابتة) and poor damping (تخفيف الاهتزازات).

**f.** Lack of an effective cutting fluid. → هاد بأدي لرفع درجة الحرارة و زيادة ال friction .

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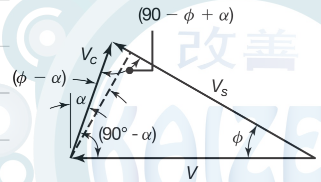
* V : cutting speed, $V_s$ : shear speed, $V_c$ : chip speed → vectors




ϕ : shear angle

α : rake angle      α → بين ال normal , ال rake face

$90° - \alpha$ → الزاوية المقابلة لل $V_s$

$90° - \phi + \alpha$ → الزاوية المقابلة لل V

$V_c < V_s < V$

- أكبر قيمة ممكن تكون لل shear speed ($V_s$) ممكن تساوي ال cutting speed ($V$) في حالة $\alpha = 0°$ (rake face عامودي)

- غير هيك بتكون $V > V_s$

} vaild in the +ve rake angles range

* depth of cut (undeform chip thickness)

r : cutting ratio

$$r = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)} < 1$$

($t_o$: depth of cut, $t_c$: chip thickness)

$Vt_o = V_c t_c$ or $V_c = Vr$,

$$V_c = V\frac{\sin\phi}{\cos(\phi - \alpha)}.$$ → نسب ال V نفس ال thickness

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# * Chip breakers.

بستفدها بشكل رئيسي في ال Continues chips

وال Continues chips اذا استمرت و ما انكسرت و صارلها tangling (تحلق حوالين ال tool) ← بنستخدم ال chip breaker

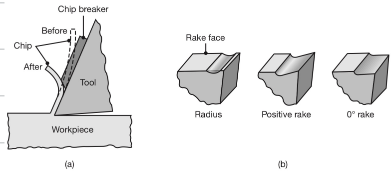



**FIGURE 8.7** (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Grooves on the rake face of cutting tools, acting as chip breakers. Cutting tools inserts generally incorporate built-in chip-breaker features.

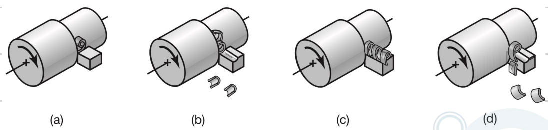



**FIGURE 8.8** Various chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially outward from workpiece; and (d) chip hits tool shank and breaks off.

to avoid the formation of continuous chips is to break the chip intermittently with a *chip breaker*. Chip breakers are now an integral part of the cutting tool itself (Fig. 8.7). Chips can also be broken by modifying the tool geometry, thus controlling chip flow, as in the turning operations illustrated in Fig. 8.8.

## 8.2.2 Mechanics of Oblique Cutting

مائل

لما تكون ال cutting edge ليست عمودية على اتجاه ال cutting velocity

- احد اسباب اي بتزيد ال curling
- رح يكون عندي اكثر من زاوية

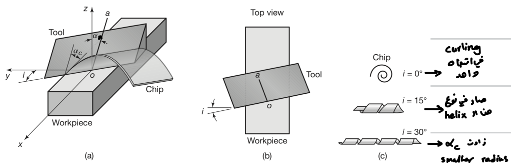



**FIGURE 8.9** (a) Schematic illustration of cutting with an oblique tool. (b) Top view, showing the inclination angle, *i*. (c) Types of chips produced with different inclination angles.

- بصير ال curling على اتجاهين :

① curling up on the rake face

② curling away from the rake face

$\alpha_c$ : chip flow angle

$\alpha_n$ : normal rake angle (between Oa & z)

i : inclination angle (between the normal of the cutting direction (y) & cutting edge)

## - Shaving and skiving.

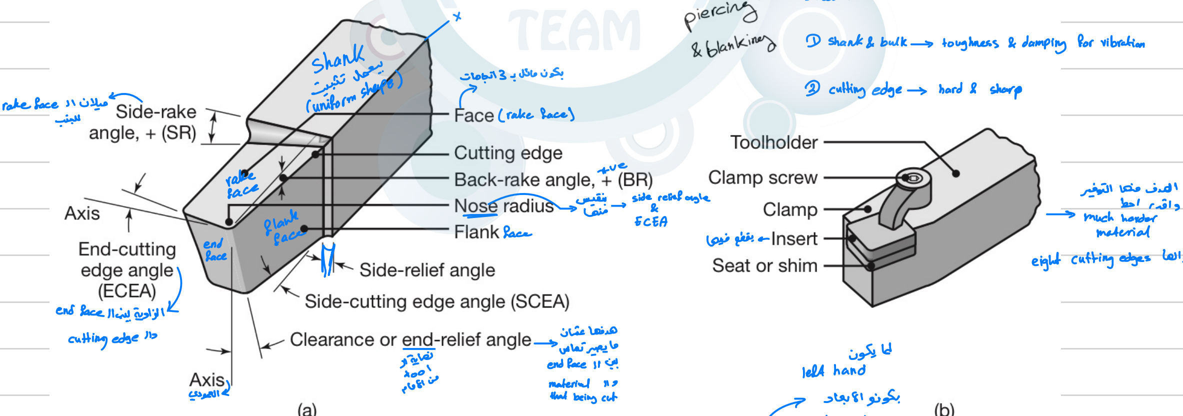
**Shaving and skiving.** Thin layers of material can be removed from straight or curved surfaces by a process similar to using a *plane* to shave wood. *Shaving* is particularly useful in improving the surface finish and dimensional accuracy of punched slugs or holes (See Fig. 7.10). Parts that are long or have a combination of angles and shapes are shaved by *skiving*, using a specially shaped cutting tool.

من نواتج piercing & blanking

- I need two functions :

① shank & bulk → toughness & damping for vibration

② cutting edge → hard & sharp




The terminology of the cutting tool

**FIGURE 8.10** (a) Schematic illustration of a right-hand cutting tool for turning. Although these tools have traditionally been produced from solid tool-steel bars, they are now replaced by inserts of carbide or other tool materials of various shapes and sizes, as shown in (b).

- ميلان ال rake face حتى يتحكم في ال curling صار في اكتر من زاوية حتى يتحكم في ال chip flow angle و ما يكون في touch بين ال surface being cut وال cutting tool

- ال side relief angle & clearance angle & end cutting edge angle ← حتى ما يكون في touch بين اي face وال surface being cut (فقط يكون ال touch مع ال tool عن ال cutting edge لوحده)

- ال side relief angle ← حتى ما يصير wear للقطعة نفسها و للسماح لل cutting fluid بالدخول لل cutting zone

- ال nose radius ← كل ما زاد ال nose radius بيساعدني اكثر علا تفادي الكسر

## 8.2.3 Forces in Orthogonal Cutting

Determining cutting forces and power requirements in machining operations is essential for the following reasons:

1. **Power requirements** must be known so that a machine tool of suitable capacity can be selected for a particular application;
2. Data on cutting forces are necessary for the proper **design of machine tools** so that they have certain specific characteristics, including stiffness (عكس flexible), in order to maintain the desired dimensional accuracy; and
3. The workpiece must be able to withstand the cutting forces without excessive **distortion**. → اذا كان في قطعة بدي اعملها cutting كبير، ممكن هاي القطعة ماتتحمل هاي ال forces ويصيرلها Distortion عالي جداً
فـ ممكن اقلل السرعات، استخدم cutting edge اصغر، اقلل ال depth of cut

The factors that significantly influence the forces and power in orthogonal cutting are:

1. **Cutting forces.** The forces acting on the tool in orthogonal cutting are shown in Fig. 8.11. The **cutting force,** $F_c$, acts in the direction of the cutting speed, $V$, and supplies the energy required for the machining operation. The **thrust force,** $F_t$, acts in the direction normal to the cutting velocity, that is, perpendicular to the workpiece. These two forces produce the **resultant force,** $R$, which can then be resolved into two components on the tool face (rake face): a **friction force,** $F$, along the tool-chip interface and a **normal force,** $N$, perpendicular to the interface. From Fig. 8.11, it can be shown that the friction force is

Friction force $$F = R\sin\beta,$$

coefficient of friction $\mu = \frac{F}{N}$

Normal force $$N = R\cos\beta.$$

β : Friction angle

ال thrust force ← fix the tool against the workpiece

we assume that at any instant velocity the cutting velocity is constant → ΣF = zero

constant speed then acceleration = zero , net resultant force (R) = zero

عشان تكون zero لازم يقابلها R → equal magnitude & opposite direction resultant force from the workpiece

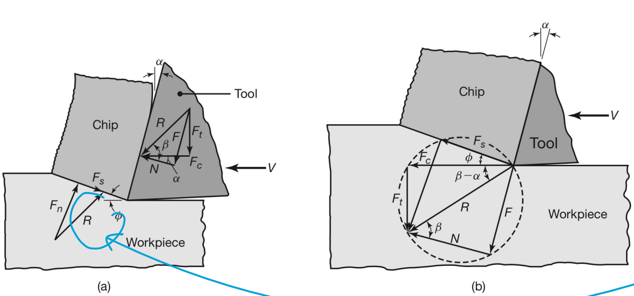



**FIGURE 8.11** (a) Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant forces, $R$, must be collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone.

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ال tool holder بكون ضاغط على ال tool بمقدار R

* Functions of R on the tool

- في ال thrust force ال +ve يكون للاسفل

① Advanced the tool ( بتعطيها ال cutting force )

هدف ال thrust force ← تثبيت ال tool against the workpiece

② thrust force بتعطيها

- طبيعة interaction بين ال chip وال tool surface ← Friction ( $F = \mu N$ )

Note also that the resultant force is balanced by an equal and opposite force on the shear plane, and is resolved into a **shear force**, $F_s$, and a **normal force**, $F_n$. From Fig. 8.11, the cutting force can be shown to be

$$F_c = R\cos(\beta - \alpha) = \frac{wt_o\tau\cos(\beta - \alpha)}{\sin\phi\cos(\phi + \beta - \alpha)}, \qquad (8.11)$$

where $\tau$ is the *average shear stress* along the shear plane.

The ratio of $F$ to $N$ is the **coefficient of friction**, $\mu$, at the tool-chip interface (see also Section 4.4.1), and the angle $\beta$ is known as the **friction angle**. The coefficient of friction can be expressed as

$$\mu = \tan\beta = \frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha}. \qquad (8.12)$$

In cutting metals, $\mu$ generally ranges from about 0.5 to 2, indicating that the chip encounters considerable frictional resistance in climbing up the rake face of the tool.

The forces in machining operations are generally found to be on the order of a few hundred or thousand newtons. However, the local stresses in the cutting zone and the normal stresses on the rake face of the tool are very high, because the contact areas are very small. The tool-chip contact length (Fig. 8.2), for example, is typically on the order of 1 mm, so that the tool is subjected to very high local stresses.

cutting force, thrust force — Tool; workpiece (reaction)

$$\vec{R} = \vec{F_c} + \vec{F_t} = \vec{F} + \vec{N} = -(\vec{F_s} + \vec{F_n})$$

($F_s$: shear force; $F_n$: the normal force of the shear force)

$F = F_N \cdot \mu$

$\sum F = 0$

Scaler $F = \mu N$

$F = R\sin\beta$ , $N = R\cos\beta$

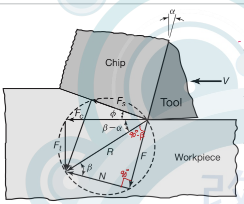
$\frac{F}{N} = \frac{R\sin\beta}{R\cos\beta} = \tan\beta$

coefficient of Friction : $\mu = \tan\beta$

→ $\mu$ ranges from about 0.5 to 2

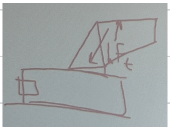
usually $\mu < 1$

- ex : if $\mu = 2$ → means that most of the energy supplied to the tool seperated as frictional heat




2. **Thrust force and its direction.** Although the thrust force does not contribute to the energy required in cutting, its magnitude is important because the tool holder, the workholding devices, and the machine tool must be sufficiently stiff to minimize deflections caused by this force. For example, if the thrust force (See Fig. 8.11) is too high and the machine tool is not sufficiently stiff, the tool will be pushed away from the workpiece surface. This deflection will, in turn, reduce the actual depth of cut, leading to loss of dimensional accuracy of the machined part and possibly to vibration and chatter (see Section 8.12).

- لا بد انو ال tool holder تكون stiff حتى تتحمل ال force



Note from Fig. 8.11 that the direction of the thrust force is *downward*. It can be shown, however, that this force can also be upward (negative), by first observing that

- stiff يعني الها high modulus of rigidity ( ما بصيرلها deflection بسهولة )

Thrust force

$$F_t = R\sin(\beta - \alpha) \qquad (8.13)$$

→ when $\alpha > \beta$ sine will be negative ∴ $F_t$ −ve (upward)

or

$$F_t = F_c\tan(\beta - \alpha). \qquad (8.14)$$

- اذا ما كانت ال tool work و work holding device ← stiff enough ال thrust force رح يرفعها للاعلى ويصير deflection
يعني ال tool بعدت عن ال workpiece ورح يقل ال depth of cut وباقي الاشياء

- thrust force → upward → −ve ; downward → +ve

* rake angle +ve ← بتكون مايلة clockwise عن ال normal

* $\beta \downarrow$ , $\alpha \uparrow$ , $F_t \downarrow$ , $F_c \uparrow$ } with constant R

لانو sin بتقل — لانو cos بزيد

* $R \downarrow$ , $F_t \downarrow$

لانو ال energy اللازمة لل cutting مارح تتغير

- بنفضل نزيد في $(\beta - \alpha)$ لحتى تصير $\alpha$ اكبر من $\beta$ رح يبدأ ال thrust force يصير negative

- لما توصل لـ $\alpha = \beta$ بتصير كل ال energy تروح على $F_c$ ويصير $F_t = zero$

- لما تصير $\alpha$ -ve بزيد ال thrust force بشكل كبير

* The sign of $F_c$ is always positive

عشان $F_c$ ازا كانت -ve رح تنسحب ال tool للخلف وما رح يصير عملية قطع

very important

The sign of $F_c$ is always positive (as shown in Fig. 8.11), but the sign of $F_t$ can be either positive or negative. Thus, when $\beta > \alpha$, $F_t$ is positive (downward), and for $\beta < \alpha$, it is negative (upward). It is therefore possible to have an upward thrust force when friction at the tool-chip interface is low and/or when the rake angle is high.

ممكن ال thrust force تكون -ve (يعني ال tool بتندفع بعيد عن سطح القطعة) وهاد الاشي مش منيح عشان مابنثبت ال tool بالتالي ال actual depth of cut رح يقل وممكن يصير vibration بيعطيني: bad surface finish & diminutional accuracy

most likly $\alpha > \beta$

. Note that at high rake angles, the thrust force is negative. A negative thrust force has important implications in the design of machine tools and in controlling the stability of the cutting process.

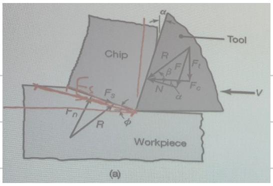
* rake angle $\downarrow$ , thrust force $\uparrow$

ثبات القطعة بكون أفضل على small rake angles

The depth of cut has an important influence; as $t_o$ increases, $R$ must also increase and thus, $F_c$ will increase as well. Note also that additional energy is required in order to remove the extra material associated with the increased depth of cut. The change in the direction and magnitude of the thrust force can play a significant role. It can, for example, lead to *instability* in machining operations, particularly if the machine tool is not sufficiently stiff.

Depth of cut $(t_o) \uparrow$ , $R \uparrow$ , $F_c \uparrow$

- كل ما زاد ال depth of cut يعني كمية ال metal اي رح تنشال رح تزيد يعني ال force بتزيد



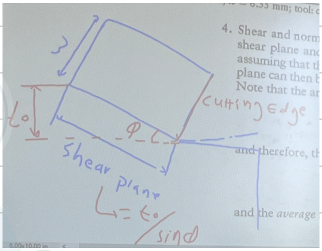

3. **Observations on cutting forces.** In addition to being a function of the strength of the workpiece material, cutting forces are influenced by other variables. Data such as those given in Tables 8.1 and 8.2 indicate that the cutting force increases with increasing depth of cut, decreasing rake angle, and decreasing cutting speed. By reviewing the data given in Table 8.2, ~~the effect of cutting speed can be attributed to the fact that as speed decreases, the shear angle decreases, and the coefficient of friction increases.~~

* rake angle ↓ , shear angle ↓ , chip thickness ↑ , $F_s$ ↑ , $F_c$ ↑

The tip radius of the tool also is an important factor: the larger the radius (hence the duller the tool), the higher the cutting force. Experimental evidence has indicated that, for depths of cut on the order of five times the tip radius or higher, the effect of tool dullness on the cutting forces becomes negligible (see also Section 8.4).

* tool radius ↑ , $F_c$ ↑

4. **Shear and normal stresses in the cutting zone.** The stresses along the shear plane and at the tool-chip interface can be analyzed by first assuming that they are uniformly distributed. The forces in the shear plane can then be resolved into shear and normal forces and stresses. Note that the area, $A_s$, of the shear plane is




$$\text{shear area} = A_s = \frac{wt_o}{\sin\phi}, \tag{8.15}$$

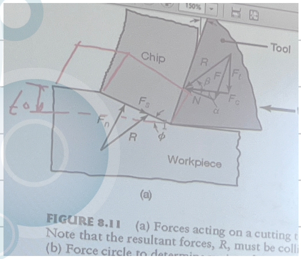
and therefore, the *average shear stress* in the shear plane is

$$\tau = \frac{F_s}{A_s} = \frac{F_s \sin\phi}{wt_o}, \tag{8.16}$$

shear stress بكون عبر ال area
normal stress ال بكون عامود عليه

and the *average normal stress* is

$$\sigma = \frac{F_n}{A_s} = \frac{F_n \sin\phi}{wt_o}. \tag{8.17}$$

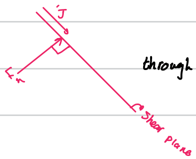



Some data on average stresses are given in Fig. 8.13, where the following conclusions can be drawn:

α ↓ , shear angle ↓ , shear force ↑

a. ~~The shear stress along the shear plane is independent of the rake angle.~~ هاي خطأ
b. The normal stress on the shear plane decreases with increasing rake angle.
c. The normal stress in the shear plane has no effect on the magnitude of the shear stress. However, normal stress strongly influences the allowable shear strain in the shear zone prior to fracture. Recall from Section 2.2.8 that the maximum shear strain to fracture increases with the normal compressive stress. For this reason, small or negative rake angles will often be used in machining less ductile materials, in order to promote shearing without fracture.

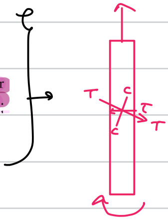
لأنو الزاوية بينهم 90° ف مركبة ال normal stress على ال shear plane zero



ال shear stress (τ) عادة بكون through the area

- بدون ال normal force ال shear strain بكون محدود لكن مع وجود ال normal force كمية ال shear قبل ال fracture بتزيد

* maximum shear strain to fracture increases with the normal compressive stress.



- اذا لفيته مارح ينفصل بال tensile واذا شديت عليه رح ينفصل بال tensile

واذا عملتله twisting رح ينفصل في ال shear

واذا ما عطيت عليه اي normal force بس مسكته وعملتله twisting رح يلف شوي بعدين يصير fracture

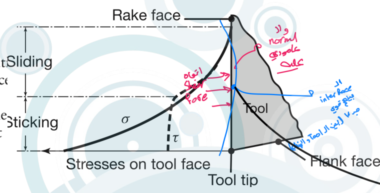
- اذا كان مع ال twisting في normal force كمية اللف بتكون اكبر قبل مايصير fracture

- مع انه ال normal stress لا يؤثر على مقدار ال shear stress في ال shear plane لكنه يؤثر على ال shear strain

shear strain : relative motion ( كم بيتحرك؟ )

*

**FIGURE 8.14** Schematic illustration of the distribution of normal and shear stresses at the tool-chip interface (rake face). Note that, whereas the normal stress increases continuously toward the tip of the tool, the shear stress reaches a maximum and remains at that value (a phenomenon known as *sticking*; see Section 4.4.1).




ال rake face عليه forces ( shear force & normal force )

في بداية ال cutting zone ما عليها أي normal force لكن

عليها constant shear stress ⟵ بس هو مش جاي من عليه

ال shearing لل material وإنما جاي من ال sticking

في ال sticking بكون في friction عالي جداً

وبعد فترة بتصير ال tool تصلا curling فبصير مجرد sliding على هاد السطح (ما في rubbing) وهاد الأشي يؤدي إلى انو ال force يتغير ن shear إى normal

13/Jul

## 8.2.5 Specific Energy

From Fig. 8.11 it can be seen that the total power in cutting is

$$\text{Power} = F_c V.$$

The specific energy, or *total energy per unit volume of material removed*, $u_t$, is then

$$u_t = \frac{F_c V}{w t_o V} = \frac{F_c}{w t_o}, \quad J/mm^3 \tag{8.24}$$

the power required to overcome friction at the tool-chip interface is the product of $F$ and $V_c$, or, in terms of **specific energy for friction**, $u_f$, as

$$u_f = \frac{F V_c}{w t_o V} = \frac{F r}{w t_o} = \frac{(F_c \sin\alpha + F_t \cos\alpha)\, r}{w t_o}. \tag{8.25}$$

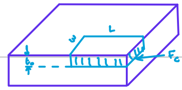
Likewise, the power dissipated along the shear plane is the product of $F_s$ and $V_s$. Thus, the **specific energy for shearing**, $u_s$, is

$$u_s = \frac{F_s V_s}{w t_o V}. \tag{8.26}$$

The **total specific energy**, $u_t$, is the sum of the two energies

$$u_t = u_f + u_s. \tag{8.27}$$

* The total energy that comes from $F_c$ will used for: 1) Shearing 2) to overcome friction




Energy = $F_c \cdot L$

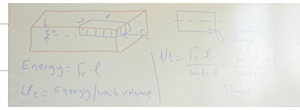
$U_t$ : Energy per unit volume

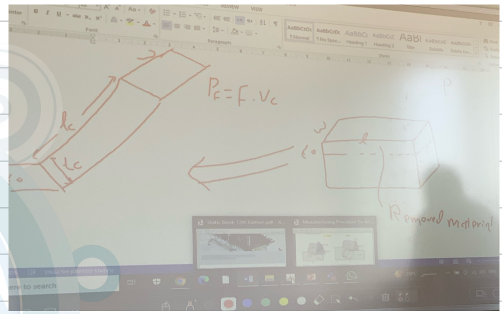
$U_t = \frac{F_c \cdot L}{w \cdot t_o \cdot L} = \frac{F_c}{w\, t_o} = J/mm^3$

2mm = 0.002

$P = F_c \cdot V$

$E = F \cdot V \cdot t$





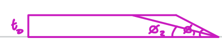

cutting ratio $r = \frac{t_o}{t_c}$

Tables 8.1 and 8.2 give some experimental data on specific energies, where it can be noted that as the rake angle increases, the frictional specific energy remains relatively constant, whereas the shear specific energy rapidly decreases. Thus, the ratio $u_f/u_t$ increases significantly as $\alpha$ increases. This trend also can be predicted by developing an expression for the energy ratio, as follows:

$$\frac{u_f}{u_t} = \frac{F V_c}{F_c V} = \frac{R \sin\beta}{R\cos(\beta-\alpha)} \cdot \frac{Vr}{V} = \frac{\sin\beta}{\cos(\beta-\alpha)} \cdot \frac{\sin\phi}{\cos(\phi-\alpha)}. \tag{8.28}$$

Experimental observations have indicated that as $\alpha$ increases, both $\beta$ and $\phi$ increase, and inspection of Eq. (8.28) indicates that the ratio $u_f/u_t$ should increase with $\alpha$.

