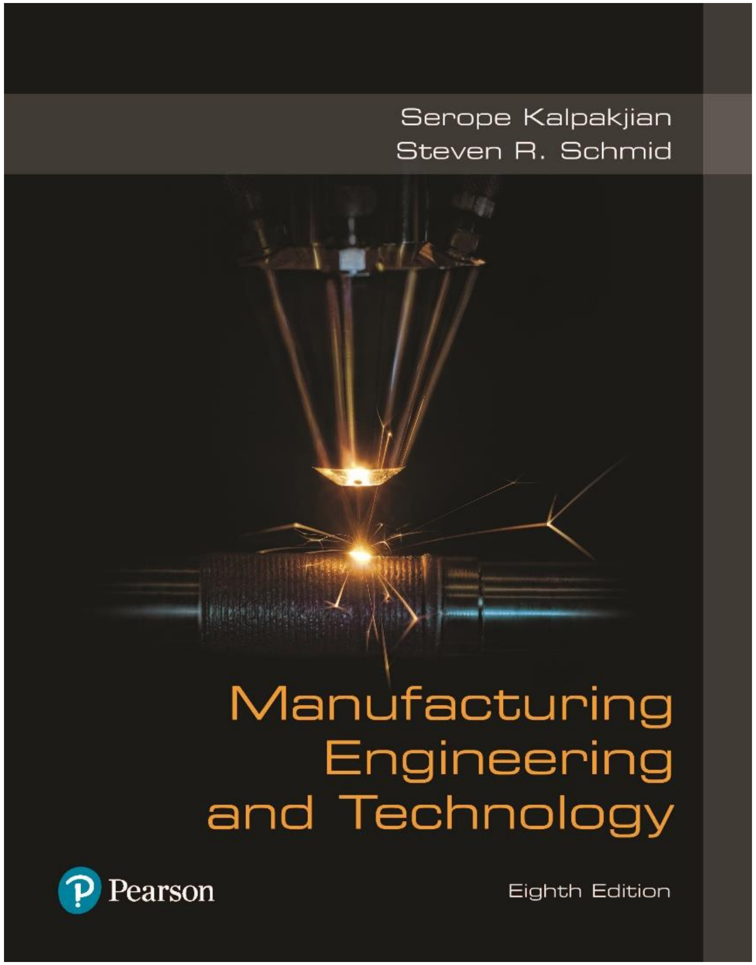
Manufacturing Engineering and Technology

Eighth Edition



Chapter 21-25

Machining

Pearson

Figure 21.1

Some examples of common machining operations.

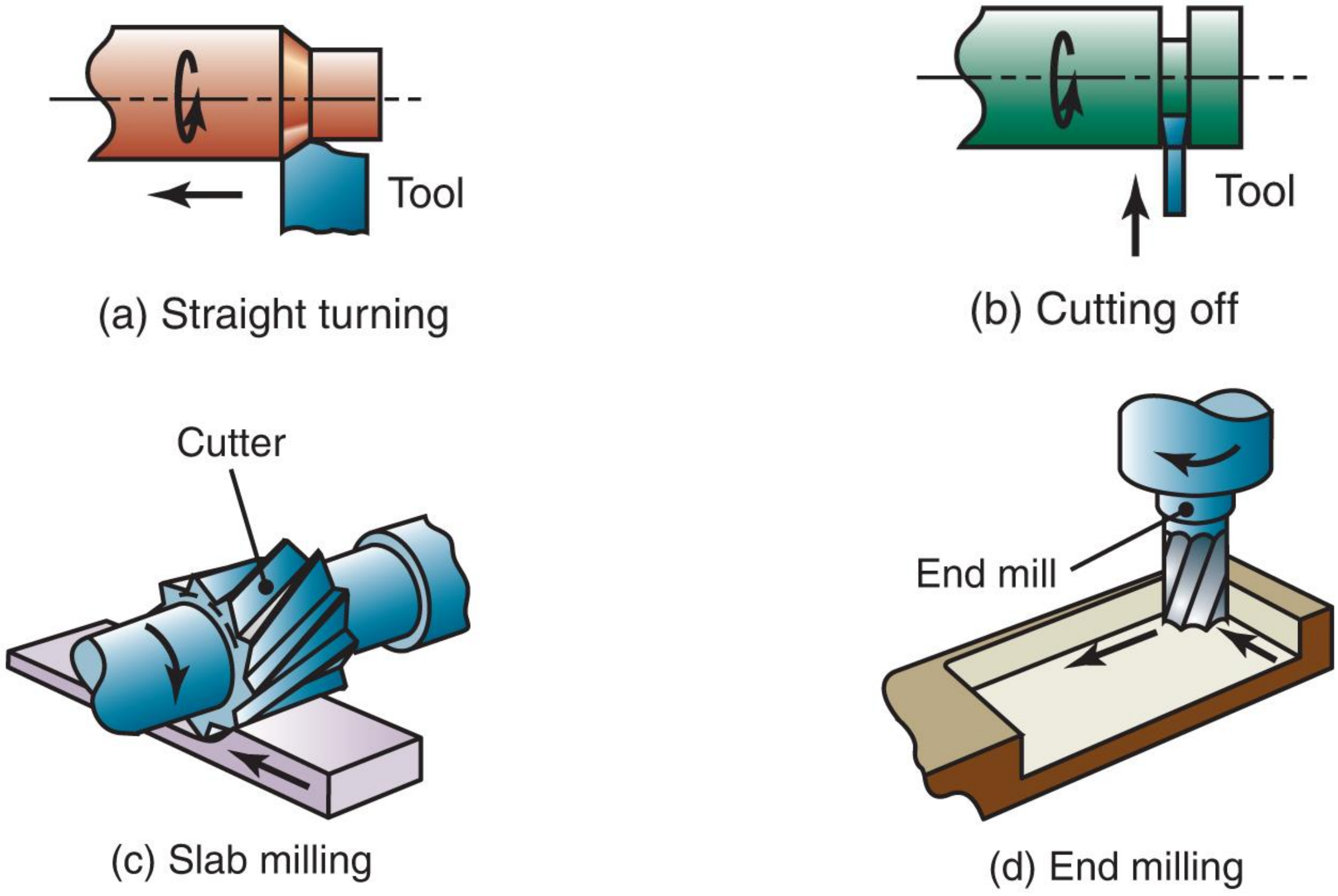


Figure 21.2

Schematic illustration of the turning operation, showing various features.

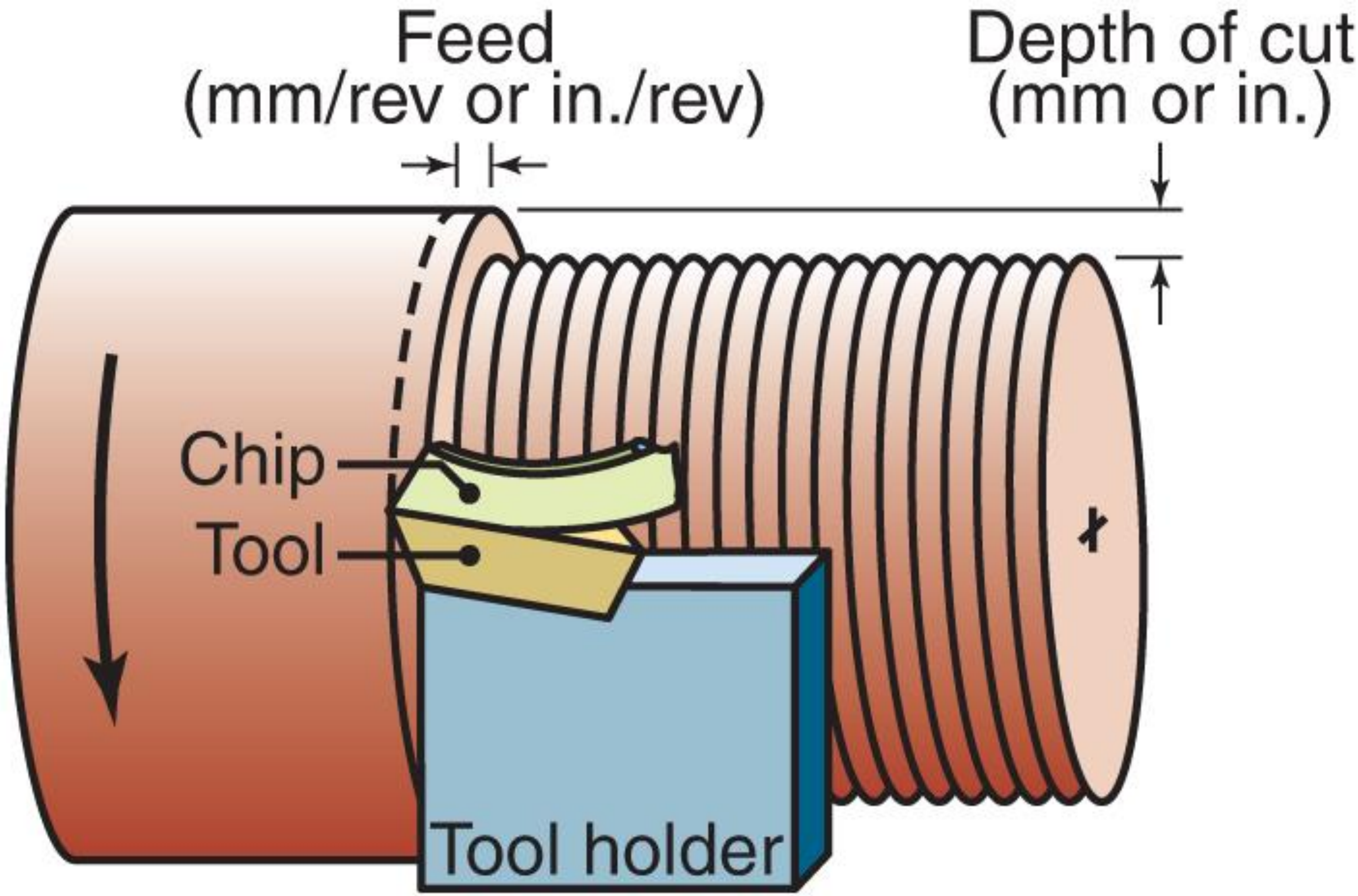
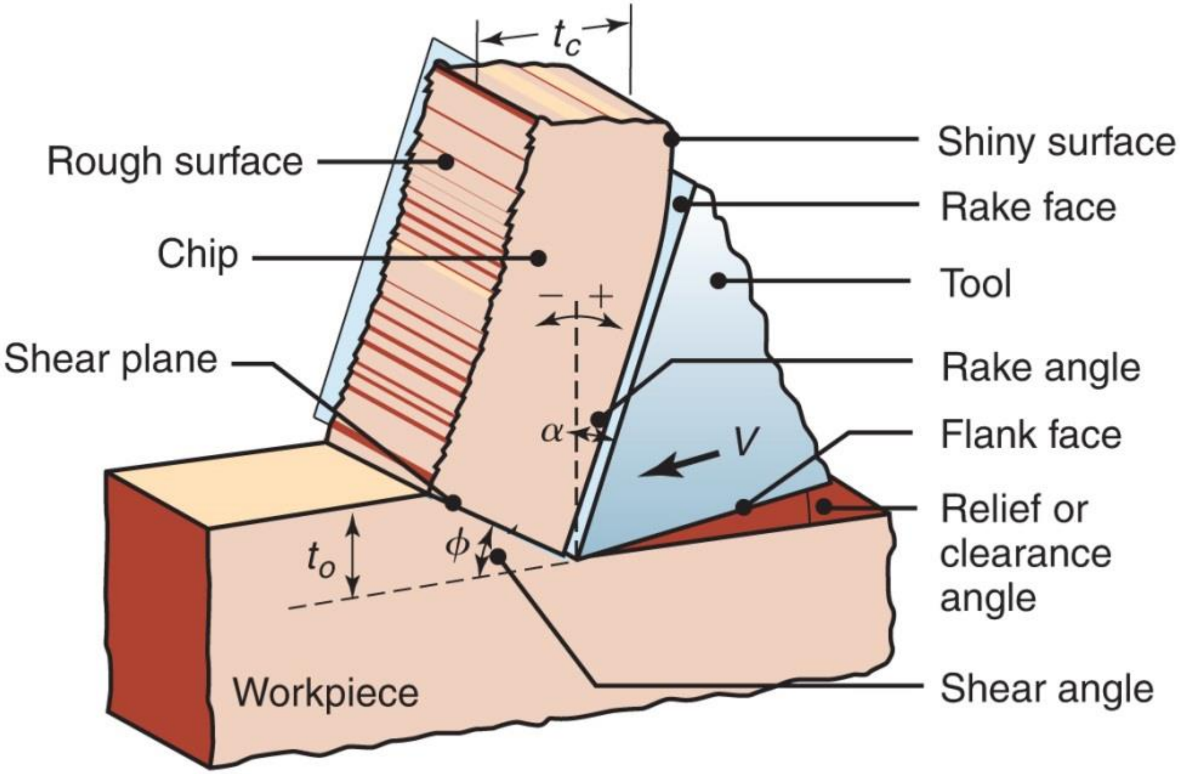


Figure 21.3 (1 of 2)

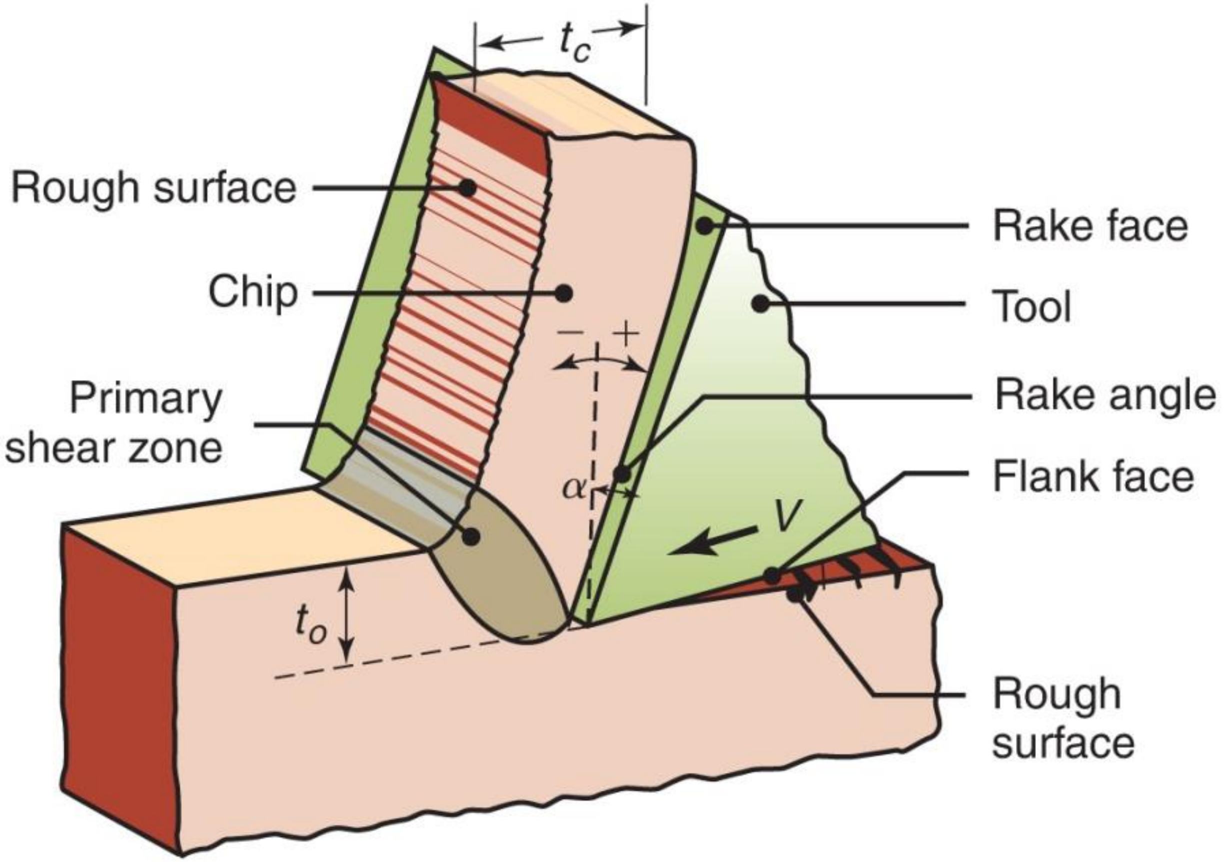
Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting: (a) Orthogonal cutting with a well-defined shear plane, also known as the M.E. Merchant model. Note that the tool shape, the depth of cut, t_o, and the cutting speed, V, are all independent variables.



(a)

Figure 21.3 (2 of 2)

Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting:
(b) Orthogonal cutting without a well-defined shear plane.



(b)

Figure 21.5

Basic types of chips produced in orthogonal metal cutting, their schematic representation, and photomicrographs of the cutting zone: (a) continuous chip, with narrow, straight, and primary shear zone, (b) continuous chip, with secondary shear zone at the chip–tool interface, (c) built-up edge, (d) segmented or nonhomogeneous chip, and (e) discontinuous chip.

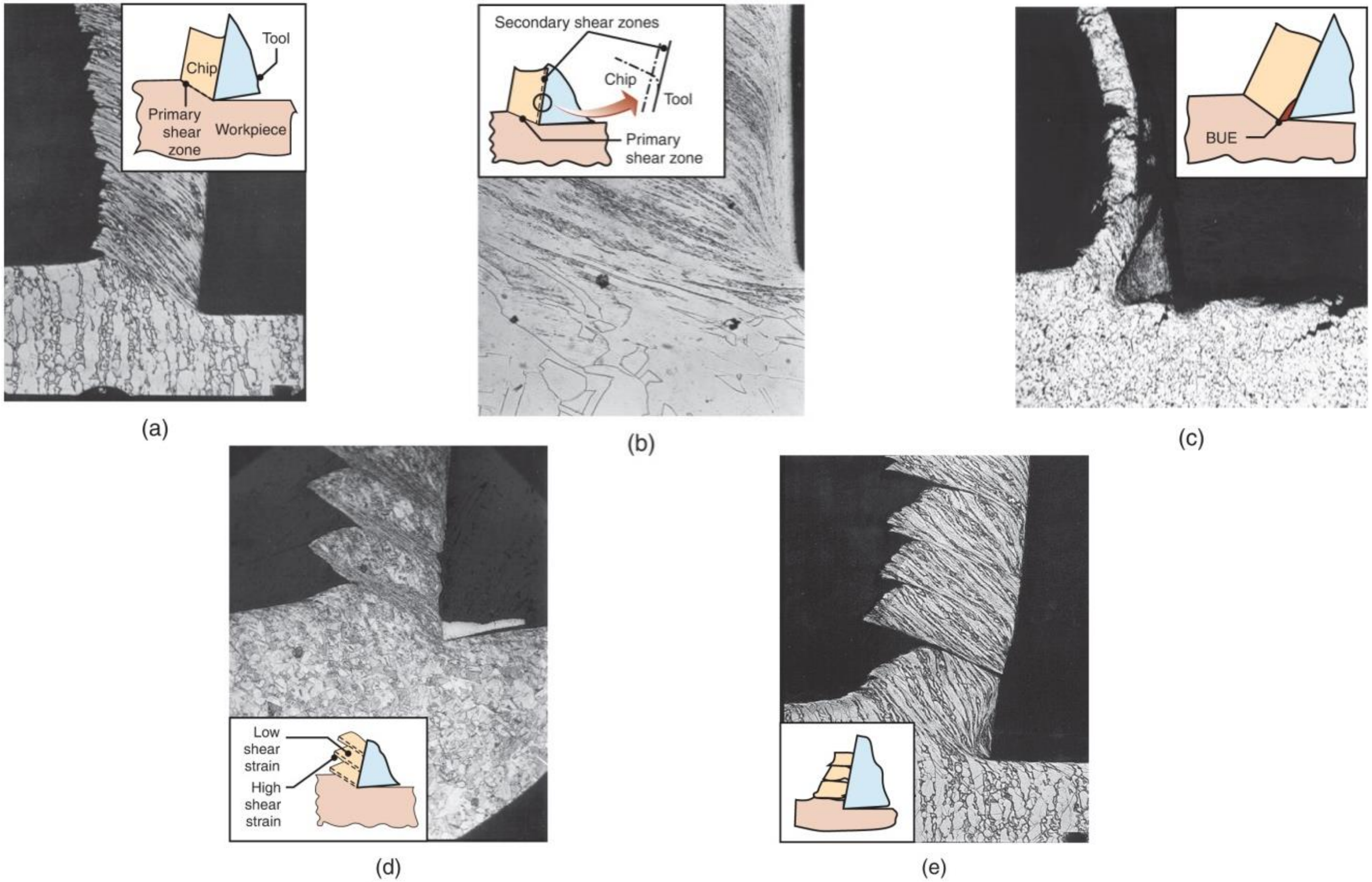
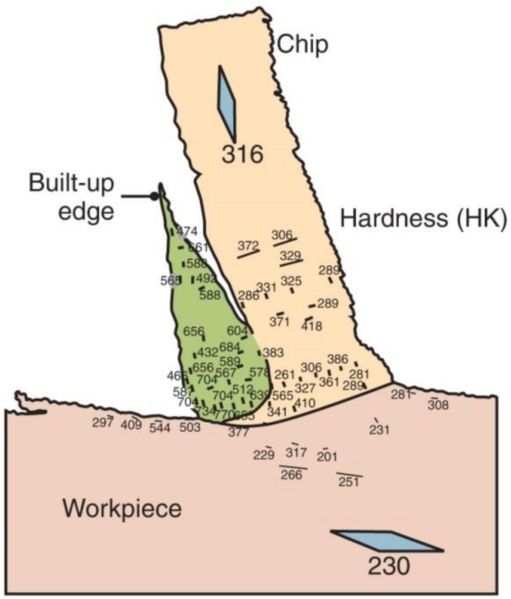
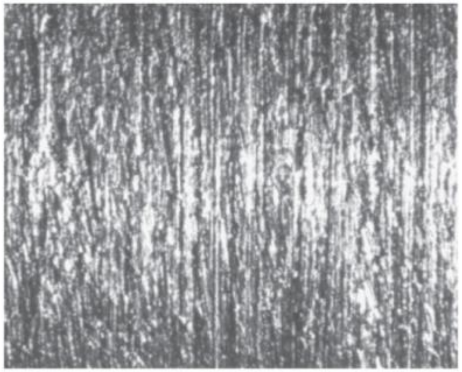


Figure 21.6 (1 of 2)

(a) Hardness distribution in a built-up edge in 3115 steel. Note that some regions within the built-up edge are as much as three times harder than the bulk metal being machined, (b) Surface finish produced in turning 5130 steel with a built-up edge. (c) Surface finish on 1018 steel in face milling. Magnifications: 15×.



(a)



(b)

(c)

Pearson

Figure 21.7 (1 of 5)

(a) Machining aluminum using an insert without a chip breaker; note the long chips that can interfere with the tool and present a safety hazard.

(a)

Source: (a) Courtesy of Kennametal, Inc.

Figure 21.7 (2 of 5)

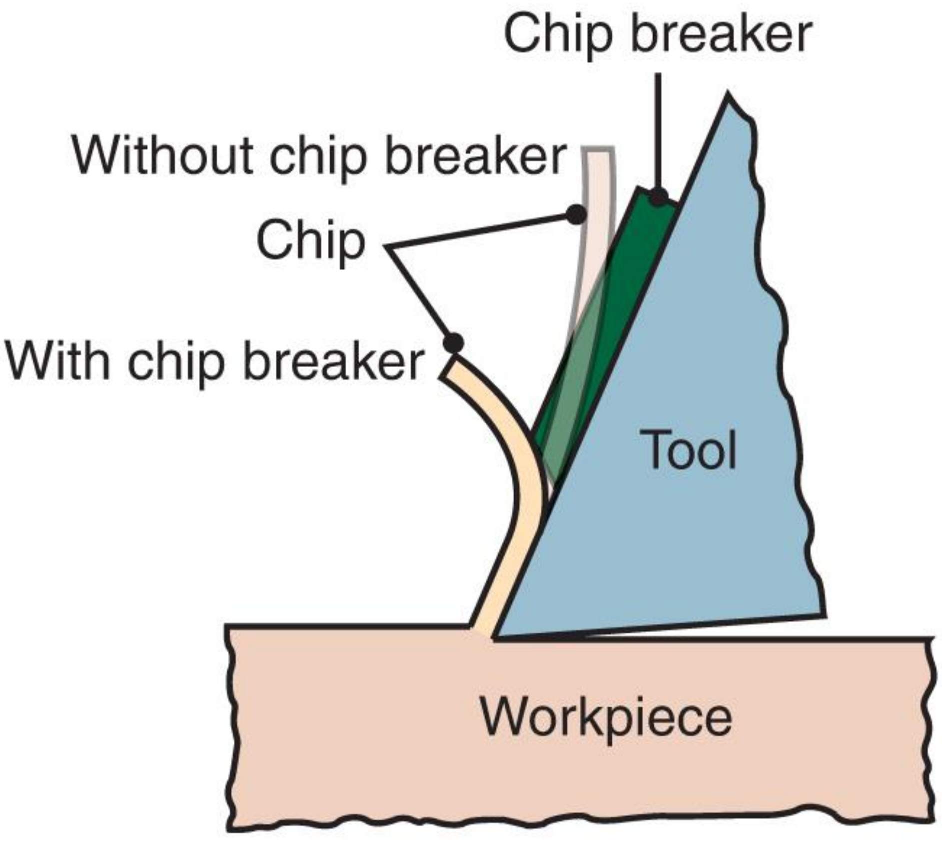
(b) Machining aluminum with a chip breaker.

(b)

Source: (b) Courtesy of Kennametal, Inc.

Figure 21.7 (3 of 5)

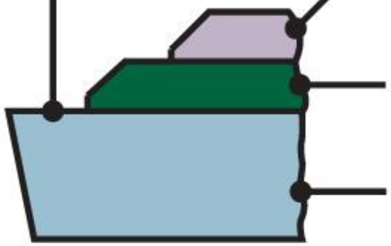
(c) Schematic illustration of the action of a chip breaker; note that the chip breaker decreases the radius of curvature of the chip and eventually breaks it.



(c)

Figure 21.7 (4 of 5)

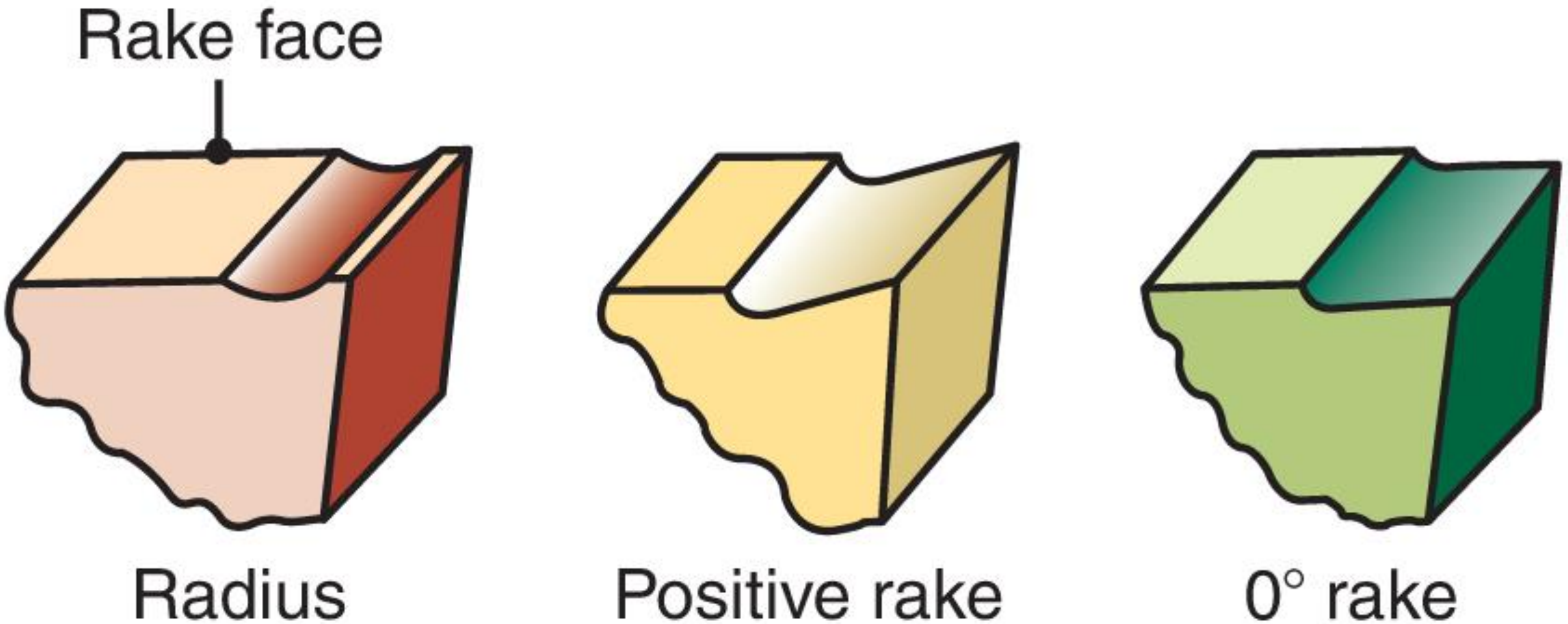
(d) Chip breaker clamped on the rake face of a cutting tool.



(d)

Figure 21.7 (5 of 5)

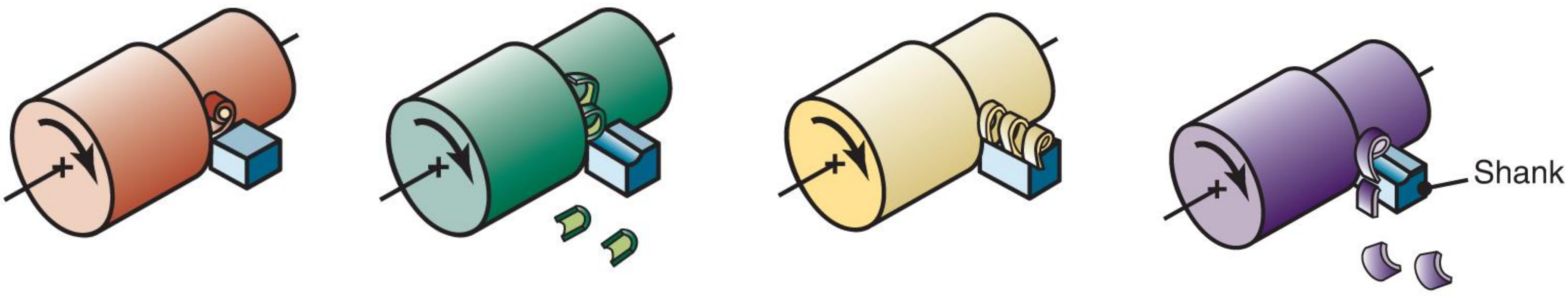
(e) Grooves in cutting tools acting as chip breakers; the majority of cutting tools are now inserts with built-in chip-breaker features.



(e)

Figure 21.8 (1 of 2)

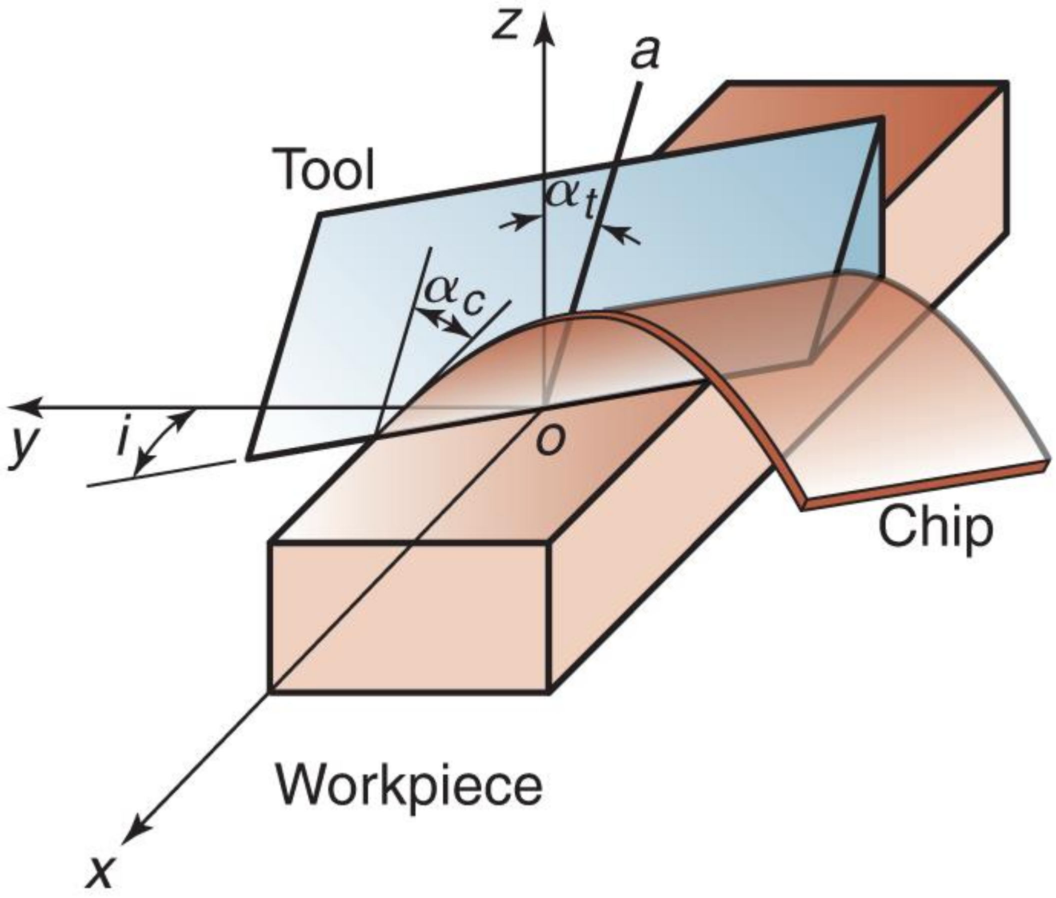
Chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks, (c) continuous chip moving radially away from workpiece; and (d) chip hits tool shank and breaks off.