As $\alpha$ increases → $\beta \approx$ constant & $U_f \approx$ constant & $\phi$ increases & shear plane decreases & $U_s$ decreases



## EXAMPLE 8.1 Relative Energies in Cutting

**Given:** An orthogonal cutting operation is being carried out in which $t_o = 0.1$ mm, $V = 2$ m/s, $\alpha = 10°$, and the width of cut $= 5$ mm. It is observed that $t_c = 0.25$ mm, $F_c = 500$ N, and $F_t = 200$ N.

**Find:** Calculate the percentage of the total energy that is dissipated in friction at the tool-chip interface.

**Solution:** The percentage of energy can be expressed as

$$\frac{\text{Friction energy}}{\text{Total energy}} = \frac{FV_c}{F_c V} = \frac{Fr}{F_c},$$

where

$$r = \frac{t_o}{t_c} = \frac{0.1}{0.25} = 0.40,$$

$$F = R \sin \beta$$

$$F_c = R \cos(\beta - \alpha)$$

and

$$R = \sqrt{F_t^2 + F_c^2} = \sqrt{200^2 + 500^2} = 538 \text{ N}.$$

Thus,

$$500 = 538 \cos(\beta - 10°),$$

from which we find that

$$\beta = 31.7° \quad \text{and} \quad F = 538 \sin 31.7° = 283 \text{ N}.$$

Therefore, the percentage of friction energy is calculated as

$$\text{Percentage} = \frac{(283)(0.40)}{500} = 0.22 = 22\%$$

$$u_t = u_f + u_s.$$

and similarly, the percentage of shear energy is calculated as 78%.

**EXAMPLE 8.2** Comparison of Forming and Machining Energies

**Given:** Two cylinders of annealed 304 stainless-steel, each with a diameter of 10 mm and a length of 150 mm, are to have their diameters reduced to 9 mm (a) for one piece by *pulling* it in tension and (b) for the other by *machining* it on a lathe (See Fig. 8.8) in one pass.

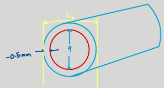
**Find:** Calculate the respective amounts of work involved, and explain the reasons for the difference in the energies dissipated.

**Solution:**

a. The work done in pulling the rod is (see Section 2.12):

a) No friction

$$W_{tension} = (u)(\text{Volume}),$$



where, from Eq. (2.56),

$$u = \int_0^{\epsilon_1} \sigma \, d\epsilon.$$

The true strain is found from Eq. (2.10) as

$$\epsilon_1 = \ln\left(\frac{D_o}{D}\right)^2 = \ln\left(\frac{10}{9}\right)^2 = 0.105.$$

From Table 2.2, the following values for $K$ and $n$ are obtained for this material:

$$K = 1275 \text{ MPa} \quad \text{and} \quad n = 0.45.$$

Thus,

$$u = \frac{K\epsilon_1^{n+1}}{n+1} = \frac{(1275)(0.105)^{1.45}}{1.45} = 33.5 \times 10^6 \text{ Nm/m}^3.$$

and

$$W_{tension} = \left(33.5 \times 10^6\right)(\pi)(0.010)^2(0.15) = 1580 \text{ Nm}.$$

b. From Table 8.3, an average value for the specific energy in machining stainless steels is taken as 4.1 W-s/mm$^3$. The volume of material machined is

$$\text{Volume} = \frac{\pi}{4}\left[(10)^2 - (9)^2\right](150) = 2240 \text{ mm}^3. \qquad V = \frac{\pi}{4}(D_i^2 - d_f^2)\,L$$

Hence, the work done in machining is

$$W_{mach} = (4.1)(2240) = 9180 \text{ Nm}.$$

It will be noted that the work done in machining is over 5 times higher than that for tension. The reasons for the large difference between the two energies are that (a) tension involves very little strain (hence very little work of deformation) and (b) there is no friction. On the other hand, machining involves significant friction, and the material removed (even though relatively small in volume) has undergone much higher strains than it does in the bulk material undergoing tension. Assuming, from Tables 8.1 and 8.2, an average shear strain of 3 [equivalent to an effective strain of 1.7; see Eq. (2.55)], the material removed in machining is subjected to a strain of 1.7/0.105 = 16 times higher than that in tension for this case.

These differences explain why machining consumes much more energy than bulk deformation. However, it can be shown that as the diameter of the rod decreases and assuming that the same depth of material is involved, the difference between the two energies becomes *smaller*. This result can be explained by noting the changes in the relative volumes involved in machining vs. tension as the diameter of the rod decreases.

**TABLE 8.3** Approximate specific energy requirements in machining operations.

| Material | Specific energy* W-s/mm$^3$ |
|---|---|
| Aluminum alloys | 0.4–1.1 |
| Cast irons | 1.6–5.5 |
| Copper alloys | 1.4–3.3 |
| High-temperature alloys | 3.3–8.5 |
| Magnesium alloys | 0.4–0.6 |
| Nickel alloys | 4.9–6.8 |
| Refractory alloys | 3.8–9.6 |
| Stainless steels | 3.0–5.2 |
| Steels | 2.7–9.3 |
| Titanium alloys | 3.0–4.1 |

*At drive motor, corrected for 80% efficiency; multiply the energy by 1.25 for dull tools.

Lubricated cutting → lowest value
High friction cutting → highest value
otherwise → average

## 8.2.6 Temperature:

- ال highest temp هو حاية عند ال cutting zone
- حجم ال workpiece بالنسبة لل cutting tool كبير جداً
بالتالي ال workpiece عبارة عن Large heat sink (يعني بتفرّغ الحرارة)
بالتالي حتى لو كانت ال temp عند ال cutting zone عالية دغري بصير
heat dissipation للقطعة وبتبرد القطعة
- اعلى Temp حاية عند ال tool chip interface وبالذات في منطقة
الوسط
- عند ال cutting zone عند ال tip بتكون ال tool ملامسة لل workpiece
بصير heat dissipation
- درجة الحرارة عبارة عن انعكاس لكمية ال heat dissipation vs heat generation

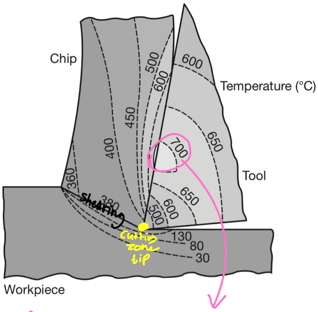



**FIGURE 8.16** Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source:* After G. Vieregge.

جاية في وسط ال secondary shear zone الي بتم عليها high friction
بين ال tool وال chip وهاد ال Friction رح يعطين حرارة جداً عالية
ولأنه كمان هاي المنطقة جاية ابعد ما يكون عن ال edges يعني محاطة
ب hot material من جميع الأماكن فـ في high heat generation لكن
ال heat dissipation قليل

As in all metalworking operations, the energy dissipated in machining operations is converted into heat, which causes a temperature rise in the cutting zone (Fig. 8.16). The rise in temperature is important because:

- High temperatures can adversely affect the strength, hardness, and wear resistance of the cutting tool;
- Control of tolerances can be made difficult by dimensional changes in the workpiece; and
- The machined surface can encounter thermal damage, adversely affecting its properties and service life.

بنلجأ لل hardness لما يكون التطبيق في high wear rates يعني في sliding او contact او rubbing لل metal against metal او metal against hard surface فـ بالتالي اذا قل ال hardness رح ينزل معاه ال wear resistance ذ رح يكون ال tool life extremely limited

ال finishing cuts بتحصل فيها على الأبعاد النهائية ، اذا ارتفعت ال Temp معنى ذلك انه ممكن يكون في non uniform cooling rates عندي مناطق مختلفة من القطعة وبالتالي ما رح احصل على ال intended dimensional accuracy

ال thermal damage هو ال surface في اكثر من نوع
1) Decarburization: خروج الكربون من المنطقة السطحية وعلى درجات حرارة عالية الكربون الموجود في ال steel بتفاعل مع الاكسجين الجو و بيبدأ عندي diffusion من الكربون للخارج وبيبدأ افقد تركيز الكربون وبالتالي ال strength بقل واذا صار هاد الأشي رح يأثر على ال Mechanical properties للقطعة وبالتالي ال useful life

1) change in chemical composition for the surface (بسبب تفاعل اي element مع الأكسجين الموجود في الجو)
2) metal Oxidation
3) phase transformation

2) Oxidation → المعدن نفسه بصير لونه اسود او زراق
وهاد رح يأثر على ال Mechanical properties
وممكن كمان اذا كانت ال Temp كافية بصير metalotical transformation

Because of the work done in shearing and in overcoming friction on the rake face of the tool, the principal sources of heat generation are the (a) primary shear zone and (b) friction at the tool-chip interface. Moreover, if the tool is worn, heat is also generated by the dull tool tip rubbing against the machined surface.

**Variables affecting temperature.** An approximate but simple expression for the *mean temperature* for orthogonal cutting is

$$T = \frac{0.000665\sigma_f}{\rho c}\sqrt[3]{\frac{Vt_o}{\kappa}}, \tag{8.29}$$

where $T$ is the *mean temperature* of the tool-chip interface in K; $\sigma_f$ is the *flow stress* of the workpiece material (in MPa); $V$ is the *cutting speed* (m/s); $t_o$ is the *depth of cut* (m); $\rho c$ is the *volumetric specific heat* of the workpiece (in kJ/m$^3$K); and $\kappa$ is the *thermal diffusivity* (ratio of thermal conductivity to volumetric specific heat) of the workpiece material (m$^2$/s). Note that because the material parameters in Eq. (8.29) themselves depend on

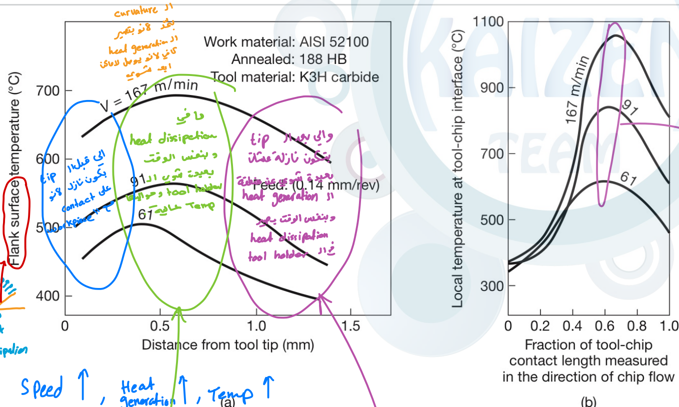



**FIGURE 8.17** Temperature distribution in turning as a function of cutting speed: (a) flank temperature; (b) temperature along the tool-chip interface. Note that the rake-face temperature is higher than that at the flank surface. *Source:* After B.T. Chao and K.J. Trigger.

cutting speed mm/min m/sec m/min — linear velocity

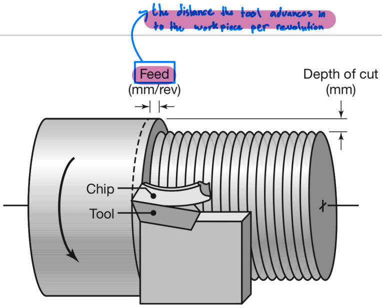
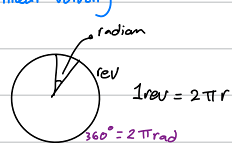



**FIGURE 8.19** Terminology used in a turning operation on a lathe, where *f* is the feed (in mm/rev) and *d* is the depth of cut. Note that feed in turning is equivalent to the depth of cut in orthogonal cutting (See Fig. 8.2), and the depth of cut in turning is equivalent to the width of cut in orthogonal cutting (See also Fig. 8.39).

N = RPm rev/min

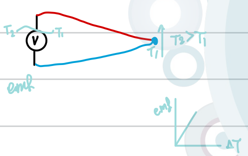
V = (π D) . N mm/min




## * Techniques for measuring temperature.

① Thermocouples

↳ two conductors in two different materials




**Techniques for measuring temperature.** Temperature and its distribution in the cutting zone may be determined by several techniques: (a) Using **thermocouples**, embedded in small holes in the tool or in the workpiece; this technique involves considerable effort. (b) Measuring **thermal emf** (electromotive force) at the tool-chip interface, which acts as a hot junction between two different materials (the tool and the chip). (c) Using a *radiation pyrometer*, monitoring the **infrared radiation** from the cutting zone; however, this technique indicates only surface temperatures and the accuracy of the results depends on the emissivity of the surfaces, which can be difficult to determine accurately.

② Radiation

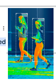
فوق البنفسجي ultraviolet

violet

Thermal imaging → self study

AI Overview

Thermal imaging, also known as infrared thermography, is **a technology that uses infrared radiation to create images showing the temperature distribution of a surface**. It allows visualization of heat patterns, even in darkness or through smoke. This technology has various applications, from building inspections to medical diagnostics.



Frequency — Red

infrared

Flank faces ← هي ال faces اي بتكون على تماس مع ال workpiece
Rake face ← هي ال faces اي بتكون على تماس مع ال chip

## * 8.3 Tool Wear and Failure

- ال cutting tools معرضة لكثير اشياء : sliding , high friction , vibration , heat , chemical affinity (قابلية اعادة ان تمسك بمادة ثانية)

- factors affect tool life : 1) combination of tool material & workpiece materials 2) cutting conditions ( speed , $t_o$ , there is rotation or not , ... )

* **Wear** : Removal of the material from the surface due to mechanical actions (mainly sliding under stress)

- factors affect tool wear : 1) cutting tool 2) workpiece material 3) physical, mechanical, chemical properties 4) processing parameters (such as : V, feed, $t_o$, ..)

- Wear is a Gradual process because the wear is caused by sliding

* Types of wear : 1) Flank wear 2) Crater wear , 3) nose wear | chipping (نتيجة wear) of the cutting edge

Recall that cutting tools are subjected to high stresses, elevated temperatures, and sliding over the machined surface; these conditions all induce wear (see Section 4.4.2). Because of its effects on the quality of the machined surface and the economics of machining, *tool wear* is one of the most important aspects of machining operations. A variety of factors affect tool wear, such as cutting tool and workpiece materials and their physical, mechanical, and chemical properties; tool geometry; cutting fluids (if used); and processing parameters, such as cutting speed, feed, and depth of cut.

In typical wear patterns in cutting tools, regions of wear are identified as *flank wear, crater wear, nose wear,* and *chipping* of the cutting edge. Whereas wear is generally a gradual process, chipping of the tool, especially *gross chipping*, is regarded as *catastrophic failure*. In addition to wear, *plastic deformation* of the tool itself also may take place, especially with tool materials that begin to lose their strength and hardness at elevated temperatures (see Section 8.6).

### - 8.3.1 Flank Wear

بيحدث على ال Flank faces ← هي ال faces اي بتكون على تماس مع ال workpiece

- factors that effect the flank wear : Temperature , cutting conditions : speed, depth of cut, feed


*Flank wear* is generally attributed to

1. Sliding of the tool along the machined surface, causing adhesive and/or abrasive wear of the tool; and
2. Temperature rise, because of its adverse effects on the mechanical properties of the tool material.

Following an extensive study, a tool-wear relationship was established for machining a variety of steels, as

$$Vt^n = C, \tag{8.31}$$

- لو استخدمنا ال machining لل cutting speed د time معين ف وجودو ان هاي العلاقة بتكون دائمًا

n ← بيعتمد على combination من ال tool materials و ال workpiece materials

where $V$ is the cutting speed, $t$ is the time that it takes to develop a flank wear land or objectionable surface finish, $n$ is an exponent that depends on workpiece and tool material as well as cutting conditions, and $C$ is a constant. Equation (8.31) is known as the *Taylor tool life equation*, after its developer, F.W. Taylor.

- ممكن انا اتنبأ بكمية ال wear ( بغيّر ال C لل wear اللي بدي اياه ف بعرف انه حل هاي المرة كم بإمكاني اشغل ال tool لأي time حتى احصل على tool wear معين )

- بشكل عام اذا زدنا السرعة، بقل ال time اللي لازم لل flank wear

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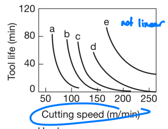
## * Tool-life curves.




| | Hardness (HB) | Ferrite | Pearlite |
|---|---|---|---|
| a. As cast | 265 | 20% | 80% |
| b. As cast | 215 | 40 | 60 |
| c. As cast | 207 | 60 | 40 |
| d. Annealed | 183 | 97 | 3 |
| e. Annealed | 170 | 100 | – |

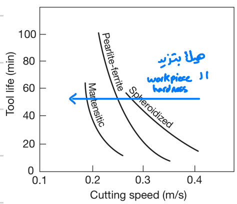
(a)

* cutting speed ↑ , tool life ↓

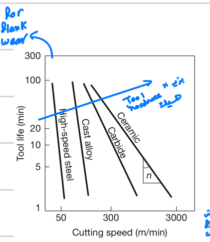
* rate of tool life decrease is higher in cutting stronger material for the same tool cut (ال rate في نزول ال tool life بزيد كل ما كانت ال material ← harder)

ال pearlite اقوى بكثير من ال Ferrite

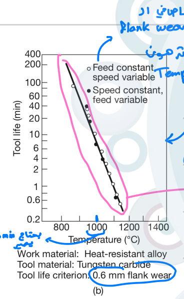
**Tool-life curves.** *Tool-life curves* are plots of experimental data obtained in machining tests (Fig. 8.20), typically for turning operations. Note that (a) tool life decreases rapidly as cutting speed increases; (b) the condition of the workpiece material has a strong influence on tool life; and (c) there is a large difference in tool life for different microstructures of the workpiece. Heat treatment of the workpiece material is important largely because of the increase in hardness. For example, ferrite has a hardness of about 100 HB, pearlite 200 HB, and martensite 300 HB to 500 HB (see Section 5.11). Impurities and hard constituents in the workpiece material also are important, because they reduce tool life due to their abrasive action on the tool (see also Section 4.4.2).




(b)




(a)




(b)

- شو ال Criteria لحتى اعرف اذا خرب ال tool صار wear او لا ؟

في هاي التجربة بعتبر انو ال tool صار فيها wear (مثبت ال wear) (constant wear) في سماكة 0.6 mm

- لو زدنا ال Feed او زدنا ال speed رح يكون نفس الاشي (رح يكون ال Temp الها نفس التأثير على ال tool life)

- Temp ↑ , tool life ↓

على أي قيمة للـ speed وال feed درجة الحرارة تأثيرها ثابت

مش زي ذلك انه الها تأثير درجة الحرارة حسب هاد ال curve

independent من ال feed & speed

- الاشي الوحيد اللي ممكن يفصلنا انو اله ما في تأثير من ال speed & feed هو ال Tool material

← Tungsten carbide (يعتبر قوي)

(الاقوى اللي بعده ال ceramics)

ال tool life من ناحية ال wear الناتج عن ال sliding بزيد اذا زاد ال hardness لكن بشكل بسيط (المادة ال harder بتتحمل اكثر)

ولكن ← hardness ↑ , brittleness ↑ , toughness ↓

مش ذلك انه ال hard اذا كان في vibration

او ما كانت ال tool ← stiff رح يصير في chipping

Although cutting speed has been found to be the most significant process variable in tool life, depth of cut and feed rate also are important; thus, Eq. (8.31) can be modified as

مع انه ال cutting speed من اهم العوامل الي بتأثر على ال tool life
بس كمان ال depth of cut & feed rate كمان مهمين.

كل هدول ال elements بس بزيدو بقللو ال tool life

$$Vt^n d^x f^y = C, \tag{8.32}$$

The linear motion per revalution

where $d$ is the depth of cut and $f$ is the feed rate (in mm/rev) in turning. The exponents $x$ and $y$ must be determined experimentally for each cutting condition. Taking $n = 0.15$, $x = 0.15$, and $y = 0.6$ as typical values encountered in practice, it can be seen that cutting speed, feed rate, and depth of cut are of decreasing order of importance.

Thus, for a constant tool life, the following observations can be made from Eq. (8.34):

1. If the feed or the depth of cut is increased, the cutting speed must be decreased, and vice versa; and
2. A reduction in the cutting speed will allow an increase in feed and/or depth of cut. Depending on the magnitude of the exponents, this can then result in an increase in the volume of the material removed.

**EXAMPLE 8.3 Increasing Tool Life by Reducing the Cutting Speed**

**Given:** A tool and material combination has $n = 0.5$ and $C = 400$.

**Find:** Calculate the percentage increase in tool life when the cutting speed is reduced by 50% using the Taylor equation [Eq. (8.31)].

**Solution:** Since $n = 0.5$, the Taylor equation can be rewritten as $V\sqrt{t} = 400$. Letting $V_1$ be the initial speed and $V_2$ the reduced speed, it can be noted that, for this problem, $V_2 = 0.5V_1$. Because $C$ is a constant,

$$0.5V_1\sqrt{t_2} = V_1\sqrt{t_1}.$$

$$Vt^n = C,$$

Simplifying this expression,

$$\frac{t_2}{t_1} = \frac{1}{0.25} = 4.0.$$

This relation indicates that the tool-life change is

انضاعفت 4 مرات ( زادت 3 مرات عن ال original time )

$$\frac{t_2 - t_1}{t_1} = \left(\frac{t_2}{t_1}\right) - 1 = 4 - 1 = 3,$$

or that it is increased by 300%. Note that the reduction in cutting speed has resulted in a major increase in tool life.

## 8.3.2 Crater Wear

Although the factors affecting flank wear also influence *crater wear*, the most significant factors in crater wear are temperature and the level of chemical affinity between the tool and the workpiece materials. Recall that the rake face of the tool is subjected to high localized stress and temperature, as well as sliding of the chip up the rake face at relatively high speeds (See Fig. 8.3b). As shown in Fig. 8.17b, peak temperatures in the cutting zone can be on the order of 1100°C. Note that the location of *maximum depth* of crater wear generally coincides with the location of maximum temperature at the tool-chip interface.

- Crater wear happens on the tool chip interface (Rake face)

- ال Peak Temp اللي في ال cutting zone ممكن توصل ل 1000°

- ال maximum temp ما بتكون على الاطراف بتكون قريب من الوسط

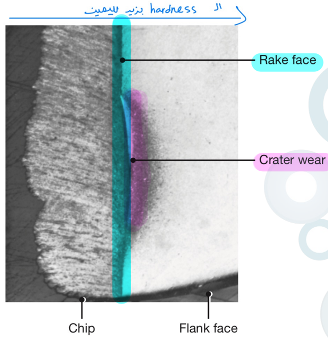



**FIGURE 8.23** Interface of chip (left) and rake face of cutting tool (right) and crater wear in cutting AISI 1004 steel at 3 m/s. Discoloration of the tool indicates the presence of high temperature (loss of temper). Note how the crater-wear pattern coincides with the discoloration pattern. Compare this pattern with the temperature distribution shown in Fig. 8.16. *Source:* Courtesy of P.K. Wright.

- اذا كان ال chemical affinity في ال workpiece نتيجة ال tool material بصير ال wear اسرع لانو بتصير ال chip تاخذ من ال material يعني بصير continuously losses in the material

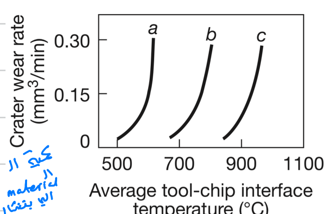



**FIGURE 8.22** Relationship between crater-wear rate and average tool-chip interface temperature in turning: (a) high-speed steel tool; (b) C1 carbide; and (c) C5 carbide. Note that crater wear increases rapidly within a narrow range of temperature. *Source:* After K.J. Trigger and B.T. Chao.

- لأي tool في minimum temp to produce the crater wear

- كل ما كانت ال tool material ← softer

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The effect of temperature on crater wear has been described in terms of a **diffusion** mechanism (the movement of atoms across the tool-chip interface). Diffusion depends on the tool-workpiece material combination and on temperature, pressure, and time; as these quantities increase, the diffusion rate increases. An example of diffusion-induced crater wear can be observed when a diamond cutting tool is used to machine steel. The high solubility of carbon in steel leads to rapid crater wear, and eventually to tool failure.

Temp ↑ , rate of diffusion ↑

Time ↑ , amount of diffusion ↑

Temp ↑ → diffusion of carbon to the chip

## 8.3.3 Chipping

wear → gradual

chipping → sudden

The term *chipping* in machining describes the sudden breaking away of a piece from the cutting edge of the tool. The pieces may be very small (*microchipping* or *macrochipping*), or they may consist of relatively large fragments (*gross chipping* or *fracture*). Two main causes of chipping are **mechanical shock** and **thermal fatigue**, such as seen in interrupted cutting operations as in milling, described in Section 8.10.

Chipping by mechanical shock may occur in a region of a cutting tool where a small crack or defect already exists. High positive rake angles also can contribute to chipping, because of the small included angle of the tool tip (See Fig. 8.31); this is a phenomenon similar to chipping of the tip of a very sharp pencil. Crater wear also may contribute to chipping, because wear progresses toward the tool tip and weakens it. Thermal cracks, which are generally perpendicular to the cutting edge, typically are caused by the thermal cycling of the tool in interrupted cutting.

cycling heating & cooling

* Two main causes of chipping:

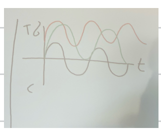
1. Mechanical shock

high feed

2. Thermal fatigue

Thermal Fatigue: nonuniform heating & cooling within the same bulk

Fatigue: Failure due to cyclic loading



under tension

* Thermal Fatigue:

nonuniform cooling & heating within the same body

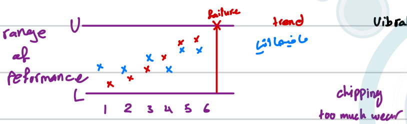
* Factors that lead to chipping.

1. High positive rake angle
   - → because of the small included angle


2. Crater wear
   - → because wear progresses toword the tool tip and weakens it

3. Thermal cracks
   - → thermal cycle like interrupted cutting

## 8.3.5 Tool-Condition Monitoring

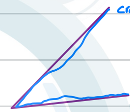



- بدي اراقب ال Tool براقب ال Vibration , Forces , Temperature

With the extensive use of computer-controlled machine tools and implementation of highly automated manufacturing systems, the reliable and repeatable performance of cutting tools is a major consideration. Once programmed properly, machine tools now operate with little direct supervision by an operator; consequently, the failure of a cutting tool will have serious detrimental effects. It is therefore essential to continuously monitor the condition of the cutting tool, such as for wear, chipping, or gross failure.

Techniques for tool-condition monitoring typically fall into two general categories: direct and indirect. The **direct method** involves *optical measurement* of wear, by periodically observing changes in the profile of the tool.

- Direct ← اذا صار يتغير زي هيك يعني في crater & flank wear



- ال In Direct ← انا ما بقيسها ( مابشوف تشكلها ) وإنما بقيس ال Forces , Temperature , vibration

وإذا وجدنا ال Force بازدياد هيك بيعطيني indication انو ال tool صارت sharp بدل dull او صار عندي wear معين

او اذا صار ارتفاع في ال Temperature نفس الأشي

**Indirect methods** of measuring wear involve correlating the tool condition with variables such as force, power, temperature rise, surface finish, and vibration and chatter. The **acoustic emission** technique utilizes a piezoroughness, waviness, flatness — surface finish | Fatigue crack — surface integrity

## 8.4 Surface Finish and Surface Integrity

geometrical reach — ما الو دخل في إضعاف القطعة — يدل على وجود وعدم وجود cracks

Surface finish: describes the geometric features of surfaces (geometrical reach)

Surface integrity: pertains to properties that are strongly influenced by the type of surface produced (يدل على وجود وعدم وجود cracks)

- من الاشياء الي بتأثر على surface finish هي انواع ال chips ← احسن surface finish ← ① continues chips
② Built up edge chips → surface finish اسوأ

* Adversely affect surface finish & integrity: ① Built up edge ② Depth of cut

**Surface finish** describes the *geometric* features of surfaces, whereas **surface integrity** pertains to *properties* that are strongly influenced by the type of surface produced (see also Section 4.3). The ranges of surface roughness in machining and other processes are given in Fig. 8.24. As can be seen, the processes are generally organized in order of increasing surface quality, which also correspond to increasing cost and machining time (See also Fig. 16.5).

Built-up edge and depth of cut can adversely affect surface finish and integrity. Figure 8.25 shows surfaces obtained in two different machining operations; note the damage to the surfaces from BUE. A shallow depth of cut (or dull tool) can also compromise surface finish. A dull cutting tool has a larger radius along its edges, just as a dull pencil or knife does. Figure 8.26 illustrates the relationship between the radius of the cutting edge and depth of cut in orthogonal cutting. Note that at small depths of cut, the rake angle of an otherwise positive-rake tool can effectively become *negative*; the tool may simply ride over the workpiece surface and not remove any material. If the radius is large in relation to the depth of cut, the tool will rub over the machined surface, generating frictional heat, inducing surface residual stresses, and causing surface damage, such as tearing and cracking. In practice, the depth of cut should generally be greater than the radius on the cutting edge.

① small depth of cut
② shallow depth of cut (بادوب على ال surface) (large tip radius)
→ -ve rake angle → رح تدفع ال metal دفع بدلما تقطعه & very bad surface finish

if the radius >>> depth of cut → رح يكون ال tangent لل radius اي داخل
ال workpiece رح يكون مائل عن ال vertical
ورح تتصرف ال tool كأنها negative rake angle
وبتعطينا surface damage زي tearing & cracking
ايجي بأثر على ال surface finish & integrity

• اقل اشي انو لازم ال depth of cut يكون اكبر من ال radius لل cutting edge
حتى انه ال tool تتصرف حسب ال rake angle الحقيقية الها

- ال negative rake angle مش دايمًا بتكون سيئة. يعني احيانًا بنتظر ناخدها negative بس لازم تكون extremely sharp

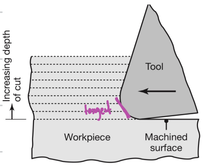



**FIGURE 8.26** Schematic illustration of a dull tool in orthogonal cutting (exaggerated). Note that at small depths of cut, the rake angle can effectively become negative. In such cases, the tool may simply ride over the workpiece surface, burnishing it, instead of cutting.

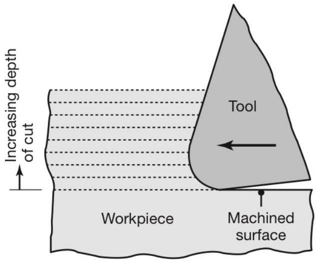



**FIGURE 8.26** Schematic illustration of a dull tool in orthogonal cutting (exaggerated). Note that at small depths of cut, the rake angle can effectively become negative. In such cases, the tool may simply ride over the workpiece surface, burnishing it, instead of cutting.

**Feed marks.** In turning, as in some other machining operations, the cutting tool leaves a spiral profile (*feed marks*) on the machined surface as it moves across the workpiece (See Fig. 8.19). As expected, the higher the feed, $f$, and the smaller the radius, $R$, the more prominent are these marks. Although not significant in rough machining operations, feed marks are important in finish machining (see Section 8.9).

The peak-to-valley roughness, $R_t$, in turning can be expressed as

$$R_t = \frac{f^2}{8R}, \quad (8.35)$$

where $f$ is the feed and $R$ is the nose radius of the tool. For the condition where $R$ is much smaller than $f$, the roughness is given by the expression

$$R_t = \frac{f}{\tan \alpha_s + \cot \alpha_e}, \quad (8.36)$$

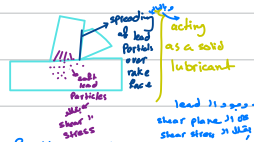


## 8.5 Machinability

The *machinability of a material* is generally defined in terms of the following four factors: (a) surface finish and integrity of the machined part; (b) tool life; (c) force and power requirements; and (d) chip control. Thus, good machinability indicates *good surface finish and integrity*, *long tool life*, *low force and power requirements*, and type of chip produced are easily collected and do not interfere with the machining operation (see Section 8.2.1).

## 8.5.1 Machinability of Steels

LOW Melting point (327°) , Lead is perfectly plastic material (مادة طرية جداً)




**Leaded steels.** Lead is added to molten steel and takes the form of dispersed fine lead particles (See Fig. 5.2a). During machining, the lead particles are sheared and smeared over the tool-chip interface; because of their low shear strength, the lead particles act as a solid lubricant (see Section 4.4.4). This behavior can be verified from the presence of high concentrations of lead on the tool-side face of the chips when machining leaded steels. In addition, lead lowers the shear stress in the primary shear zone, thus reducing cutting forces and power consumption. Leaded steels are identified by the letter L between the second and third numerals, such as 10L45. Because of its toxicity and environmental concerns, the trend has been toward eliminating the use of lead in favor of such elements as bismuth and tin (*lead-free steels*).

يقلل ال friction بين ال chip و ال tool

- ال lead بيعمل عل ال Lubricant

- ال primary shear zone هي ال zone الي بصير عليها ال shearing و بتتحول فيها ال material ل chip و بيقل عليها ال stresses لأنو جزء منها يكون lead particles بيكون قصها سهل جداً

**Resulfurized and rephosphorized steels.** *Sulfur* in steels forms *manganese-sulfide inclusions* (second-phase particles; see Fig. 8.27). ~~These particles act as stress raisers in the primary shear zone;~~ as a result, the chips produced are small and they break up easily, thus improving machinability. *Phosphorus* in steels improves machinability by virtue of strengthening the ferrite, thereby increasing the hardness of steels and producing less continuous chips.

Steals (Fe, Mn)
Mn: desulphurizing agent


- round edge فيها stress raisers هون ما بصير

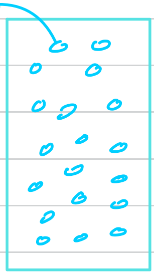
- بالغالب بنضيف ال Mn على ال steel حتى نتخلص من ال Sulfur

( ال sulfur عبارة عن impurity )

- ال Sulfides بيكون الها حسنة لما احنا بدنا ال steel نستخدمه فقط للـ Machining لما بدنا ال Mechanical properties زي tensile strength بدنا بس

( compressive stress ) ( عشان ال tensile stresses رح يفتح cracks )

**Calcium-deoxidized steels.** In these steels, oxide flakes of *calcium aluminosilicate* (CaO, $SiO_2$, and $Al_2O_3$) are formed. These flakes, in turn, lower the strength of the secondary shear zone, thus reducing tool-chip interface friction and wear, and hence lowering the temperature. As a result, these steels develop less crater wear of the tool, especially at high cutting speeds when temperatures are higher.



**Effects of other elements on the machinability of steels.** (a) The presence of *aluminum* and *silicon* in steels is always harmful, because these elements combine with oxygen to form aluminum oxide and silicates, which are hard and abrasive. (b) *Carbon* and *manganese* have various effects on the machinability of steels, depending on their composition. As the carbon content increases, machinability decreases, although plain low-carbon steels (less than 0.15% C) can produce poor surface finish due to forming a built-up edge. Alloying elements, such as nickel, chromium, molybdenum, and vanadium (which improve the properties of steels) generally reduce machinability. (c) Cast steels have a machinability similar to that of wrought steels. (d) Tool and die steels are very difficult to machine, usually requiring annealing prior to machining them.

- لحد تقريباً ال 0.15 كربون بتكون ال Machinability جيدة لأنه تحت ال 0.15% بيبدأ ال Tendency لتكوين ال builtup edge

- اعلى من 0.15 ما بكون في تكوين لل builtup edge لكن ال strength بتزيد وبالتالي صح ال surface finish جيد ولكن ال tool life رح تقل وال force وال energy requirement رح تزيد

- إضافة ال Alloying elements زي ال nickel, chromium, ... ← بيرفعوا ال Strength لل steel بالتالي رح يقل ال Machinability بسبب ال tool life & Force & power requirements

- ليش ال cold working بقلل من ال Tendency لتكوين ال builtup edge ؟

← لأنه في ال cold working بزيد ال Strength بسبب ال Strain hardening وبالتالي ال ductility رح تقل وبالتالي ال Tendency لتكوين ال builtup edge بتقل

## 8.5.2 Machinability of Various Metals

*Aluminum* is generally easy to machine, although the softer grades tend to form built-up edge, and thus, poor surface finish. High cutting speeds, rake angles, and relief angles are recommended. Wrought aluminum alloys with high silicon content and cast alloys may be abrasive, thus requiring harder tool materials. Dimensional control may be a challenge in machining aluminum, because of its low elastic modulus and relatively high thermal coefficient of expansion.

*Gray-cast irons* are generally machinable, although they are abrasive. Free carbides in castings reduce machinability and cause tool chipping and fracture, thus requiring tools with high toughness. Nodular and malleable irons are machinable, using hard tool materials.

*Cobalt-base alloys* are abrasive and highly work hardening; they require sharp and abrasion-resistant tool materials and low feeds and speeds.

ductility عالية ← *Wrought copper* can be difficult to machine, because of built-up edge formation, although cast copper alloys are easy to machine. *Brasses* are easy to machine, especially those containing lead (*leaded free-machining brass*). *Bronzes* are more difficult to machine than brass.

## 8.6 Cutting-Tool Materials

The selection of appropriate cutting-tool materials for a specific application is among the more important considerations in machining operations, as is the selection of mold and die materials for forming and shaping processes. Recall that in machining, the tool is subjected to high localized temperatures, high contact stresses, rubbing on the workpiece surface, and the chip climbing up the rake face of the tool (see Section 8.2). Consequently, a cutting tool must possess the following characteristics:

- **Hardness**, particularly at elevated temperatures (**hot hardness**), so that the strength of the tool is maintained at the temperatures encountered in machining operations (Fig. 8.28);
- **Toughness**, so that impact forces on the tool in interrupted cutting operations, such as milling or turning a splined shaft, do not chip or fracture the tool;
- **Wear resistance**, so that the tool has an acceptable tool life before it is indexed or replaced; and

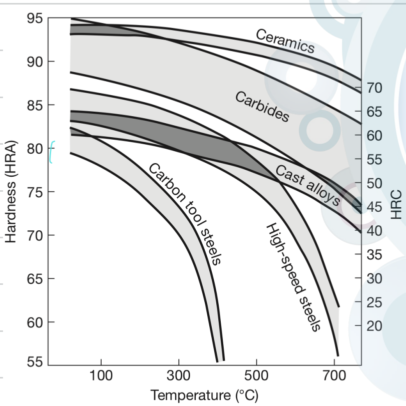



**FIGURE 8.28** Hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of tool materials results from the variety of compositions and treatments available for that group.

### 8.6.1 Carbon and Medium-Alloy Steels

*Carbon steels* are the oldest of tool materials, and have been used widely for drills, taps, broaches, and reamers since the 1880s. Low-alloy and medium-alloy steels were developed later for similar applications, but with longer tool life. Although inexpensive and easily shaped and sharpened, these steels do not have sufficient hot hardness and wear resistance for machining at high cutting speeds, where temperature rise is significant. Note in Fig. 8.28, for example, how rapidly the hardness of carbon steels decreases as the temperature increases. The use of these steels is thus limited to very low-speed machining operations or woodworking.

### 8.6.2 High-Speed Steels

*High-speed steel* (HSS) tools are so named because they were developed to machine at speeds higher than previously possible. First produced in the early 1900s, high-speed steels are the most highly alloyed of tool steels (see also Section 3.10.4). They can be hardened to various depths, have good wear resistance, and are relatively inexpensive. Because of their high toughness and resistance to chipping and fracture, high-speed steels are especially suitable for (a) high positive-rake-angle tools (that is, small included angle; see Fig. 8.2); (b) interrupted cuts; and (c) use on machine tools that, because of their low stiffness, are subject to vibration and chatter. High-speed steels are the most commonly used tool materials, followed closely by various die steels and carbides. They are especially used in machining operations that require complex tool shapes, such as drills, reamers, taps, and gear cutters.

There are two basic types of high-speed steels: **molybdenum** (*M series*) and **tungsten** (*T series*). The *M* series contains up to about 10% molybdenum, with chromium, vanadium, tungsten, and cobalt as alloying elements. The *T* series contains 12 to 18% tungsten, with chromium, vanadium, and cobalt as alloying elements. The *M* series generally has higher abrasion resistance than the *T* series, undergoes less distortion during heat treating, and is less expensive.

High-speed steel tools are available in wrought, cast, and sintered (see *powder-metallurgy*, Chapter 11) conditions. They can be **coated** for improved performance (see Section 8.6.5), and may also be subjected to surface treatments, such as case hardening (Section 4.5.1), for improved hardness and wear resistance.

* Types of High speed steels :

① Molybdenum (M series) contains 10% Molybdenum (Mo), chromium (Cr), vanadium (V), tungsten (W), cobalt (Co)
الي بيعطيني القوة

② Tungsten (T series) contains 12 to 18% tungsten (W), chromium (Cr), vanadium (V), cobalt (Co)

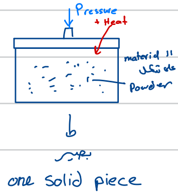
- ال carbides عبارة عن مواد قاسية جداً لذلك بنضيف هاي العناصر للـ steels حتى تعطينا hardness و بالذات Hot hardness (hardness at high temp)
W8 ال carbides كثير stable على high temp,

* The *M* series generally has higher abrasion resistance than the *T* series, undergoes less distortion during heat treating, and is less expensive.

* High-speed steel tools are available in wrought, cast, and sintered (see *powder-metallurgy*, Chapter 11) conditions. They can be **coated** for improved performance (see Section 8.6.5), and may also be subjected to surface treatments, such as case hardening (Section 4.5.1), for improved hardness and wear resistance.

(wrought: يعني صنعه بلا forming)

Sintering




Sintering: high-pressure compaction under elevated temps

## 8.6.3 Cast-Cobalt Alloys

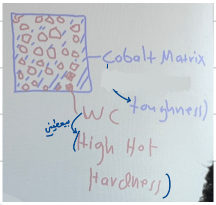
*Cast-cobalt alloys* have high hardness, typically 58 to 64 HRC (hardness rockwell C scal), good wear resistance, and maintain their hardness at elevated temperatures. Their composition ranges from 38 to 53% cobalt, 30 to 33% chromium, and 10 to 20% tungsten (carbide foils). Commonly known as *Stellite* tools, these alloys are cast and ground into relatively simple tool shapes. Because they are not as tough as high-speed steels, and are sensitive to impact forces, they less suitable than high-speed steels for interrupted cutting operations.

(ما رح اقدر استخدمهم على high rake angles)

## 8.6.4 Carbides

The tool materials described thus far possess sufficient toughness, impact strength, and thermal shock resistance for numerous applications; however, they have significant limitations regarding such important characteristics as strength and hardness, particularly hot hardness. Consequently, they cannot be used as effectively where high cutting speeds, and hence high temperatures, are involved, and their tool life can be relatively short. *Carbides*, also known as **cemented** or **sintered carbides**, were introduced in the 1930s to meet the challenge of higher machining speeds for higher productivity.

Because of their high hardness over a wide range of temperatures (as can be seen in Fig. 8.28), high elastic modulus, high thermal conductivity, and low thermal expansion, carbides are among the most important, versatile, and cost-effective tool and die materials for a wide range of applications. The two basic categories of carbides are *tungsten carbide* and *titanium carbide*. In order to differentiate them from coated tools (see Section 8.6.5), plain carbide tools are usually referred to as **uncoated carbides**.



1. **Tungsten carbide.** *Tungsten carbide* (WC) is a *composite material*, consisting of tungsten-carbide particles bonded together in a *cobalt* matrix. Tungsten carbide is often compounded with carbides of titanium and niobium to impart special properties to carbide tools and dies. The amount of cobalt significantly affects the properties of carbide tools; as the cobalt content increases, strength, hardness, and wear resistance decrease, while toughness increases (Fig. 8.29). Tungsten-carbide tools are generally used for machining steels, cast irons, and abrasive nonferrous materials. The tools are manufactured by powder-metallurgy techniques.
2. **Titanium carbide.** *Titanium carbide* (TiC) has higher wear resistance than tungsten carbide, but it is not as tough. With a *nickel-molybdenum* alloy as the matrix, TiC is suitable for machining hard materials, mainly steels and cast irons, and for machining at speeds higher than those for tungsten carbide.