(a) (b) (c) (d)

Figure 21.9 (1 of 3)

(a) Schematic illustration of cutting with an oblique tool; note the direction of chip movement.



(a)

Figure 21.9 (2 of 3)

(b) Top view, showing the inclination angle, i.

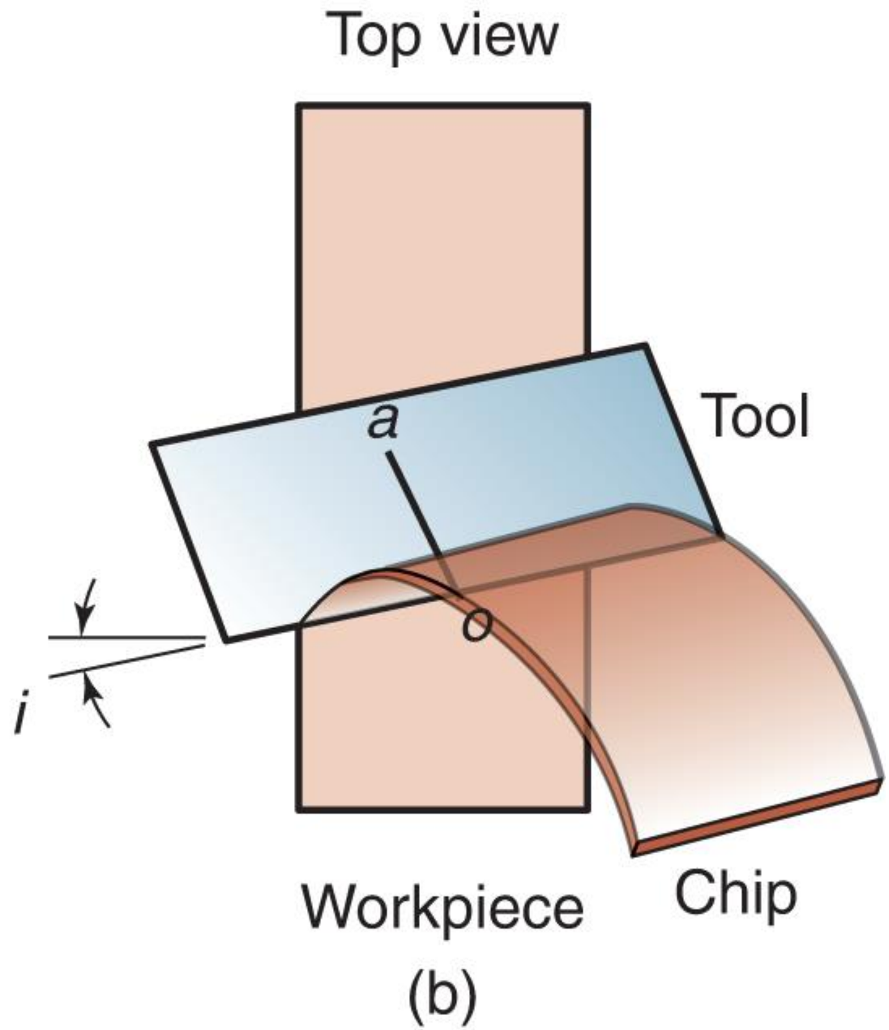


Figure 21.9 (3 of 3)

(c) Types of chips produced with tools at increasing inclination angles.

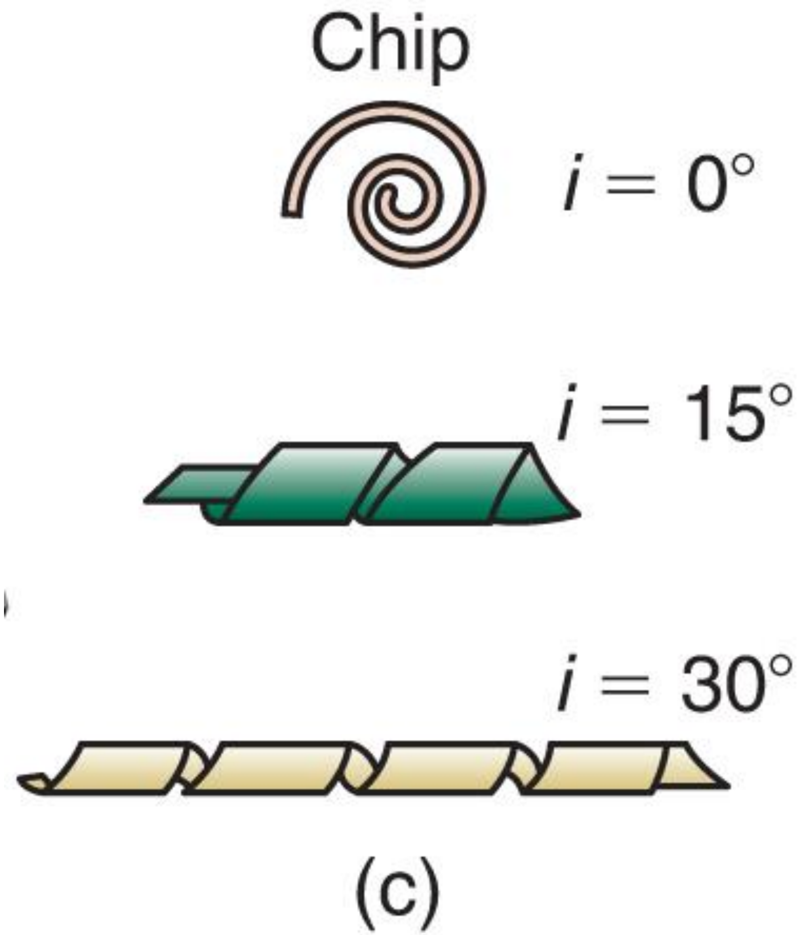


Table 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool, Corrected for 80% Efficiency (for dull tools, multiply by 1.25).

	Specific energy	
Material	$W\text{-}s/mm^3$	$hp\text{-}min/in^3$
Aluminum alloys	0.4–1	0.15–0.4
Cast irons	1.1–5.4	0.4–2
Copper alloys	1.4–3.2	0.5–1.2
High-temperature alloys	3.2–8	1.2–3
Magnesium alloys	0.3–0.6	0.1–0.2
Nickel alloys	4.8–6.7	1.8–2.5
Refractory alloys	3–9	1.1–3.5
Stainless steels	2–5	0.8–1.9
Steels	2–9	0.7–3.4
Titanium alloys	2–5	0.7–2

Figure 21.12

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.

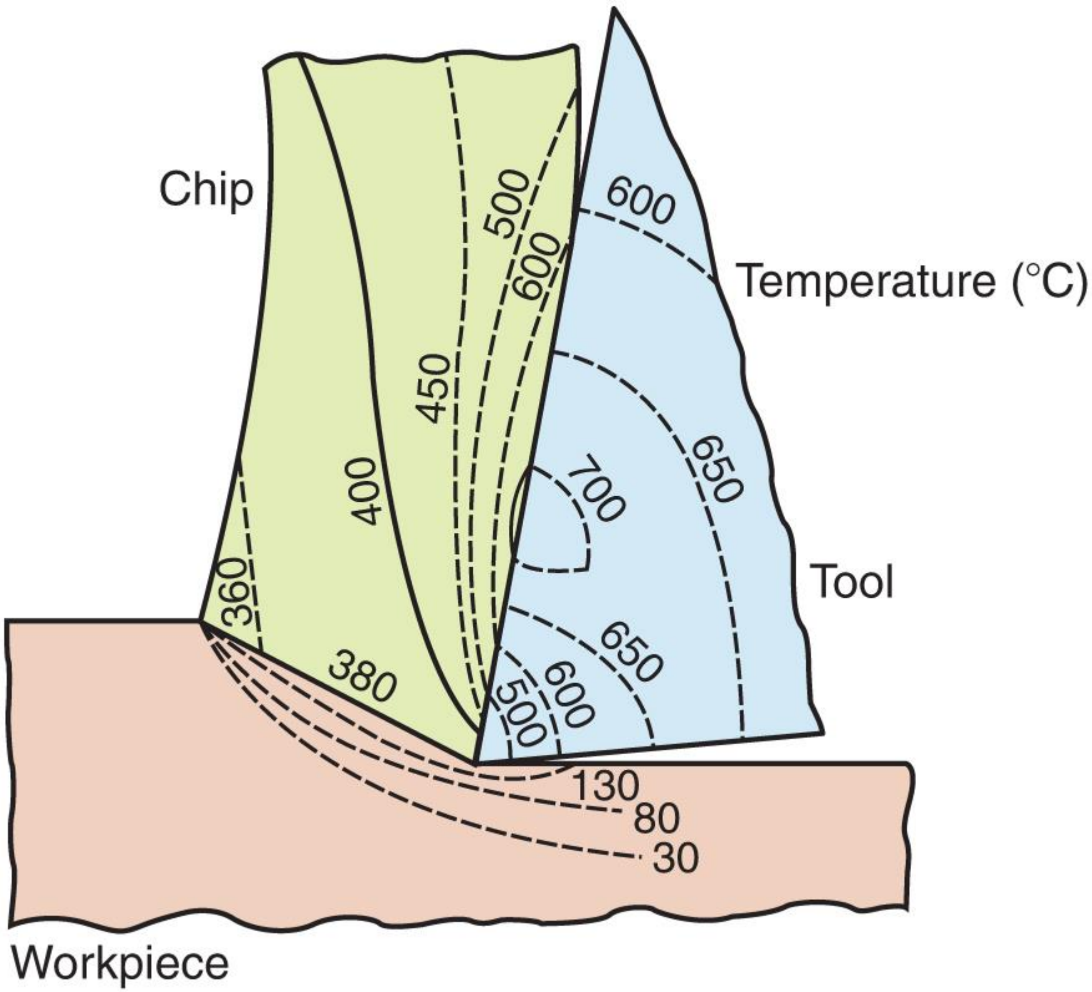


Figure 21.13 (1 of 2)

Temperatures developed in turning 52100 steel: (a) flank temperature distribution, (b) tool–chip interface temperature distribution.

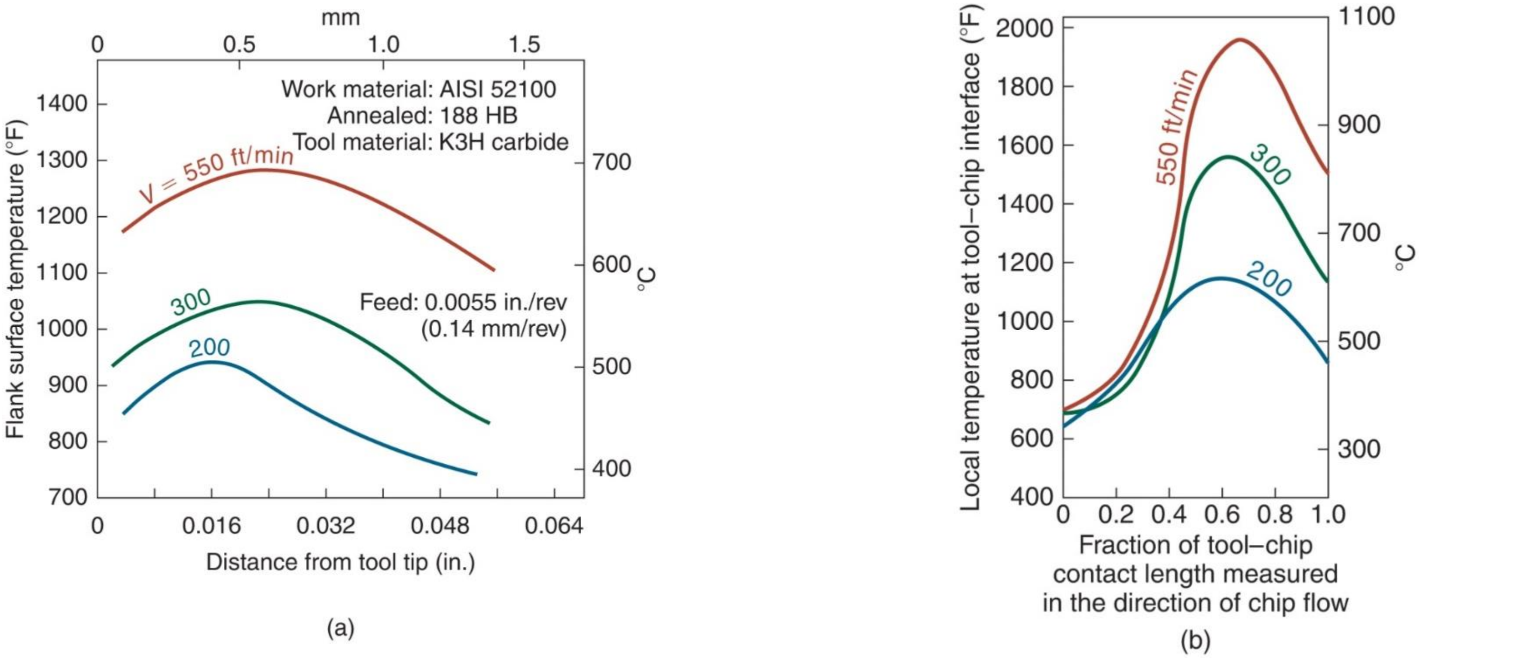


Figure 21.14

Proportion of the heat generated in cutting transferred to the tool, workpiece, and chip as a function of the cutting speed. Note that the chip removes most of the heat.

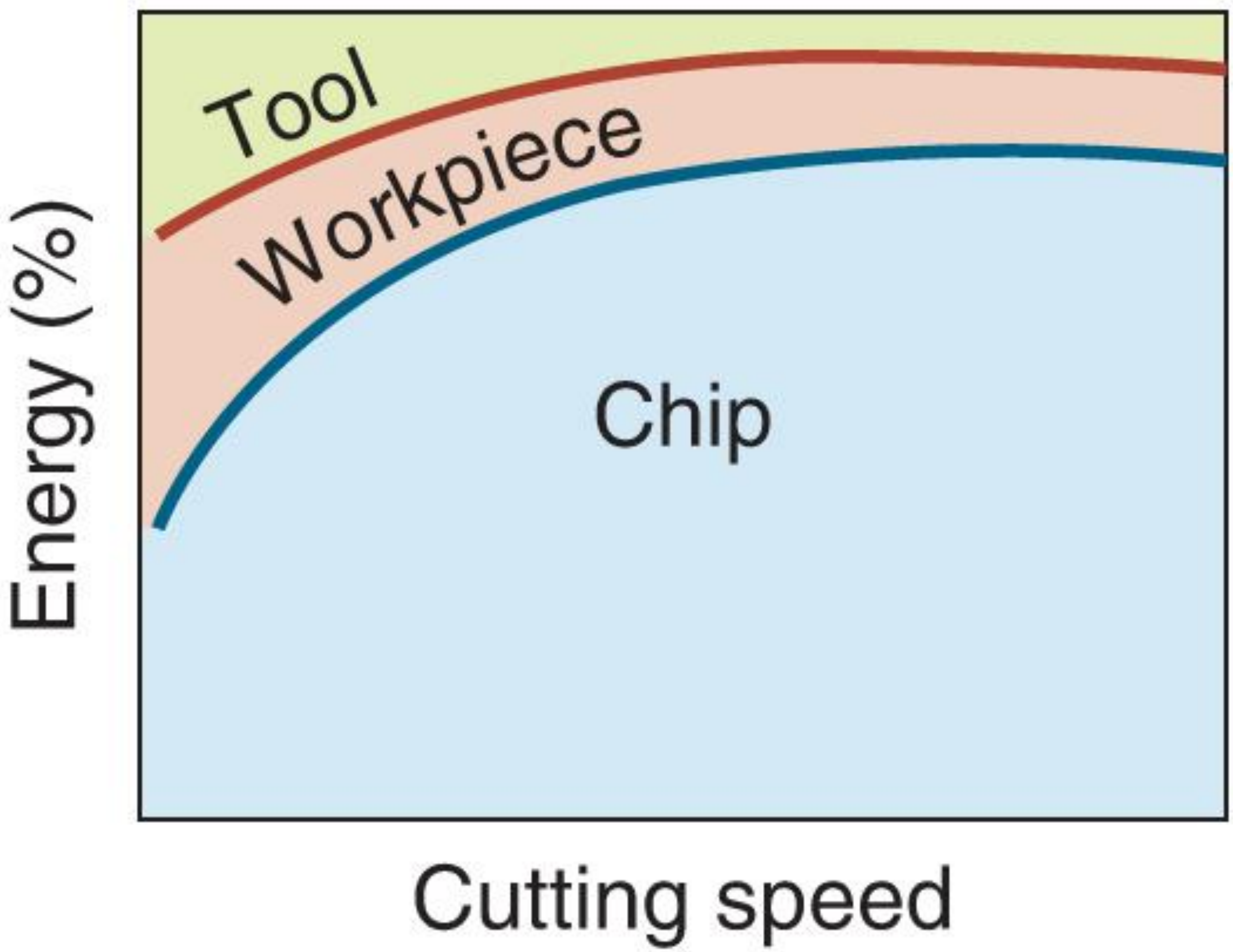


Figure 21.15 (1 of 5)

(a) Features of tool wear in a turning operation. The VB indicates average flank wear, (b) flank wear, (c) crater wear, (d) thermal cracking, (e) flank wear and built-up edge

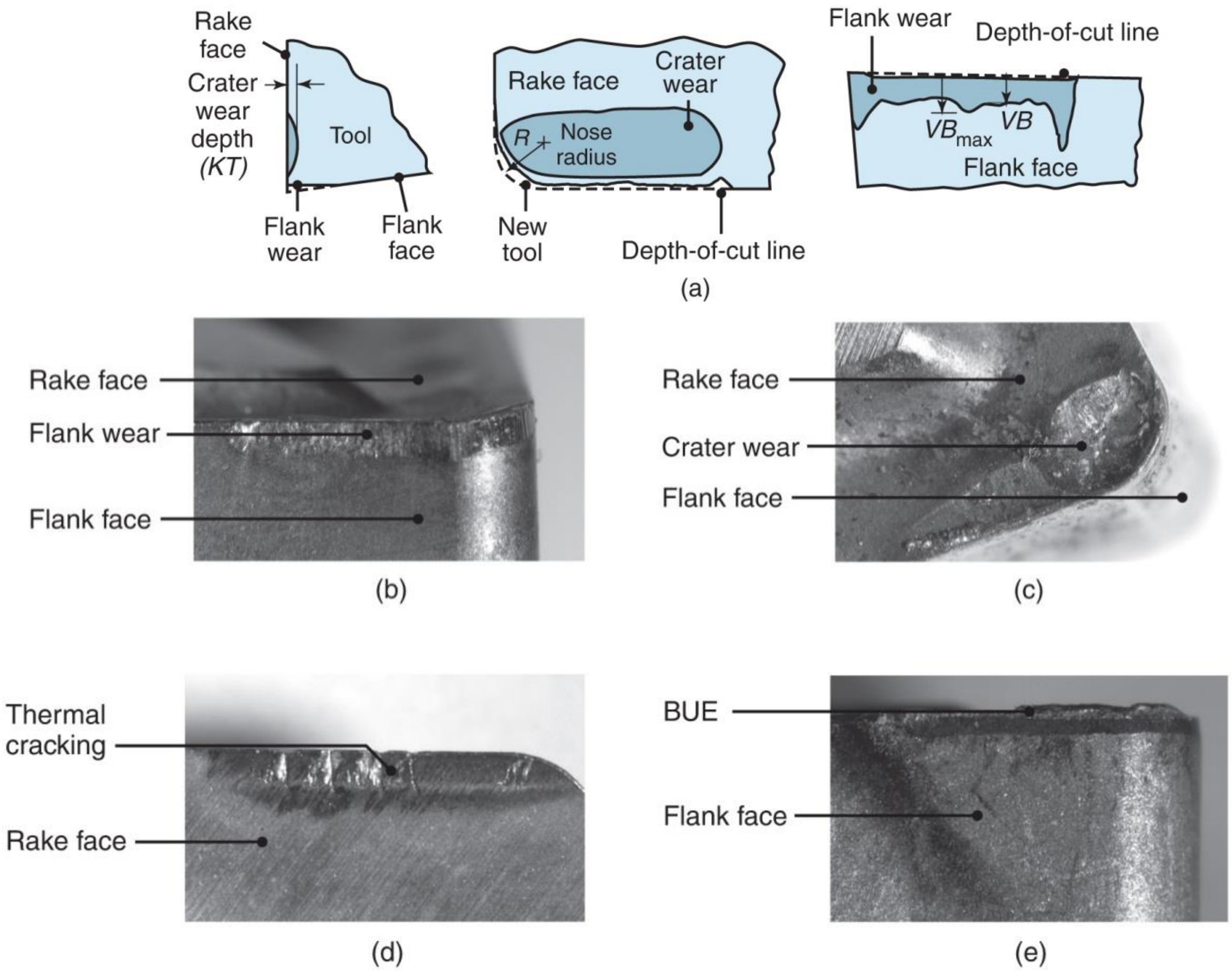
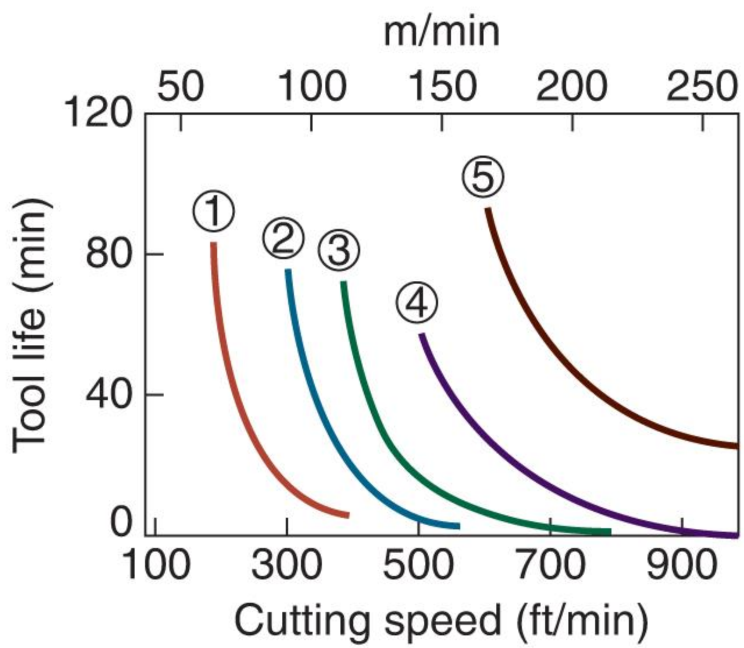


Figure 21.16

Effect of workpiece hardness and microstructure on tool life in turning ductile cast iron. Note the rapid decrease in tool life (approaching zero) as the cutting speed increases. Tool materials have been developed that resist high temperatures, such as carbides, ceramics, and cubic boron nitride, as described in Chapter 22.



		Hardness (HB)	Ferrite	Pearlite
①	As cast	265	20%	80%
②	As cast	215	40	60
③	As cast	207	60	40
④	Annealed	183	97	3
⑤	Annealed	170	100	—

Figure 21.17

Tool-life curves for a variety of cutting-tool materials. The negative reciprocal of the slope of these curves is the exponent *n* in the Taylor tool-life equation [Eq. (21.25)], and *C* is the cutting speed at *T* = 1 min, ranging from about 200 to 10,000 ft/min in this figure.

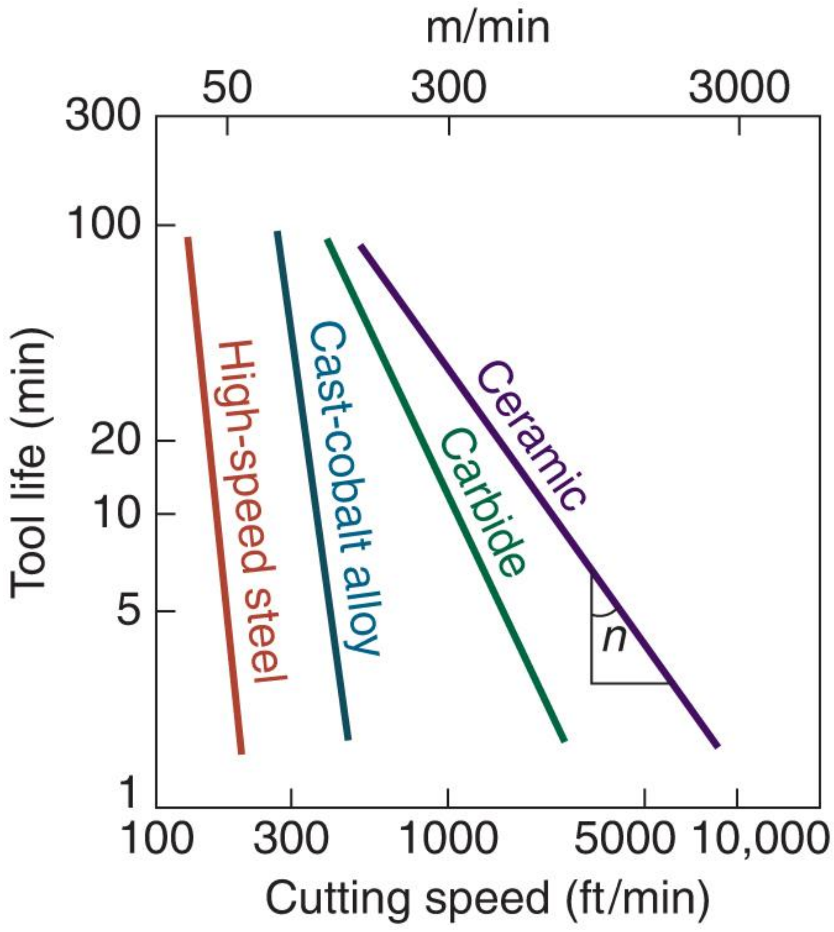


Table 21.4

Allowable Average Wear Land (see *VB* in Fig. 21.15a) for Cutting Tools in Various Machining Operations.

	Allowable wear land (mm)	
Operation	**High-speed steel tools**	**Carbide tools**
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

Note: Allowable wear for ceramic tools is about 50% higher. Allowable notch wear (see Section 21.5.3), VB_{max}, is about twice that for VB.

Figure 21.18

(a) Schematic illustrations of types of wear observed on various cutting tools, (b) Schematic illustrations of catastrophic tool failures. A wide range of parameters influence these wear and failure patterns.

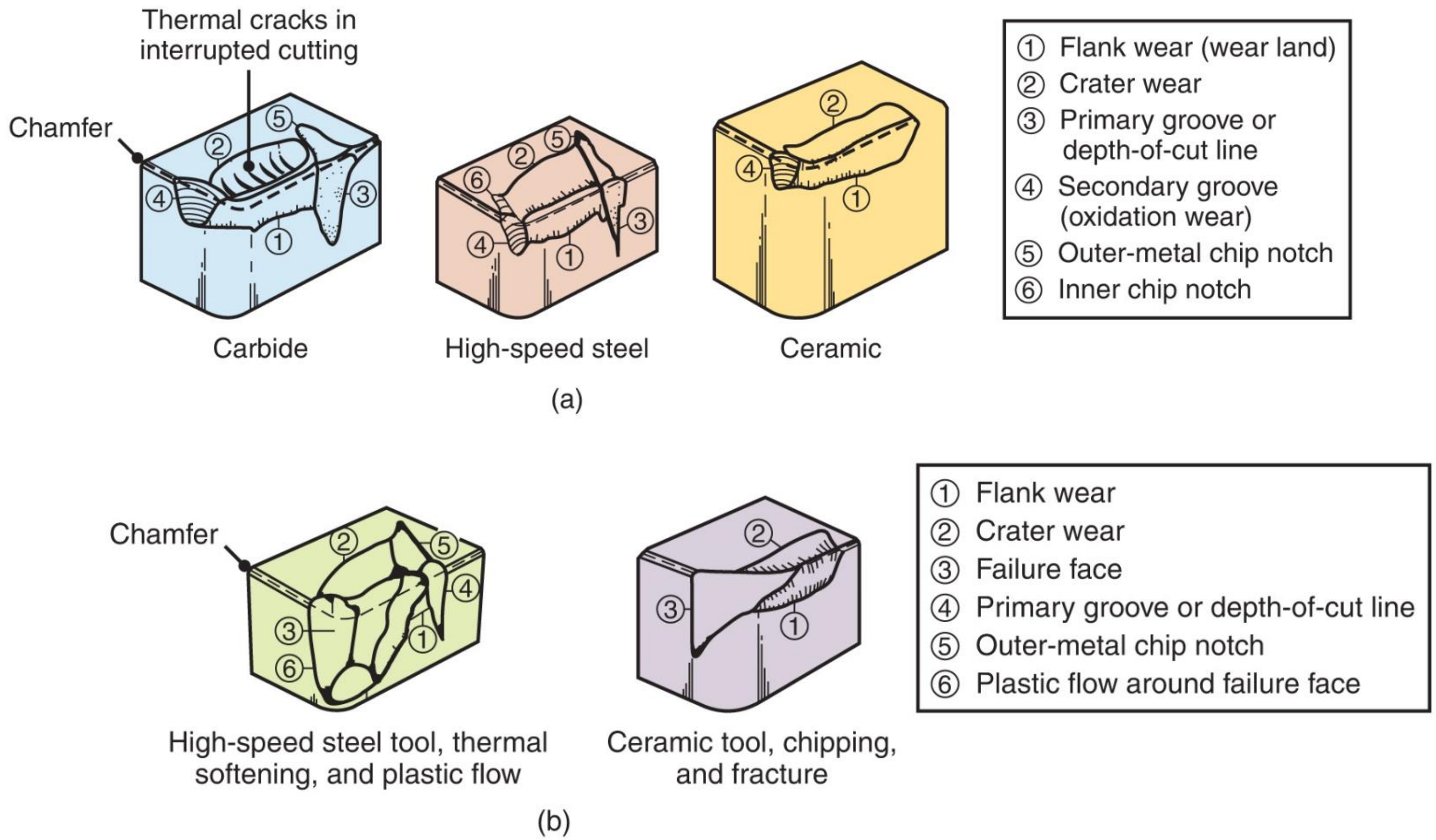
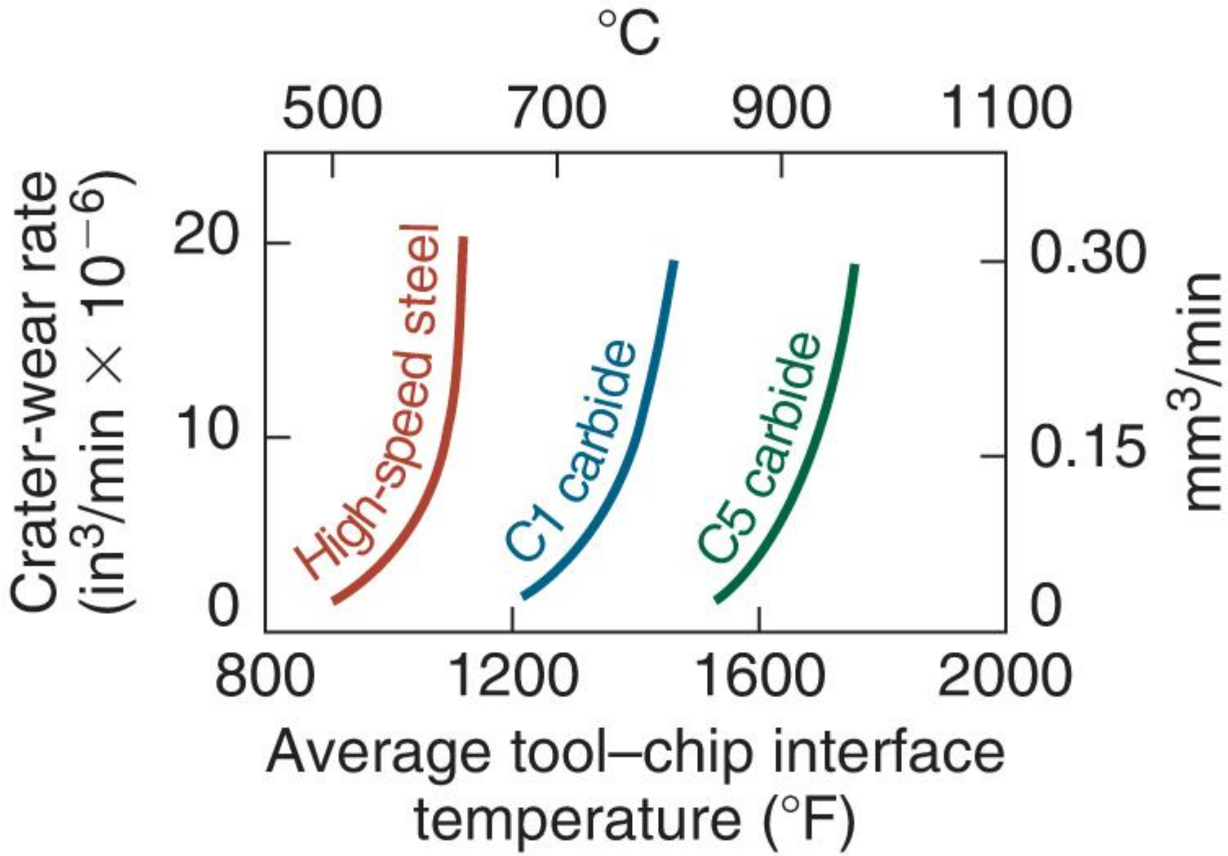


Figure 21.19

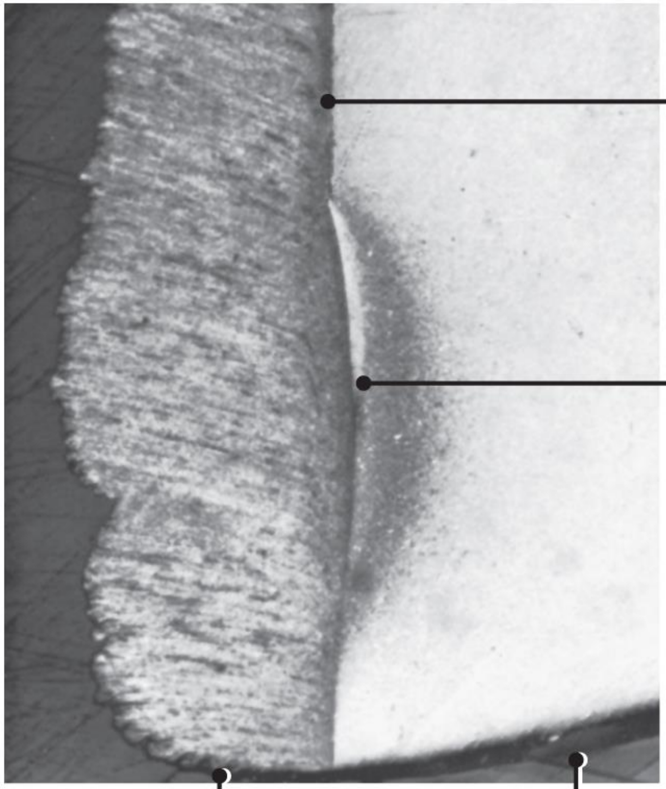
Relationship between crater-wear rate and average tool–chip interface temperature: (1) highspeed steel, (2) C1 carbide, and (3) C5 carbide (see Table 22.5). Note how rapidly crater-wear rate increases with an incremental increase in temperature.