**Inserts.** High-speed steel and carbon-steel cutting tools can be produced in various geometries (See Fig. 8.10), including drills and milling cutters. However, after the cutting edges wear and become dull, the tool has to be removed from its holder and reground, a time-consuming process. The need for a more efficient method led to the development of *inserts*, that are individual cutting tools with a number of cutting edges in various shapes (Fig. 8.30). A square insert, for example, has eight cutting edges, and a triangular insert has six. Inserts also are available with a wide variety of **chip-breaker** features (see Section 8.2.1) for controlling chip flow, reducing vibration, and reducing the heat generated.

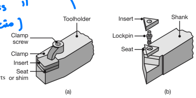


**FIGURE 8.30** Methods of mounting inserts on toolholders: (a) clamping, and (b) wing lockpins. *Source:* Courtesy of Valenite.

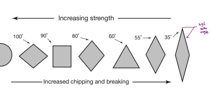


**FIGURE 8.31** Relative edge strength and tendency for chipping and breaking of inserts with various shapes. Strength refers to that of the cutting edge shown by the included angles. *Source:* Courtesy of Kennametal, Inc.

Inserts are usually clamped on the tool *shank*, using various locking mechanisms (Figs. 8.30a and b); less frequently, inserts may also be *brazed* (see Section 12.14.1) to the tool shank (See Fig. 8.36). However, because of the difference in thermal expansion between the insert and the tool-shank materials, brazing must be done properly in order to avoid cracking or warping. Clamping is the preferred method because after a cutting edge is worn, it is *indexed* so that a new edge can be used. In addition to those shown in Fig. 8.30, a wide variety of other toolholders also is available

## 8.6.5 Coated Tools

A variety of materials are available as coatings, typically over high-speed steel and carbide tools. Because of their unique properties, **coated tools** can be used at high cutting speeds, thus reducing the machining time, and hence costs. It has been shown that coated tools can improve tool life by an order of magnitude over uncoated tools; note in Fig. 8.33, for example,

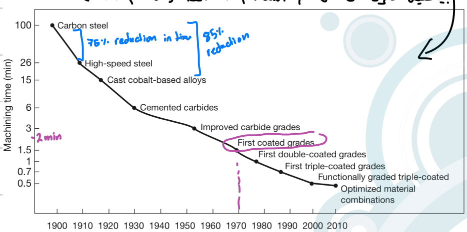



**FIGURE 8.33** Relative time required to machine with various cutting-tool materials, with indication of the year the tool materials were introduced. Note that, within one century, machining time has been reduced by two orders of magnitude. *Source:* After Sandvik Coromant.

that the machining time has been reduced by a factor of more than 100 since 1900.

Commonly used *coating materials* include titanium nitride, titanium carbide, titanium carbonitride, and aluminum oxide ($Al_2O_3$), as described below. Generally in the thickness range of 2–10 $\mu$m, coatings are applied by **chemical vapor deposition** (CVD) and **physical-vapor deposition** (PVD) techniques, described in Section 4.5. The CVD process is the most common method for carbide tools with multiphase and ceramic coatings. The PVD-coated carbides with TiN coatings, on the other hand, have higher cutting-edge strength, lower friction, lower tendency to form a built-up edge, and are smoother and more uniform in thickness, which is generally in the range of 2–4 $\mu$m. **Medium-temperature chemical-vapor deposition** (MTCVD) provides higher resistance to crack propagation than do CVD coatings.

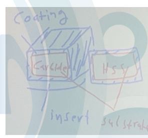
Coatings must have the following general characteristics:

- High hardness at elevated temperatures;
- Chemical stability and inertness to the workpiece material;
- Low thermal conductivity;
- Good bonding to the substrate; and
- Little or no porosity.

The effectiveness of coatings is enhanced by hardness, toughness, and high thermal conductivity of the substrate, which may be carbide or high-speed steel. Honing (see Section 9.7) of the cutting edges is an important procedure to maintain the strength of the coating and to prevent chipping at sharp edges and corners.

Various coatings are described below.

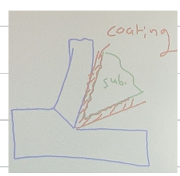
1. **Titanium nitride.** *Titanium nitride* (TiN) coatings have low coefficient of friction, high hardness, good high temperature properties, and good adhesion to the substrate. These properties greatly improve the life of high-speed steel tools and of carbide tools, drills, and cutters. Titanium-nitride coated tools (gold in color) perform well at higher cutting speeds and feeds; they do not perform as well as uncoated tools at low speeds, because the coating is susceptible to chip adhesion. Using appropriate cutting fluids to discourage chip-tool adhesion is therefore important. Flank wear is significantly lower than for uncoated tools (Fig. 8.34), and flank surfaces can be reground after use without removing the coating on the rake face of the tool.
2. **Titanium carbide.** *Titanium carbide* (TiC) coatings (silver-gray in color) over tungsten-carbide inserts have high resistance to flank wear, especially in machining abrasive materials.
3. **Titanium carbonitride.** *Titanium carbonitride* (TiCN), violet to mauve red in color (depending on carbon content), is deposited by physical-vapor deposition techniques, and is harder and tougher than TiN. It can be used over carbide and high-speed steel tools, and is particularly effective in cutting stainless steels.
4. **Ceramic coatings.** Because of their high-temperature performance, chemical inertness, low thermal conductivity, and resistance to flank and crater wear, ceramics are attractive coating materials. The most commonly used ceramic coating is *aluminum oxide* ($Al_2O_3$). However, because ceramic coatings are not chemically reactive, oxide coatings generally bond weakly to the substrate and thus they may have a tendency to peel off the tool.
5. **Multiphase coatings.** The desirable properties of various coatings can be combined and optimized by using *multiphase coatings* (Fig. 8.35). Coated carbide tools are available with two or three layers of such coatings, and are particularly effective in machining cast irons and steels.



In the example shown in Fig. 8.36, the first layer over the tungsten-carbide substrate is TiC, followed by $Al_2O_3$, and then TiN. It is important for (a) the first layer to bond well to the substrate; (b) the outer layer to resist wear and have low thermal conductivity; and (c) the intermediate layer to bond well and be compatible with both layers.

Typical applications of multiple-coated tools are:

a. High-speed, continuous cutting: $TiC/Al_2O_3$;
b. Heavy-duty, continuous cutting: $TiC/Al_2O_3/TiN$; and
c. Light, interrupted cutting: TiC/TiC + TiN/TiN.



Coatings consisting of **alternating multiphase layers**, with layers that are thinner than in typical multiphase coatings. The thickness of these layers is in the range of 2–10 $\mu$m. The reason for using thinner coatings is that coating hardness increases with decreasing grain size, a phenomenon that is similar to the Hall-Petch effect (see Section 3.4.1).

6. **Diamond coatings.** Polycrystalline diamond is used as a thin coating, particularly over tungsten-carbide and silicon-nitride inserts. The films are deposited on substrates by PVD and CVD techniques, whereas thick films are produced by growing a large sheet of pure diamond, which is then laser cut to shape and brazed to a carbide shank. Diamond-coated tools are particularly effective in machining abrasive materials, such as aluminum-silicon alloys, graphite, and fiber-reinforced and metal-matrix composite materials (see Section 11.14). Improvements in tool life of as much as tenfold have been obtained over other coated tools.

7. **Other coating materials.** Advances are continually being made in developing and testing new coating materials. **Titanium aluminum nitride** (TiAlN) is effective in machining aerospace alloys. Chromium-based coatings, such as **chromium carbide** (CrC), have been found to be effective in machining softer metals that tend to adhere to the cutting tool, such as aluminum, copper, and titanium. Other coating materials include **zirconium nitride** (ZrN) and **hafnium nitride** (HfN), **nanocoatings** with carbide, boride, nitride, oxide, or some combination, and **composite coatings**, using a variety of materials.

### 8.6.6 Alumina-Base Ceramics

Ceramic tool materials, introduced in the early 1950s, consist primarily of fine-grained, high-purity **aluminum oxide**. They are pressed into inserts, under high pressure and at room temperature, then sintered (see Section 11.4); they are called **white, or cold-pressed, ceramics** (see also Section 11.9.3). Titanium carbide and zirconium oxide can be added to improve such properties as toughness and resistance to thermal shock.

*Alumina-base ceramic* tools have very high abrasion resistance and hot hardness (Fig. 8.35). Chemically, they are more stable than high-speed steels and carbides, thus they have lower tendency to adhere to metals during machining and hence lower tendency to form a built-up edge. Consequently, good surface finish is obtained, particularly in machining cast irons and steels. However, ceramics lack toughness, which can result in premature tool failure by chipping or fracture. The shape and setup of ceramic tools also are important; negative rake angles, hence large included angles, are generally preferred in order to avoid chipping. Tool failure can be reduced by increasing the stiffness and damping capacity of machine tools and workholding devices, thus reducing vibration and chatter (see Section 8.12).

**Cermets.** *Cermets* (from the words *ceramic* and *metal*), also called **black or hot-pressed ceramics** (carboxides), typically contain 70% aluminum oxide and 30% titanium carbide. Other cermets may contain molybdenum carbide, niobium carbide, or tantalum carbide. The performance of cermets is between that of ceramics and carbides (See Fig. 8.35).

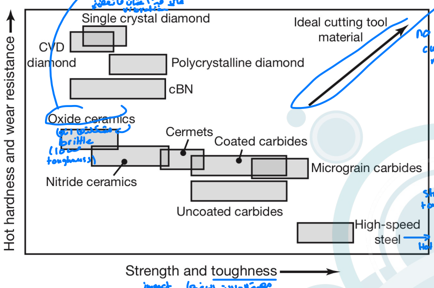



**FIGURE 8.35** Ranges of properties for various groups of cutting-tool materials. (See also Tables 8.1 through 8.5.)

## 8.6.7 Cubic Boron Nitride

Next to diamond, *cubic boron nitride* (cBN) is the hardest material presently available. The cutting tools are made by bonding a 0.5 to 1 mm layer of *polycrystalline cubic boron nitride* to a carbide substrate, by sintering under pressure (Fig. 8.36). While the carbide provides toughness, the cBN layer provides very high wear resistance and cutting-edge strength. Cubic-boron-nitride tools are also made in small sizes without a substrate. At elevated temperatures, cBN is chemically inert to iron and nickel and its resistance to oxidation is high; it is therefore particularly suitable for machining hardened ferrous and high-temperature alloys (see also *hard turning*, in Section 8.9.2). Because cBN tools are brittle, stiffness and damping capacity of the machine tool and fixturing devices is important in order to avoid vibration and chatter. Cubic boron nitride is also used as an abrasive, as described in Section 9.2.

### 8.6.8 Silicon-Nitride-Base Ceramics

*Silicon-nitride-base ceramic* (SiN) tool materials consist of silicon nitride with additions of aluminum oxide, yttrium oxide, and titanium carbide. These tools have high toughness, hot hardness, and good thermal-shock resistance. A common example is **sialon**, after the elements *si*licon, *al*uminum, oxygen, and *n*itrogen in its composition. It has higher resistance to thermal shock than silicon nitride and is recommended for machining cast irons and nickel-base superalloys, at intermediate cutting speeds. However, because of their chemical affinity to steels, SiN-base tools are not suitable for machining steels.

### 8.6.9 Diamond

The hardest substance of all known materials is *diamond*, a crystalline form of carbon (see also Section 11.13). As a cutting tool, it has low tool-chip friction, high wear resistance, and thus the ability to maintain a sharp cutting edge. Diamond is used where very fine surface finish and dimensional accuracy are required, particularly in machining abrasive nonmetallic materials and soft nonferrous alloys. *Single-crystal diamond* is used for special applications, such as machining copper-front high-precision optical mirrors. Diamond is brittle, and tool shape and sharpness are thus important; low rake angles and large included angles are normally used for a strong-cutting edge. Wear of diamond tools may occur by microchipping (caused by thermal stresses and oxidation) and transformation to carbon (caused by the high temperatures generated during machining).

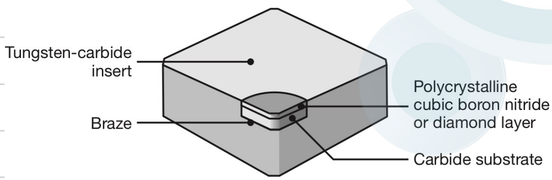



**FIGURE 8.36** Construction of polycrystalline cubic-boron-nitride or diamond layer on a tungsten-carbide insert.

Single-crystal single-point diamond tools have been largely replaced by **polycrystalline diamond** tools (called *compacts*), that are also used as wire-drawing dies for fine wire (see Section 6.5). Compacts consist of very small synthetic crystals, fused to a thickness of about 0.5–1 mm, by a high-pressure, high-temperature process, and bonded to a carbide substrate, similar to cBN tools (See Fig. 8.36). The random orientation of the diamond crystals prevents the propagation of cracks through the compact, significantly improving its toughness.

Diamond tools can be used satisfactorily at almost any speed but are suitable mostly for light and uninterrupted finishing cuts. In order to minimize tool fracture, a single-crystal diamond tool must be resharpened as soon as it becomes dull. Because of its strong chemical affinity, diamond is not recommended for machining plain-carbon steels (as is the case with sialon tools) and titanium, nickel, and cobalt-base alloys. Diamond is also used as an abrasive in grinding and polishing operations (Chapter 9), and as a wear-resistant coating (see Section 4.5).

## 8.7 Cutting Fluids

*Cutting fluids* are used extensively in machining operations to:

- Cool the cutting zone, thus reducing workpiece temperature and distortion, and improving tool life;
- Reduce friction and wear, thus improving tool life and surface finish;
- Reduce forces and energy consumption;
- Wash away chips; and
- Protect the newly machined surfaces from environmental attack.

A cutting fluid predominantly serves as a **coolant** and/or as a **lubricant** (see Section 4.4.4). Its effectiveness in machining operations depends on several factors, such as the method of application, temperature, cutting speed, and type of machining operation. There are situations, however, in which the use of cutting fluids can be detrimental. For example, in interrupted cutting operations, such as milling (Section 8.10), the cooling action of the cutting fluid increases the extent of alternate heating and cooling (*thermal cycling*) to which the cutter teeth are subjected, a condition that can lead to the development of thermal cracks (*thermal fatigue* or *thermal shock*). Moreover, cutting fluids may also cause the chip to become more curled (i.e., smaller radius of curvature), concentrating the stresses on the tool closer to its tip, thus concentrating the heat closer to the tool tip and reduce tool life.

Cutting fluids can present **biological** and **environmental hazards** (see also Section 4.4.4), requiring proper recycling and disposal, and adding to cost. For these reasons, **dry cutting**, or **dry machining**, has become an increasingly important approach, in which no coolant or lubricant is used in the machining operation (see Section 8.7.2). Even though this approach would suggest that higher temperatures and thus more rapid tool wear would occur, some tool materials and coatings maintain an acceptable tool life. Dry cutting has been associated with high-speed machining, because higher cutting speeds transfer a greater amount of heat to the chip (See Fig. 8.18), which is an incentive for reducing the need for a coolant. See also Section 3.9.7 on possible detrimental effects of cutting fluids on some cutting tools, called *selective leaching*, such as in carbide tools with cobalt binders.

## 8.7.1 Types of Cutting Fluids and Methods of Application

There are four basic types of cutting fluids commonly used in machining operations: **oils, emulsions, semisynthetics,** and **synthetics** (see Section 4.4.4). Cutting-fluid recommendations for specific machining operations are given throughout the rest of this chapter. In selecting an appropriate cutting fluid, considerations should be given to its possible detrimental effects on the workpiece material (such as corrosion, stress-corrosion cracking, staining), machine tool components, biological and environmental effects, and recycling and disposal of chips.

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

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

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

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

### 8.7.2 Near-Dry and Dry Machining

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

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

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

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

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

### 8.7.3 Cryogenic Machining

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

* The Mid exam :

The University of Jordan
Department of Industrial Engineering
Manufacturing Processing II (Metal Cutting)
First Exam, Thursday, 14/8/2025, 9:45 – 10:45 am

19/30

**Q- 1 (25 points) choose the right answer**

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1- The highest temperature on the tool occurs within: D

a- The tip region of the tool on the flank face
b- The middle region of the contact between chip and flank face
c- The tip region of the tool on the rake face
d- The middle region of the contact between chip and rake face

2- The width of crater wear is limited by: C

a- The work piece material
b- The depth of cut
c- The chip width
d- The highest temperature

3- Flank wear increases as: A

a- The back relief angle decreases
b- The shear angle decreases
c- The rake angle decreases
d- The rake angle increases

4- Toughness of the cutting tool materials in necessary for: A

a- Resisting mechanical shock during cutting
b- Long tool life and wear resistance
c- Resisting high temperatures during cutting
d- Resistance for corrosion during cutting

5- In the cutting process the following variable is an independent variable: B

a- Surface finish dep
b- Type of cutting fluid
c- Type of chip
d- Temperature rise

6- As the shear angle increases:

a- Cutting force increases but power decreases
b- Both cutting force and power increase
c- Both cutting force and power decrease
d- Cutting force decreases but power increases

7- In the cutting process the following variable is a dependent variable:

a- Wear of the tool
b- Tool shape
c- Cutting conditions
d- Fixturing device

8- Serrated chips are also known as

a- Nonhomogeneous chips
b- Discontinuous chips
c- Built up edge
d- Continuous chips

9- The secondary shear zone is located at

a- The interface between the work piece and the flank face
b- The interface between the chip and the rake face
c- The interface between the work piece and the rake face
d- The interface between the chip and the flank face

10- Which of the following is true?

a- The cutting force is normal to the friction force
b- The thrust force acts in the same direction as the shear force
c- The normal force is normal to the cutting force
d- The cutting force is normal to the thrust force

11- If a Tungsten carbide tool is performing well at a certain machine, what would you change in its composition if it is to be used on a machine with less stiffness and damping control?

a- Increase both the carbides and cobalt proportions
b- Increase the carbide proportion only
c- Increase the cobalt proportion only
d- Decrease cobalt proportion only

12- The ratio of the frictional specific energy to the total specific energy is equal to:

a- $F.w/F_c$
b- $F.r/F_c$
c- $F_c/F.t_o$
d- $F/F_c$

13- Which of these variables is likely to increase the temperature most within the cutting zone?

a- The workpiece thermal diffusivity
b- The tool thermal conductivity
c- The workpiece flow stress
d- The depth of cut

14- Which of the following is true?

a- Increasing carbon always improves machinability of steels
b- Increasing carbon always lowers machinability of steels
c- Increasing carbon has no effect on machinability of steels
d- Non of the above



15- In coated tools:

a- The coating and the substrate should have good thermal conductivities
b- The coating and the substrate should have low thermal conductivities
c- The coating should have good thermal conductivity but the substrate should have low thermal conductivity
d- The coating should have low thermal conductivity but the substrate should have good thermal conductivity

16- In which of the following situations cutting fluids may have undesirable effects?

a- In heavy roughing machining
b- In interrupted cutting
c- In high speed continuous cutting
d- In low speed continuous cutting

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**Q- 2 (5 points) answer the following questions**

Two materials (A and B) with characteristics shown below; which of these two materials is likely to develop segmented chips if they have similar thermal conductivities? Why?

| Material | UTS (Room Temp.) | UTS (750 °C) |
|---|---|---|
| A | 600 MPa | 450 MPa |
| B | 750 MPa | 300 MPa |

Material B because the difference of stresses (rate of reduction) with Temp rise is bigger

Material B because the segmented chips loose strength quickly at high temperatures

A: 600 - 450 = 150

B: 750 - 300 = 450

4

Two materials (C and D) with characteristics shown below; which of these two materials is likely to have better surface finish if they are machined using the same cutting tool? Why?

| Material | UTS (Room Temp.) | Strain hardening index (n) |
|---|---|---|
| C | 600 MPa | 0.3 |
| D | 300 MPa | 0.5 |

Material C because of the lower strain hardening ?

shear strain ↑, strain hardening ↑, T ↑, hardness ↑

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

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

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

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

## 8.9 Cutting Processes and Machine Tools for Producing Round Shapes

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

**TABLE 8.7** General characteristics of machining processes.

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

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

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

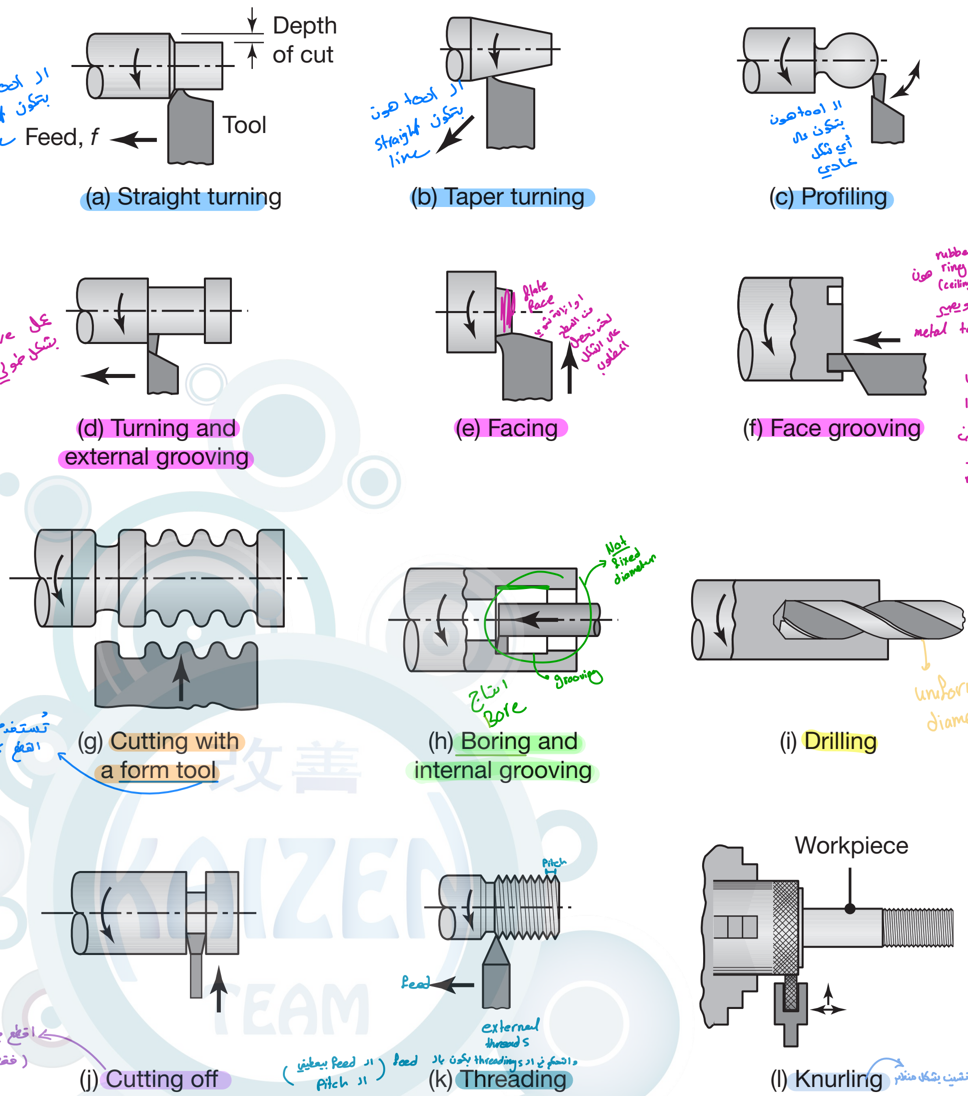



**FIGURE 8.37** Examples of the wide variety of machining operations that can be performed on a lathe and similar machine tools.

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

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

### 8.9.1 Turning Parameters

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

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

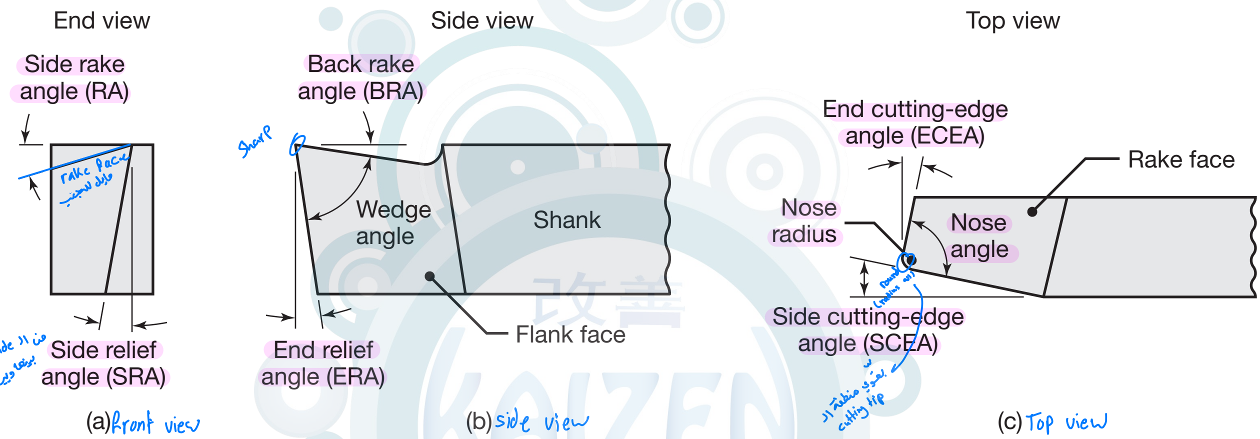



**FIGURE 8.38** Designations and symbols for a right-hand cutting tool. The designation "right hand" means that the tool travels from right to left, as shown in Fig. 8.19.

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

| Material | High-speed steel | | | | | Carbide inserts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Back rake | Side rake | End relief | Side relief | Side and end cutting edge | Back rake | Side rake | End relief | Side relief | Side and end cutting edge |
| Aluminum and magnesium alloys | 20 | 15 | 12 | 10 | 5 | 0 | 5 | 5 | 5 | 15 |
| Copper alloys | 5 | 10 | 8 | 8 | 5 | 0 | 5 | 5 | 5 | 15 |
| Steels | 10 | 12 | 5 | 5 | 15 | –5 | –5 | 5 | 5 | 15 |
| Stainless steels | 5 | 8–10 | 5 | 5 | 15 | –5–0 | –5–5 | 5 | 5 | 15 |
| High-temperature alloys | 0 | 10 | 5 | 5 | 15 | 5 | 0 | 5 | 5 | 45 |
| Refractory alloys | 0 | 20 | 5 | 5 | 5 | 0 | 0 | 5 | 5 | 15 |
| Titanium alloys | 0 | 5 | 5 | 5 | 15 | –5 | –5 | 5 | 5 | 5 |
| Cast irons | 5 | 10 | 5 | 5 | 15 | –5 | –5 | 5 | 5 | 15 |
| Thermoplastics | 0 | 0 | 20–30 | 15–20 | 10 | 0 | 0 | 20–30 | 15–20 | 10 |
| Thermosets | 0 | 0 | 20–30 | 15–20 | 10 | 0 | 15 | 5 | 5 | 15 |

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

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

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

$$\text{MRR} = \pi D_{avg} dfN. \qquad (8.38)$$

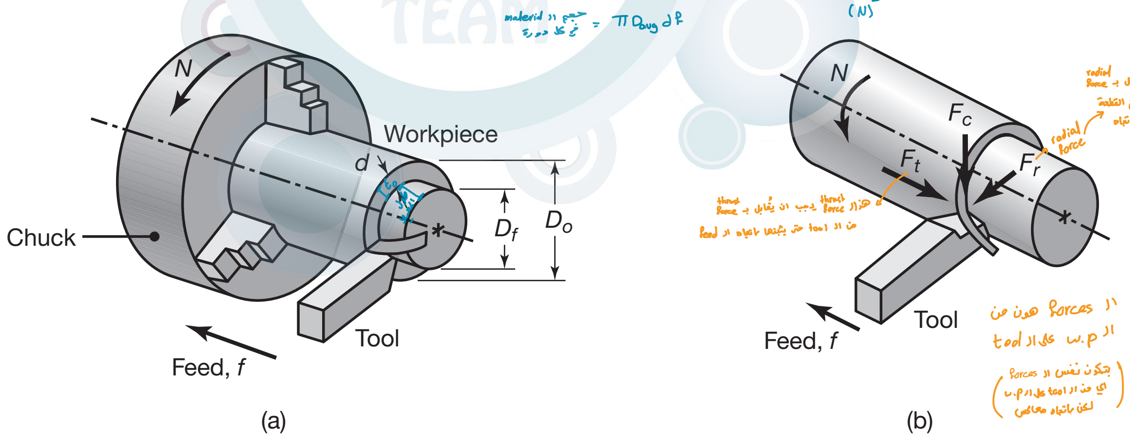



**FIGURE 8.39** (a) Schematic illustration of a turning operation, showing depth of cut, $d$, and feed, $f$. Cutting speed is the surface speed of the workpiece at the tool tip. (b) Forces acting on a cutting tool in turning. $F_c$ is the cutting force; $F_t$ is the thrust or feed force (in the direction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

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

$$t = \frac{l}{fN}. \quad (8.39)$$

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

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

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

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

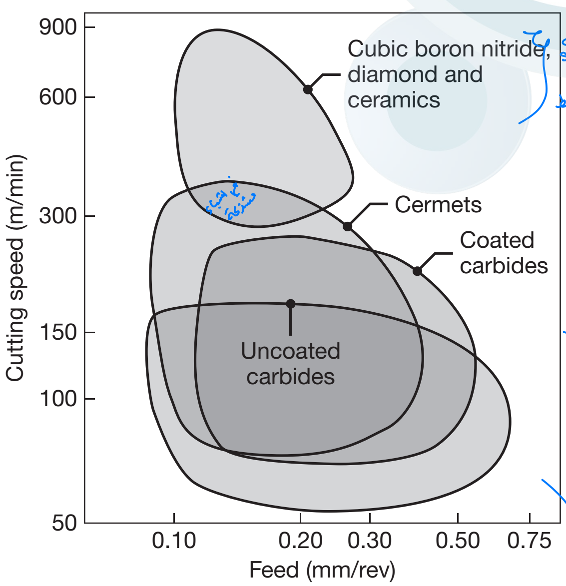



**FIGURE 8.40** The range of applicable cutting speeds and feeds for a variety of cutting-tool materials.

**TABLE 8.9** Approximate ranges of recommended cutting speeds for turning operations.

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

*Note:* (a) The speeds given in this table are for carbides and ceramic cutting tools. Speeds for high-speed steel tools are lower than indicated. The higher ranges are for coated carbides and cermets. Speeds for diamond tools are significantly higher than any of the values indicated in the table.
(b) Depths of cut, $d$, are generally in the range of 0.5–12 mm.
(c) Feeds, $f$, are generally in the range of 0.15–1 mm/rev.

gives a broad range of cutting speeds and feeds applicable for these tool materials. Specific recommendations for cutting speeds for turning various workpiece materials and for cutting tools are given in Table 8.9.

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

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

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

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

$$V = \pi D_o N.$$

Thus,

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

The cutting speed at the machined diameter is

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

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

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

and the feed is

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

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

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

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

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

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

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

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

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

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

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

## 8.9.2 Lathes and Lathe Operations

Lathes are generally considered to be the oldest machine tools. Although woodworking lathes were first developed during the period 1000–1 B.C., metalworking lathes, with lead screws, were not built until the late 1700s. The most common type of lathe, shown in Fig. 8.41, was originally called an **engine lathe**, because it was powered with overhead pulleys and belts from nearby engines.

1. **Lathe components.** Lathes are typically equipped with a variety of components and accessories, as shown in Fig. 8.41. The *bed* supports all the other major components of the lathe. The *carriage*, or *carriage assembly*, which slides along the *ways*, consists of an assembly of the *cross slide*, *tool post*, and *apron*. The cutting tool is mounted on the *tool post*, usually with a *compound rest* that swivels to allow for tool positioning and adjustments. The *headstock*, which is fixed to the bed, is equipped with motors, pulleys, and V-belts that supply power to the *spindle* at various rotational speeds. Headstocks have a hollow spindle to which workholding devices, such as *chucks* and *collets*,

**QR Code 8.1** Turning and profiling on a turning center. *Source:* Courtesy of Haas Automation, Inc.

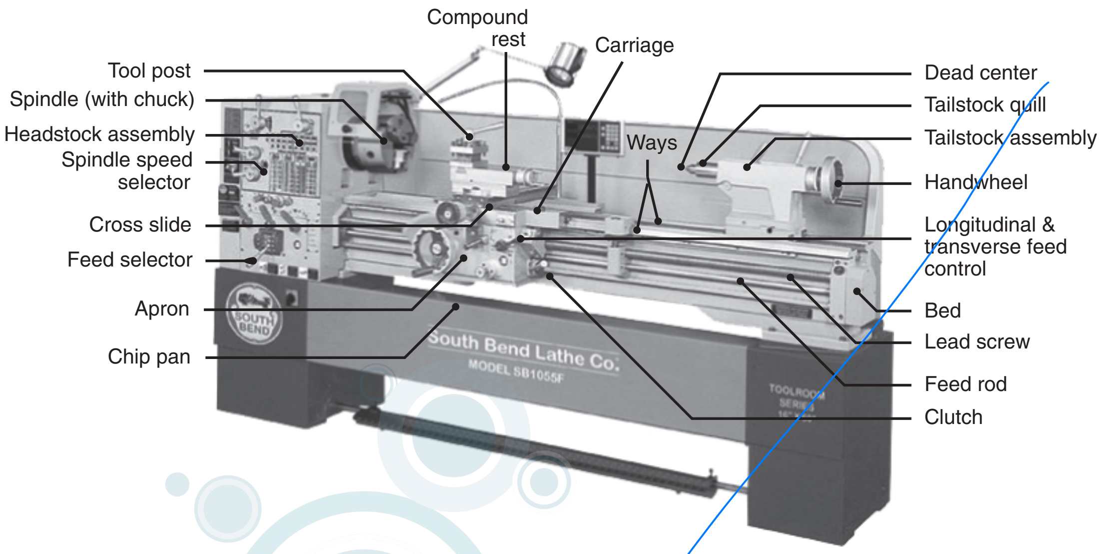



**FIGURE 8.41** General view of a typical lathe, showing various components. *Source:* Courtesy of South Bend Lathe Co.

are attached. The *tailstock*, which can slide along the ways and be clamped at any position, supports the opposite end of the workpiece. The *feed rod*, which is powered by a set of gears from the headstock, rotates during operation of the lathe and provides movement to the carriage and the cross slide. The *lead screw*, which is used for accurately cutting threads, is engaged with the carriage by closing a split nut around the lead screw.

A lathe is generally specified by (a) its *swing* (the maximum diameter of the workpiece that can be machined); (b) the maximum distance between the headstock and tailstock centers; and (c) the length of the bed. The wide variety of lathes include *bench lathes, toolroom lathes, engine lathes, gap lathes,* and *special-purpose lathes*.

*Tracer lathes*, also called *duplicating lathes* or *contouring lathes*, are capable of turning parts to various contours, where the cutting tool follows a path that duplicates the contour of a template. *Automatic lathes*, also called *chucking machines* or *chuckers*, are used for machining individual pieces of regular or irregular shapes. *Turret lathes* are capable of performing multiple machining operations on the same workpiece, such as turning, boring, drilling, thread cutting, and facing. Several cutting tools can be mounted on the hexagonal *main turret*. The lathe usually also has a *square turret* on the cross slide, with as many as four cutting tools mounted on it.

2. **Computer-controlled lathes.** In modern lathes, the movement and control of the machine tool and its components are accomplished by **computer numerical controls** (CNCs); the features of such a lathe are shown in Fig. 8.42. These lathes are typically equipped with one or more turrets; each turret is equipped with a variety of cutting tools and performs several operations on different surfaces of the

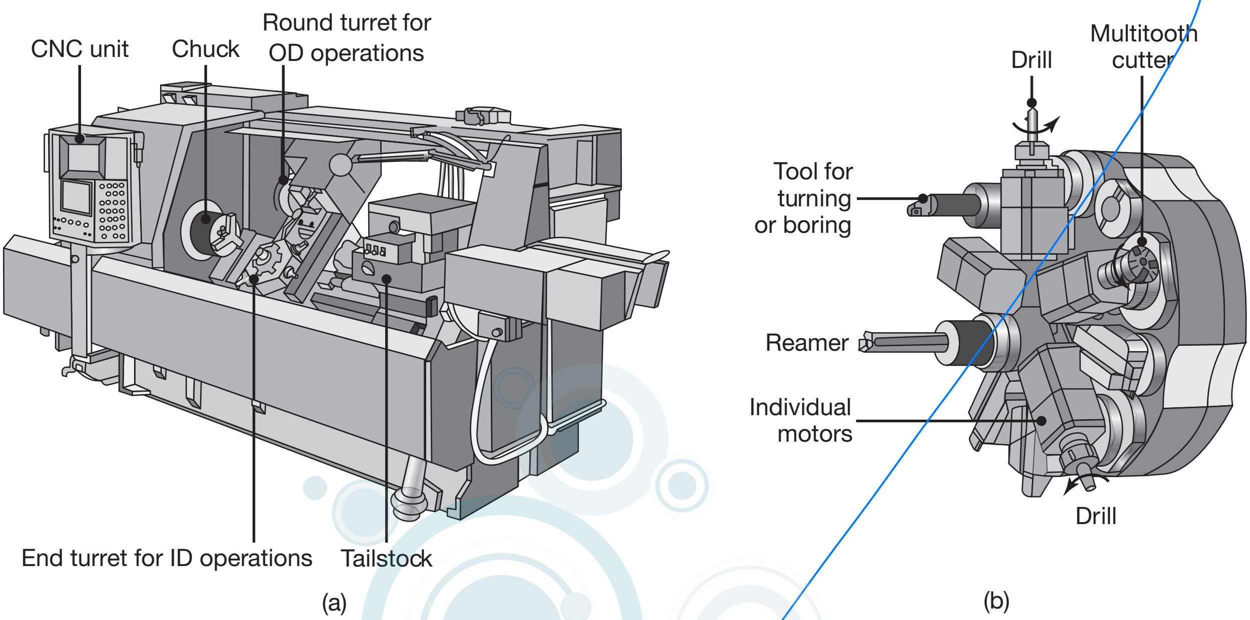



**FIGURE 8.42** (a) A computer-numerical-control lathe, with two turrets; these machines have higher power and spindle speed than other lathes in order to take advantage of advanced cutting tools with enhanced properties; (b) a typical turret equipped with 10 cutting tools, some of which are powered.

workpiece. These machine tools are highly automated, the operations are repetitive, they maintain the desired dimensional accuracy, and, once the machine is set up, less skilled labor is required than with common lathes. These lathes are suitable for low to medium volumes of production. Details of the controls are given in Chapters 14 and 15.

## EXAMPLE 8.5 Typical Parts Made on CNC Turning Machine Tools

Figure 8.43 illustrates the capabilities of CNC turning machine tools. Workpiece materials, the number of cutting tools used, and machining times are indicated for each part. These parts also can be made on manual or turret lathes, but with more difficulty, higher cost, and less consistency.

*Source:* Monarch Machine Tool Company.

3. **Turning process capabilities.** Table 8.10 lists relative *production rates* for turning, as well as for other machining operations described in the rest of this chapter. These rates have an important bearing on productivity in machining operations; note that there is a wide range in the production rates of these processes. The differences are due not only to the inherent characteristics of the processes and machine tools, but also to various other factors, such as setup times and the types and sizes of the workpieces involved. The proper selection of a process and the machine tool for a particular product is important

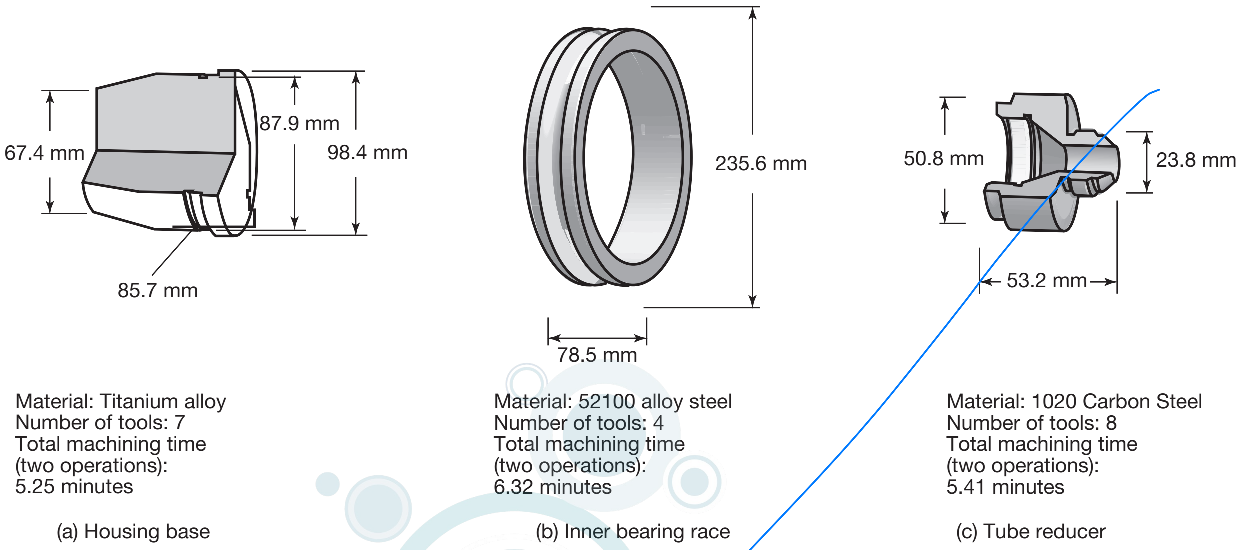



**FIGURE 8.43** Typical parts made on computer-numerical-control machine tools.

**TABLE 8.10** Typical production rates for various cutting operations.

| Operation | Rate |
|---|---|
| Turning | |
| Engine lathe | Very low to low |
| Tracer lathe | Low to medium |
| Turret lathe | Low to medium |
| Computer-control lathe | Low to medium |
| Single-spindle chucker | Medium to high |
| Multiple-spindle chucker | High to very high |
| Boring | Very low |
| Drilling | Low to medium |
| Milling | Low to medium |
| Planing | Very low |
| Gear cutting | Low to medium |
| Broaching | Medium to high |
| Sawing | Very low to low |

*Note:* Production rates indicated are relative: *Very low* is about one or more parts per hour; *medium* is approximately 100 parts per hour; *very high* is 1000 or more parts per hour.

for minimizing production costs, as outlined in Section 8.15 and Chapter 16.

The ratings given in Table 8.10 are relative, and there can be significant variations in specific applications. For example, high-carbon cast-steel rolls (for rolling mills; see Section 6.3) can be machined on special lathes at material-removal rates as high as 6000 $cm^3$/min, using multiple cermet tools. The important factor in this operation (also called **high-removal-rate machining**) is the very high stiffness of the machine tool (to avoid tool breakage due to chatter; see Section 8.12) and its high power, which can be up to 450 kW.

The surface finish and dimensional accuracy obtained in turning and related operations depend on such factors as the characteristics and condition of the machine tool, stiffness, vibration and chatter, processing parameters, tool geometry, tool wear, cutting fluids, machinability of the workpiece material, and operator skill. Consequently, a wide range of surface finishes can be obtained, as shown in Fig. 8.24 (See also Fig. 9.28).

4. **Ultraprecision machining.** There are continued demands for precision manufactured components for computer, electronics, nuclear energy, and defense applications. Examples include optical mirrors and components for optical-systems, with surface finish requirements in the range of tens of nanometers ($10^{-9}$ m or 0.001 $\mu$m) and shape accuracies in the $\mu$m and sub-$\mu$m range. The cutting tool for these *ultraprecision machining* applications is exclusively a single-crystal diamond (hence, the process is also called **diamond turning**), with a polished cutting edge that has a radius as small as a few tens of nanometers; thus, wear of the diamond can be a significant problem.

   The workpiece materials for ultraprecision machining include copper alloys, aluminum alloys, silver, gold, electroless nickel, infrared materials, and plastics (acrylics). The depths of cut involved are in the nanometer range. In this range, hard and brittle materials produce continuous chips (known as **ductile-regime cutting**; see also the discussion of *ductile-regime grinding* in Section 9.5.3); deeper cuts tend to produce discontinuous chips.

   The machine tools for ultraprecision machining are built with very high precision and high machine, spindle, and workholding-device stiffness. These machines, some parts of which are made of structural materials with low thermal expansion and good dimensional stability, are located in a dust-free environment (*clean rooms*) where the temperature is controlled within a fraction of one degree. In **cryogenic diamond turning**, the tooling system is cooled by liquid nitrogen to a temperature of about −120°C (see also Section 8.7.3). Vibrations from external and internal sources must be avoided as much as possible. Feed and position controls are made through laser metrology, and the machines are equipped with highly-advanced computer control systems, which also include thermal and geometric error-compensating features.