Source: After B.T. Chao and K.J. Trigger.

Figure 21.20

Interface of a cutting tool (right) and chip (left) in machining plain-carbon steel. The discoloration of the tool indicates the presence of high temperatures. Compare this figure with the temperature profiles shown in Fig. 21.12.



Source: After P.K. Wright.

Figure 22.1

The hardness of various cutting-tool materials as a function of temperature. The wide range in each group of materials is due to the variety of tool compositions and treatments available for that particular group.

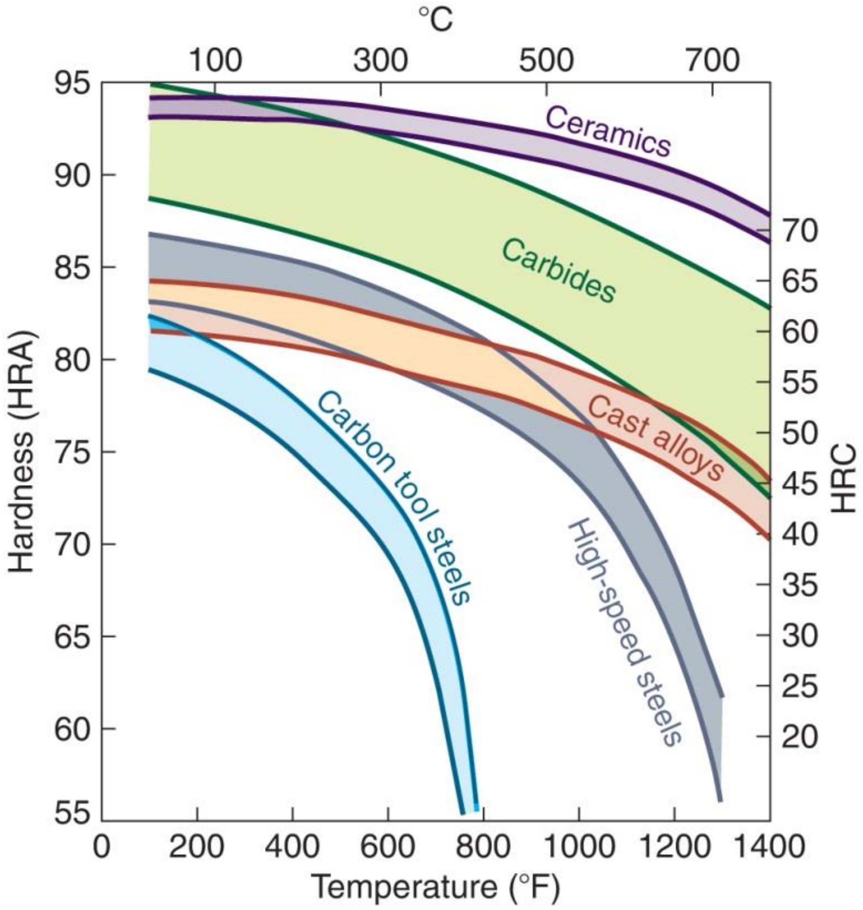


Table 22.1 (1 of 2)

General Characteristics of Tool Materials.

Property	High-speed steels	Cast-cobalt alloys	Carbides WC	Carbides TiC	Ceramics	Cubic boron nitride	Single-crystal diamond*
Hardness	83–86 HRA	82–84 HRA 46–62 HRC	90–95 HRA 1800–2400 HK	91–93 HRA 1800–3200 HK	91–95 HRA 2000–3000 HK	4000–5000 HK	7000–8000 HK
Compressive strength,							
MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
psi $\times 10^3$	600–650	220–335	600–850	450–560	400–650	1000	1000
Transverse rupture strength,							
MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
psi $\times 10^3$	350–700	200–300	150–375	200–275	50–135	105	200
Impact strength,							
J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	< 0.1	< 0.5	< 0.2
in.-lb	12–70	3–11	3–12	7–11	< 1	< 5	< 2
Modulus of elasticity,							
GPa	200	–	520–690	310–450	310–410	850	820–1050
psi $\times 10^6$	30	–	75–100	45–65	45–60	125	120–150

*The values for polycrystalline diamond are generally lower, except for impact strength, which is higher.

Table 22.1 (2 of 2)

General Characteristics of Tool Materials.

Density,							
kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
lb/in^3	0.31	0.29–0.31	0.36–0.54	0.2–0.22	0.14–0.16	0.13	0.13
Volume of hard phase, %							
	7–15	10–20	70–90	–	100	95	95
Melting or decomposition temperature,							
°C	1300	–	1400	1400	2000	1300	700
°F	2370	–	2550	2550	3600	2400	1300
Thermal conductivity, W/m K							
	30–50	–	42–125	17	29	13	500–2000
Coefficient of thermal expansion, $\times 10^{-6}/°C$							
	12	–	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

*The values for polycrystalline diamond are generally lower, except for impact strength, which is higher.

Table 22.2

General Characteristics of Cutting-tool Materials. These Materials Have a Wide Range of Compositions and Properties; Overlapping Characteristics Exist in Many Categories of Tool Materials.

	High-speed steels	Cast-cobalt alloys	Uncoated carbides	Coated carbides	Ceramics	Polycrystalline cubic boron nitride	Diamond
Hot hardness	→						
Toughness	←						
Impact strength	←						
Wear resistance	→						
Chipping resistance	←						
Cutting speed	←						
Thermal-shock resistance	←						
Tool material cost	→						
Depth of cut	Light	Light	Light	Light	Light	Light	Very light
Depth of cut	to	to	to	to	to	to	for single-crystal
Depth of cut	heavy	heavy	heavy	heavy	heavy	heavy	diamond
Processing method	Wrought,	Cast	Cold	CVD	Cold pressing	High-pressure,	High-pressure,
Processing method	cast,	and	pressing	or	and sintering	high-	high-
Processing method	HIP*	HIP	and	PVD**	or HIP	temperature	temperature
Processing method	sintering	sintering	sintering		sintering	sintering	sintering

Source: After R. Komanduri.

* Hot-isostatic pressing.

** Chemical-vapor deposition, physical-vapor deposition.

Table 22.3

General Operating Characteristics of Cutting-tool Materials.

Tool materials	General characteristics	Modes of tool wear or failure	Limitations
High-speed steels	High toughness, resistance to fracture, wide range of roughing and finishing cuts, good for interrupted cuts	Flank wear, crater wear	Low hot hardness, limited hardenability, and limited wear resistance
Uncoated carbides	High hardness over a wide range of temperatures, toughness, wear resistance, versatile, wide range of applications	Flank wear, crater wear	Cannot be used at low speeds because of cold welding of chips and microchipping
Coated carbides	Improved wear resistance over uncoated carbides, better frictional and thermal properties	Flank wear, crater wear	Cannot be used at low speeds because of cold welding of chips and microchipping
Ceramics	High hardness at elevated temperatures, high abrasive wear resistance	Depth-of-cut line notching, microchipping, gross fracture	Low strength and low thermomechanical fatigue strength
Polycrystalline cubic boron nitride (cBN)	High hot hardness, toughness, cutting-edge strength	Depth-of-cut line notching, chipping, oxidation, graphitization	Low strength, and lower chemical stability than ceramics at higher temperature
Diamond	High hardness and toughness, abrasive wear resistance	Chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperatures

Pearson

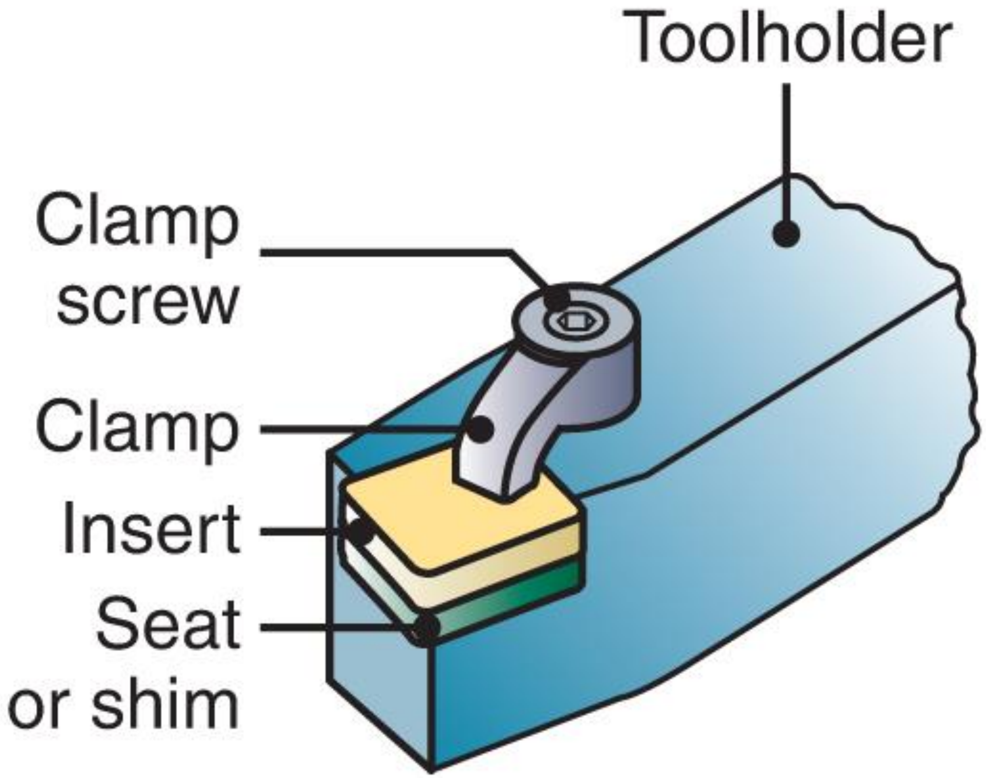
Figure 22.2

Typical cutting tool inserts with various shapes and chip-breaker features: Round inserts also are available, as can be seen in Figs. 22.3c and 22.4. The holes in the inserts are standardized for interchangeability in toolholders.

Source: Courtesy of Kennametal, Inc.

Figure 22.3 (1 of 2)

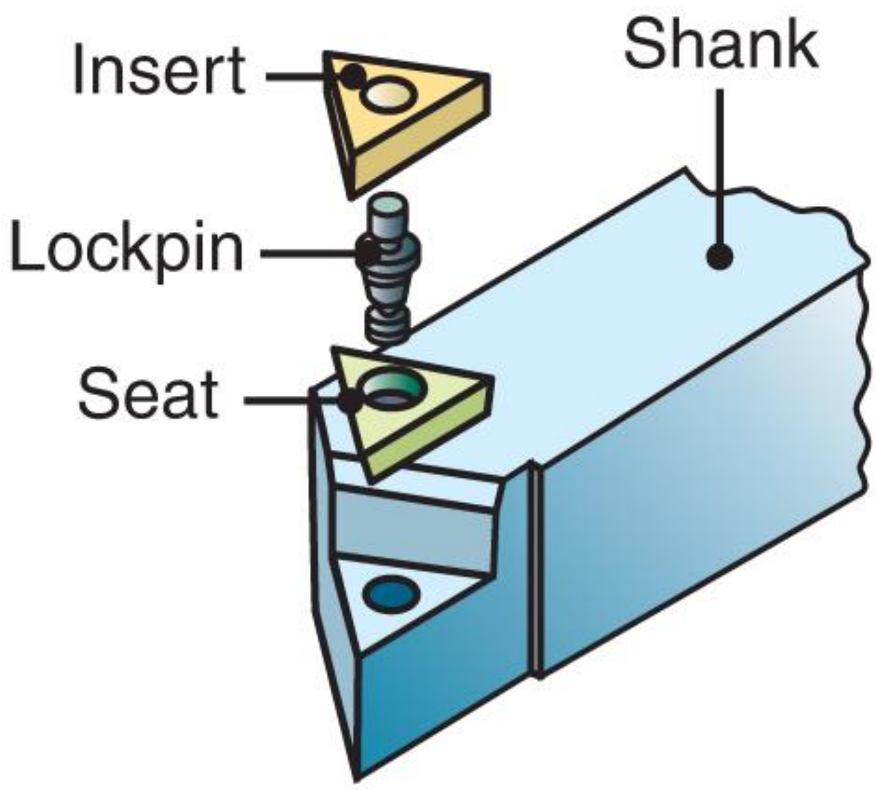
Methods of mounting inserts on toolholders: (a) clamping.



(a)

Figure 22.3 (2 of 2)

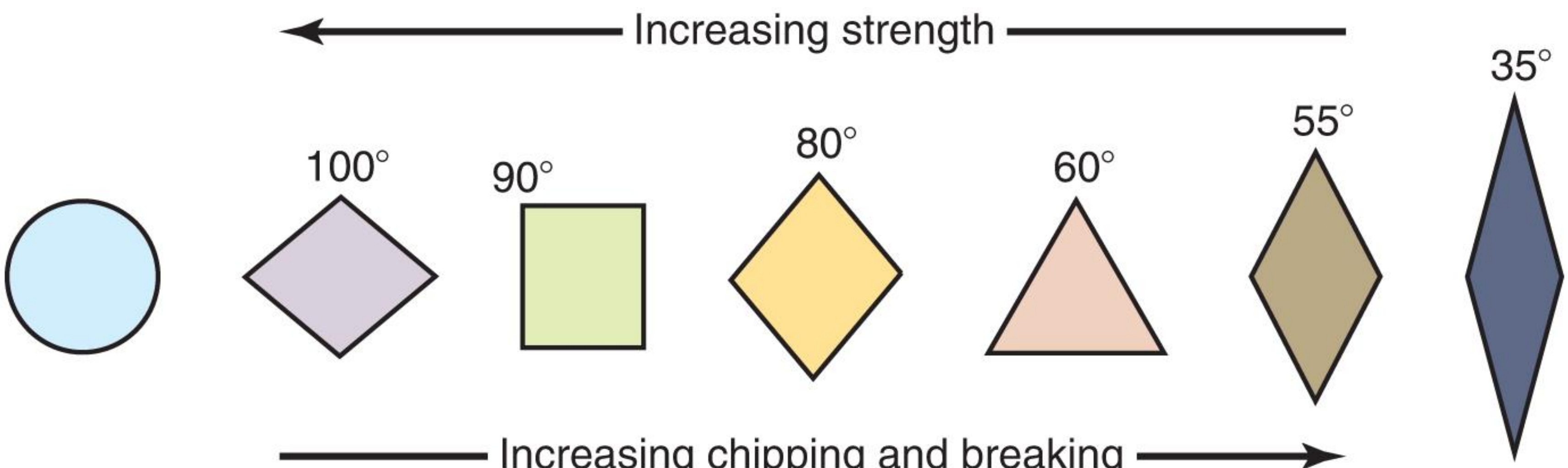
Methods of mounting inserts on toolholders: (b) wing lockpins.



(b)

Figure 22.4

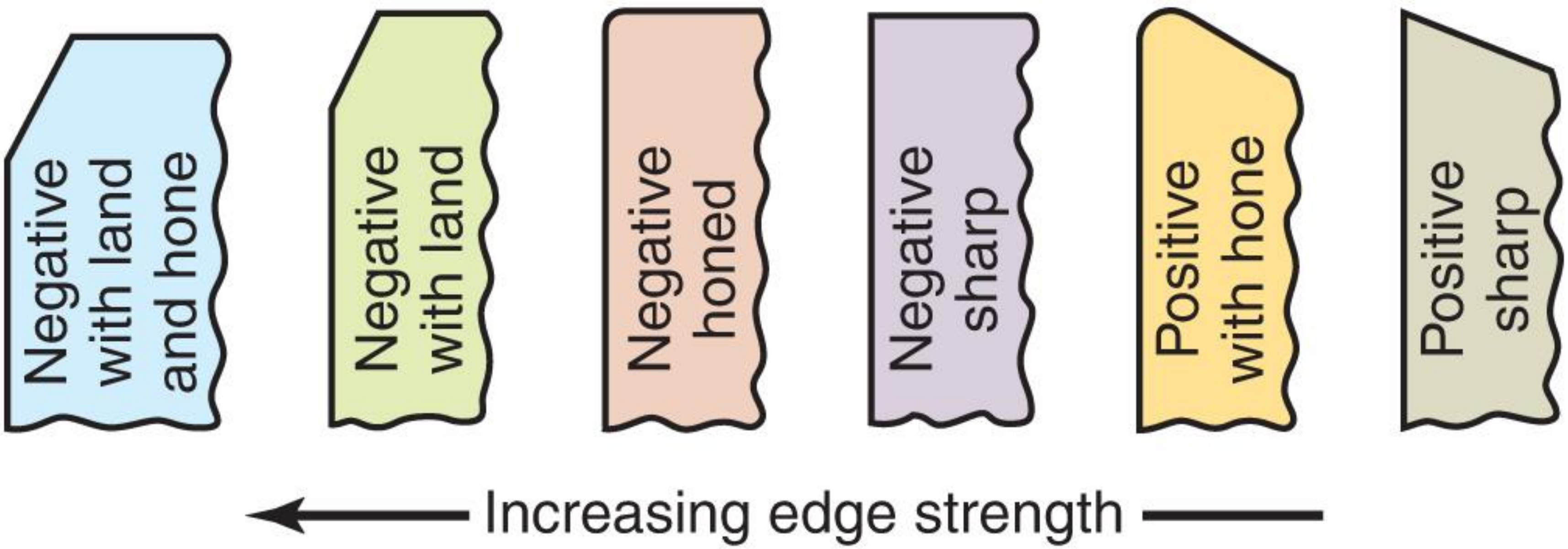
Relative edge strength and tendency for chipping of inserts with various shapes. Strength refers to the cutting edge indicated by the included angles.



Source: Courtesy of Kennametal Inc.

Figure 22.5

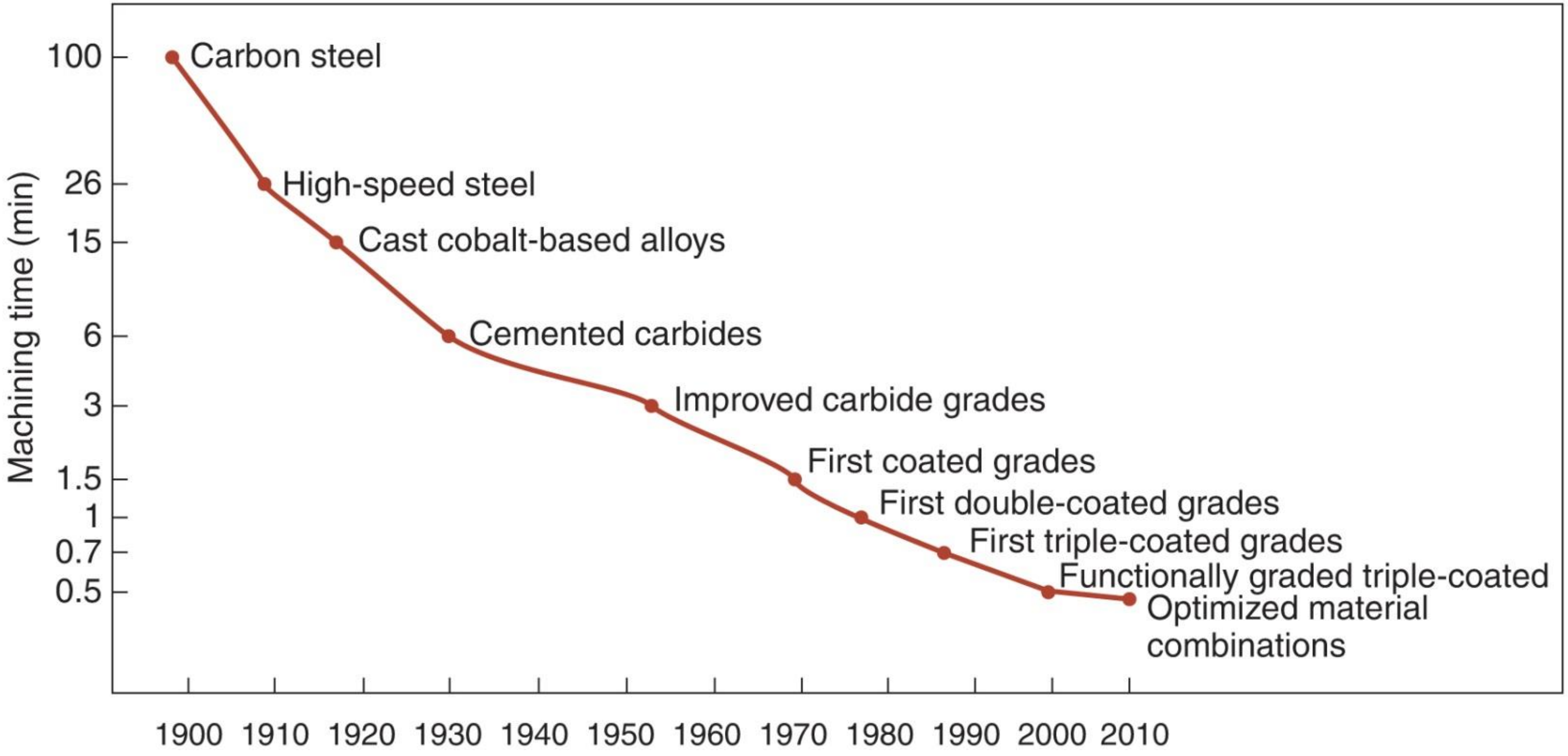
Edge preparation for inserts to improve edge strength.



Source: Courtesy of Kennametal Inc.

Figure 22.6

Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced. Note that machining time has been reduced by two orders of magnitude within a hundred years.



Source: Courtesy of Sandvik.

Figure 22.7

Schematic illustration of typical wear patterns on uncoated high-speed steel tools and titanium nitride-coated tools. Note that flank wear is significantly lower for the coated tool.

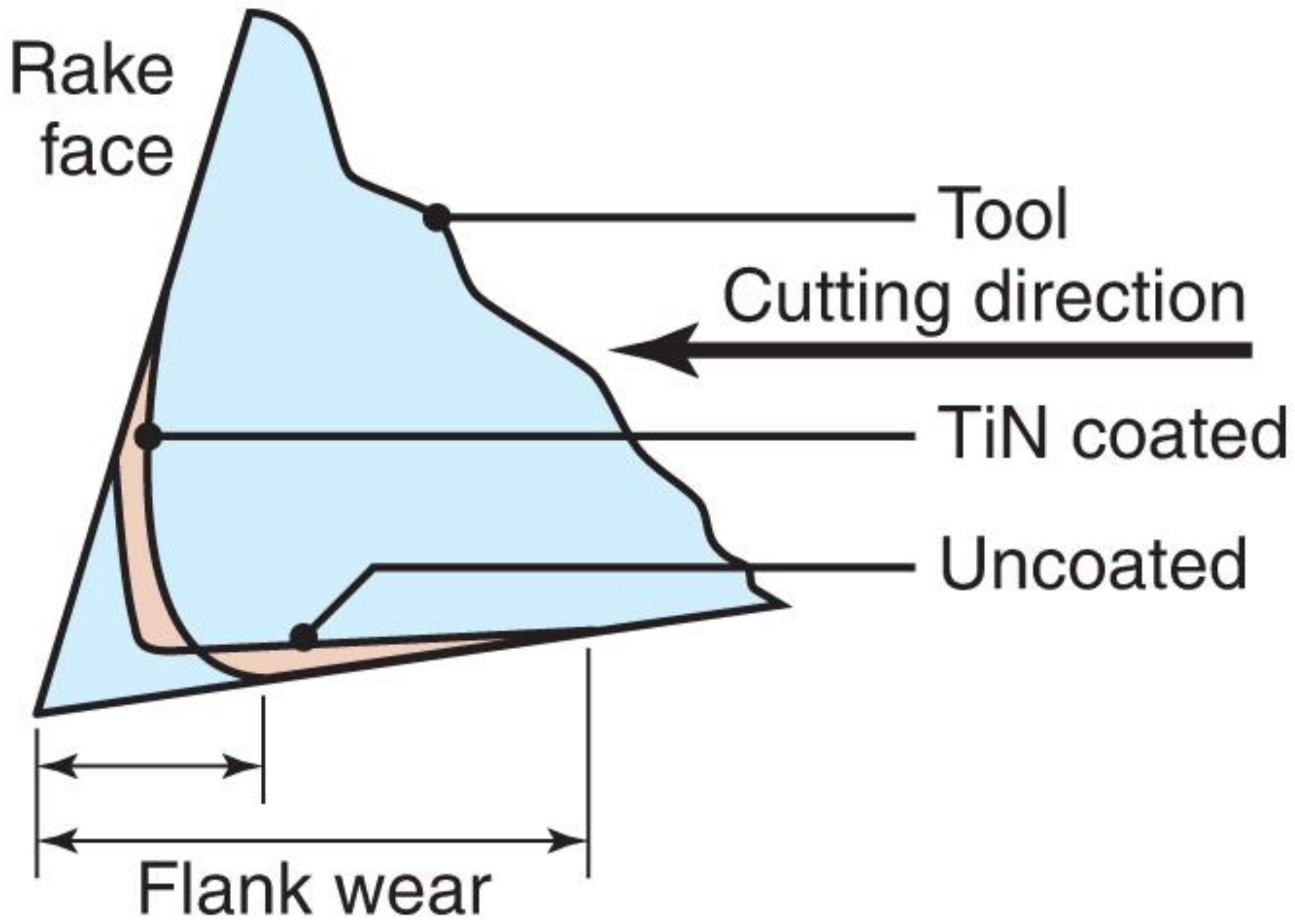
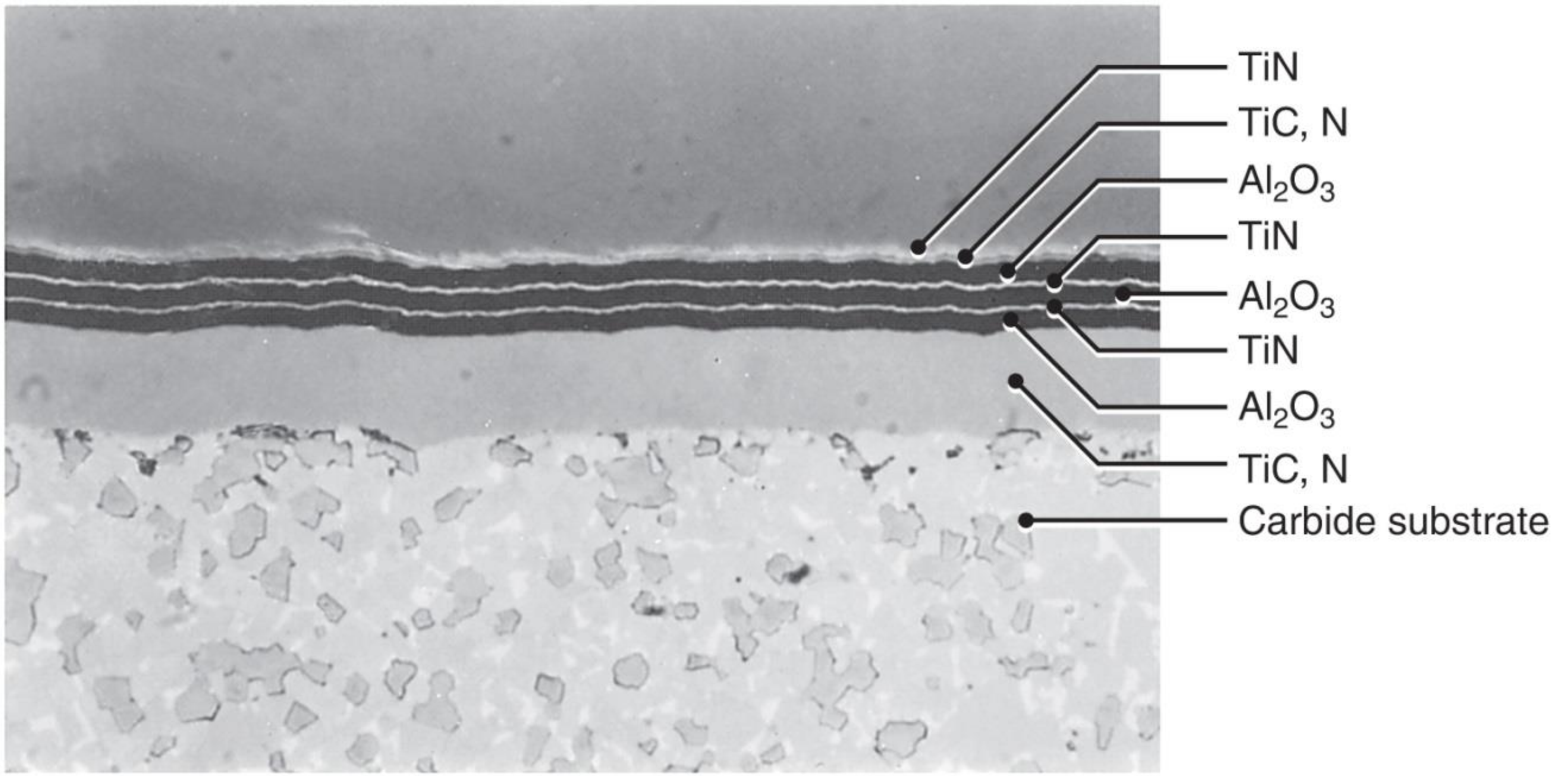


Figure 22.8

Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made. Coating thicknesses are typically in the range from 2 to 10 μm.



Source: Courtesy of Kennametal Inc.

Figure 22.9

Ranges of mechanical properties for various groups of tool materials (see also Tables 22.1 through 22.5).

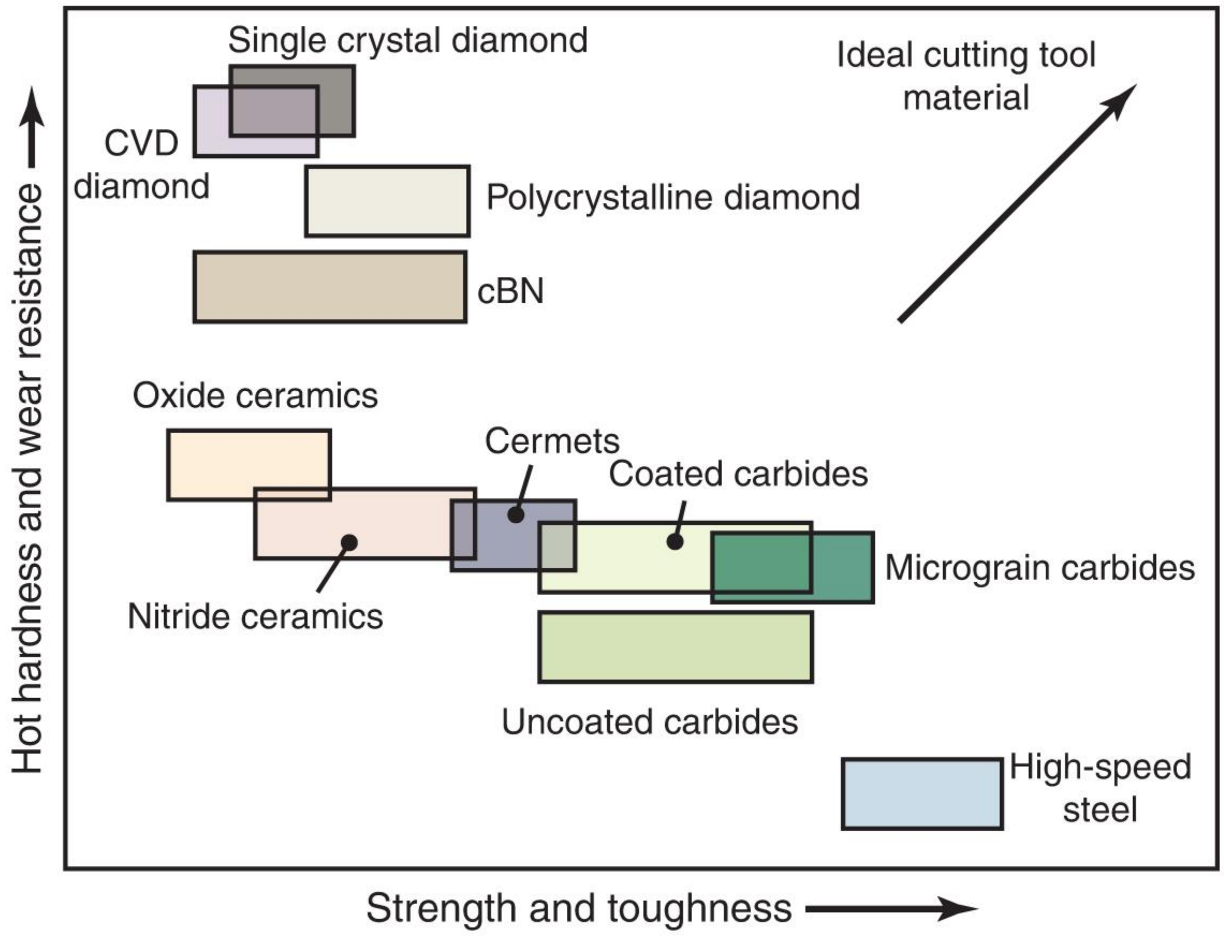


Figure 22.10

An insert of a polycrystalline cubic boron nitride or a diamond layer on tungsten carbide.

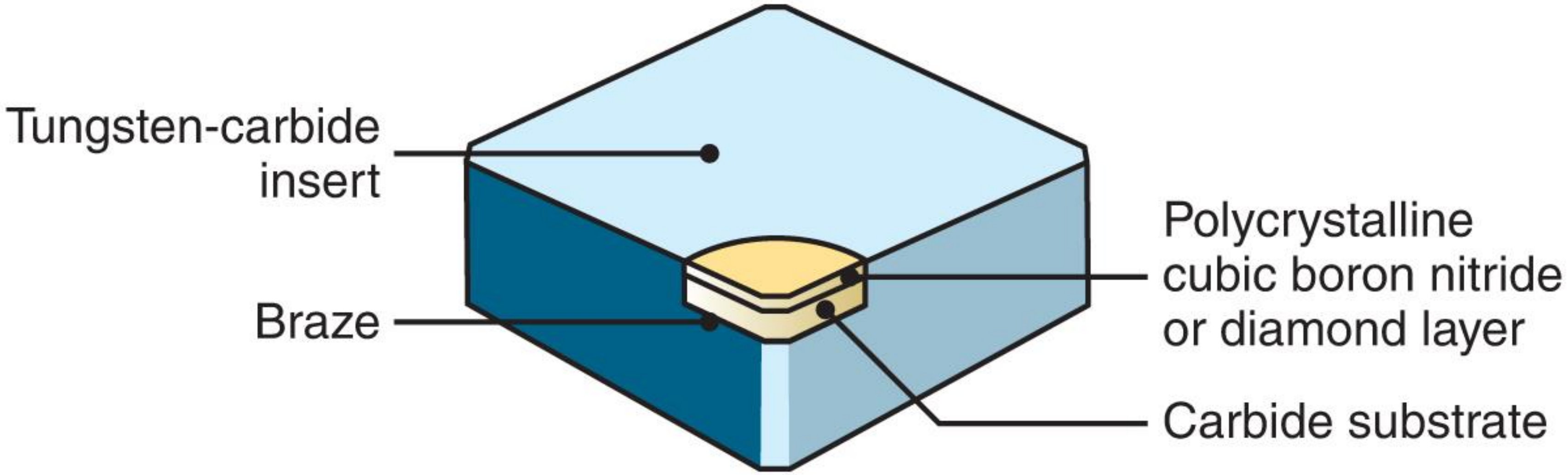
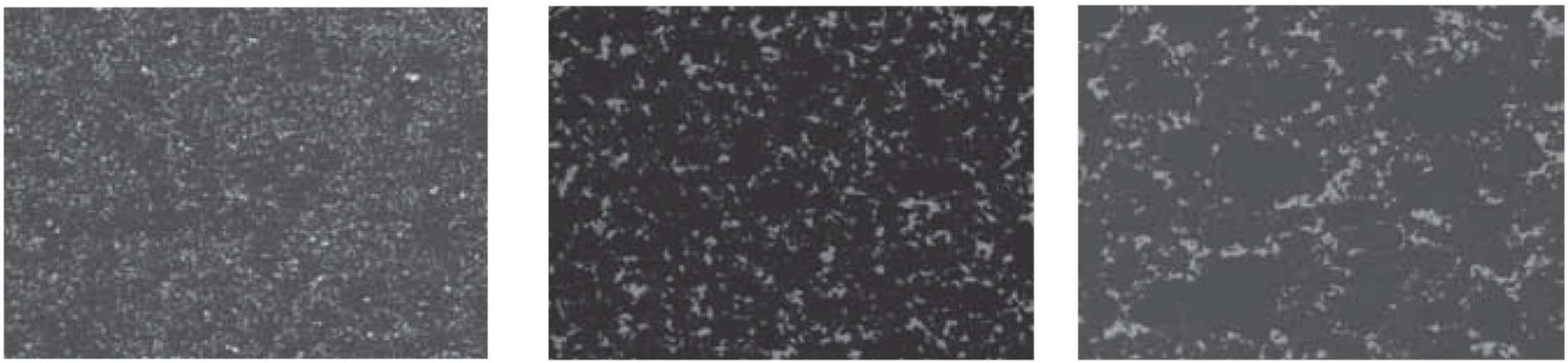


Figure 22.11 (1 of 3)

Microphotographs of diamond compacts: (a) fine-grained diamond, with mean grain size around 2 *μ*m, (b) medium grain, with mean grain size around 10 *μ*m, (c) coarse grain, with grain size around 25 *μ*m.



(a) (b) (c)

Figure 22.12

Schematic illustration of the proper methods of applying cutting fluids (flooding) in various machining operations: (a) turning, (b) milling, (c) thread grinding, (d) drilling

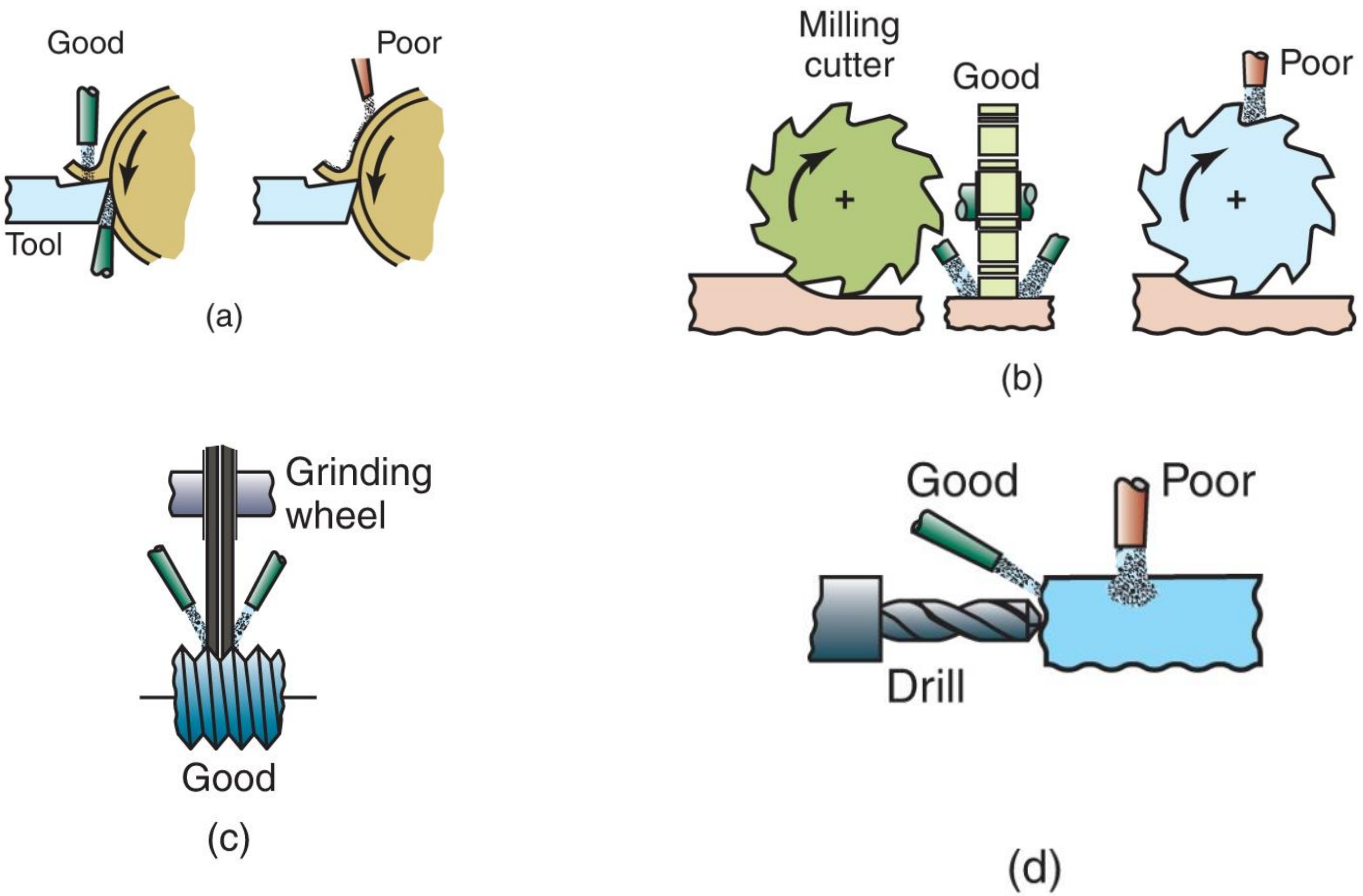
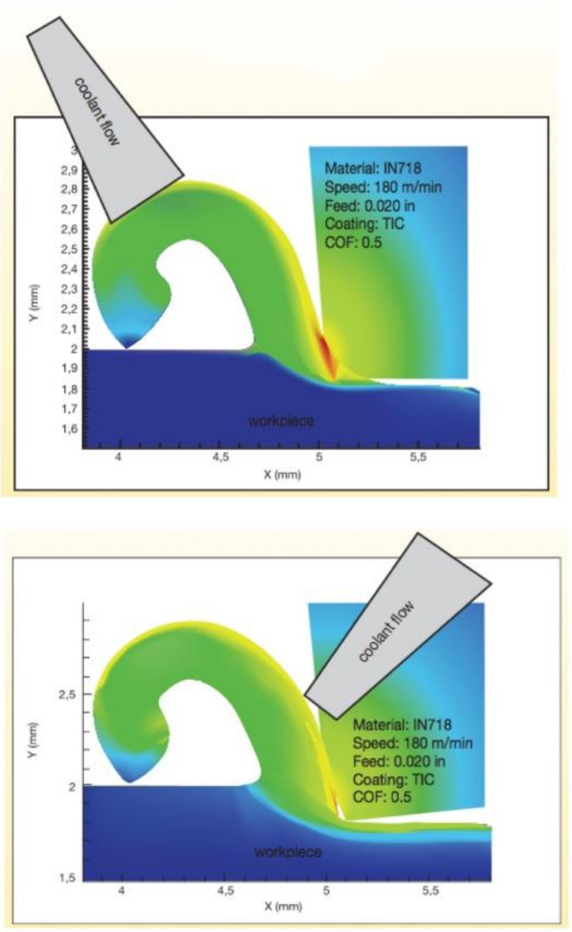


Figure 22.13 (1 of 3)

(a) A turning insert with coolant applied through the tool, (b) comparison of temperature distributions for conventional and through-the-tool application.

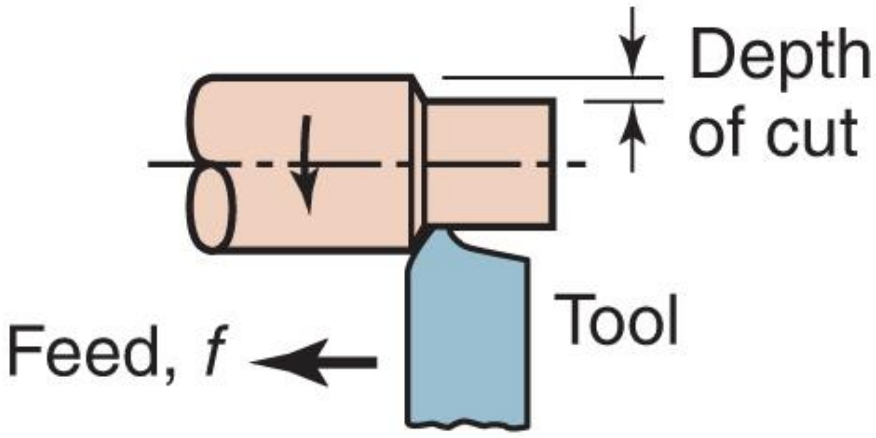
(a)



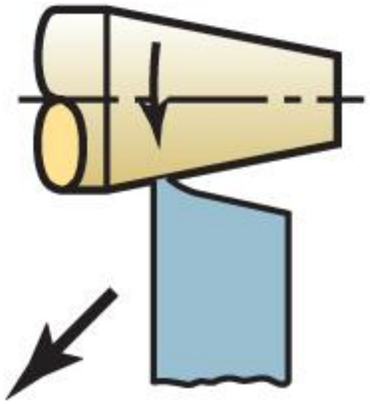
(b)

Figure 23.1 (1 of 6)

Miscellaneous cutting operations that can be performed on a lathe. Note that all parts are axisymmetric. The tools used, their shape, and the processing parameters are described in detail throughout this chapter.

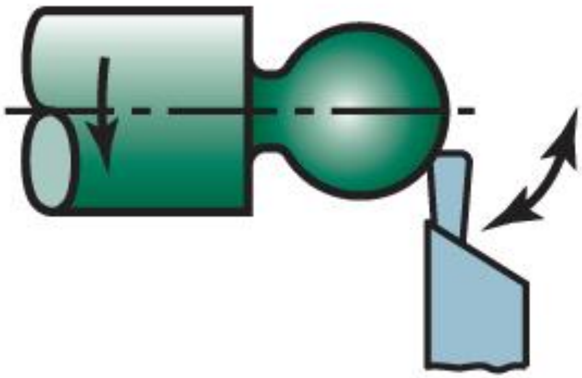


(a) Straight turning

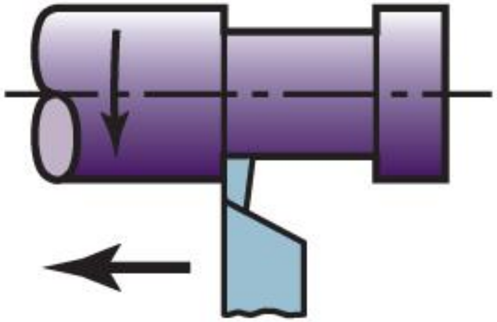


(b) Taper turning

Figure 23.1 (2 of 6)

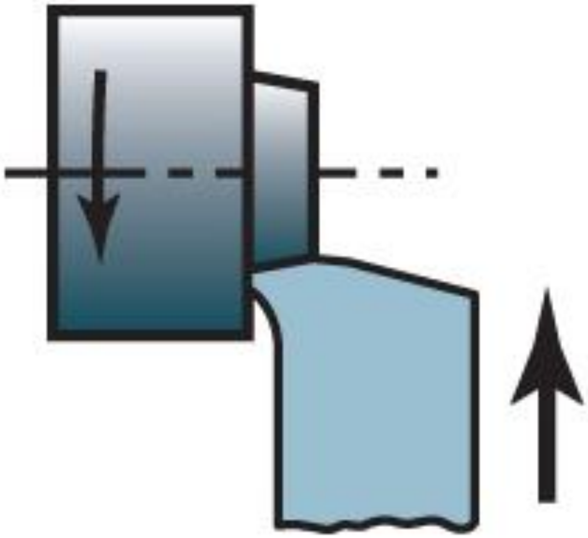


(c) Profiling

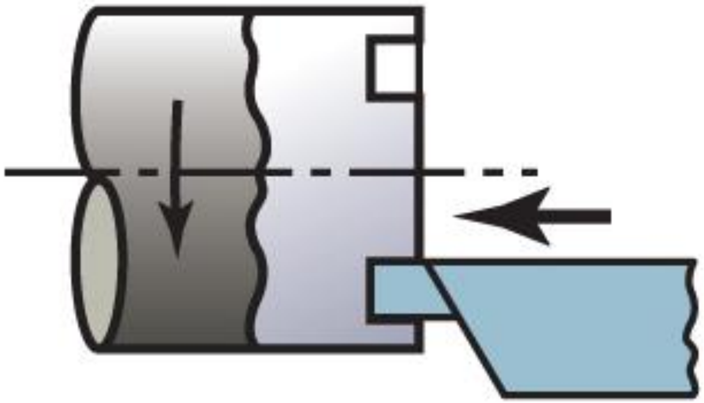


(d) Turning and external grooving

Figure 23.1 (3 of 6)

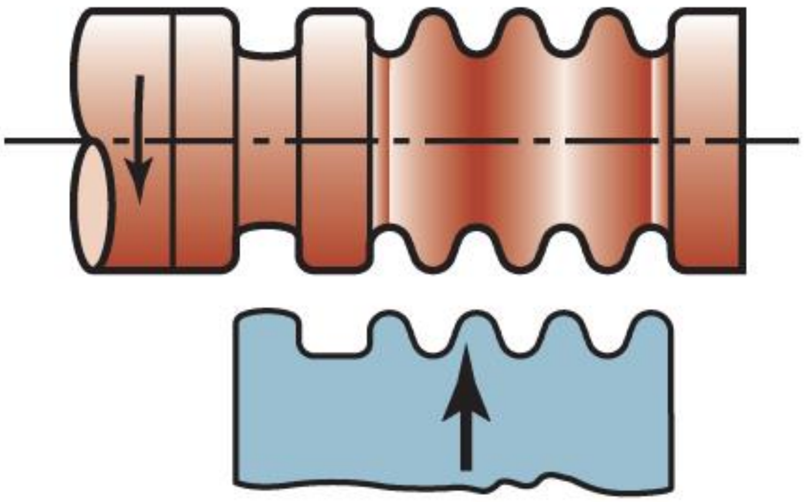


(e) Facing

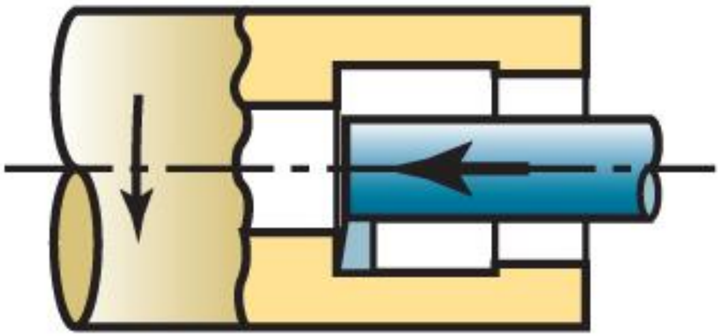


(f) Face grooving

Figure 23.1 (4 of 6)

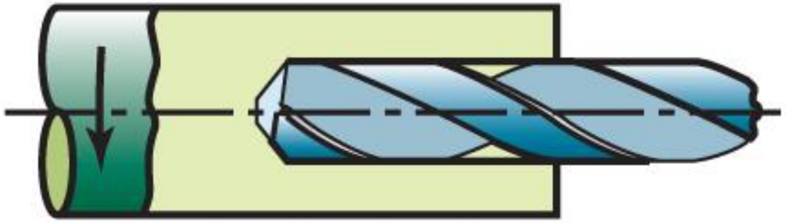


(g) Cutting with a form tool

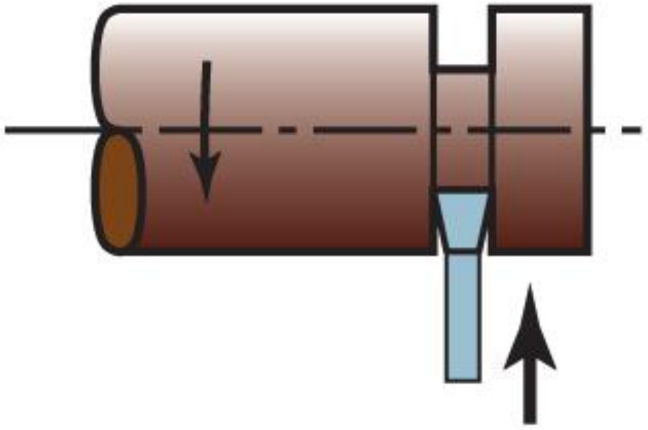


(h) Boring and internal grooving

Figure 23.1 (5 of 6)

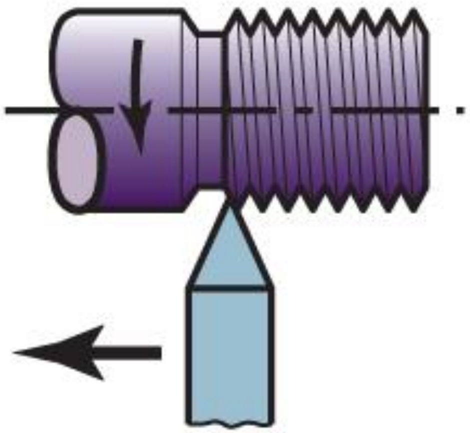


(i) Drilling

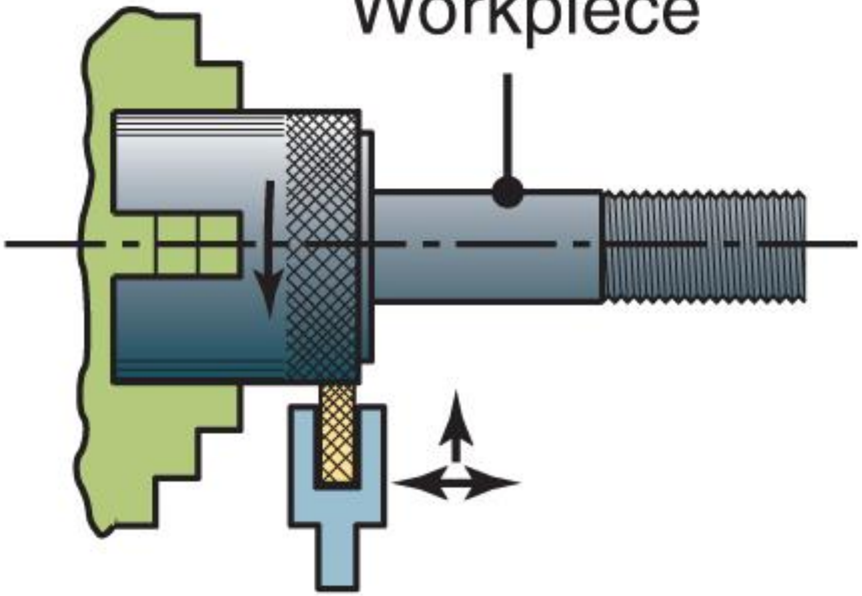


(j) Cutting off

Figure 23.1 (6 of 6)



(k) Threading



(l) Knurling

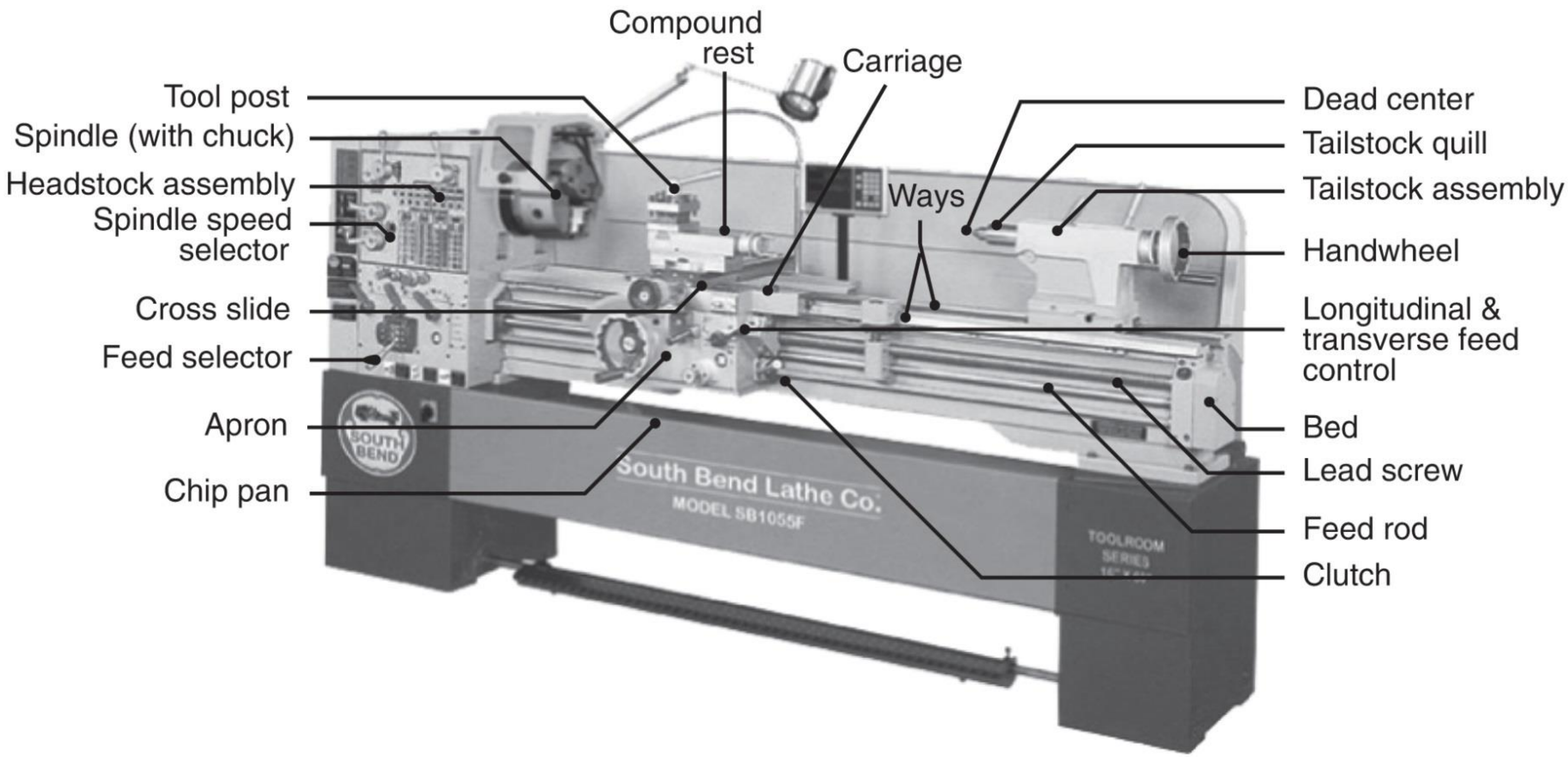
Table 23.1

General Characteristics of Machining Processes and Typical Dimensional Tolerances.

Process	Characteristics	Typical dimensional tolerances, ±mm (in.)
Turning	Turning and facing operations on all types of materials, uses single-point or form tools; engine lathes require skilled labor; low production rate (but medium-to-high rate with turret lathes and automatic machines) requiring less skilled labor	Fine: 0.025–0.13 (0.001–0.005) Rough: 0.13 (0.005)
Boring	Internal surfaces or profiles with characteristics similar to turning; stiffness of boring bar important to avoid chatter	0.025 (0.001)
Drilling	Round holes of various sizes and depths; high production rate; labor skill required depends on hole location and accuracy specified; requires boring and reaming for improved accuracy	0.075 (0.003)
Milling	Wide variety of shapes involving contours, flat surfaces, and slots; versatile; low-to-medium production rate; requires skilled labor	0.13–0.25 (0.005–0.01)
Planing	Large flat surfaces and straight contour profiles on long workpieces, low-quantity production, labor skill required depends on part shape	0.08–0.13 (0.003–0.005)
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; low-quantity production; labor skill required depends on part shape	0.05–0.13 (0.002–0.003)
Broaching	External and internal surfaces, slots, and contours; good surface finish; costly tooling; high production rate; labor skill required depends on part shape	0.025–0.15 (0.0010–0.006)
Sawing	Straight and contour cuts on flat or structural shapes; not suitable for hard materials unless saw has carbide teeth or is coated with diamond; low production rate; generally low labor skill	0.8 (0.03)

Figure 23.2

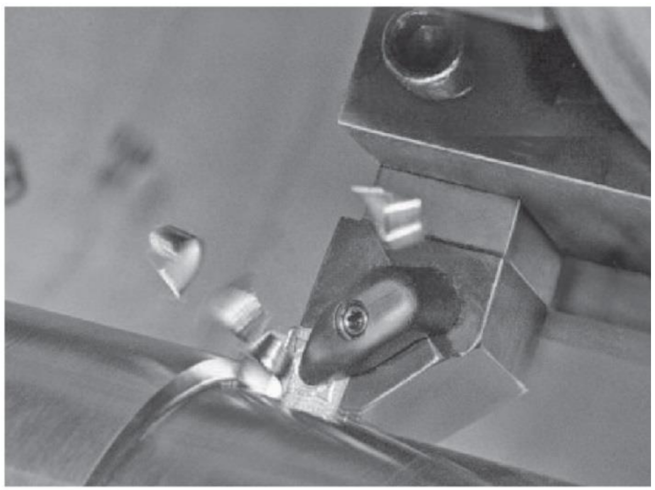
General view of a typical lathe, showing various components.



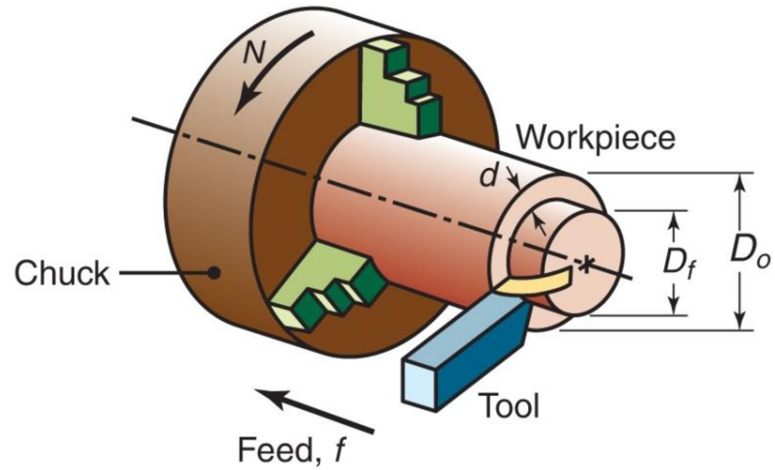
Source: Courtesy of South Bend Lathe Co.

Figure 23.3

(a) Photograph of a turning operation, showing insert and discontinuous chips. The cutting tool is traveling from right to left in this photograph, (b) Schematic illustration of the basic turning operation, showing depth of cut, *d*; feed, *f*; and spindle rotational speed, *N*, in rev/min. The cutting speed is the surface speed of the workpiece at the tool tip.



(a)



(b)

Figure 23.11

(a) A computer-numerical-control lathe with two turrets, (b) A typical turret equipped with 10 tools, some of which are powered.

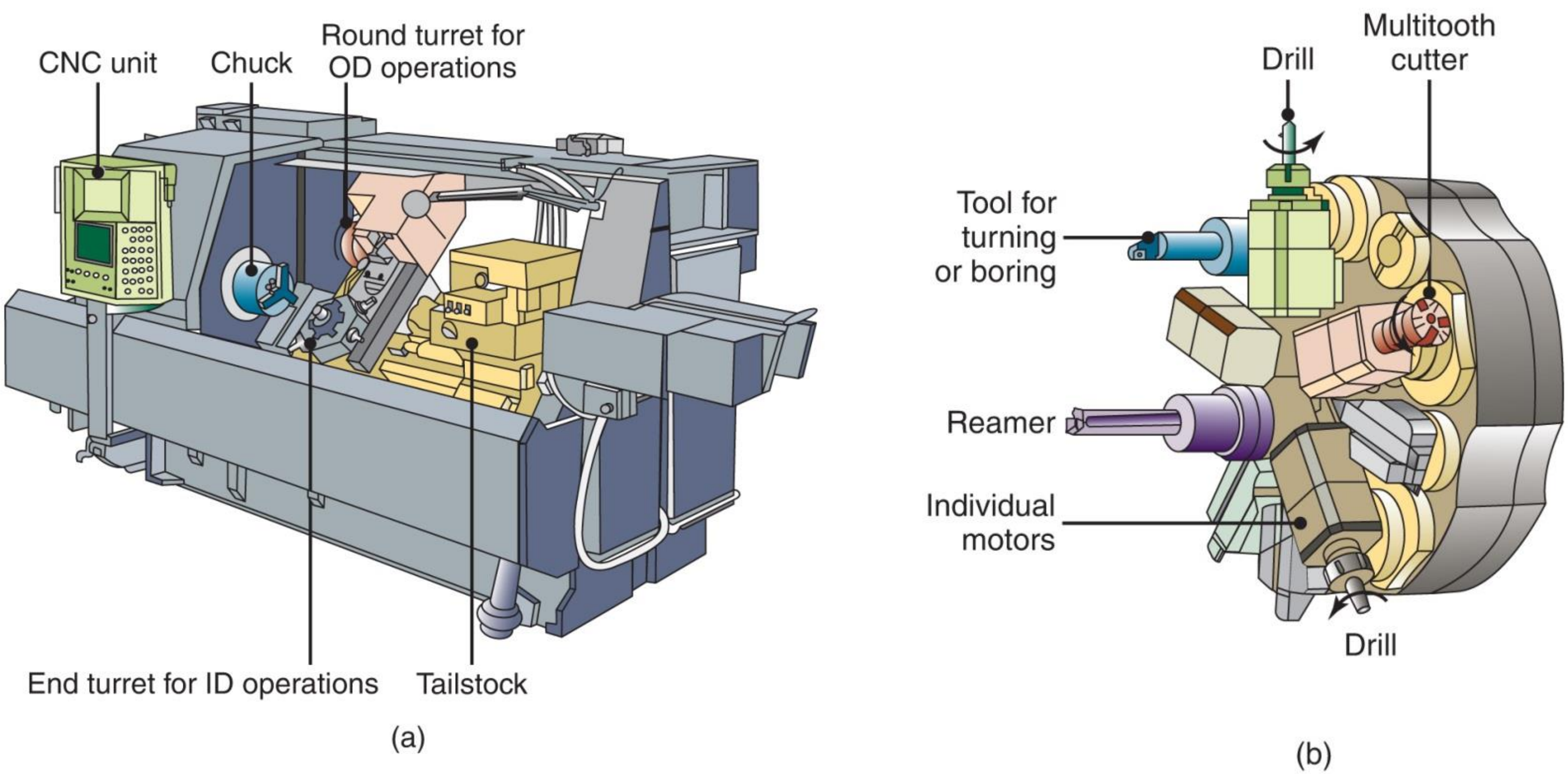


Table 23.9

Typical Production Rates for Various Machining Operations.