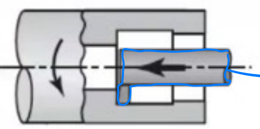
5. **Hard turning.** As described in Chapter 9, there are several other processes, particularly grinding, and nonmechanical methods of removing material economically from hard or hardened metals. However, it is still possible to apply traditional machining processes to hard metals and alloys by selecting an appropriate tool material and a machine tool with high stiffness. One common example is finish machining of heat-treated steel (45 to 65 HRC) machine and automotive

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

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

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

### 8.9.3 Boring and Boring Machines



(h) Boring and internal grooving

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

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

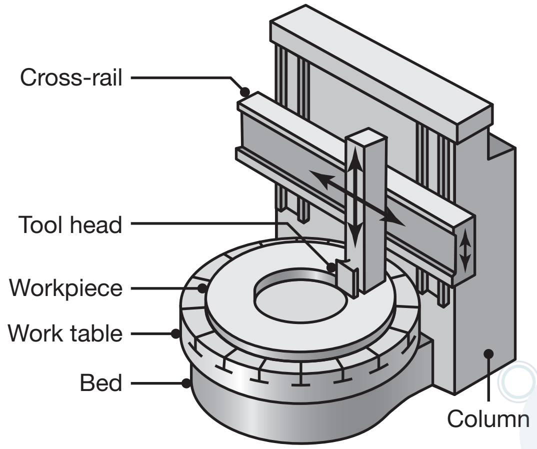



**FIGURE 8.44** Schematic illustration of the components of a vertical boring mill.

### 8.9.4 Drilling, Reaming, and Tapping

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

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

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

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

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

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

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

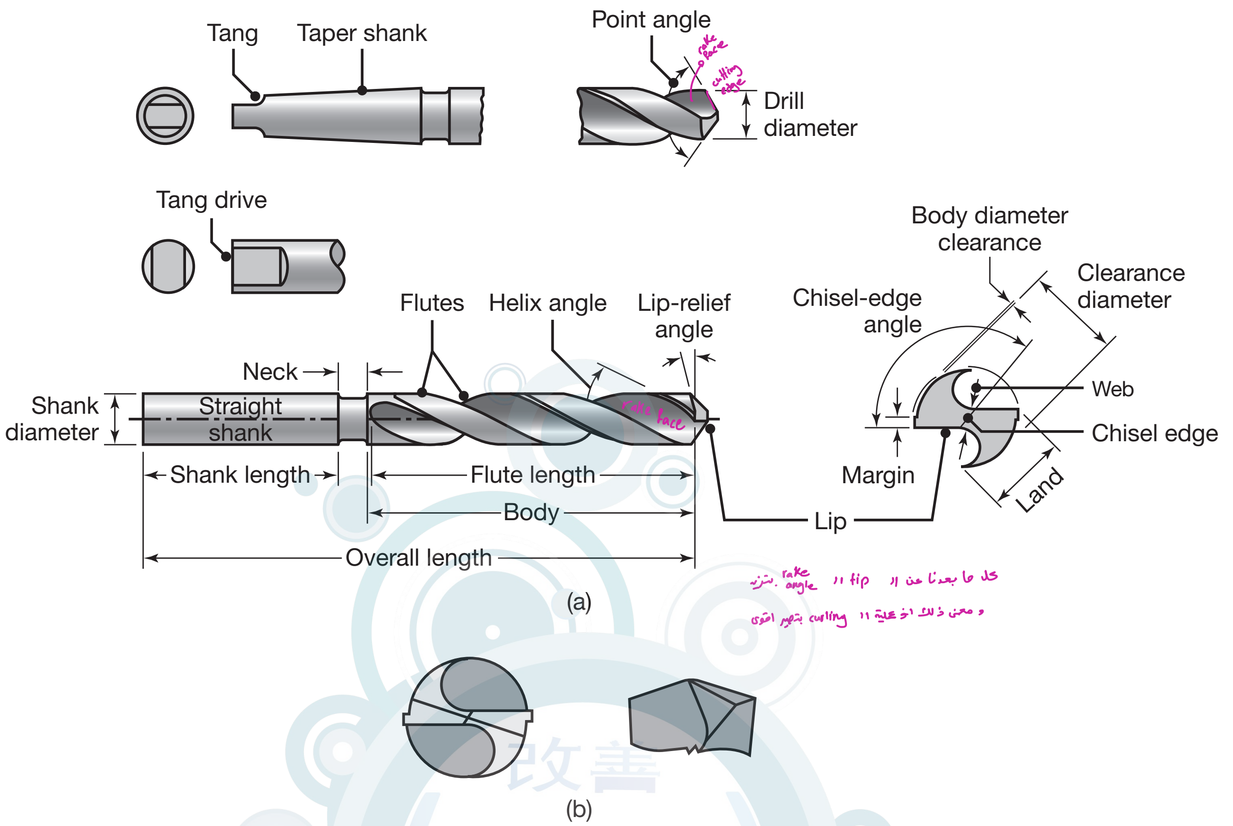



**FIGURE 8.45** Two common types of drills: (a) Chisel-point drill. The function of the pair of margins is to provide a bearing surface for the drill against walls of the hole as it penetrates into the workpiece. Drills with four margins (double-margin) are available for improved drill guidance and accuracy.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

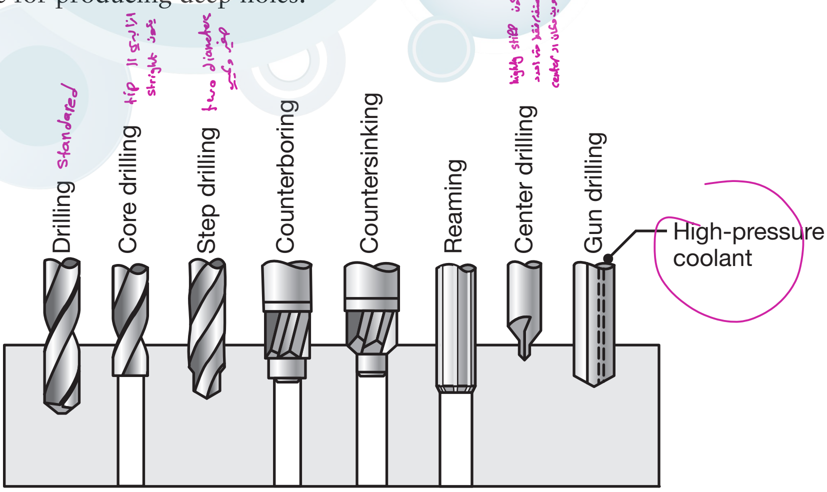



**FIGURE 8.46** Various types of drills and drilling operations.

**TABLE 8.11** General recommendations for speeds and feeds in drilling.

| Workpiece material | Surface speed m/min | Feed, mm/rev drill diameter 1.5 mm | 12.5 mm | Spindle speed (rpm) drill diameter 1.5 mm | 12.5 mm |
|---|---|---|---|---|---|
| Aluminum alloys | 30–120 | 0.025 | 0.30 | 6400–25,000 | 800–3000 |
| Magnesium alloys | 45–120 | 0.025 | 0.30 | 9600–25,000 | 1100–3000 |
| Copper alloys | 15–60 | 0.025 | 0.25 | 3200–12,000 | 400–1500 |
| Steels | 20–30 | 0.025 | 0.30 | 4300–6400 | 500–800 |
| Stainless steels | 10–20 | 0.025 | 0.18 | 2100–4300 | 250–500 |
| Titanium alloys | 6–20 | 0.010 | 0.15 | 1300–4300 | 150–500 |
| Cast irons | 20–60 | 0.025 | 0.30 | 4300–12,000 | 500–1500 |
| Thermoplastics | 30–60 | 0.025 | 0.13 | 6400–12,000 | 800–1500 |
| Thermosets | 20–60 | 0.025 | 0.10 | 4300–12,000 | 500–1500 |

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

force depends on such factors as the strength of the workpiece material, feed, rotational speed, cutting fluids, drill diameter, and drill geometry; thus accurate prediction of the thrust force in drilling has proven to be difficult. Experimental data are available in the technical literature as an aid in the design and use of drills and drilling equipment. Thrust forces in drilling typically range from a few newtons for small drills, to as high as 100 kN in drilling high-strength materials using large drills.

The *torque* during drilling is also difficult to predict accurately, although it can be estimated by using the data in Table 8.3. The power dissipated during drilling is the product of torque and angular velocity. The torque in drilling can range up to 4000 N-m. **Drill life**, as well as tap life, is usually measured by the number of holes drilled before the drill becomes dull and the drilling forces become excessive.

*Drilling machines*, for drilling holes, tapping, reaming, and other general-purpose, small-diameter boring operations, are generally vertical, the most common type being a **drill press**. The workpiece is placed on an adjustable table, and is clamped directly into the slots and holes on the table, or by holding it in a vise that can be clamped to the table. The drill is then lowered, either manually (by using the hand wheel or by power feed) at preset rates. Drill presses are usually designated by the largest workpiece diameter that can be accommodated on the table; sizes typically range from 150 to 1250 mm.

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

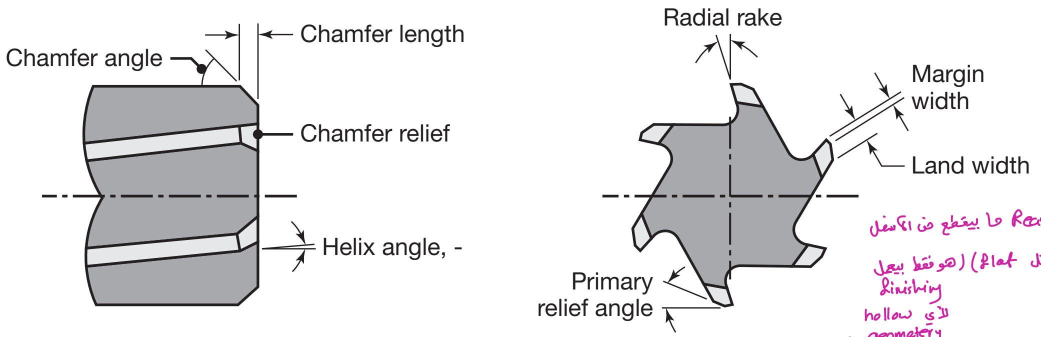



**FIGURE 8.47** Terminology for a helical reamer.

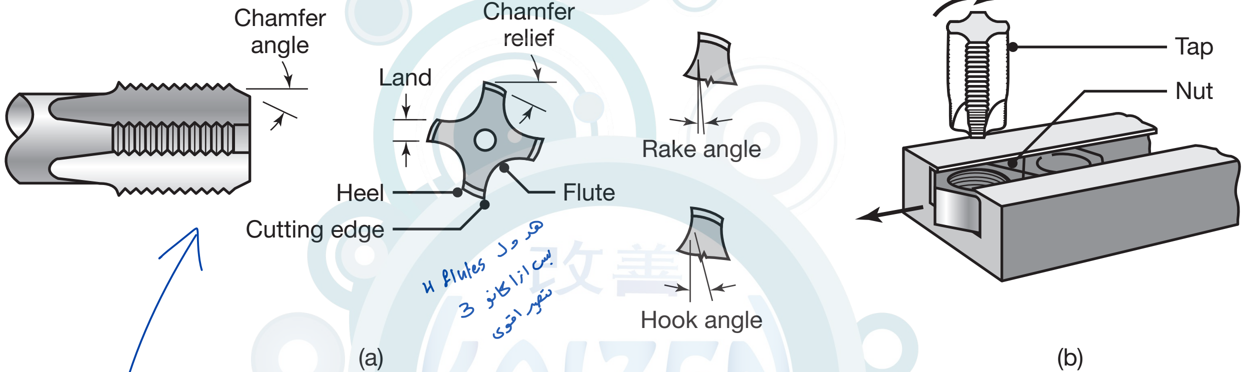



**FIGURE 8.48** (a) Terminology for a tap; (b) illustration of tapping of steel nuts in high production.

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

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

## 8.10 Cutting Processes and Machine Tools for Producing Various Shapes

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

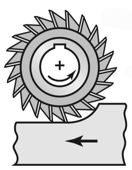
### 8.10.1 Milling Operations

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

The basic types of milling operations are described as follows.

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

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



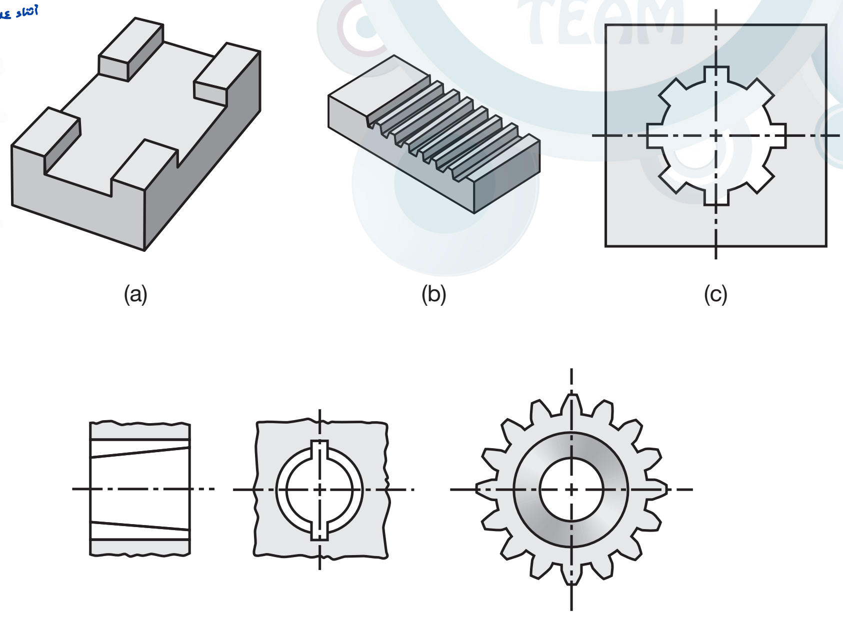




**FIGURE 8.49** Typical parts and shapes produced by the machining processes described in Section 8.10.

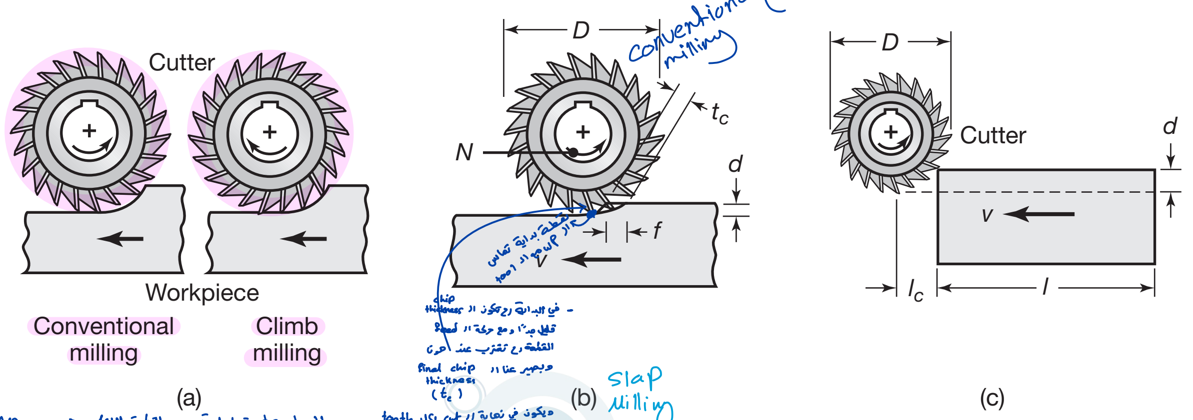
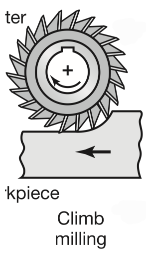



**FIGURE 8.50** (a) Illustration showing the difference between conventional milling and climb milling. (b) Slab-milling operation, showing depth of cut, $d$; feed per tooth, $f$; chip depth of cut, $t_c$ and workpiece speed, $v$. (c) Schematic illustration of cutter travel distance, $l_c$, to reach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

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




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

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

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

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

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

where $f$ is the feed per tooth of the cutter (measured along the workpiece surface, that is, the distance the workpiece travels per tooth of the cutter, in mm/tooth), and $d$ is the depth of cut. With increasing $t_c$, the force on the cutter tooth also increases.

Feed per tooth is determined from the equation

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

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

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

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

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

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

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

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

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

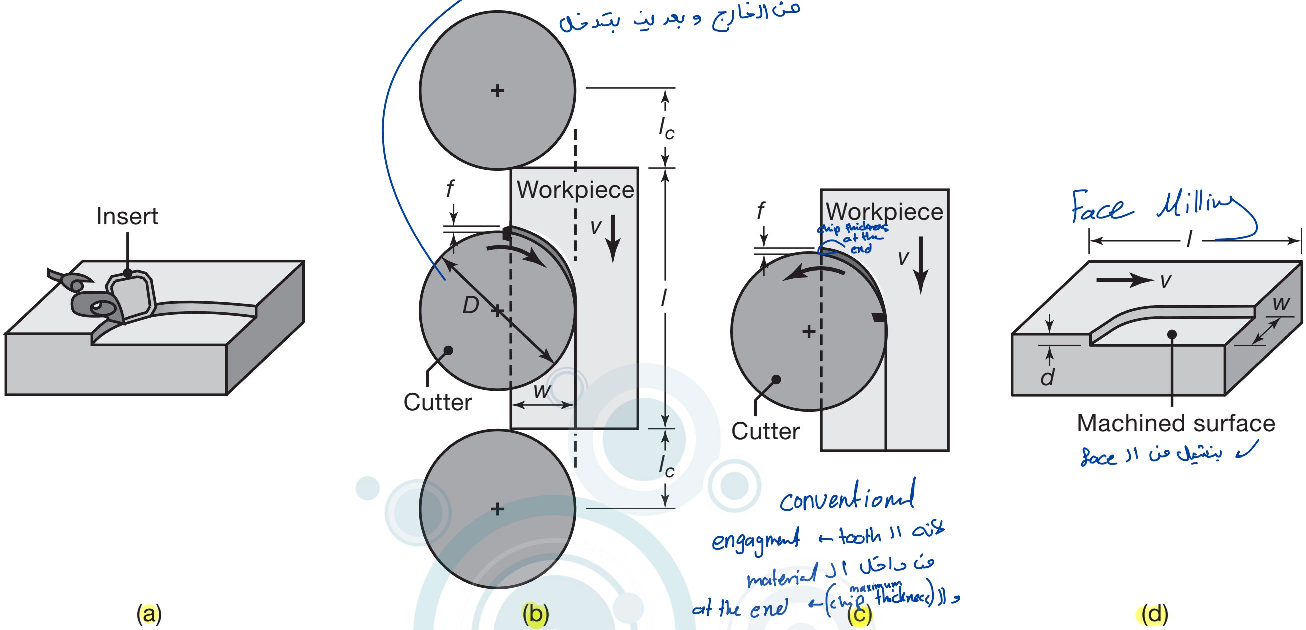



**FIGURE 8.51** Face-milling operation showing (a) action of an insert in face milling with the cutter removed for clarity; (b) climb milling; (c) conventional milling; and (d) dimensions in face milling.

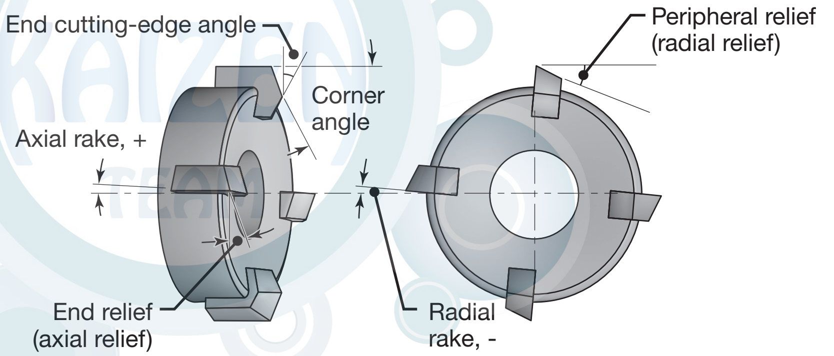



**FIGURE 8.52** Terminology for a face-milling cutter.

for most face-milling cutters is typically from 0° to 45°. The lead angle also influences forces in milling; as the lead angle decreases, the vertical force (axial force on the cutter spindle) decreases.

A wide variety of milling cutters is available. The cutter diameter, $D$, should be chosen so that it will not interfere with fixtures, workholding devices, and other components in the setup of the machine tool. In a typical face-milling operation, the ratio of the cutter diameter to the width of cut should be no less than 3:2. The cutting tools are usually carbide or high-speed steel inserts and are mounted on the cutter body (See Fig. 8.52).

The relationship of cutter diameter and insert angles, and their position relative to the surface to be milled, is important, because

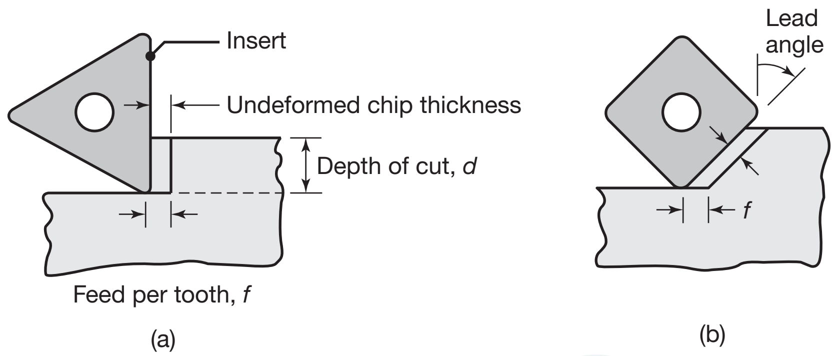



**FIGURE 8.53** The effect of lead angle on the undeformed chip thickness in face milling. Note that as the lead angle increases, the undeformed chip thickness (and hence chip thickness) decreases, and the length of contact (and hence the width of the chip) increases. Note that the insert must be sufficiently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

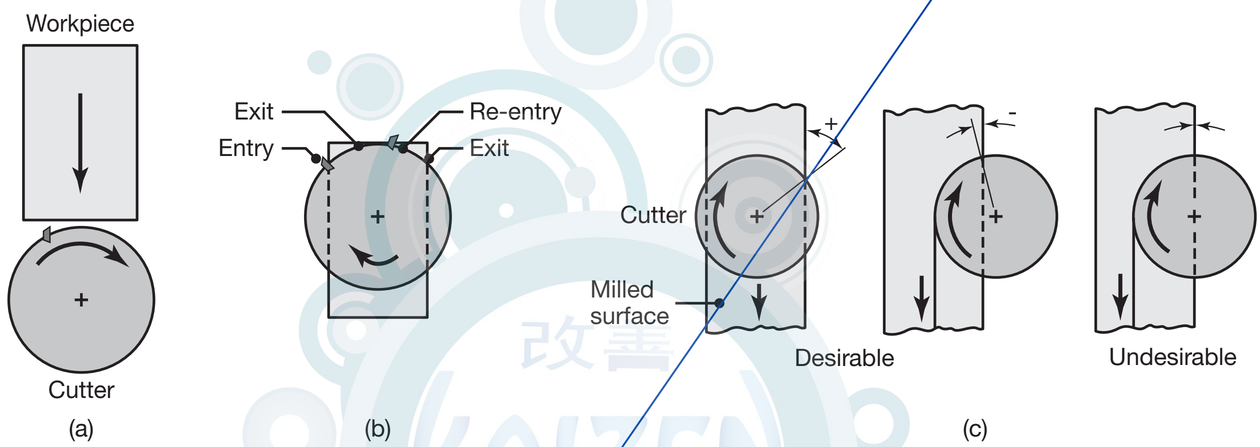



**FIGURE 8.54** (a) Relative position of the cutter and the insert as it first engages the workpiece in face milling; (b) insert positions at entry and exit near the end of cut; and (c) examples of exit angles of the insert, showing desirable (positive or negative angle) and undesirable (zero angle) positions. In all figures, the cutter spindle is perpendicular to the page.

they determine the angle at which an insert enters and exits the workpiece. Note in Fig. 8.51b for climb milling that if the insert has zero axial and radial rake angles (See Fig. 8.52), the rake face of the insert engages the workpiece directly, thus subjecting it to a high impact force. However, as can be seen in Fig. 8.54a and b, the same insert will engage the workpiece at different angles, depending on the relative positions of the cutter and the workpiece. In Fig. 8.54a, the edge of the insert makes the first contact, and hence there is potential for the cutting edge to chip off. In Fig. 8.54b, on the other hand, the contacts (at entry, reentry, and the two exits) are at a certain angle and away from the edge of the insert. As a result, there is less of a tendency for the insert to chip off, because the force on the insert increases and decreases gradually. Note from Fig. 8.52 that the radial and axial rake angles also will affect the tendency for the insert material to chip off.