Operation	Rate
Turning	
Engine lathe	Very low to low
Tracer lathe	Low to medium
Turret lathe	Low to medium
Computer-controlled lathe	Low to medium
Single-spindle chuckers	Medium to high
Multiple-spindle chuckers	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 1 or more parts per hour, *medium* is approximately 100 parts per hour, and *very high* is 1000 or more parts per hour.

Figure 23.14 (1 of 2)

The range of surface roughnesses obtained in various processes; note the wide range within each group, especially in turning and boring.

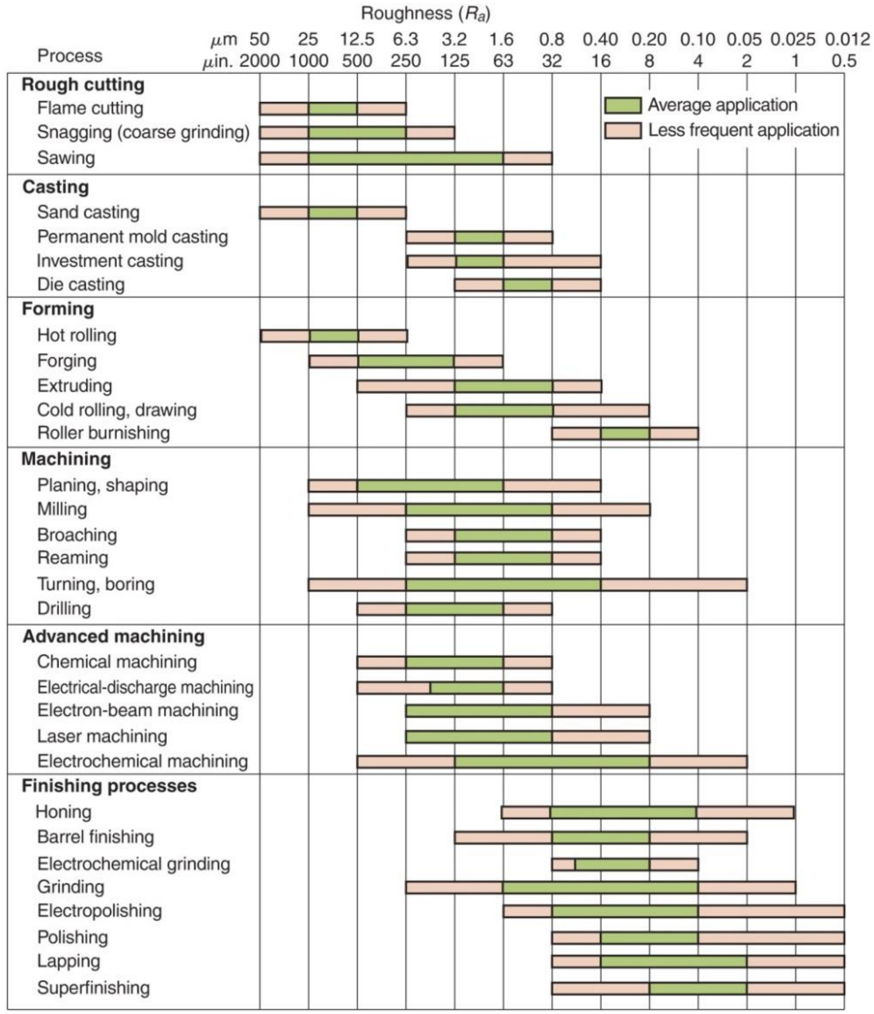


Figure 23.15 (1 of 2)

Range of dimensional tolerances in various machining processes as a function of workpiece size. Note that there is one order of magnitude difference between small and large workpieces.

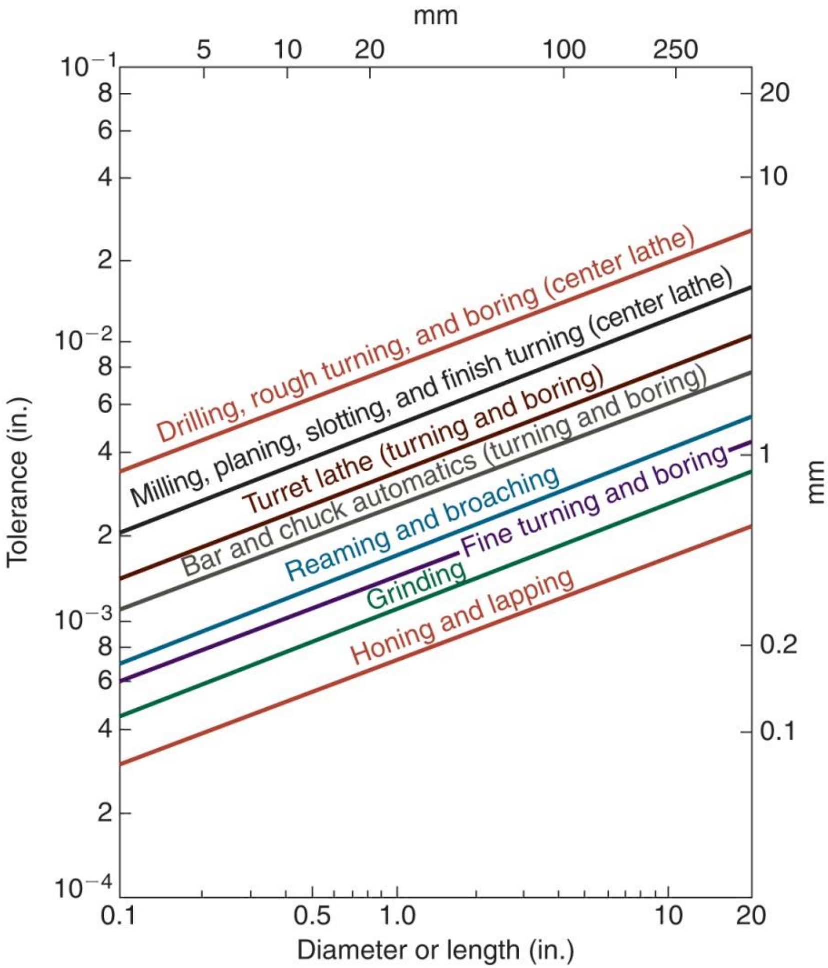


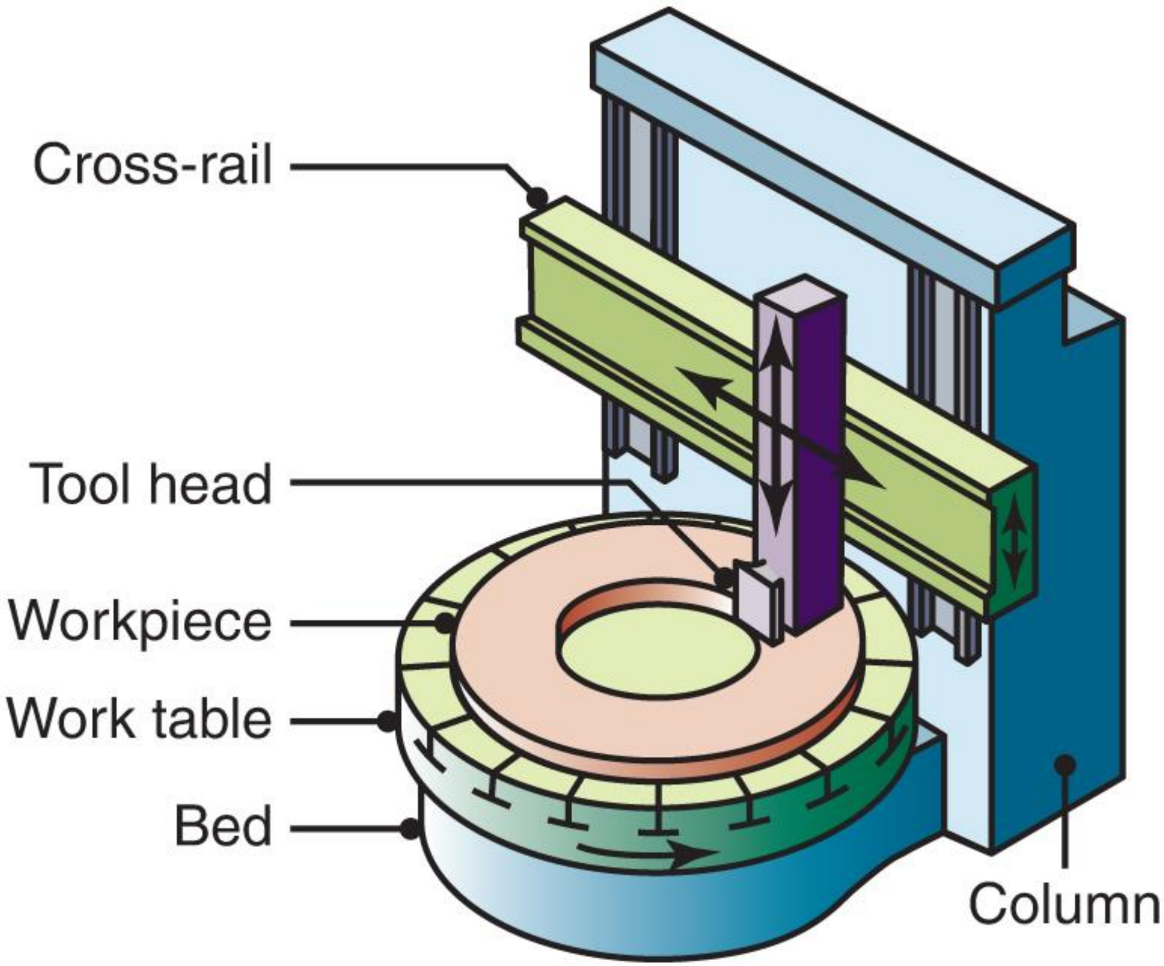
Table 23.10

General Troubleshooting Guide for Turning Operations.

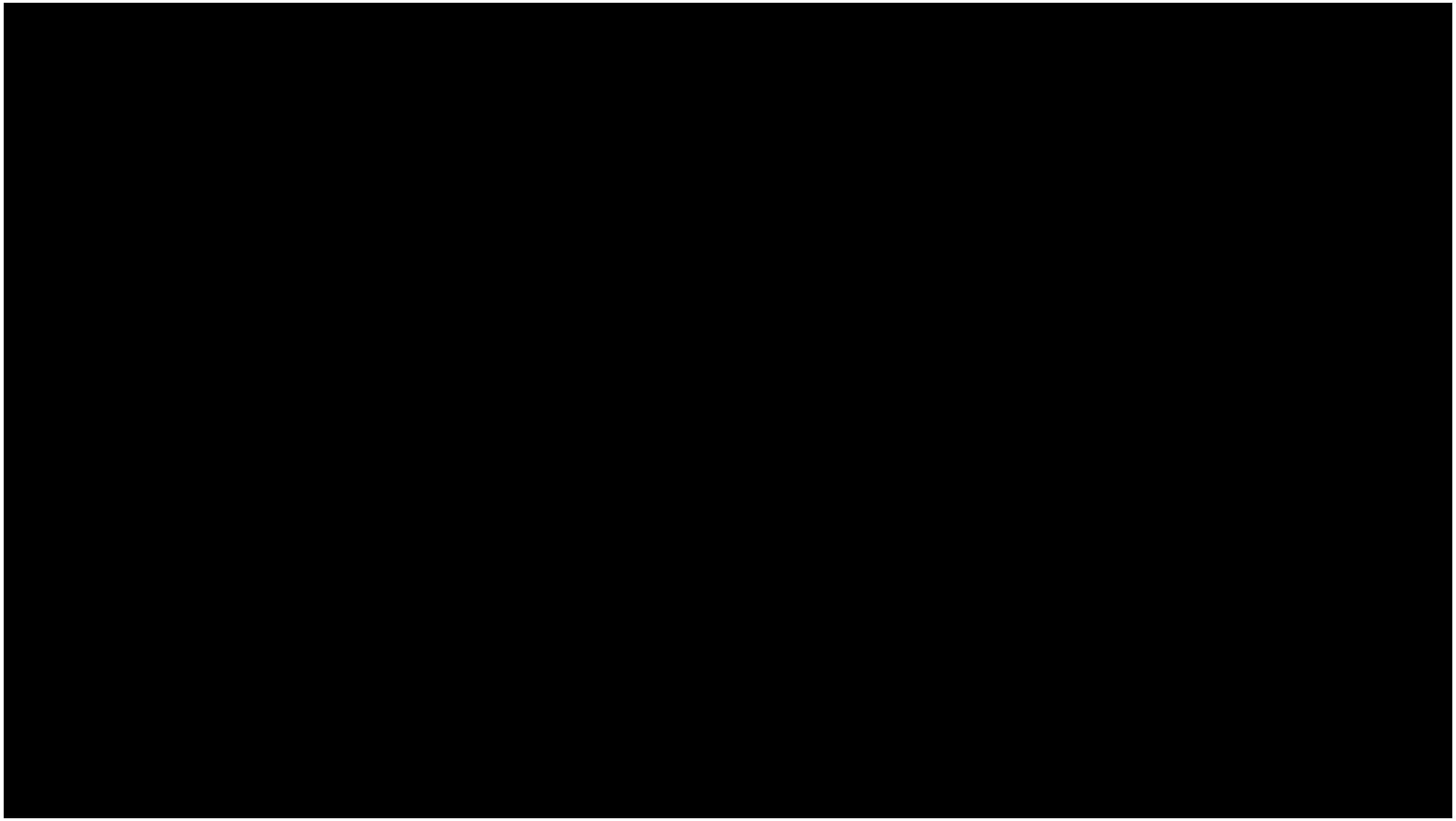
Problem	Probable causes
Tool breakage	Tool material lacks toughness, improper tool angles, machine tool lacks stiffness, worn bearings and machine components, machining parameters too high
Excessive tool wear	Machining parameters too high, improper tool material, ineffective cutting fluid, improper tool angles
Rough surface finish	Built-up edge on tool; feed too high; tool too sharp, chipped, or worn; vibration and chatter
Dimensional variability	Lack of stiffness of machine tool and work-holding devices, excessive temperature rise, tool wear
Tool chatter	Lack of stiffness of machine tool and work-holding devices, excessive tool overhang, machining parameters not set properly

Figure 23.19

Schematic illustration of a vertical boring mill. Such a machine can accommodate workpiece sizes as large as 2.5 m (98 in.) in diameter.



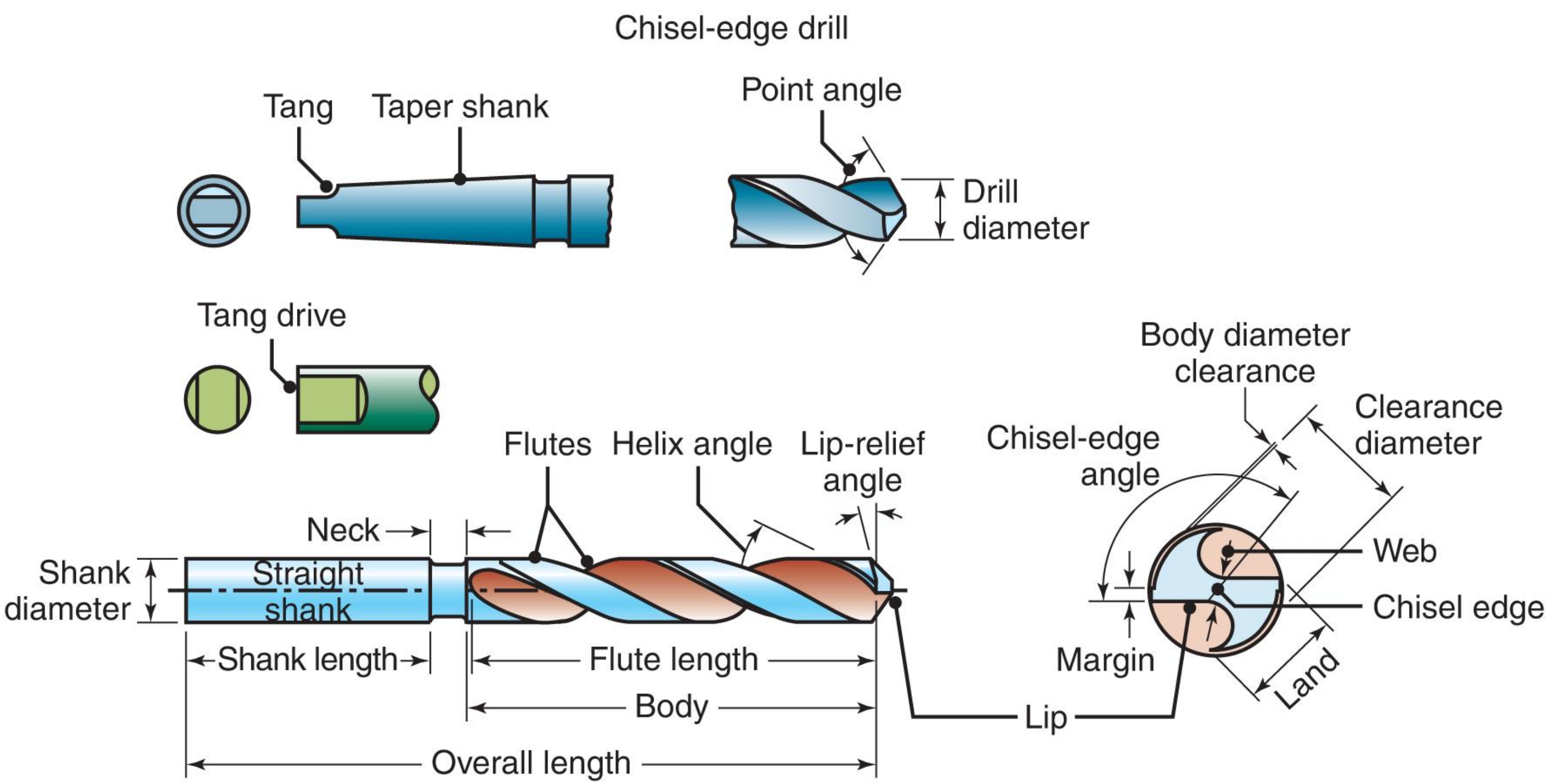
Vertical Boring Machine



https://youtu.be/daqYyzPC1Rs

Figure 23.20 (1 of 2)

Two common types of drills: (a) Chisel-edge 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 the workpiece. Drills with four margins (*double-margin*) are available for improved guidance and accuracy. Drills can have chip-breaker features.

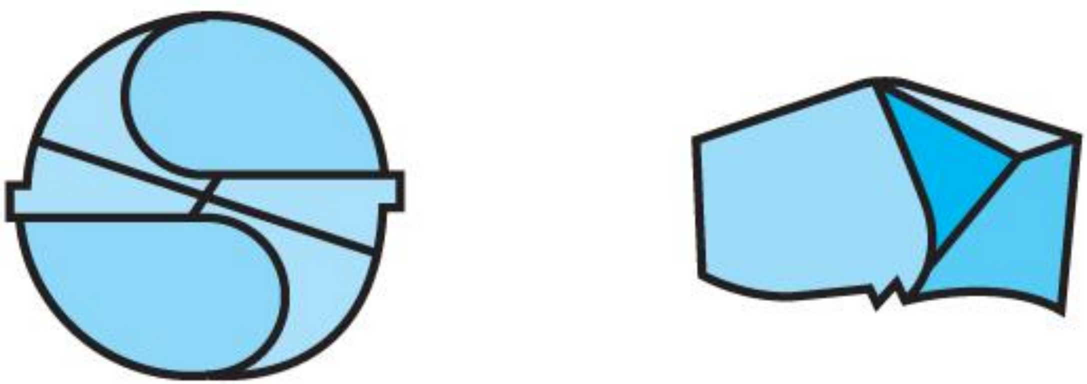


(a)

Figure 23.20 (2 of 2)

Two common types of drills: (b) Crankshaft drill. These drills have good centering ability, and because the chips tend to break up easily, crankshaft drills are suitable for producing deep holes.

Crankshaft-point drill



(b)

Table 23.13

General Troubleshooting Guide for Drilling Operations.

Problem	Probable causes
Drill breakage	Dull drill, drill seizing in hole because of chips clogging flutes, feed too high, lip relief angle too small
Excessive drill wear	Cutting speed too high, ineffective cutting fluid, rake angle too high, drill burned and strength lost when drill was sharpened
Tapered hole	Drill misaligned or bent, lips not equal, web not central
Oversize hole	Same as previous entry, machine spindle loose, chisel edge not central, side force on workpiece
Poor hole surface finish	Dull drill, ineffective cutting fluid, welding of workpiece material on drill margin, improperly ground drill, improper alignment

Figure 24.1

Typical parts and shapes that can be produced with the machining processes described in this chapter.

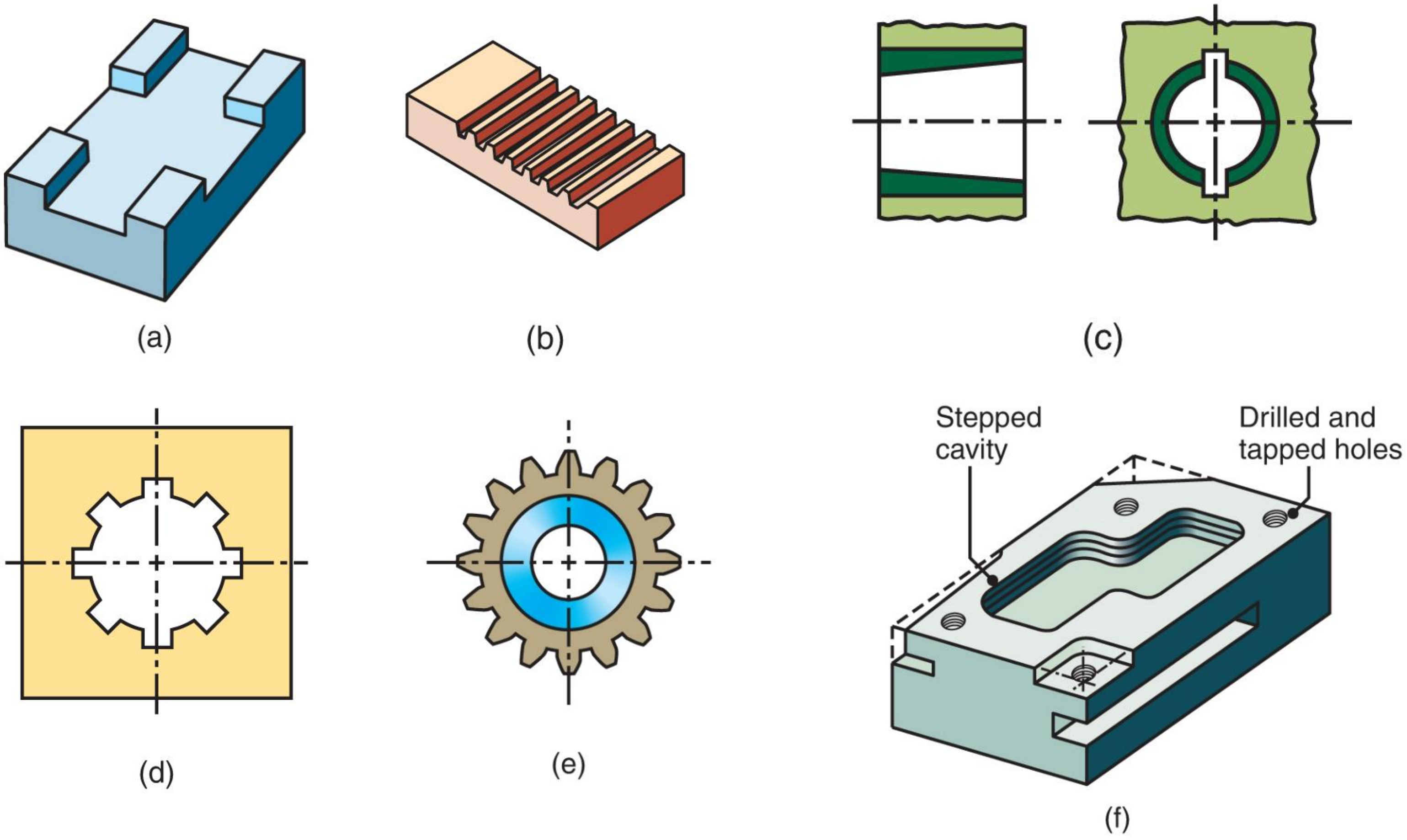


Figure 24.2 (1 of 6)

Some basic types of milling cutters and milling operations. (a) Face milling, (b) end or shoulder milling, (c) profile milling, (d) slot milling, (e) slot and groove milling, (f) thread milling and tapping

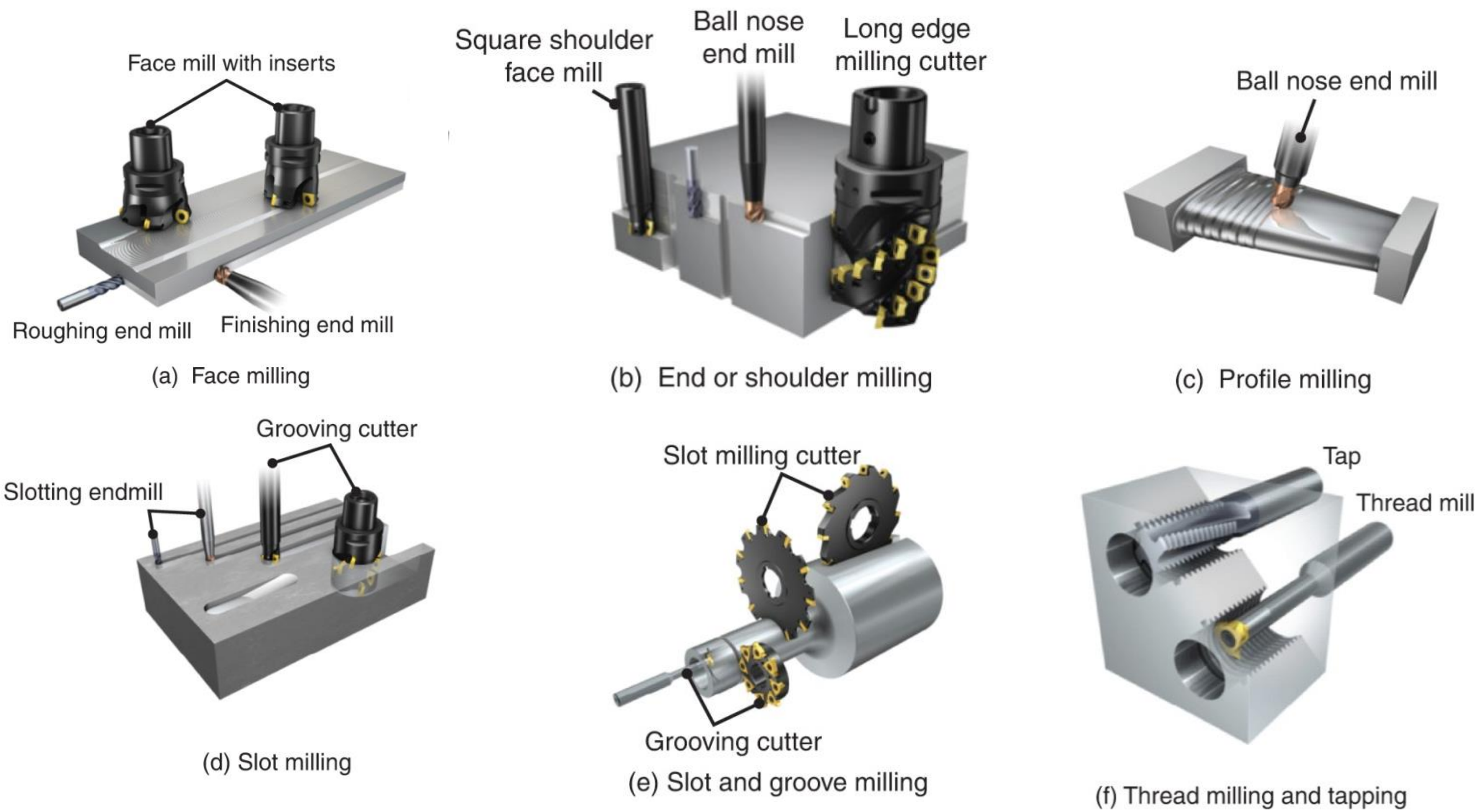


Figure 24.3

Photograph of the cutting action of a milling cutter that uses a number of inserts to remove metal in the form of chips.

Source: Courtesy of Sandvik Coromant.

Figure 24.4

Schematic illustration of peripheral milling.

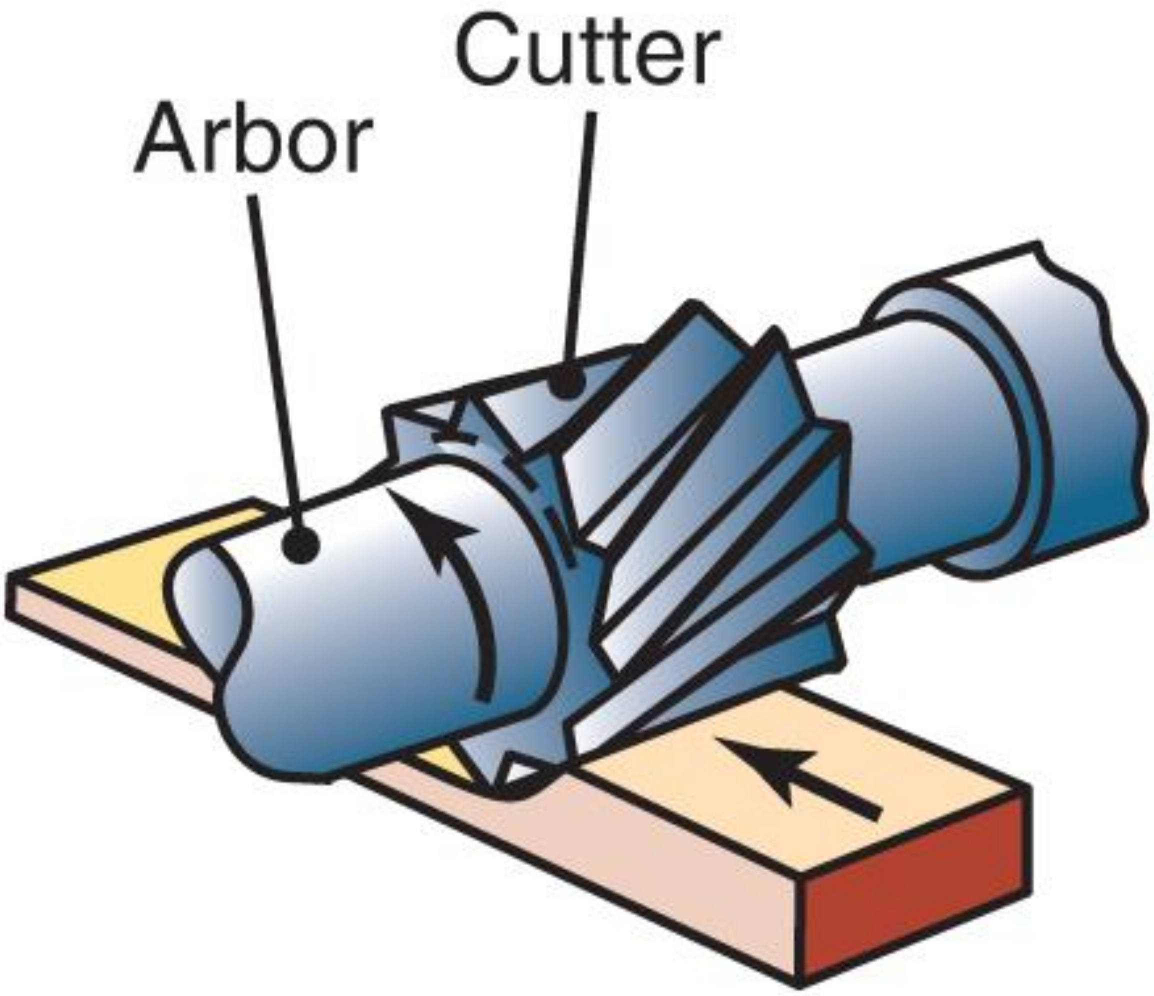


Figure 24.5 (1 of 3)

(a) Schematic illustration of 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.

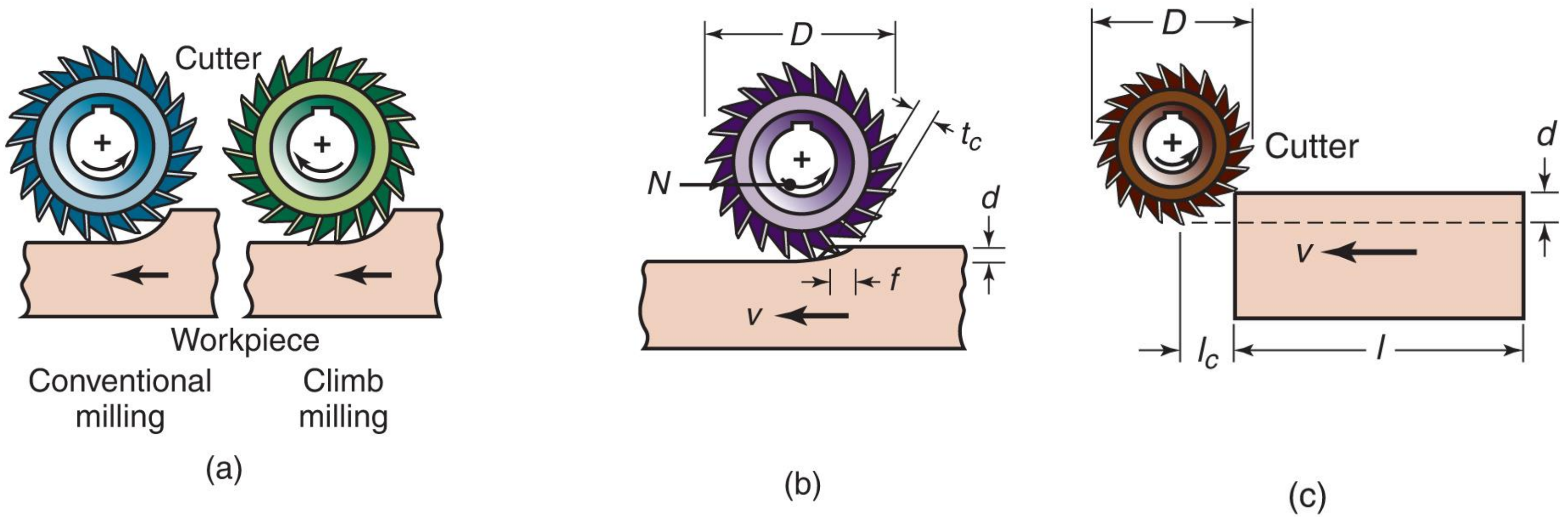


Figure 24.7

A face-milling cutter with indexable inserts.

Source: Courtesy of Ingersoll Cutting Tool Company.

Figure 24.8 (1 of 4)

Schematic illustration of the effect of insert shape on feed marks on a face-milled surface: (a) small corner radius, (b) corner flat on insert, (c) wiper, consisting of a small radius followed by a large radius, resulting in smoother feed marks, (d) Feed marks due to various insert shapes

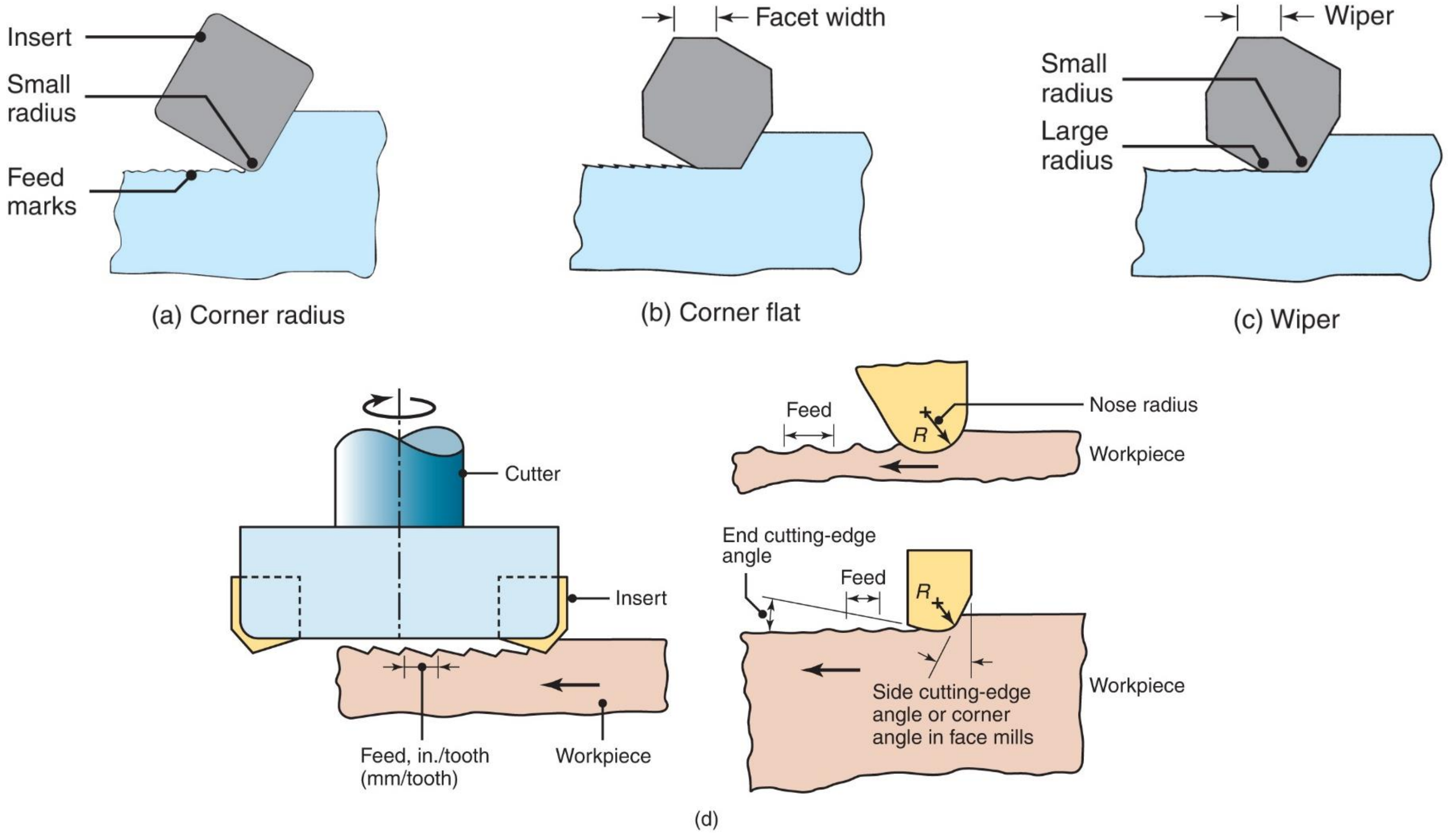


Figure 24.14

Cutters for (a) straddle milling, (b) form milling, (c) slotting.

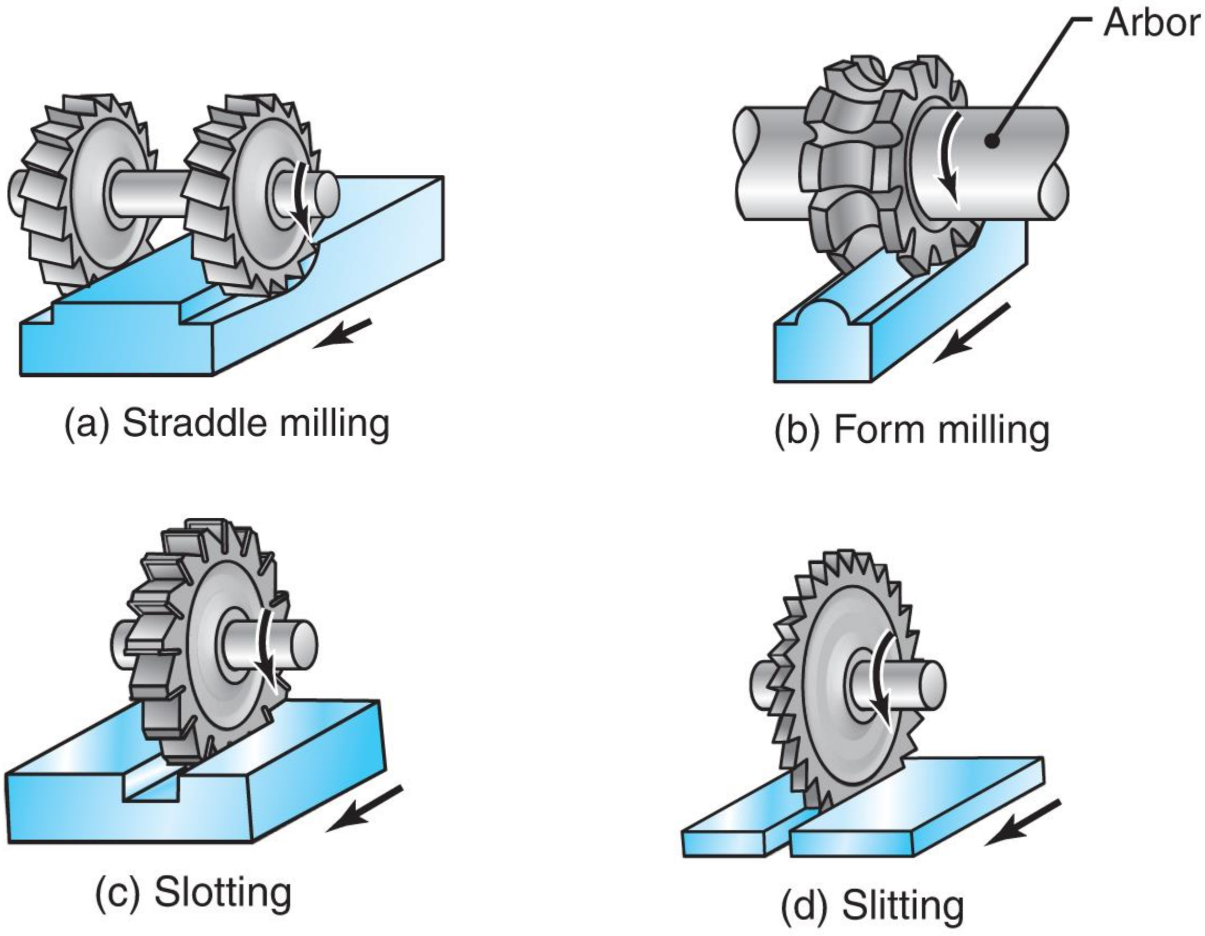


Figure 24.15

(a) T-slot cutting with a milling cutter, (b) A shell mill.

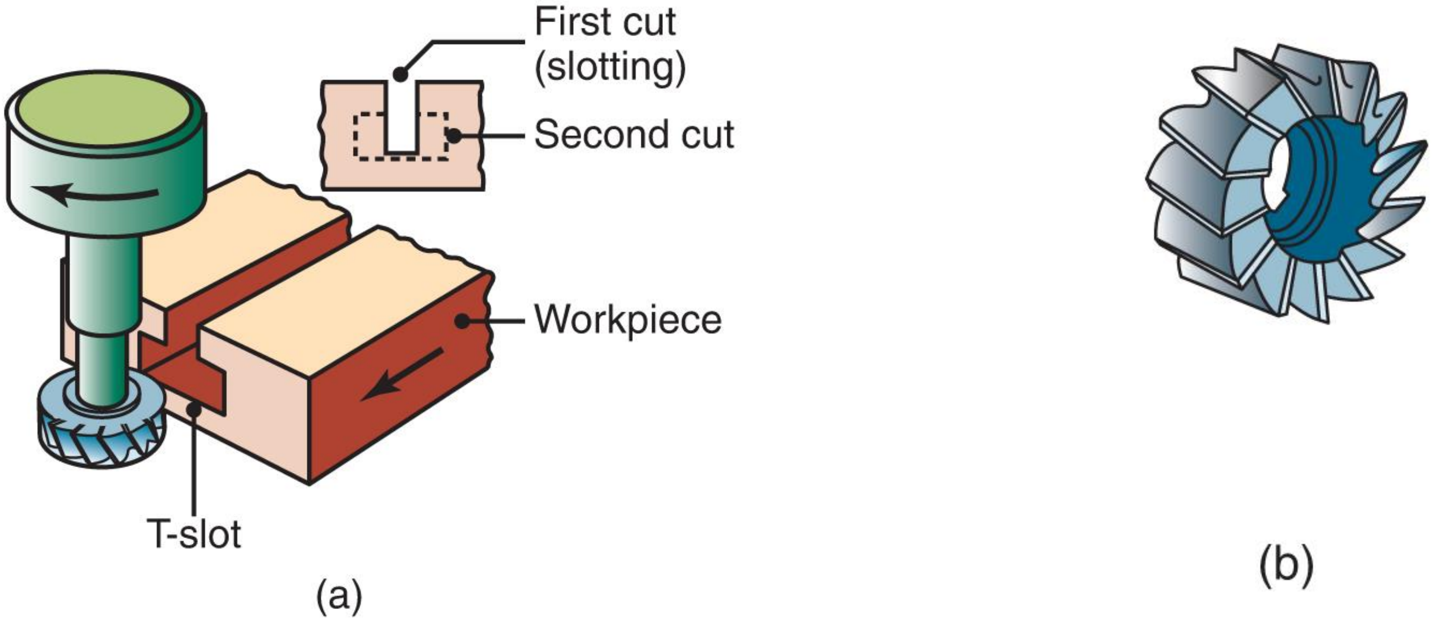


Table 24.2 (1 of 2)

General Recommendations for Milling Operations. Note that these values are for a particular machining geometry and are often exceeded in practice.

		General-purpose starting conditions		Range of conditions	
Material	Cutting tool	Feed mm/tooth (in./tooth)	Speed m/min (ft/min)	Feed mm/tooth (in./tooth)	Speed m/min (ft/min)
Low-carbon and free-machining steels	Uncoated carbide, coated carbide, cermets	0.13-0.20 (0.005-0.008)	100-472 (320-1550)	0.085-0.38 (0.003-0.015)	90-425 (300-1400)
Alloy steels					
Soft	Uncoated, coated cermets	0.10–0.18 (0.004–0.007)	100–260 (360–860)	0.08–0.30 (0.003–0.012)	60–370 (200–1200)
Hard	Cermets, PcBN	0.10–0.15 (0.004–0.006)	90–220 (310–720)	0.08–0.25 *0.003–0.010)	75–460 (250–1500)
Cast iron, gray					
Soft	Uncoated, coated, cermets, SiN	0.10–0.20 (0.004–0.008)	160–440 (530–1440)	0.08–0.38 (0.003–0.015)	90–1370 (300–4500)
Hard	Cermets, SiN, PcBN	0.10–0.20 (0.004–0.008)	120–300 (400–960)	0.08–0.38 (0.003–0.015)	90–460 (300–1500)

Source: Based on data from Kennametal, Inc.

Note: Depths of cut, *d*, usually are in the range of 1–8 mm (0.04 to 0.3 in.). PcBN: polycrystalline cubic-boron nitride. PCD: polycrystalline diamond. See also Table 23.4 for range of cutting speeds within tool material groups.

Table 24.2 (2 of 2)

General Recommendations for Milling Operations. Note that these values are for a particular machining geometry and are often exceeded in practice.

Stainless steel, Austenitic	Uncoated, coated, cermets	0.13–0.18 (0.005–0.007)	120–370 (370–680)	0.08–0.38 (0.003–0.015)	90–500 (300–1800)
High-temperature alloys Nickel based	Uncoated, coated, cermets, SiN, PcBN	0.10–0.18 (0.004–0.007)	30–370 (100–1200)	0.08–0.38 (0.003–0.015)	30–550 (90–1800)
Titanium alloys	Uncoated, coated, cermets	0.13–0.15 (0.005–0.006)	50–60 (175–200)	0.08–0.38 (0.003–0.015)	40–140 (125–450)
Aluminum alloys					
Free machining	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	1200–1460 (3920–4790)	0.08–0.46 (0.003–0.018)	300–3000 (1000–10,000)
High silicon	PCD	0.13 (0.005)	610 (2000)	0.08–0.38 (0.003–0.015)	370–910 (1200–3000)
Copper alloys	Uncoated, coated, PCD PCD	0.13–0.23 (0.005–0.009)	300–760 (1000–2500)	0.08–0.46 (0.003–0.018)	90–1070 (300–3500)
Plastics	Uncoated, coated, PCD PCD	0.13–0.23 (0.005–0.009)	270–460 (900–1500)	0.08–0.46 (0.003–0.018)	90–1370 (300–4500)

Source: Based on data from Kennametal, Inc.

Note: Depths of cut, *d*, usually are in the range of 1–8 mm (0.04 to 0.3 in.). PcBN: polycrystalline cubic-boron nitride. PCD: polycrystalline diamond. See also Table 23.4 for range of cutting speeds within tool material groups.

Table 24.3

General Troubleshooting Guide for Milling Operations.

Problem	Probable causes
Tool breakage	Tool material lacks toughness, improper tool angles, machining parameters too high
Excessive tool wear	Machining parameters too high, improper tool material, improper tool angles, improper cutting fluid
Rough surface finish	Feed per tooth too high, too few teeth on cutter, tool chipped or worn, built-up edge, vibration and chatter
Tolerances too broad	Lack of spindle and work holding device stiffness, excessive temperature rise, dull tool, chips clogging cutter
Workpiece surface burnished	Dull tool, depth of cut too low, radial relief angle too small
Back striking	Dull cutting tools, tilt in cutter spindle, negative tool angles
Chatter marks	Insufficient stiffness of system; external vibrations; feed, depth of cut, and width of cut too large; select stable processing parameters
Burr formation	Dull cutting edges or too much honing, incorrect angle of entry or exit, feed and depth of cut too high, incorrect insert shape
Breakout	Lead angle too low, incorrect cutting-edge geometry, incorrect angle of entry or exit, feed and depth of cut too high

Figure 24.16

Machined surface features in face milling (see also Fig. 24.8).

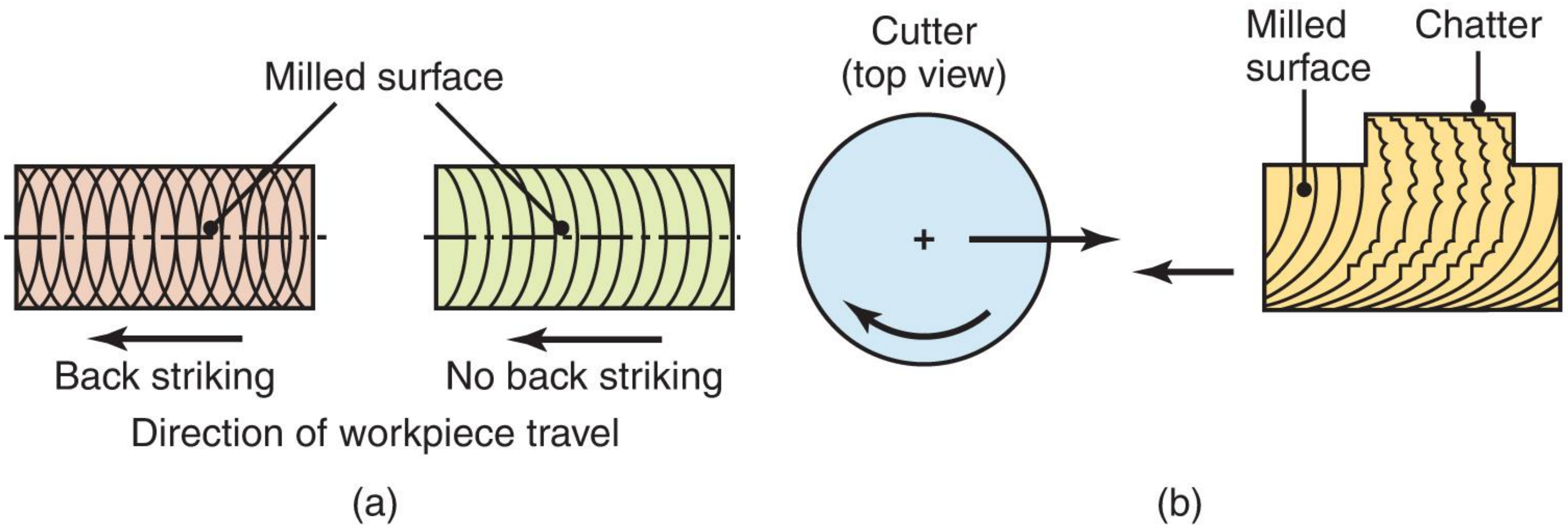


Figure 24.18

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

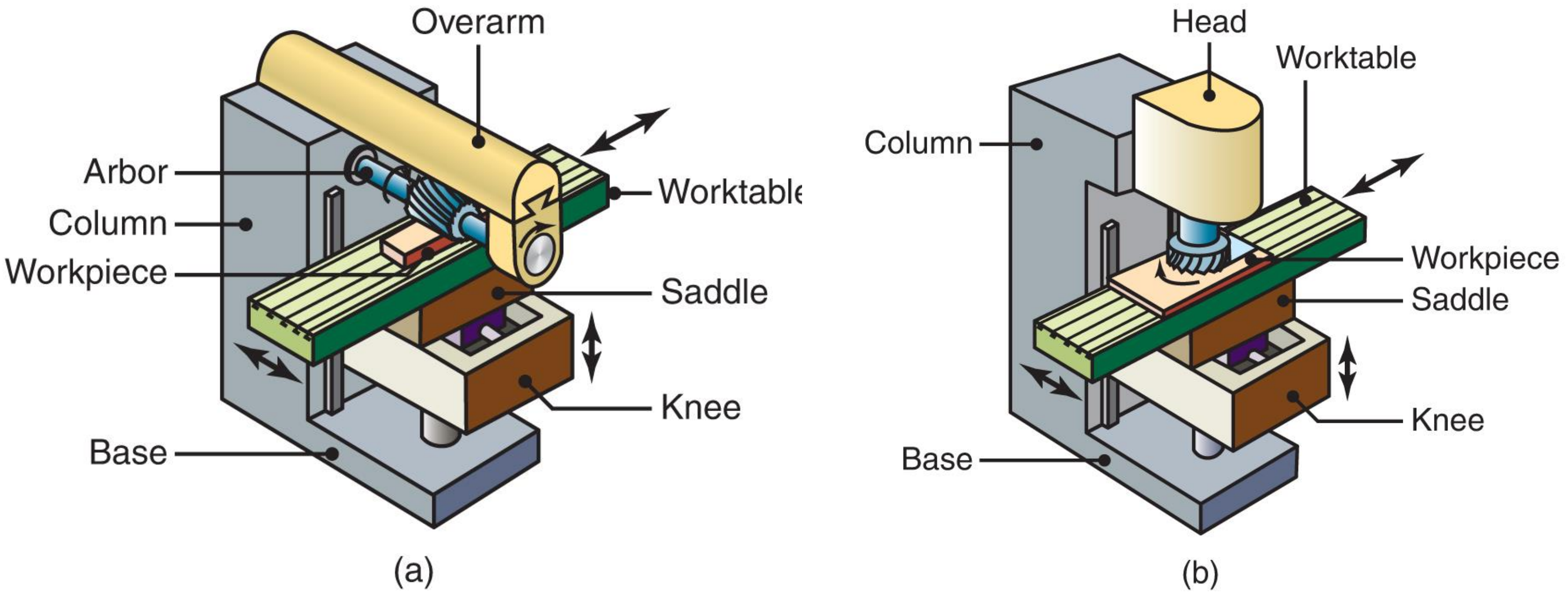


Figure 24.19

Schematic illustration of a bed-type milling machine.

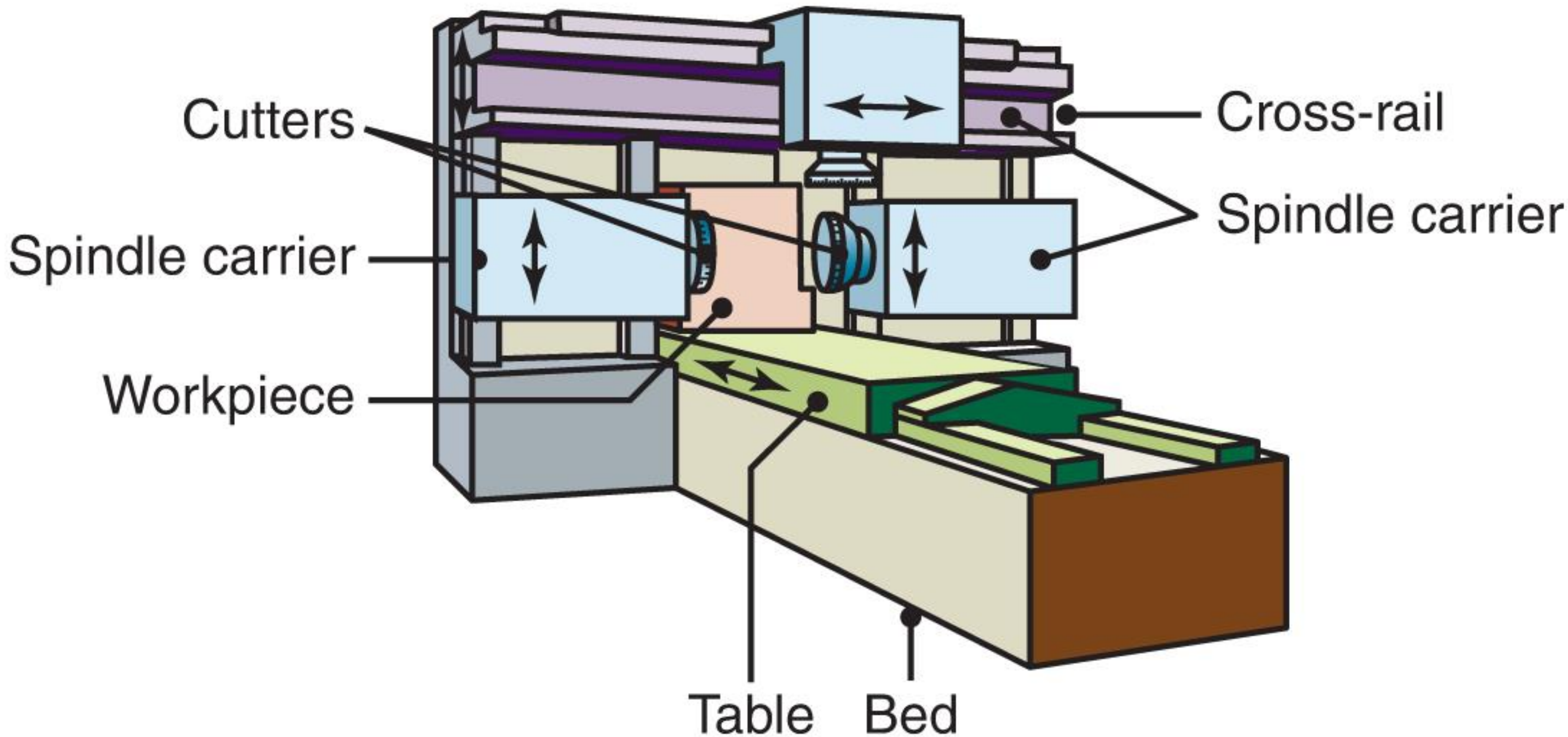
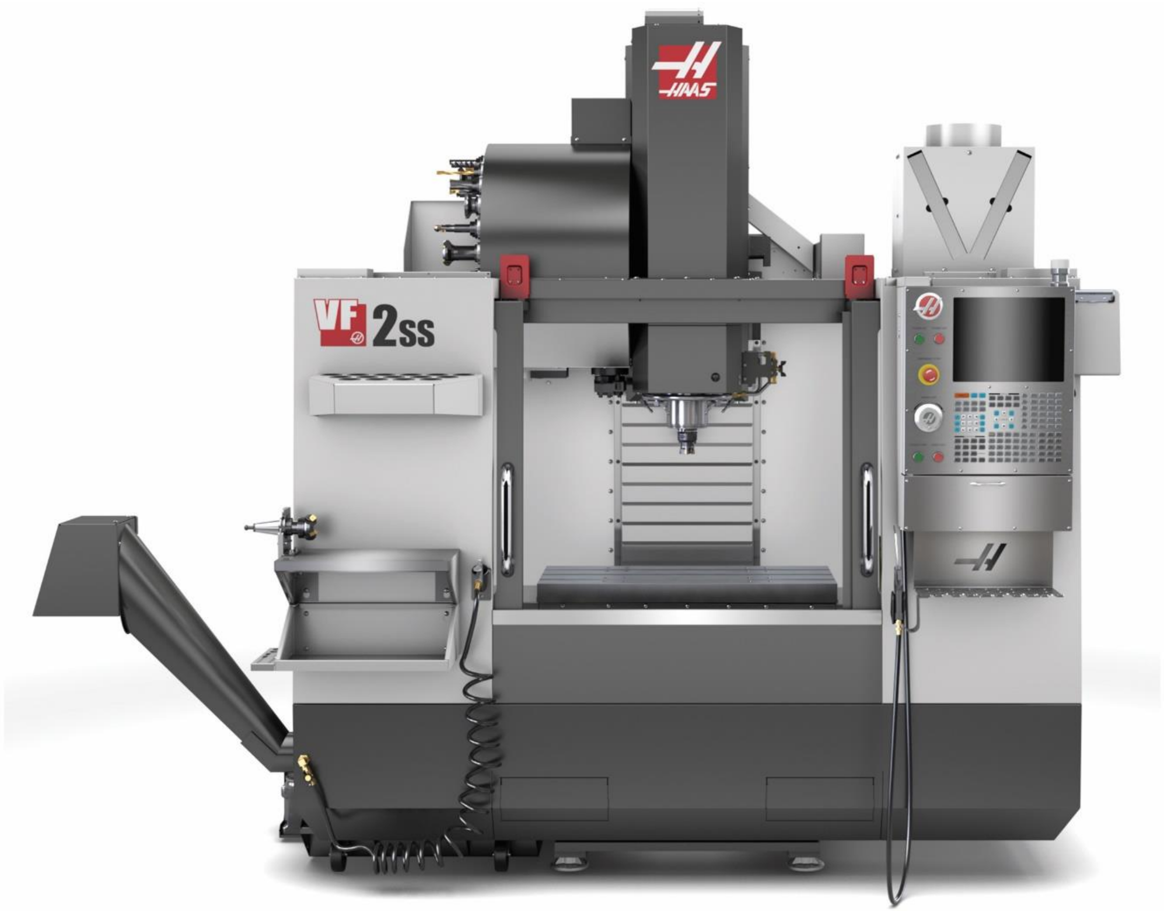


Figure 24.20

A computer numerical-control (CNC) vertical-spindle milling machine. This is one of the most versatile machine tools.



Source: Haas Automation, Inc.

Figure 24.21

Schematic illustration of a five-axis profilemilling machine. Note that there are three principal linear and two angular movements of machine components.

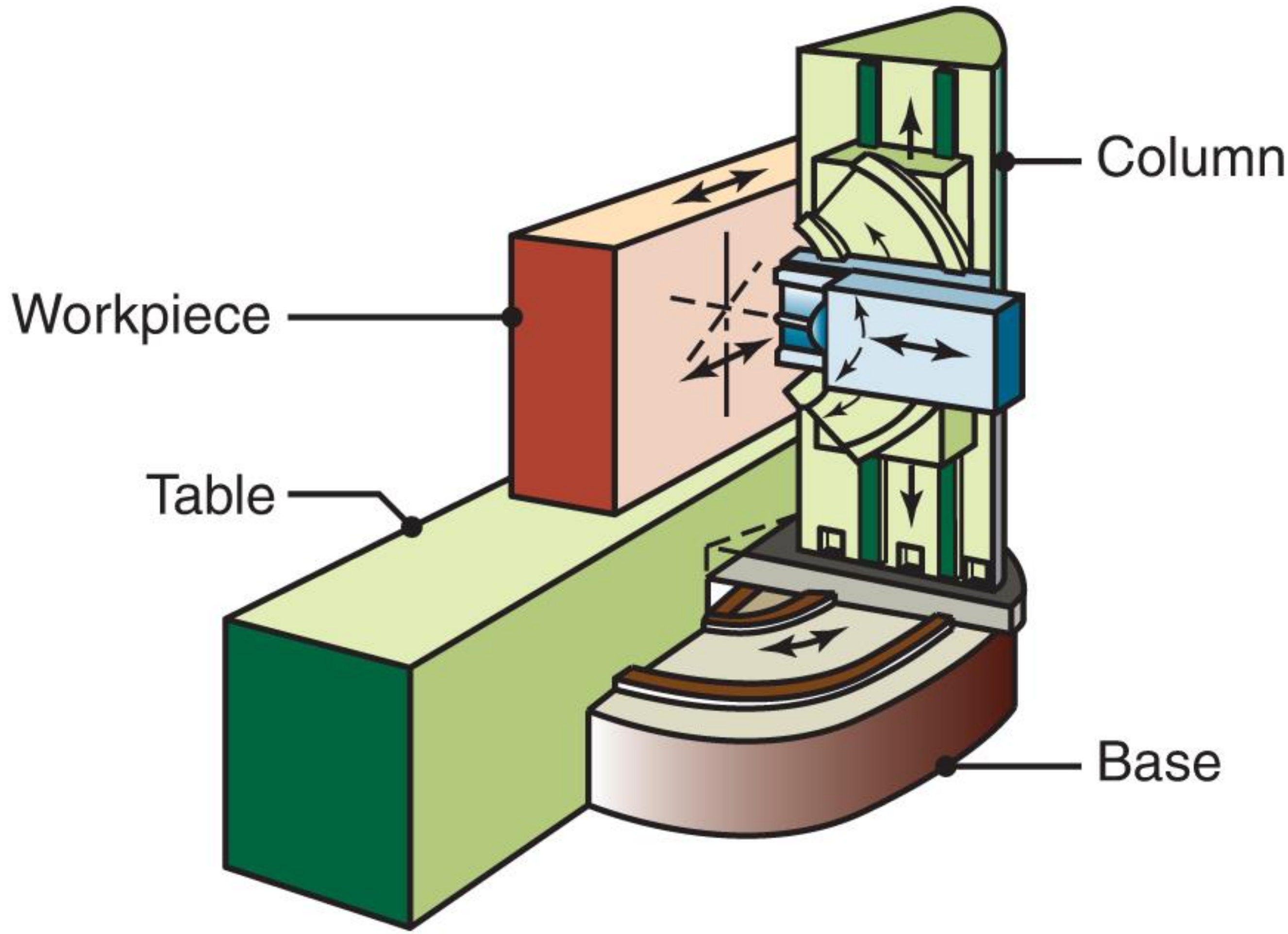


Figure 24.22

Typical parts that can be made on a planer.