### EXAMPLE 8.6 Calculation of Material-Removal Rate, Power Required, and Cutting Time in Face Milling

**Given:** Referring to Fig. 8.51, assume that $D = 150$ mm, $w = 60$ mm, $l = 500$ mm, $d = 3$ mm, $v = 0.6$ m/min, and $N = 100$ rpm. The cutter has 10 inserts and the workpiece material is a high-strength aluminum alloy.

**Find:** Calculate the material-removal rate, cutting time, and feed per tooth, and estimate the power required.

**Solution:** The cross section of the cut is $wd = (60)(3) = 180$ mm$^2$. Since the workpiece speed $v$ is 0.6 m/min = 600 mm/min, the material-removal rate is

$$\text{MRR} = (180)(600) = 108{,}000 \text{ mm}^3/\text{min}.$$

The cutting time is given by Eq. (8.44) as

$$t = \frac{l + 2l_c}{v}.$$

Note from Fig. 8.51 that for this problem,

$$l_c^2 + \left(\frac{D}{2} - w\right)^2 = \left(\frac{D}{2}\right)^2,$$

so that $l_c = \sqrt{Dw - w^2}$, or 73.5 mm. Thus, the cutting time is

$$t = \frac{[500 + 2(73.5)](60)}{600} = 64.7 \text{ s} = 1.08 \text{ min}.$$

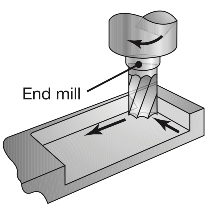
The feed per tooth is obtained from Eq. (8.43). Noting that $N = 100$ rpm $= 1.67$ rev/s,

$$f = \frac{10}{(1.67)(10)} = 0.6 \text{ mm/tooth}.$$

For this material, the unit power can be taken from Table 8.3 to be 1.1 W-s/mm$^3$; hence, the power can be estimated as

$$\text{Power} = (1.1)(1800) = 1980 \text{ W} = 1.98 \text{ kW}.$$

The exit angles for various cutter positions in face milling are shown in Fig. 8.54c. Note that in the first two examples, the insert exits the workpiece at an angle, whereby the force on the insert diminishes to zero at a slower rate (desirable) than in the third example, where the insert exits suddenly (undesirable).



(d) End milling

3. **End milling.** The cutter in *end milling*, shown in Fig. 8.1d, has either a straight or a tapered shank for smaller and larger cutter sizes, respectively. The cutter usually rotates on an axis perpendicular to the workpiece, but it can be tilted to produce inclined surfaces. Some

end mills have cutting teeth on their end faces, allowing the end mill to be used as a drill to start a cavity. End mills are also available with hemispherical ends (called *ball-nose end mills*), for producing curved surfaces, as in making molds and dies. *Hollow end mills* have *internal* cutting teeth and are used for machining the cylindrical surface of solid round workpieces, as in preparing stock with accurate diameters for automatic bar machines.

Section 8.8 described high-speed machining and its typical applications. One of the more common applications is **high-speed milling**, using an end mill and with the same general requirements regarding the stiffness of machines and workholding devices, described in Section 8.12. A typical application is milling aluminum-alloy aerospace components and honeycomb structures (See Fig. 7.47), with spindle speeds on the order of 20,000 rpm. Another application is in *die sinking*, i.e., producing cavities in die blocks. Chip collection and disposal can be a significant problem in these operations, because of the high rate of material removal (see Section 8.8).

4. **Various milling operations and milling cutters.** Several other types of milling operations and cutters are used to machine various surfaces. In *straddle milling*, two or more cutters are mounted on an arbor, and are used to machine two *parallel* surfaces on the workpiece (Fig. 8.55a). *Form milling* is used to produce curved profiles, using cutters with specially shaped teeth (Fig. 8.55b); such cutters are also used for cutting gear teeth (see Section 8.10.7).

   *Circular cutters* are used for slotting and slitting operations. The teeth may be staggered, as in a saw blade (see Section 8.10.5), to provide clearance for the cutter in making deep slots. *Slitting saws* are relatively thin, usually less than 5 mm. *T-slot cutters* are used to mill T-slots, such as those in machine-tool worktables (See Fig. 8.56). The slot is first milled with an end mill; a T-slot cutter then cuts the complete profile of the slot in one pass. *Key-seat cutters* are used

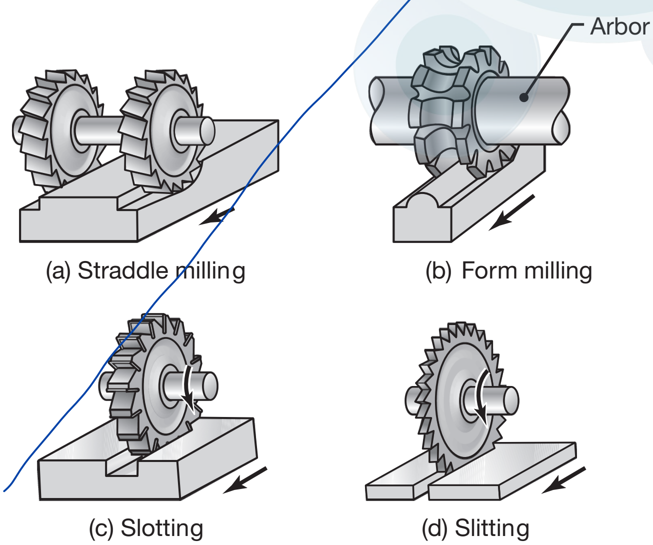



**FIGURE 8.55** Cutters for milling operations.

CHAPTER 9

# Abrasive and Other Material Removal Processes

**This chapter describes the important features of finishing operations, commonly performed to improve dimensional tolerances and surface finish of products. Among the topics covered are:**

- The characteristics of grinding wheels and mechanics of grinding operations.
- Types of grinding machines and advanced abrasive machining processes.
- Abrasive machining operations, including lapping, honing, polishing, chemical mechanical polishing, and the use of coated abrasives.
- Nonmechanical means of material removal, including chemical and electrochemical machining, electrical-discharge machining, laser and electron beam machining, and abrasive jet machining.
- Deburring operations.
- Design and economic considerations for the processes described in this chapter.



## Symbols

| | |
|---|---|
| $A$ | area, $m^2$ |
| $b$ | kerf, m |
| $c_o$ | elastic wave speed, m/s |
| $C$ | cutting points per area, $m^{-2}$; also, electrochemical machining constant, $mm^3$/A-min |
| $d$ | depth of cut, m; also, laser spot diameter, m |
| $d_w$ | wire diameter, m |
| $D$ | diameter, m |
| $D_w$ | workpiece diameter, m |
| $E$ | cell voltage, V |
| $f$ | feed rate, m/min |
| $F$ | force, N; also, Faraday's constant |
| $G$ | grinding ratio; also, mass, g |
| $h$ | thickness, m |
| $I$ | amperage, A |
| $l$ | undeformed chip length, m |
| $L$ | length ground, m |
| $K$ | electrical conductivity, $\Omega^{-1}mm^{-1}$; also, workpiece material factor, $mm^3$/A-min |
| $K_p$ | coefficient of loss |
| $m$ | mass, kg |
| $P$ | power, Nm/s |
| $r$ | ratio of chip width to average chip thickness; also, radius, m |

$R$ ratio of workpiece to electrode wear
$s$ gap, m
$t$ chip thickness, m
also, cutting depth, m
$t_o$ contact time, s
$T_r$ ratio of workpiece to electrode melting temperature
$T_t$ melting point of electrode, °C
$T_w$ melting point of workpiece, °C
$\Delta T$ temperature change, °C
$u$ specific energy, W-s/m$^3$
$v$ velocity, m/s
$V$ grinding speed, m/s
also, voltage, V
$V_f$ wire feed rate, m/s
$V_s$ grinding wheel penetration, m/s
$w$ width of chip, m
$W_t$ electrode wear rate, mm$^3$/min
$\alpha_n$ normal rake angle, deg
also, inclination angle, deg
$\phi$ shear angle, deg
$\eta$ current efficiency
$\rho$ density, kg/m$^3$

### Subscripts

avg average
$c$ cutting
$n$ normal
$o$ original, optimum

## 9.1 Introduction

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

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

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

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

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

## 9.2 Abrasives

The abrasives commonly used in manufacturing are:

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

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

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

**TABLE 9.1** Knoop hardness range for various materials and abrasives.

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

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

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

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

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

## 9.3 Bonded Abrasives

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

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

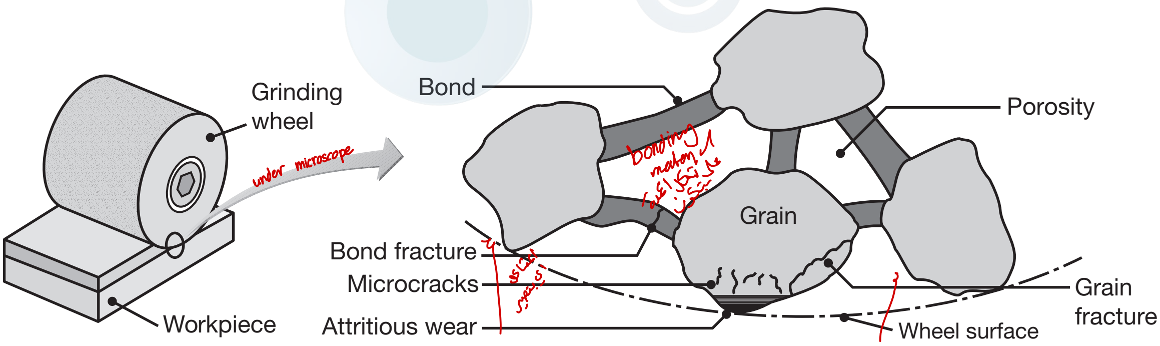



**FIGURE 9.1** Schematic illustration of a physical model of a grinding wheel, showing its structure and grain wear and fracture patterns.

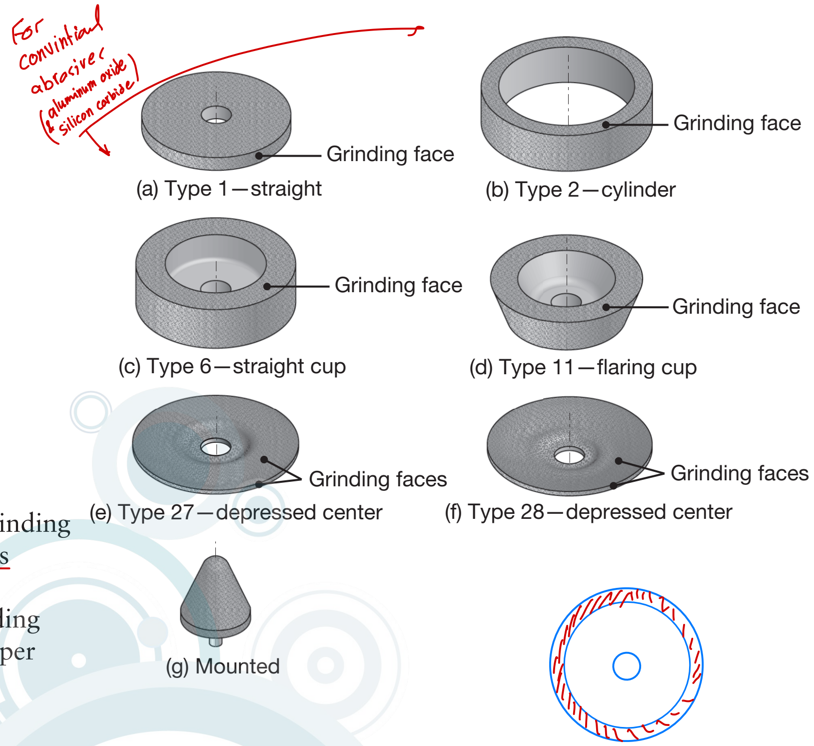



**FIGURE 9.2** Some common types of grinding wheels made with conventional abrasives (aluminum oxide and silicon carbide). Note that each wheel has a specific grinding face; grinding on other surfaces is improper and unsafe.

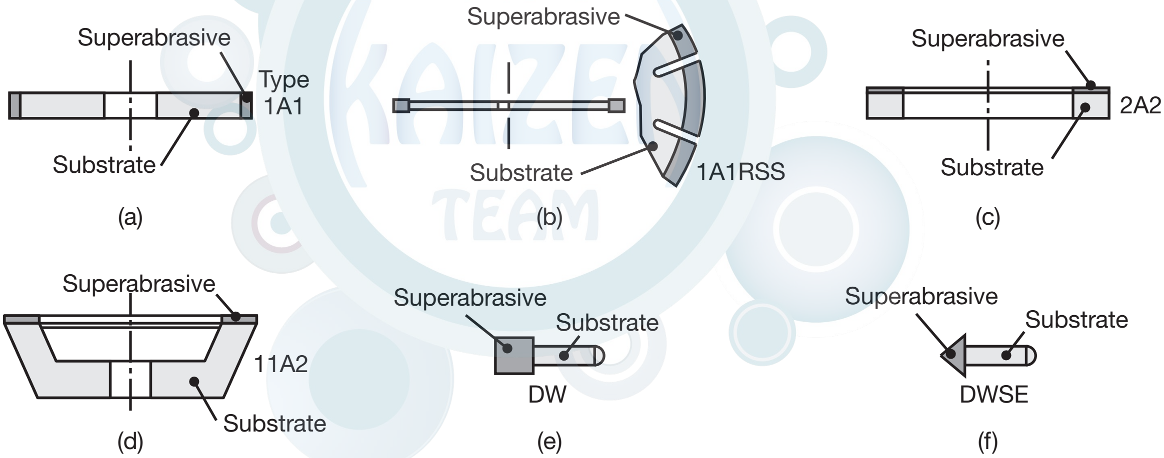



**FIGURE 9.3** Examples of superabrasive wheel configurations. The rim consists of superabrasives and the wheel itself (core) is generally made of metal or composites. Note that the basic numbering of wheel types (such as 1, 2, and 11) is the same as that shown in Fig. 9.2. The bonding materials for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

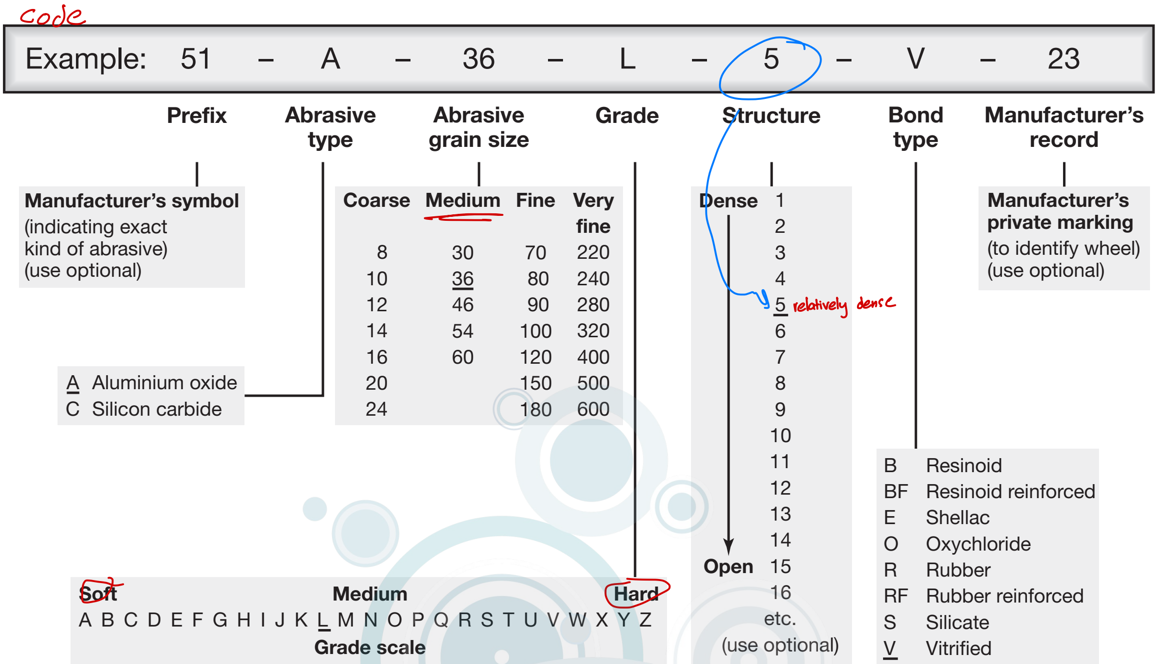



**FIGURE 9.4** Standard marking system for aluminum-oxide and silicon-carbide bonded abrasives.

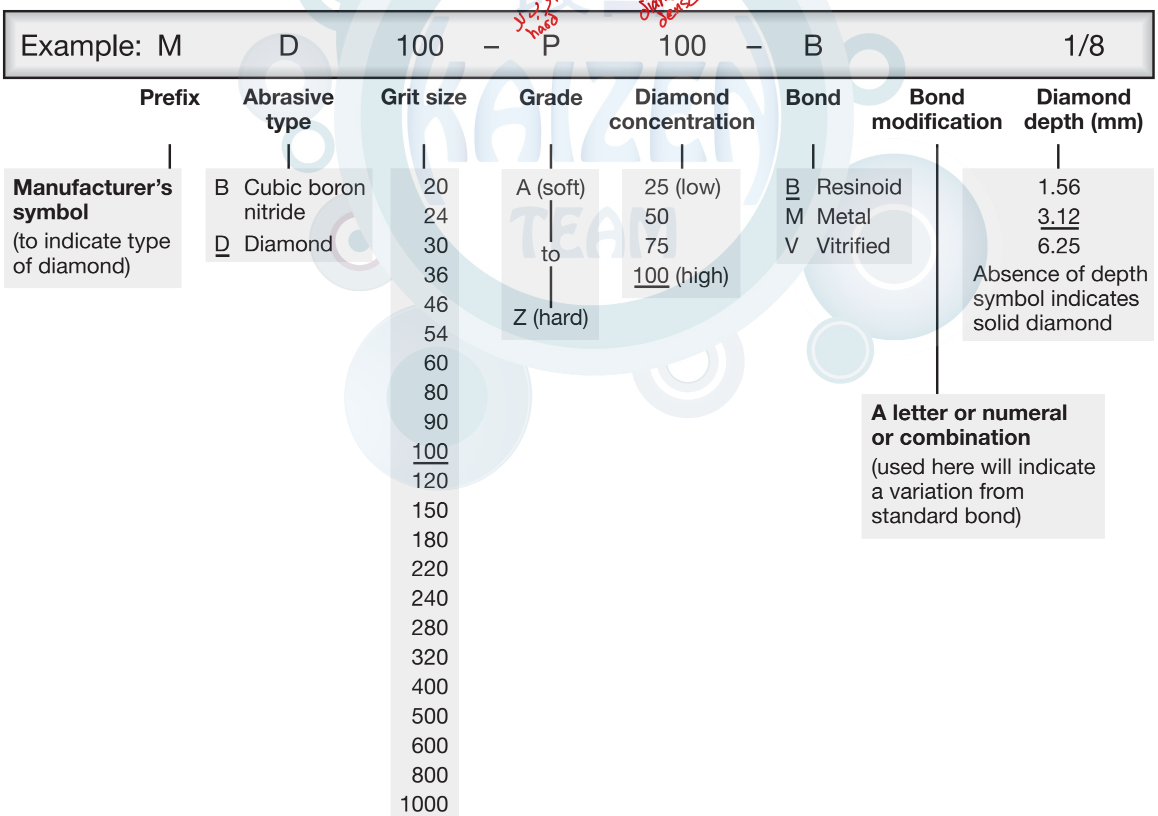


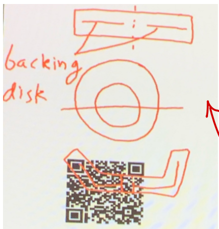

**FIGURE 9.5** Standard marking system for diamond and cubic-boron-nitride bonded abrasives.

### 9.3.1 Bond Types

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

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

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




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

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

**QR Code 9.1** Resin bond grinding wheels. *Source:* Courtesy of Abrasive Technology.

**QR Code 9.2** Resin bond diamond grinding wheels. *Source:* Courtesy of Abrasive Technology.

3. **Rubber.** The most flexible bond used in abrasive wheels is *rubber*. The wheels are made by (a) mixing crude rubber, sulfur, and abrasive grains together; (b) rolling the mixture into sheets; (c) cutting out circles; and (d) heating them under pressure to vulcanize the rubber. Thin wheels (called *cut-off blades*) are made in this manner, and are used like saws for cutting-off operations.
4. **Metal bonds.** Abrasive grains, usually diamond or cubic boron nitride, are bonded in a metal matrix to the periphery of a metal disc, typically to depths of 6 mm or less (See Fig. 9.3). Bonding is carried out under high pressure and temperature. The wheel itself (core)

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

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

### 9.3.2 Wheel Grade and Structure

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



## 9.4 Mechanics of Grinding

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

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

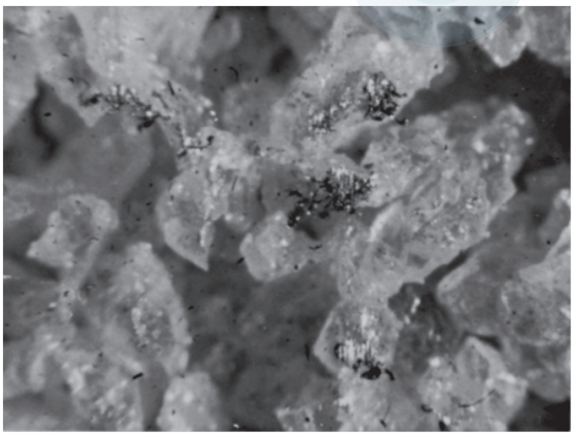


**FIGURE 9.6** The grinding surface of an abrasive wheel (A46-J8V), showing grains, porosity, wear flats on grains (See also Fig. 9.7b), and metal chips from the workpiece adhering to the grains. Note the random distribution and shape of the abrasive grains. Magnification: 50×. *Source:* After S. Kalpakjian.

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

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

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

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

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

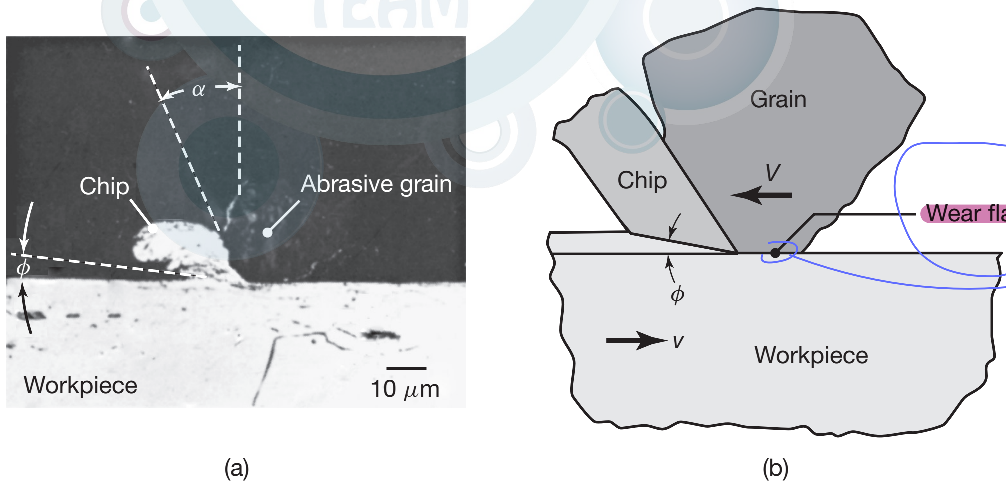



**FIGURE 9.7** (a) Grinding chip being produced by a single abrasive grain. Note the large negative rake angle of the grain. *Source:* After M.E. Merchant. (b) Schematic illustration of chip formation by an abrasive grain. Note the negative rake angle, the small shear angle, and the wear flat on the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

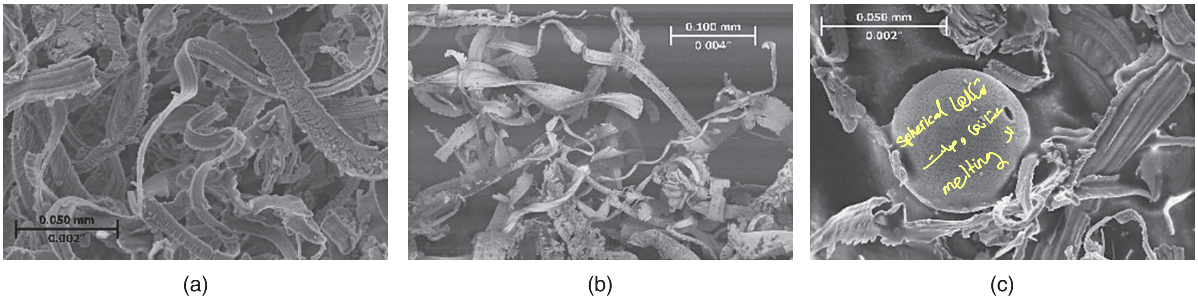



**FIGURE 9.8** Typical chips, or swarf, from grinding operations. (a) Swarf from grinding a conventional HSS drill bit; (b) swarf from a tungsten carbide workpiece using a diamond wheel; and (c) swarf of cast iron, showing a melted globule among the chips. *Source:* Courtesy of J. Badger.

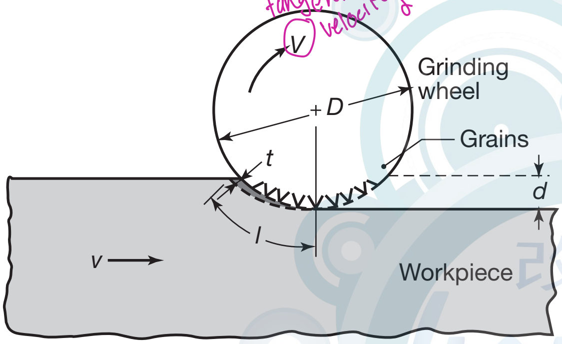



**FIGURE 9.9** Basic variables in surface grinding. In actual grinding operations, the wheel depth of cut, $d$, and contact length, $l$, are much smaller than the wheel diameter, $D$. The dimension $t$ is called the *grain depth of cut*.

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

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

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

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

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

and for *internal grinding*,

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

where $D_w$ is the diameter of the workpiece.

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

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

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

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,

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

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 $\mu$m.

## 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:

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

Therefore,

$$l = \sqrt{(200)(0.05)} = 3.2 \text{ mm},$$

and

$$t = \sqrt{\frac{(4)(0.5)}{(30)(2)(15)}\sqrt{\frac{0.05}{200}}} = 0.006 \text{ mm}.$$

Note that because of plastic deformation, the *actual* length of the chip is shorter and the thickness greater than these values (See Fig. 9.7).

### 9.4.1 Grinding Forces

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

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

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

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 $u_{\text{chip}}$ is the specific energy required for chip formation by plastic deformation; $u_{\text{plowing}}$ is the specific energy required for plowing, which is plastic deformation without chip removal (Fig. 9.10); and the last term, $u_{\text{sliding}}$, 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.

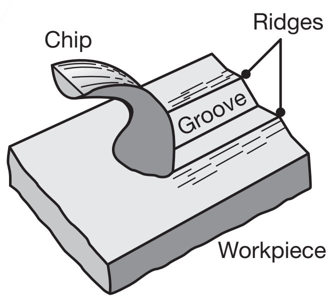



**FIGURE 9.10** Chip formation and plowing (plastic deformation without chip removal) of the workpiece surface by an abrasive grain.

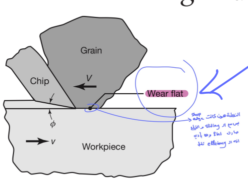


**TABLE 9.3** Approximate specific-energy requirements for surface grinding.

| 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

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

where $T$ is the torque and is equal to $(F_c)(D/2)$,

$$76,875 = (F_c)\left(\frac{0.25}{2}\right)(418.9),$$

and therefore, $F_c = 1468$ N. The thrust force, $F_n$, can then be calculated as

$$F_n = (1.3)(1468) = 1908 \text{ N}.$$

### 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*, $\Delta T$, 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

$$\Delta T \propto \frac{uwLd}{wL} \propto ud. \tag{9.8}$$

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

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

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:

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,

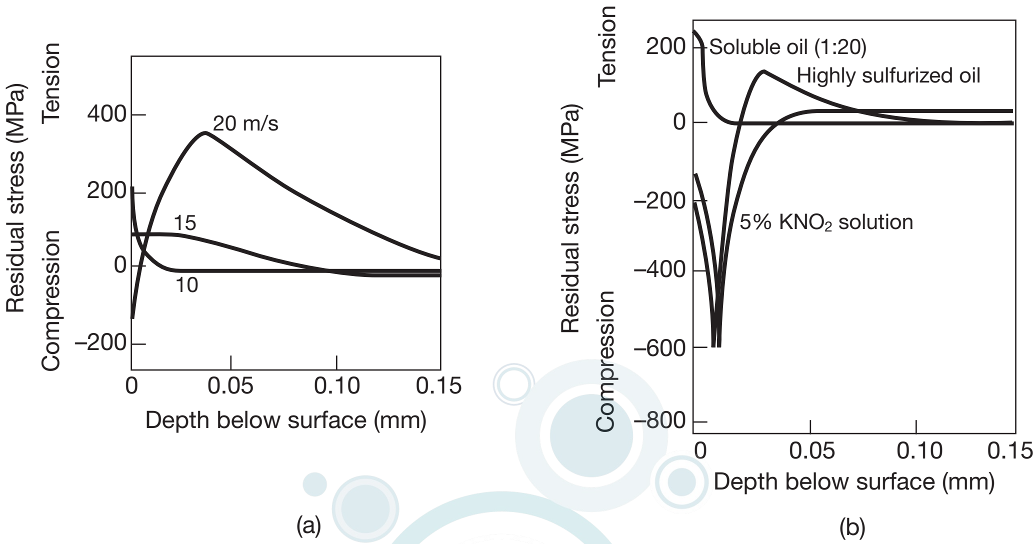



**FIGURE 9.11** Residual stresses developed on the workpiece surface in grinding tungsten: (a) effect of wheel speed and (b) effect of type of grinding fluid. Tensile residual stresses on a surface are detrimental to the fatigue life of ground components. The variables in grinding can be controlled to minimize residual stresses, a process known as *low-stress grinding*. *Source:* After N. Zlatin.

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 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.

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 $\mu$m, but for a cBN wheel, it is 2 to 10 $\mu$m. Modern dressing systems have a resolution as low as 0.25 to 1 $\mu$m.

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

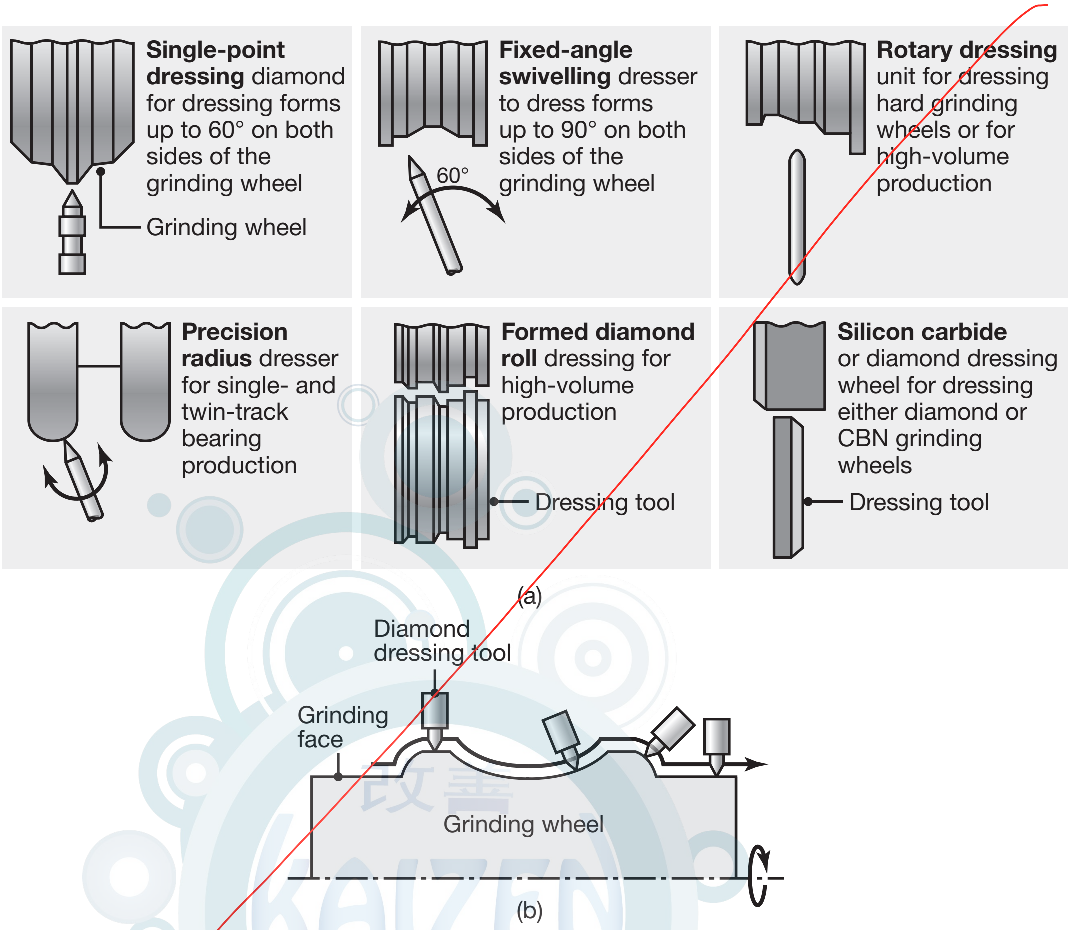



**FIGURE 9.12** (a) Methods of grinding wheel dressing. (b) Shaping the grinding face of a wheel by dressing it with computer-controlled shaping features. Note that the diamond dressing tool is normal to the wheel surface at point of contact. *Source:* OKUMA America Corporation.

### 9.5.2 Grinding Ratio

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

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

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

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

**EXAMPLE 9.3 Action of a Grinding Wheel**

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

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

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

### 9.5.3 Wheel Selection and Grindability of Materials

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

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

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

## 9.6 Grinding Operations and Machines

Grinding operations are typically carried out using a wide variety of wheel-workpiece configurations. The selection of a particular grinding process for a specific application depends on (a) part shape; (b) part size; (c) required tolerances; (d) ease of fixturing, and (e) production rate required. The basic types of grinding operations are surface, cylindrical, internal, and centerless grinding (see below). The movement of the wheel in these operations may be along the surface of the workpiece (*traverse grinding, through feed grinding,* or *cross-feeding*), or it may be radially *into* the workpiece (*plunge grinding*). Surface grinders are the most common machine type, followed by bench grinders (usually with two grinding wheels), cylindrical grinders, and tool grinders. Because grinding wheels are brittle and are operated at high speeds, certain safety procedures must be carefully followed in their handling, storage, and use.

Modern grinding machines are computer controlled, with various features, such as automatic part loading and unloading, clamping, cycling, gaging, dressing, and wheel shaping. Grinders can also be equipped with probes and gages for determining the relative position of the wheel and workpiece surfaces, as well as with tactile sensing features, whereby breakage of the diamond dressing tool, if any, can be detected during the dressing cycle.

### 9.6.1 Surface Grinding

*Surface grinding* is one of the most common grinding operations (Fig. 9.13) and basically involves grinding flat surfaces. Typically, the workpiece is secured on a magnetic chuck mounted on the worktable of a **surface**

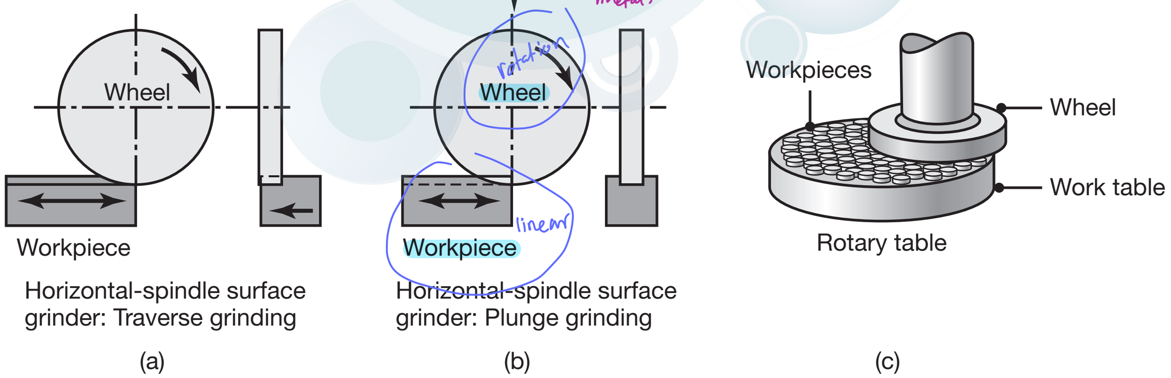



**FIGURE 9.13** Schematic illustrations of surface-grinding operations. (a) Traverse grinding with a horizontal-spindle surface grinder. (b) Plunge grinding with a horizontal-spindle surface grinder, producing a groove in the workpiece. (c) Vertical-spindle rotary-table grinder (also known as the *Blanchard-type* grinder).

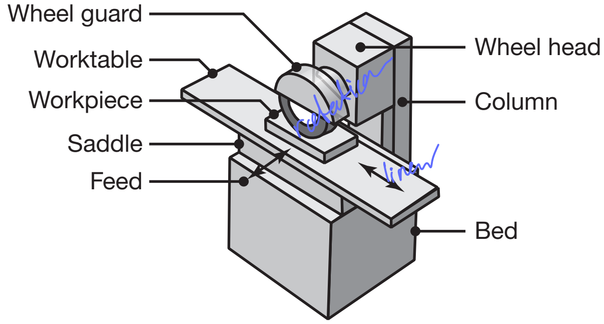



**FIGURE 9.14** Schematic illustration of a horizontal-spindle surface grinder.

**grinder** (Fig. 9.14); nonmagnetic materials generally are held by vises, vacuum chucks, double-sided adhesive tapes, or special fixtures. In this operation, a straight wheel is mounted on the *horizontal spindle* of the grinder; traverse grinding is done as the table reciprocates longitudinally and feeds laterally after each stroke. In *plunge grinding*, the wheel is moved radially into the workpiece, as in grinding a groove illustrated in Fig. 9.13b. The size of a surface grinder is specified by the surface dimensions of length and width that can be ground on the machine. Other types of surface grinders include *vertical spindles* and *rotary tables* (Fig. 9.13c), also called *Blanchard-type* grinders. These configurations allow a number of parts to be ground in one setup, thus improving productivity.

### 9.6.2 Cylindrical Grinding

In *cylindrical grinding*, also called *center-type grinding*, the external cylindrical surfaces and shoulders of the workpiece are ground, such as crankshaft bearings, spindles, pins, bearing rings, and rolls for rolling mills. The rotating cylindrical workpiece reciprocates laterally along its axis, although in grinders used for large and long workpieces, the grinding wheel reciprocates. The latter design is called a *roll grinder* and is capable of grinding rolls as large as 2 m in diameter, used for metal rolling operations (See Fig. 6.29).

The workpiece in cylindrical grinding is held between *centers*, held in a chuck, or mounted on a faceplate in the headstock of the grinder. For straight cylindrical surfaces, the axes of rotation of the wheel and workpiece are parallel; separate motors drive the wheel and workpiece at different speeds. Long workpieces with two or more diameters are ground on cylindrical grinders. Cylindrical grinding also can produce shapes in which the wheel is dressed to the form to be ground on the workpiece, called *form grinding* or *plunge grinding*. Cylindrical grinders are specified by the maximum diameter and length of the workpiece that can be ground, similar to lathes (Section 8.9.2).

In *universal grinders*, both the workpiece and the wheel axes can be moved and swiveled around a horizontal plane, thus permitting the grinding of tapers and other shapes. Cylindrical grinders can also be equipped with computer control, so that *noncylindrical* parts (such as cams) can be ground on rotating workpieces. The workpiece spindle speed is synchronized with the grinding wheel position such that the distance between the

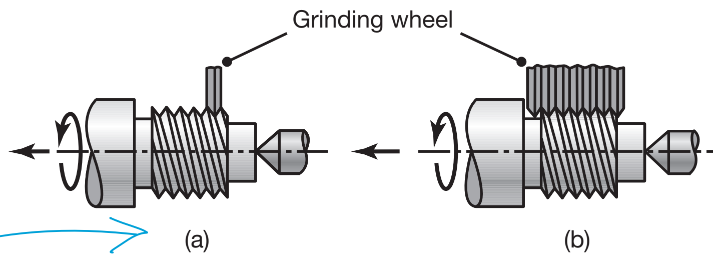



**FIGURE 9.15** Threads produced by (a) traverse and (b) plunge grinding.

workpiece and wheel axes is varied continuously to produce a particular shape.

**Thread grinding** is done on cylindrical grinders, as well as on centerless grinders (Section 9.6.4), with specially dressed wheels that match the shape of the threads (Fig. 9.15). The workpiece and wheel movements are synchronized to produce the proper pitch of the thread, usually in about six passes. Although this operation is costly, it produces more accurate threads than any other manufacturing process, and the threads have a very fine surface finish.

### 9.6.3 Internal Grinding

In *internal grinding* (Fig. 9.16), a small wheel is used to grind the inside diameter of axisymmetric parts, such as bushings and bearing races. The workpiece is held in a rotating chuck, and the wheel rotates at 30,000 rpm or higher. Internal profiles also can be ground with profile-dressed wheels that move radially into the workpiece. The headstock of internal grinders can be swiveled on a horizontal plane to grind tapered holes.

### 9.6.4 Centerless Grinding

*Centerless grinding* is a high-production process for continuously grinding cylindrical surfaces, where the workpiece is supported not by centers (hence the term *centerless*) but by a blade, as shown in Fig. 9.17. Typical parts that are centerless ground include cylindrical roller bearings, piston pins, engine valves, camshafts, and similar components. Parts with diameters as small as 0.1 mm can be ground using this process. Centerless

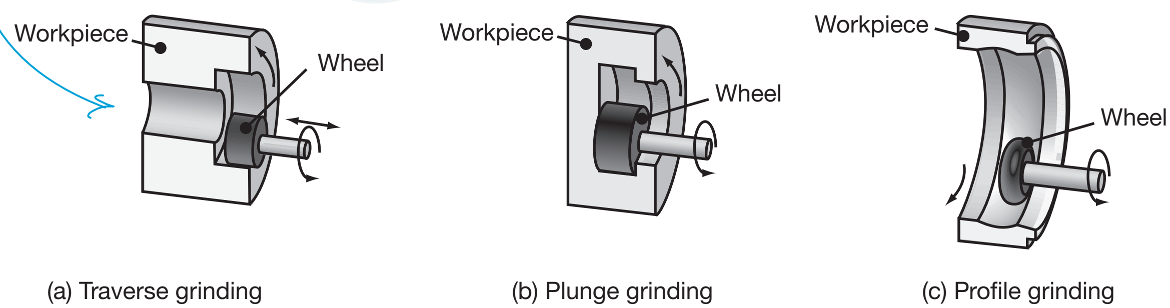



**FIGURE 9.16** Schematic illustrations of internal-grinding operations.