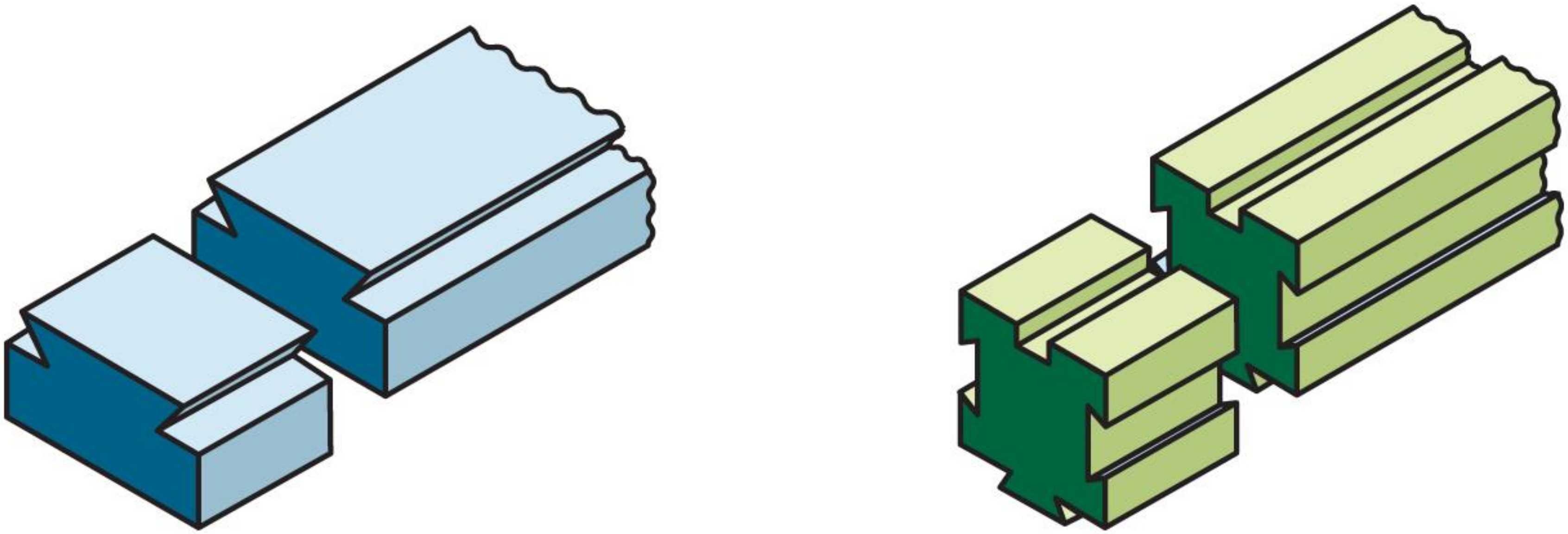
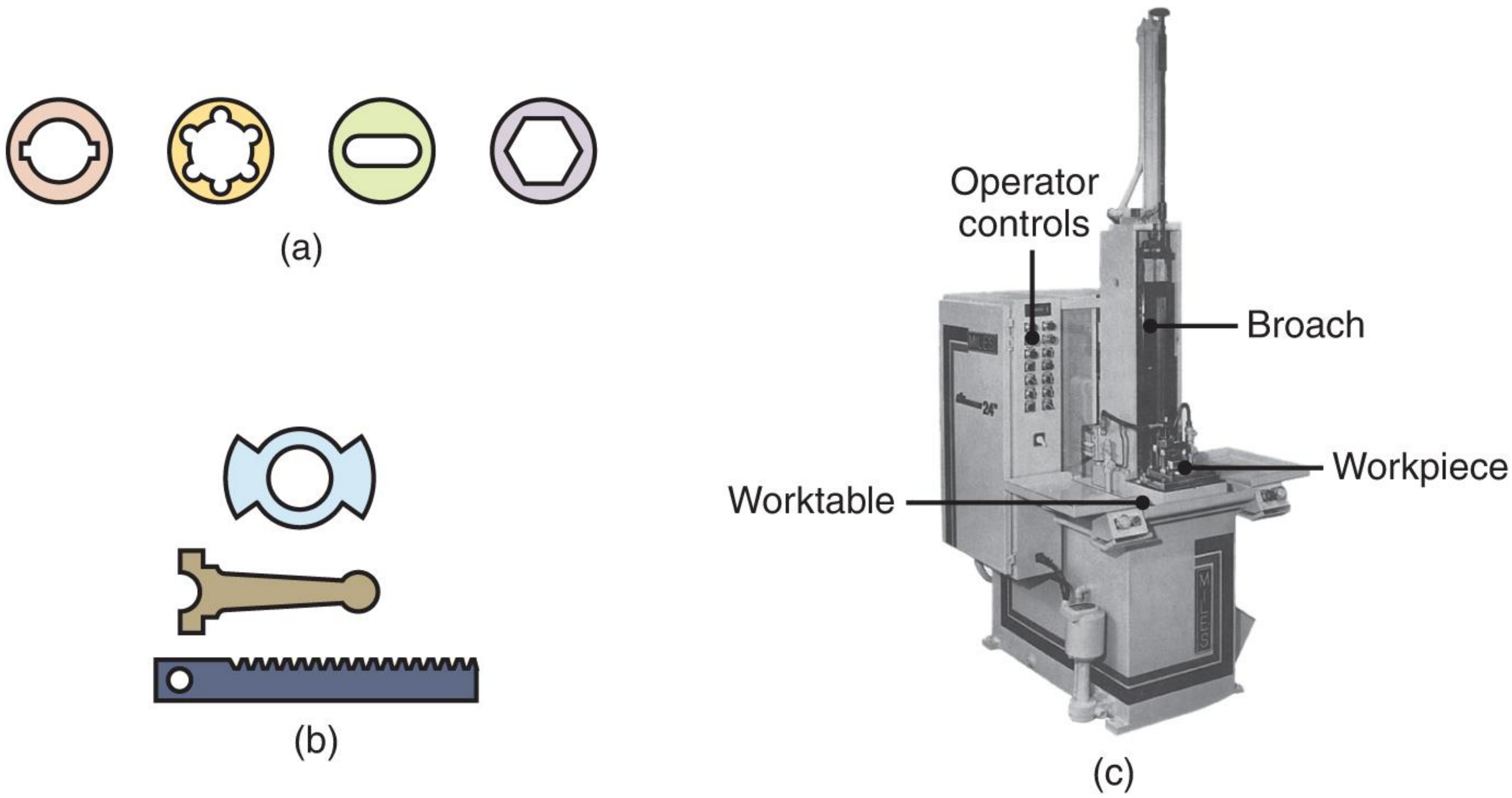


Figure 24.23

(a) Typical parts made by internal broaching, (b) Parts made by surface broaching, (c) Vertical broaching machine.



Source: (a) Courtesy of General Broach and Engineering Company.

Figure 24.24

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

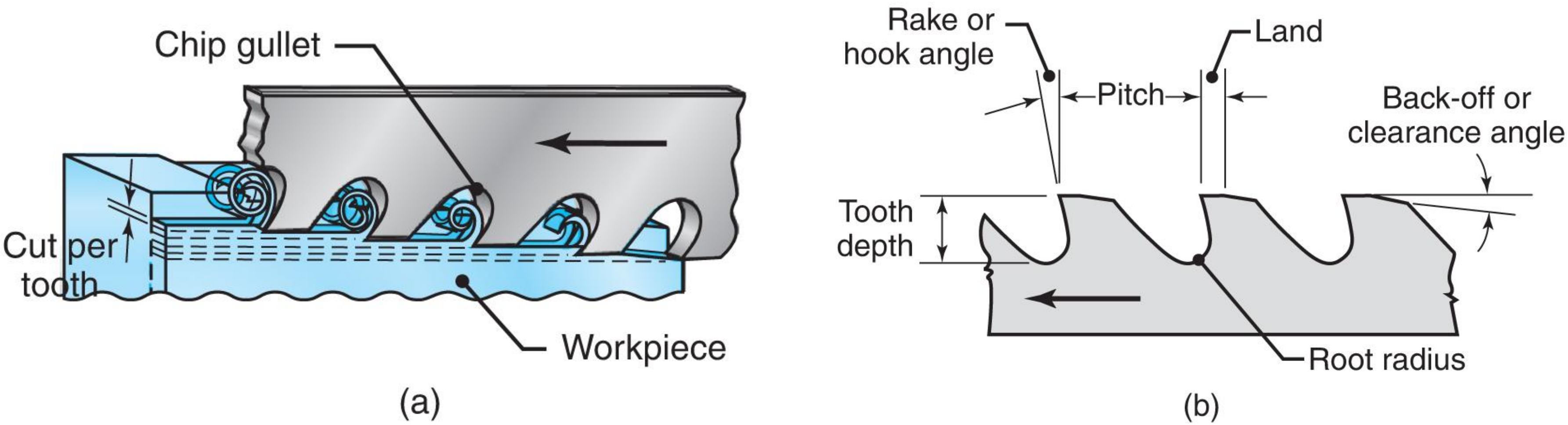


Figure 24.25 (1 of 2)

Chip breaker features on (a) a flat broach, (b) a round broach.

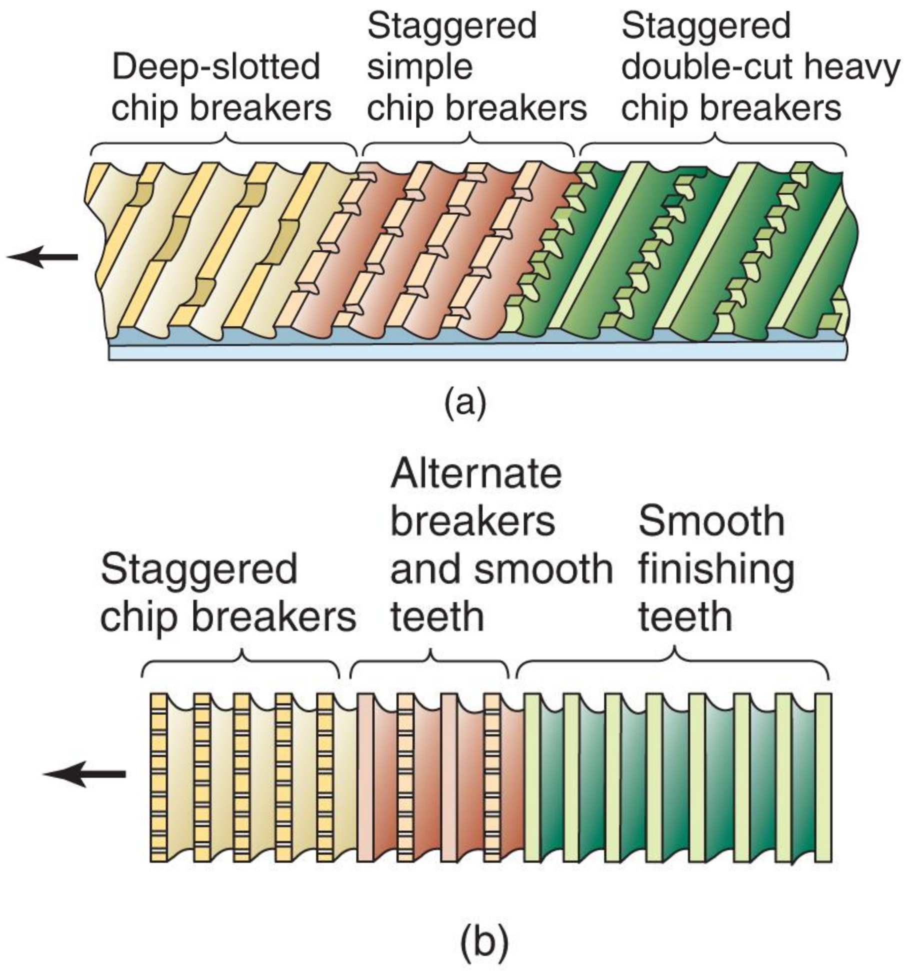
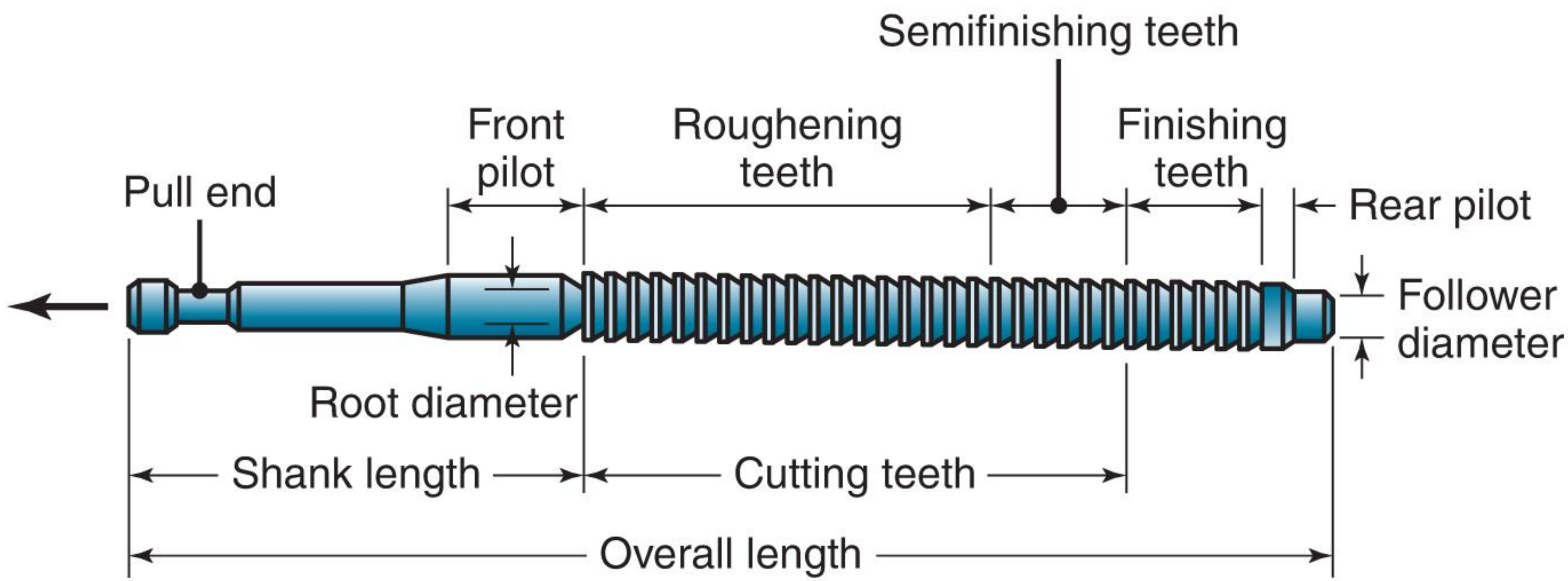
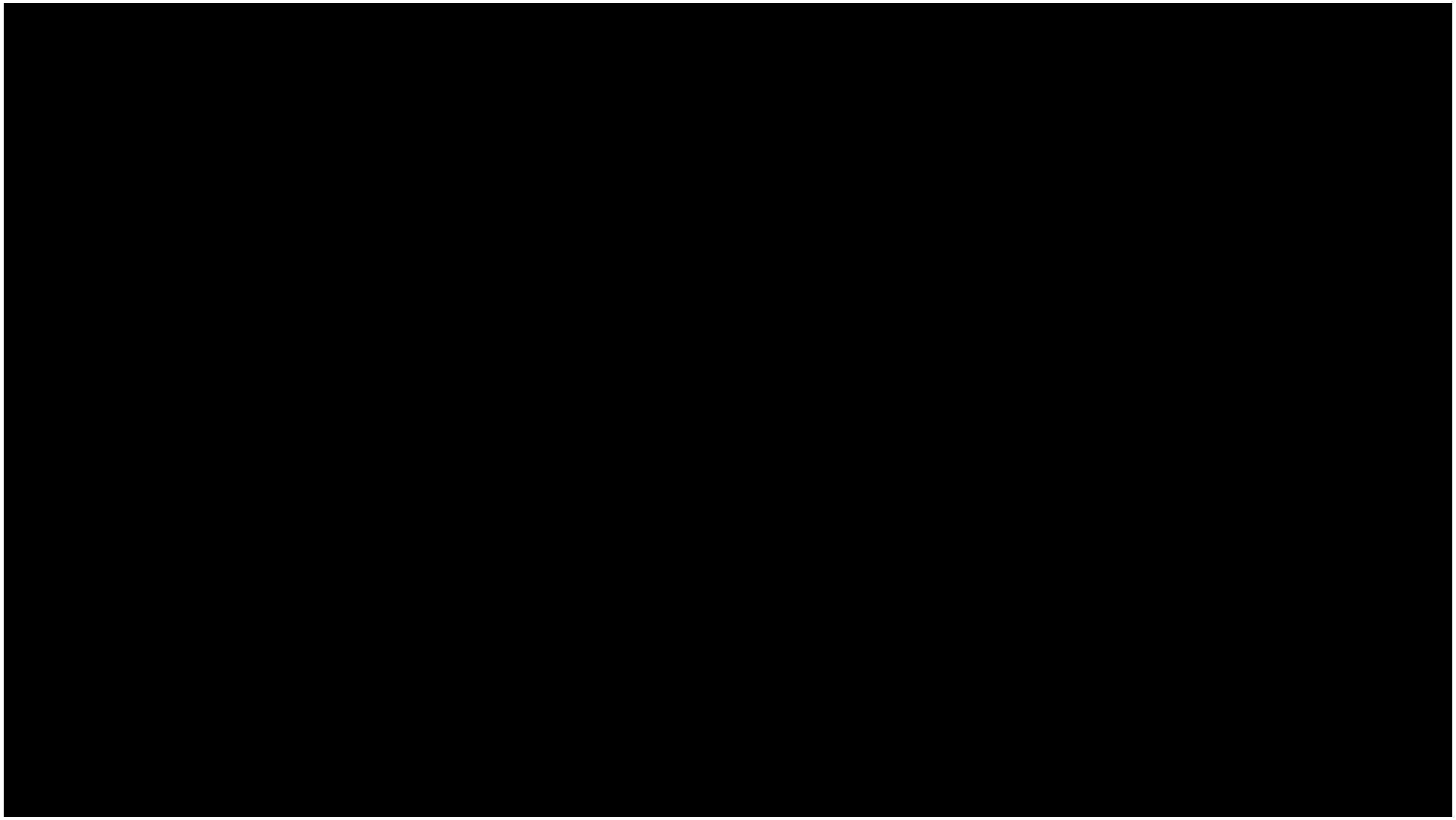


Figure 24.26

Terminology for a pull-type internal broach used for enlarging long holes.



Broaching Machine



https://youtu.be/jKi_oiiFd7c

Figure 24.28

Examples of various sawing operations.

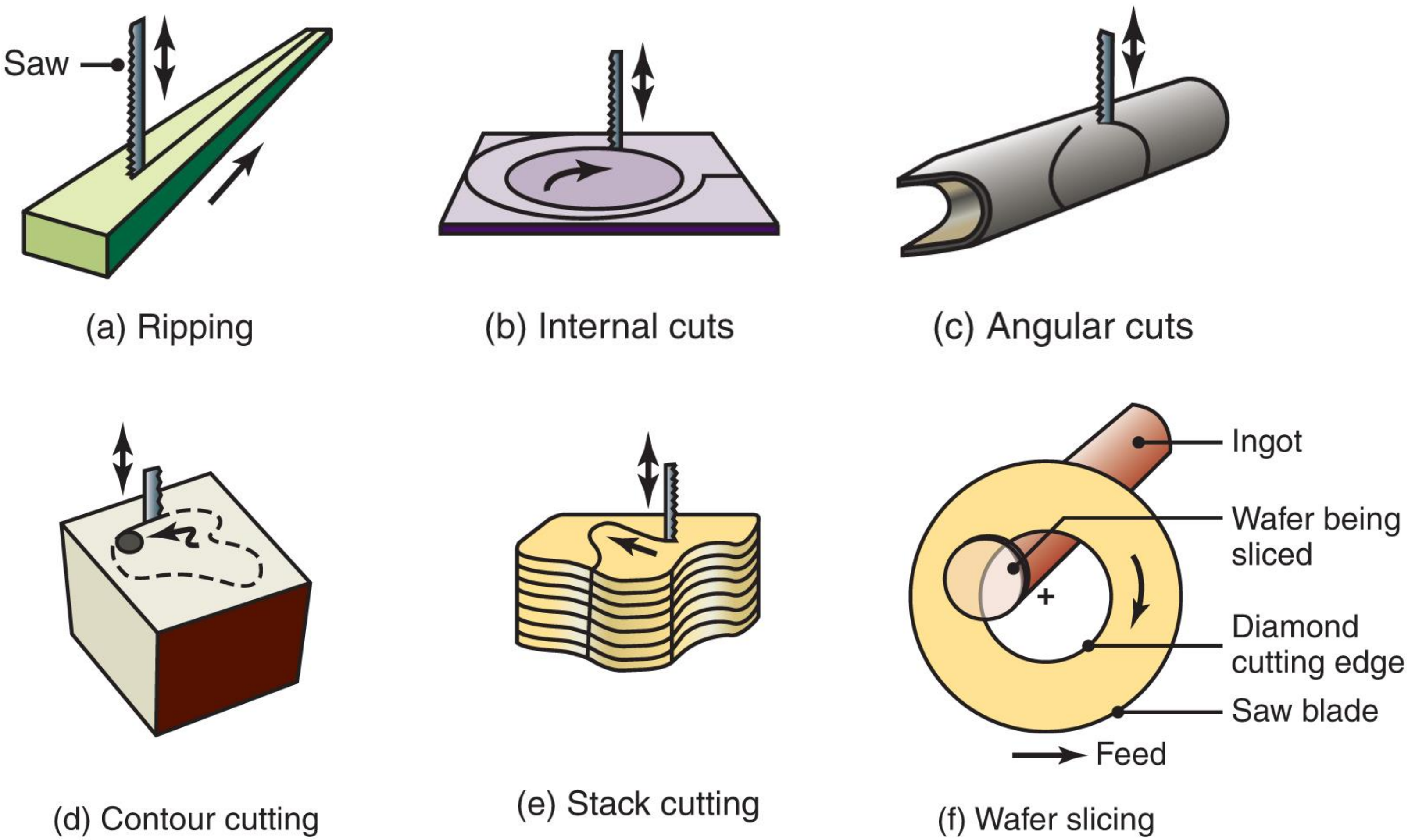


Figure 24.30

(a) High-speed-steel teeth welded onto a steel blade, (b) Carbide inserts brazed to blade teeth.

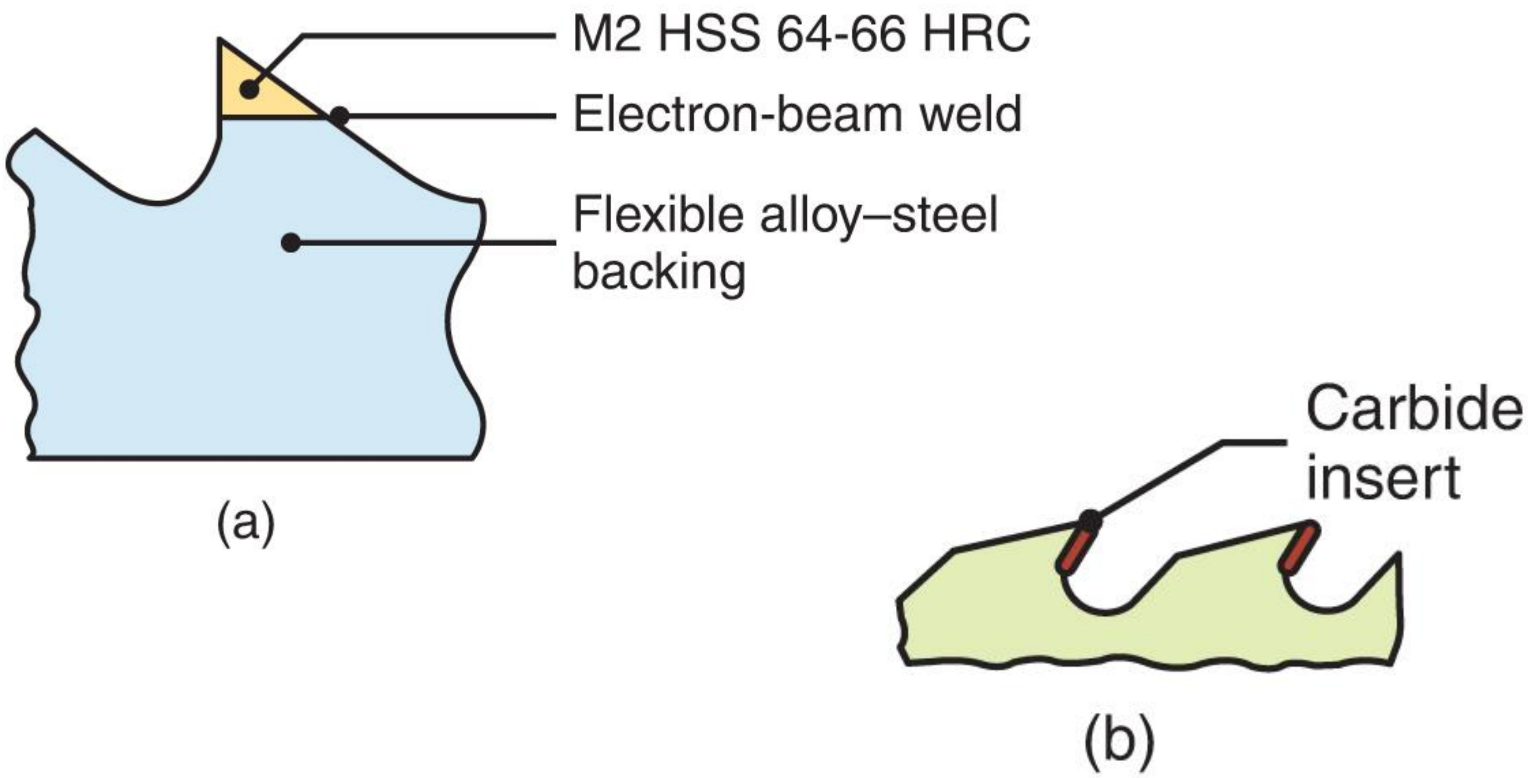


Figure 24.33

(a) Producing gear teeth on a blank by form cutting, (b) Schematic illustration of gear generating with a pinion-shaped gear cutter, (c) Gear generating in a gear shaper using a pinion-shaped cutter. Note that the cutter reciprocates vertically, (d) Gear generating in a gear shaper using a pinion-shaped cutter. Note that the cutter reciprocates vertically, (e) Gear generating with rack-shaped cutter.

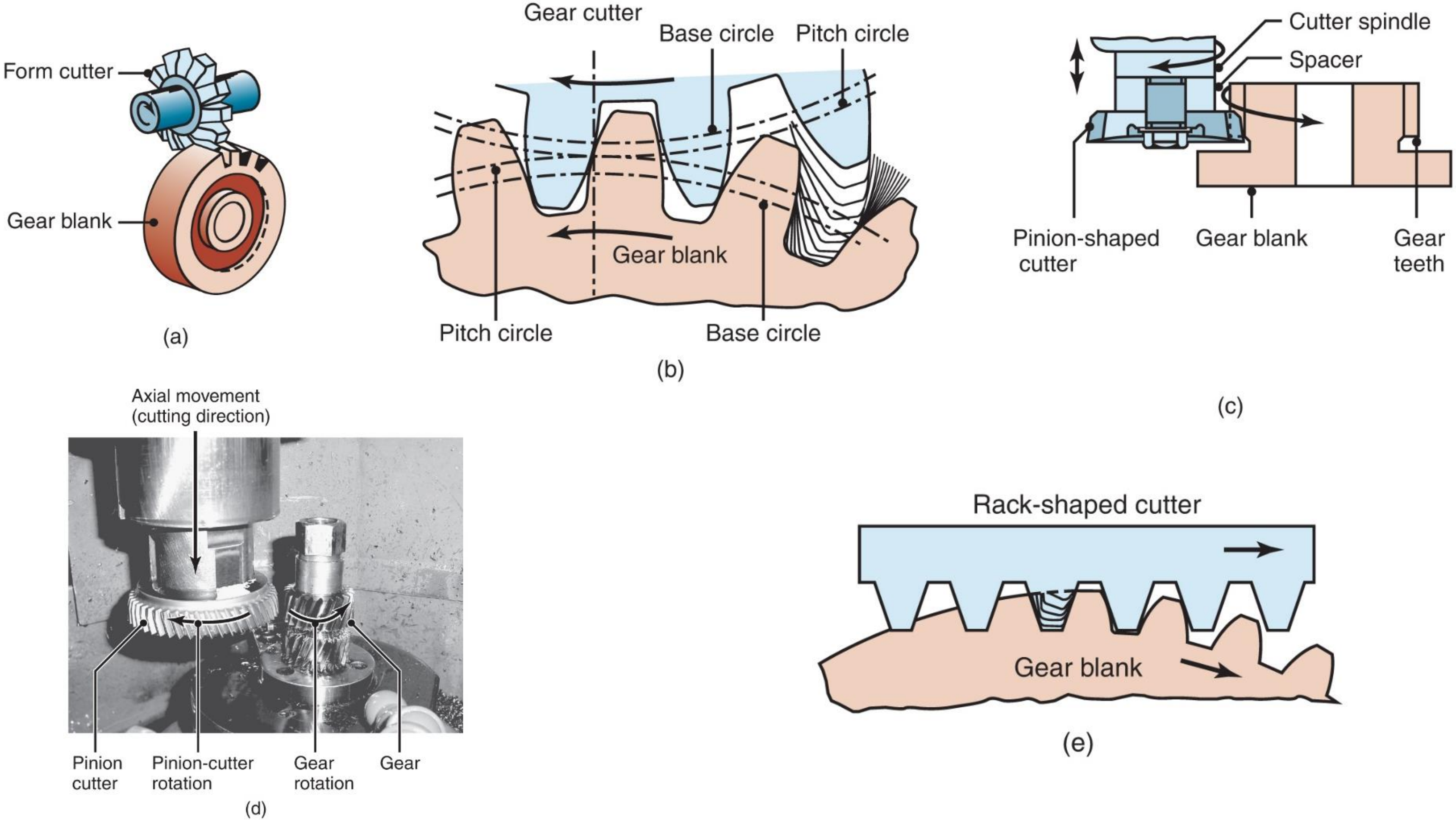
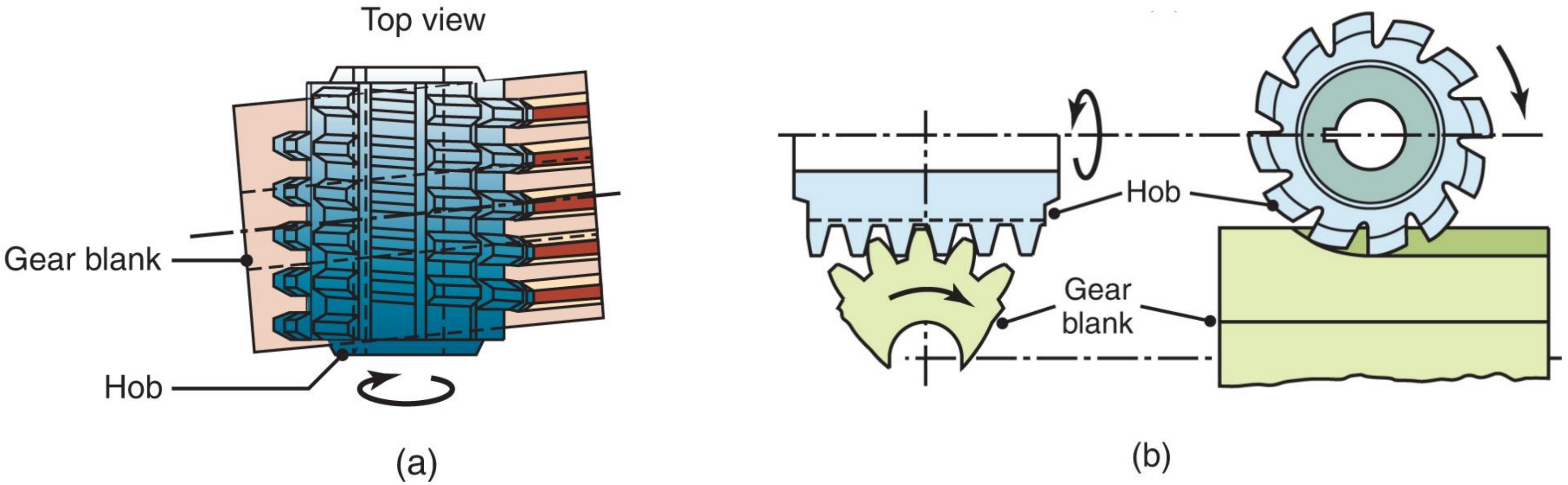


Figure 24.34

(a) Hobs, used to machine gear teeth, (b) schematic illustration of gear cutting with a hob.



Source: (a) Courtesy of Sandvik Coromant.

Figure 24.35

(a) Cutting a straight bevel-gear blank with two cutters, (b) Cutting a helical bevel gear.

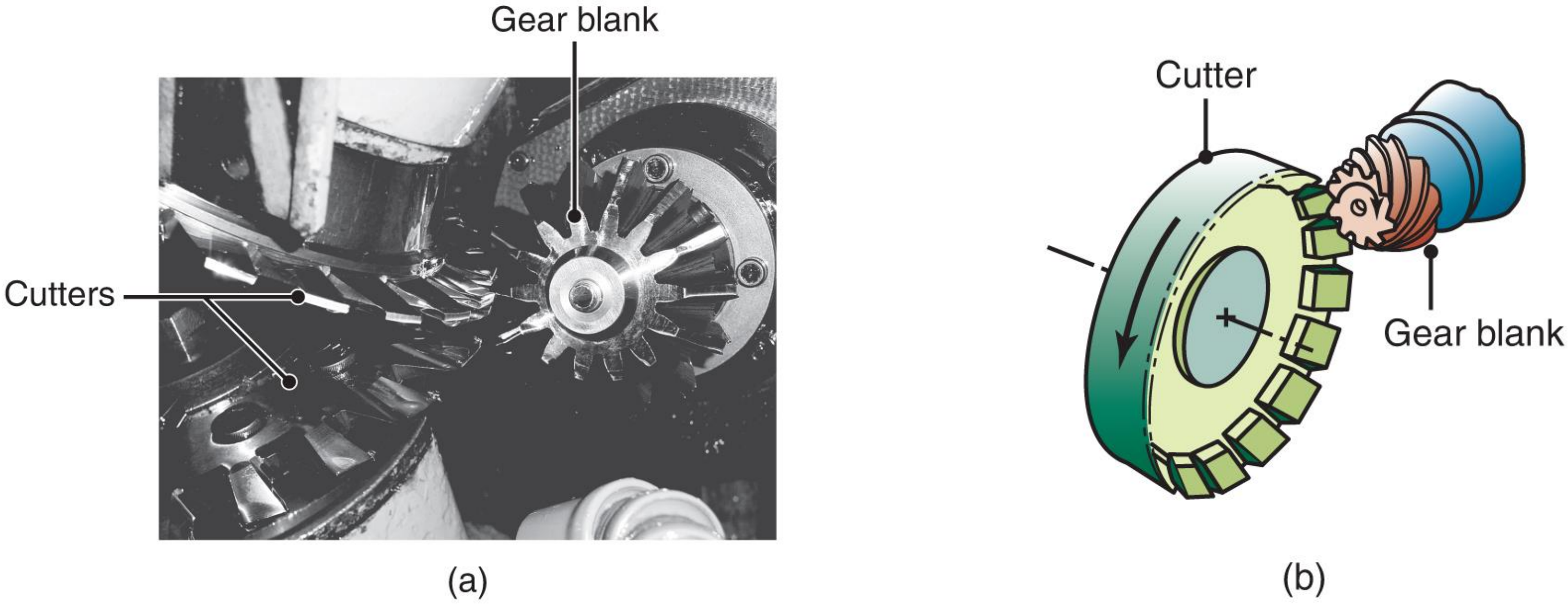
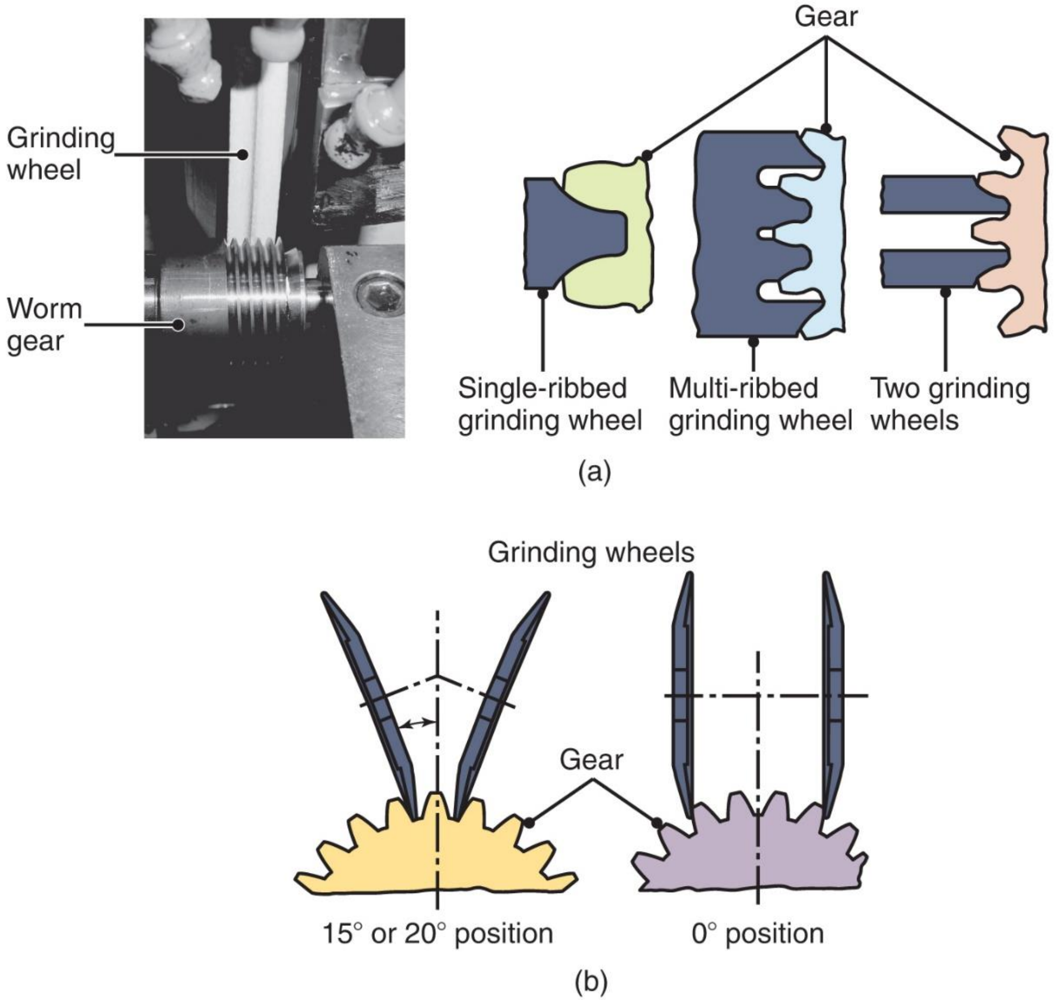
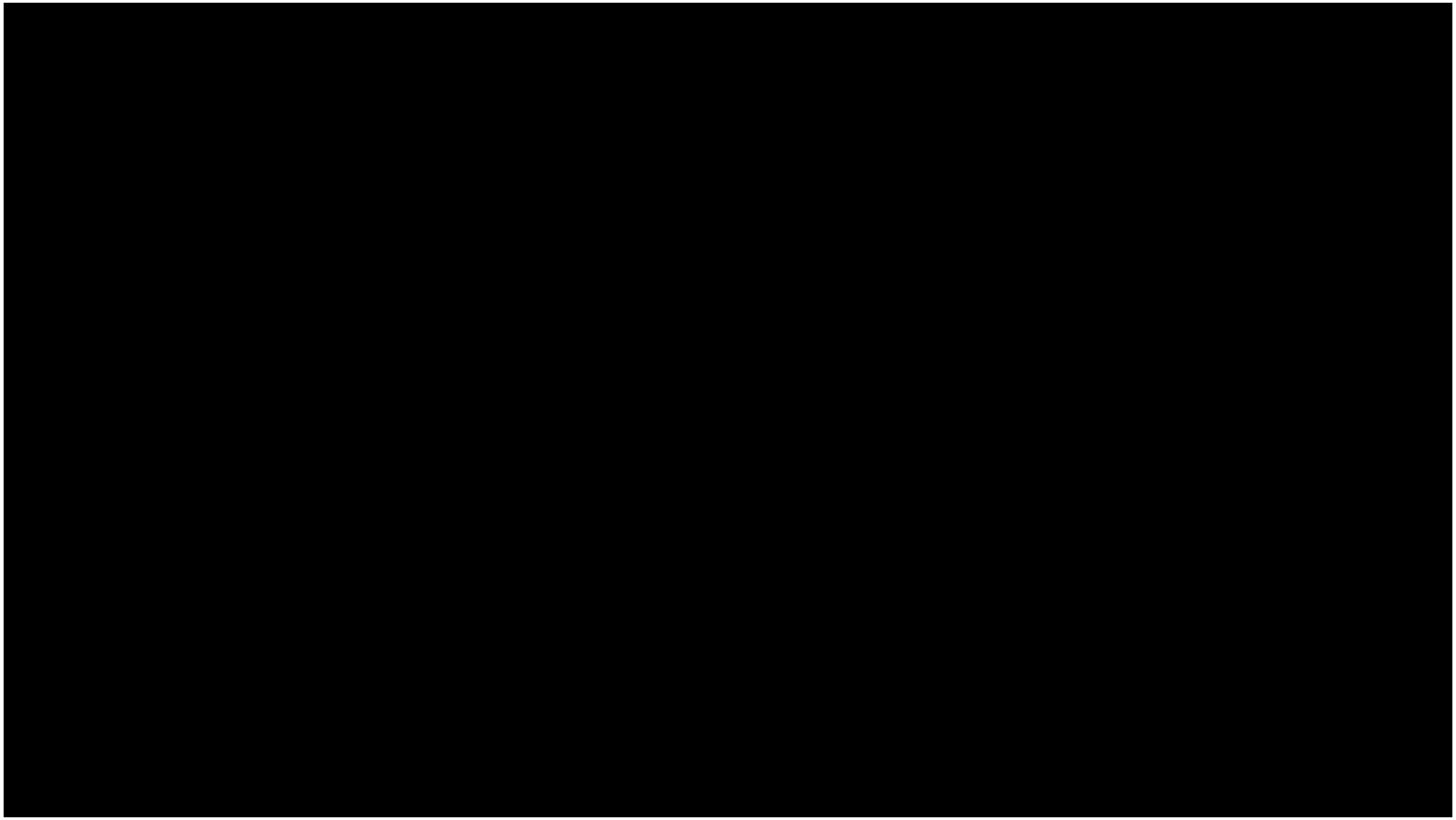


Figure 24.36

Finishing gears by grinding: (a) form grinding with shaped grinding wheels, (b) grinding by generating, using two wheels.



Gear Hobbing Machine



https://youtu.be/0rnTh6c19HM

Figure 24.38

(a) The Ping Anser® golf putter, (b) CAD model of rough machining of the putter outer surface, (c) rough machining on a vertical machining center, (d) machining of the lettering in a vertical machining center; the operation was paused to take the photo, as normally the cutting zone is flooded with a coolant.

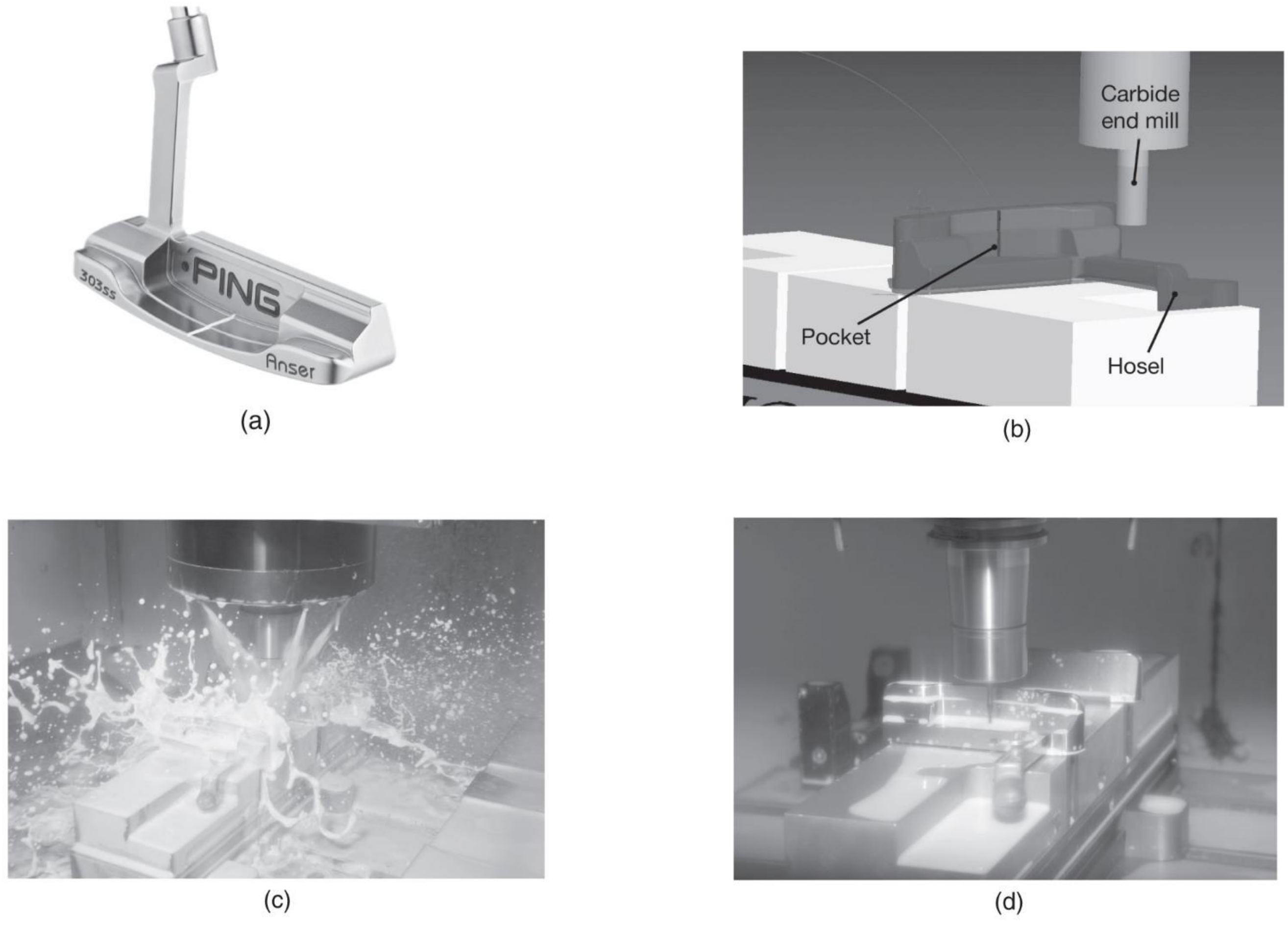


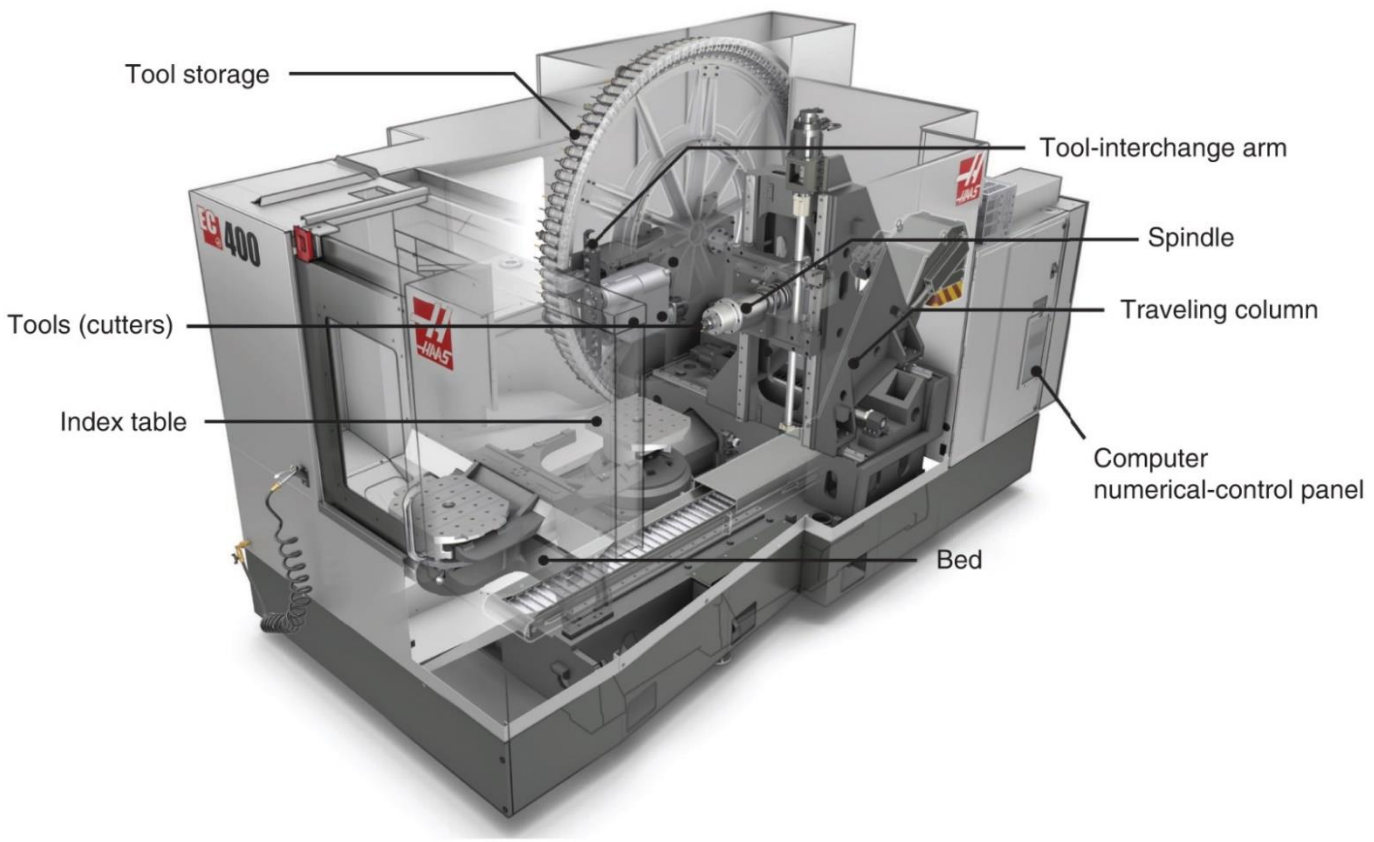
Figure 25.1

Examples of parts that can be machined on machining centers, using processes such as turning, facing, milling, drilling, boring, reaming, and threading. Such parts ordinarily would require the use of a variety of machine tools. Forged motorcycle wheel, finish machined to tolerance and subsequently polished and coated.

Source: Courtesy of R.C. Components.

Figure 25.2

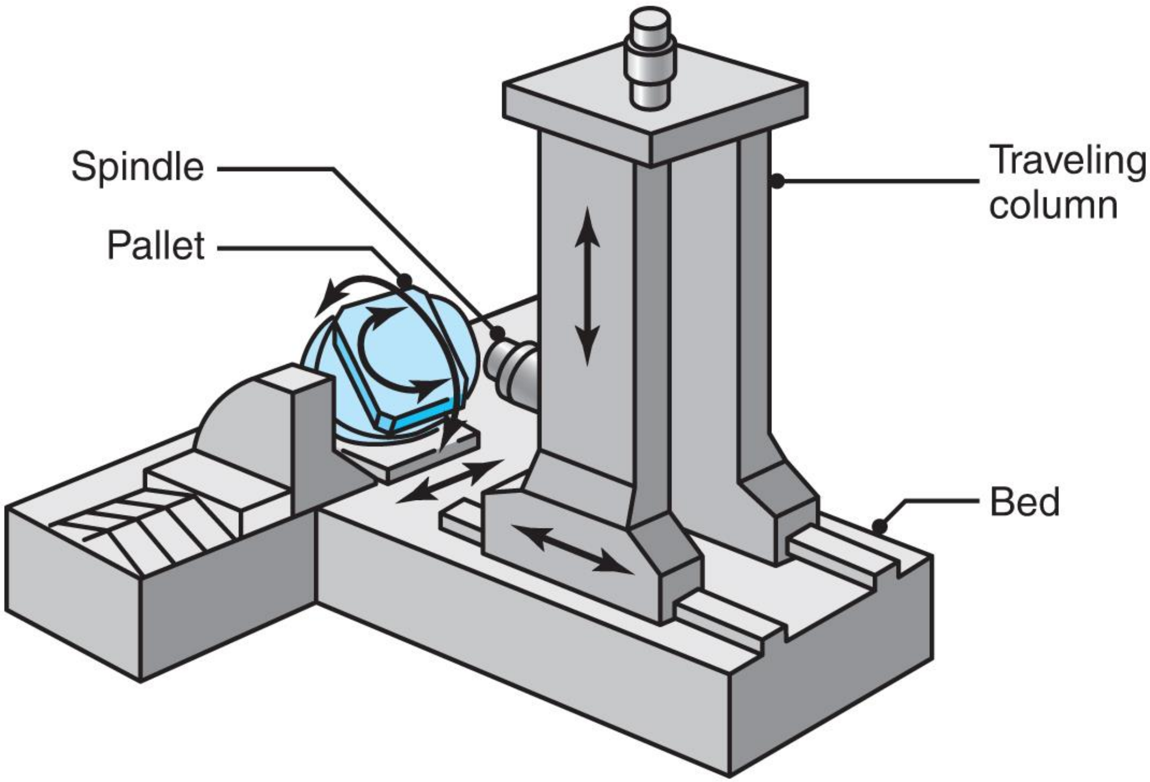
A horizontal-spindle machining center equipped with an automatic tool changer. Tool magazines can store up to 200 cutting tools of various functions and sizes.



Source: Courtesy Haas Automation, Inc.

Figure 25.3

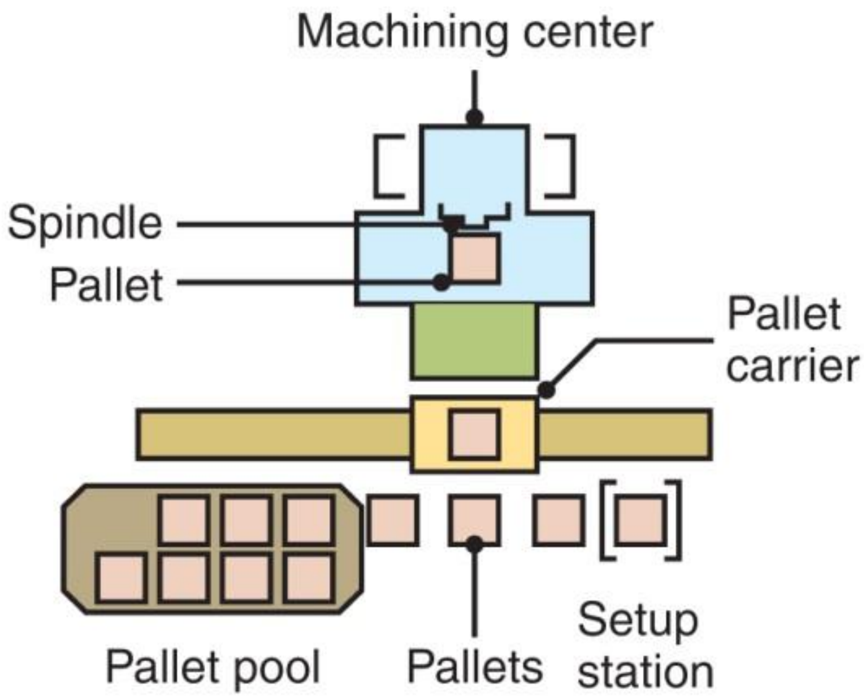
Schematic illustration of the principle of a five-axis machining center. The pallet, which supports and transfers the workpiece, has three axes of movement and can be swiveled around two axes (thus a total of five axes), allowing the machining of complex shapes, such as those shown in Fig. 25.1.



Source: Courtesy of Toyoda Machinery.

Figure 25.4 (1 of 3)

(a) Schematic illustration of the top view of a horizontal-spindle machining center, showing the pallet pool, setup station for a pallet, pallet carrier, and an active pallet in operation (shown directly below the spindle of the machine).

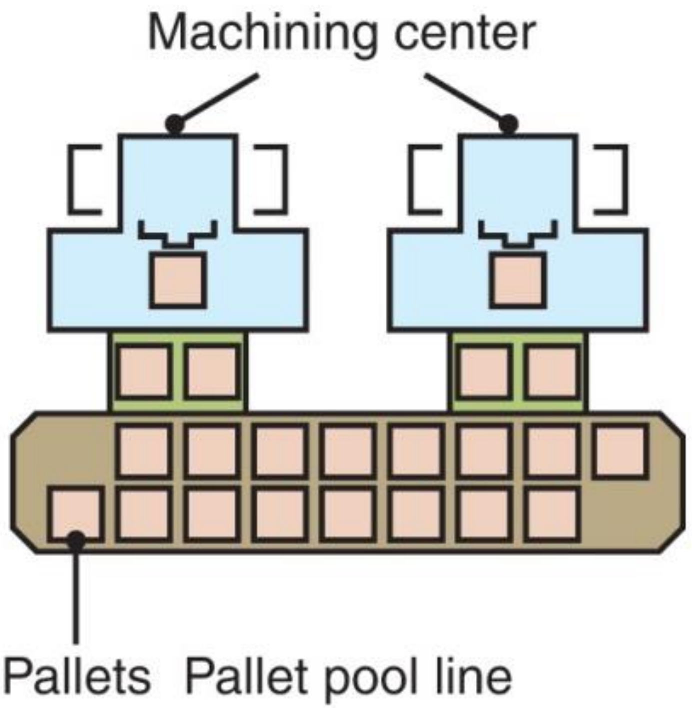


(a)

Source: (a) Courtesy of Hitachi Seiki Co., Ltd.

Figure 25.4 (2 of 3)

(b) Schematic illustration of two machining centers, with a common pallet pool.

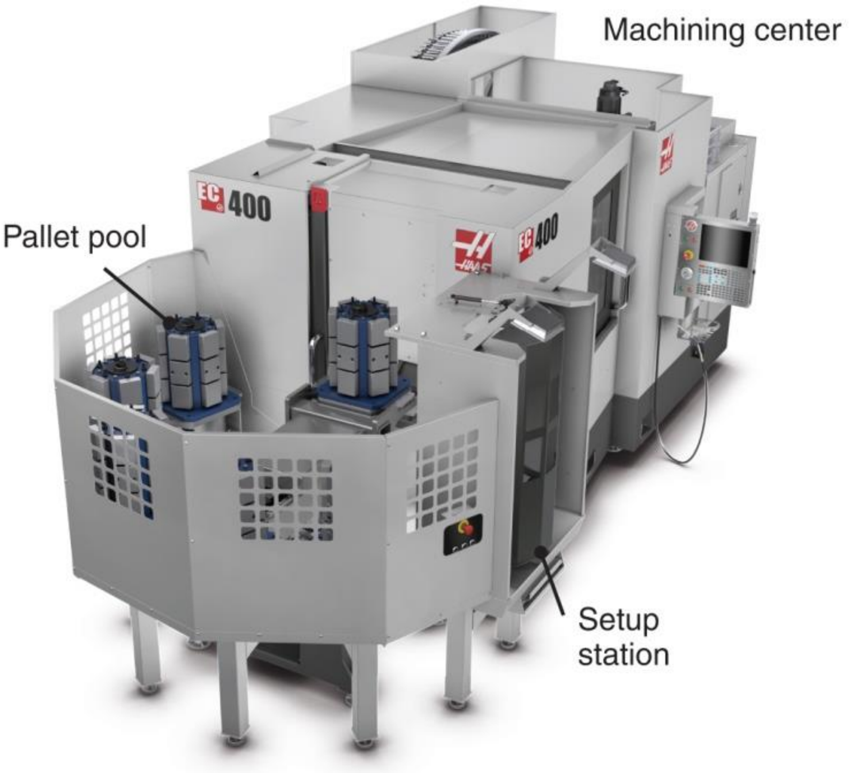


(b)

Source: (b) Courtesy of Hitachi Seiki Co., Ltd.

Figure 25.4 (3 of 3)

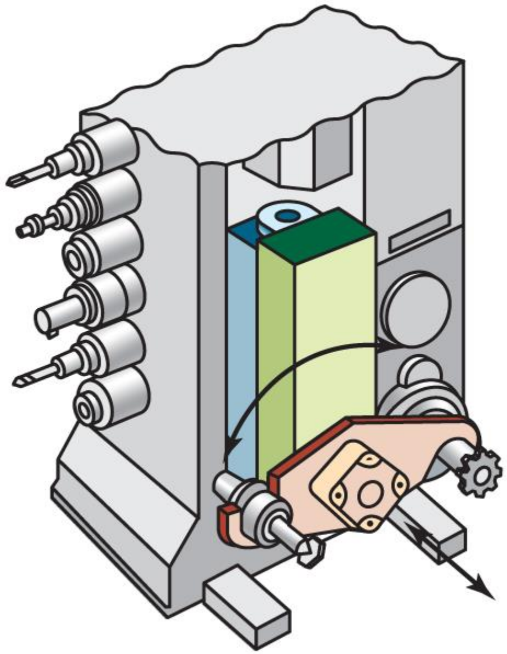
(c) A pallet pool for a horizontal-spindle machining center. Various other pallet arrangements are possible in such systems.



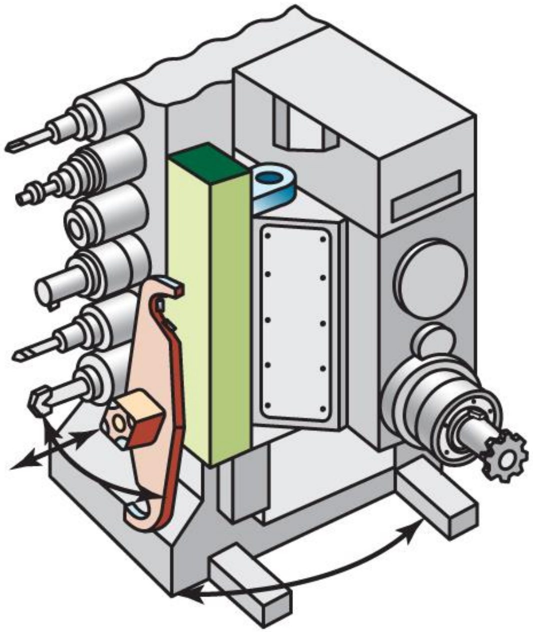
(c)

Figure 25.5

Swing-around tool changer on a horizontal-spindle machining center. (a) The tool-exchange arm is placing a toolholder, with a cutting tool, into the machine spindle. Note the axial and rotational movements of the arm, (b) The arm is returning to its home position. Note its rotation along a vertical axis after placing the tool, and the two degrees of freedom in its home position.



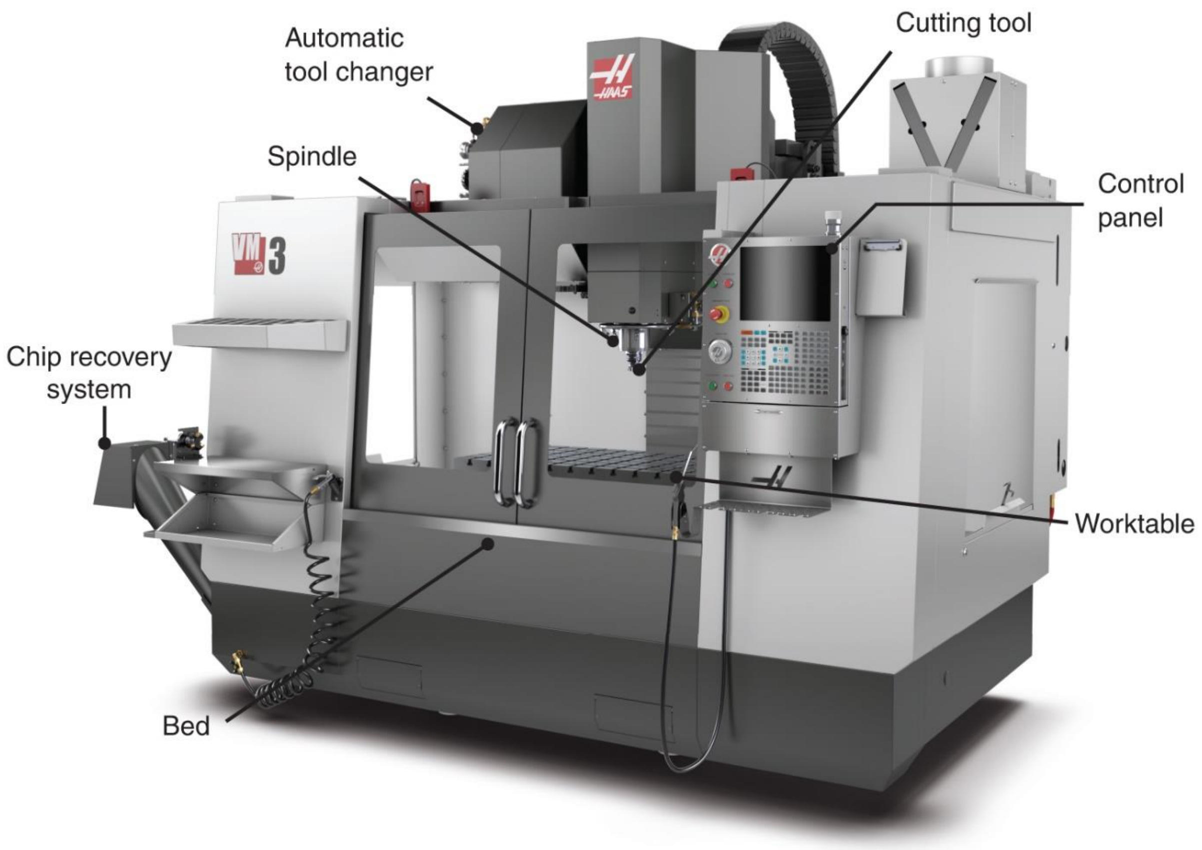
(a)



(b)

Figure 25.7

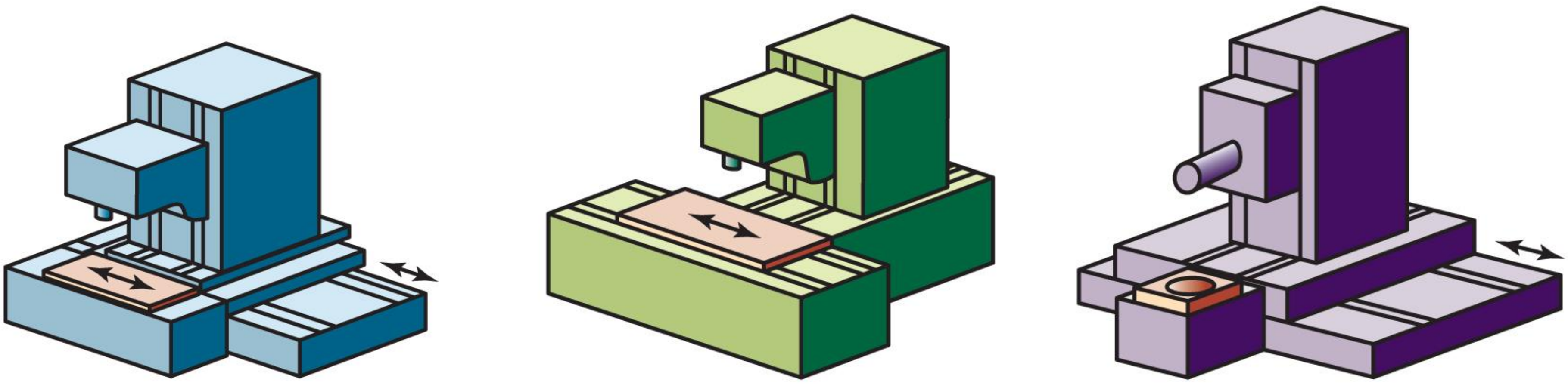
A vertical-spindle machining center. The tool changer is on the left of the machine, and has a 40 tool magazine.



Source: Courtesy of Haas Automation, Inc.

Figure 25.10

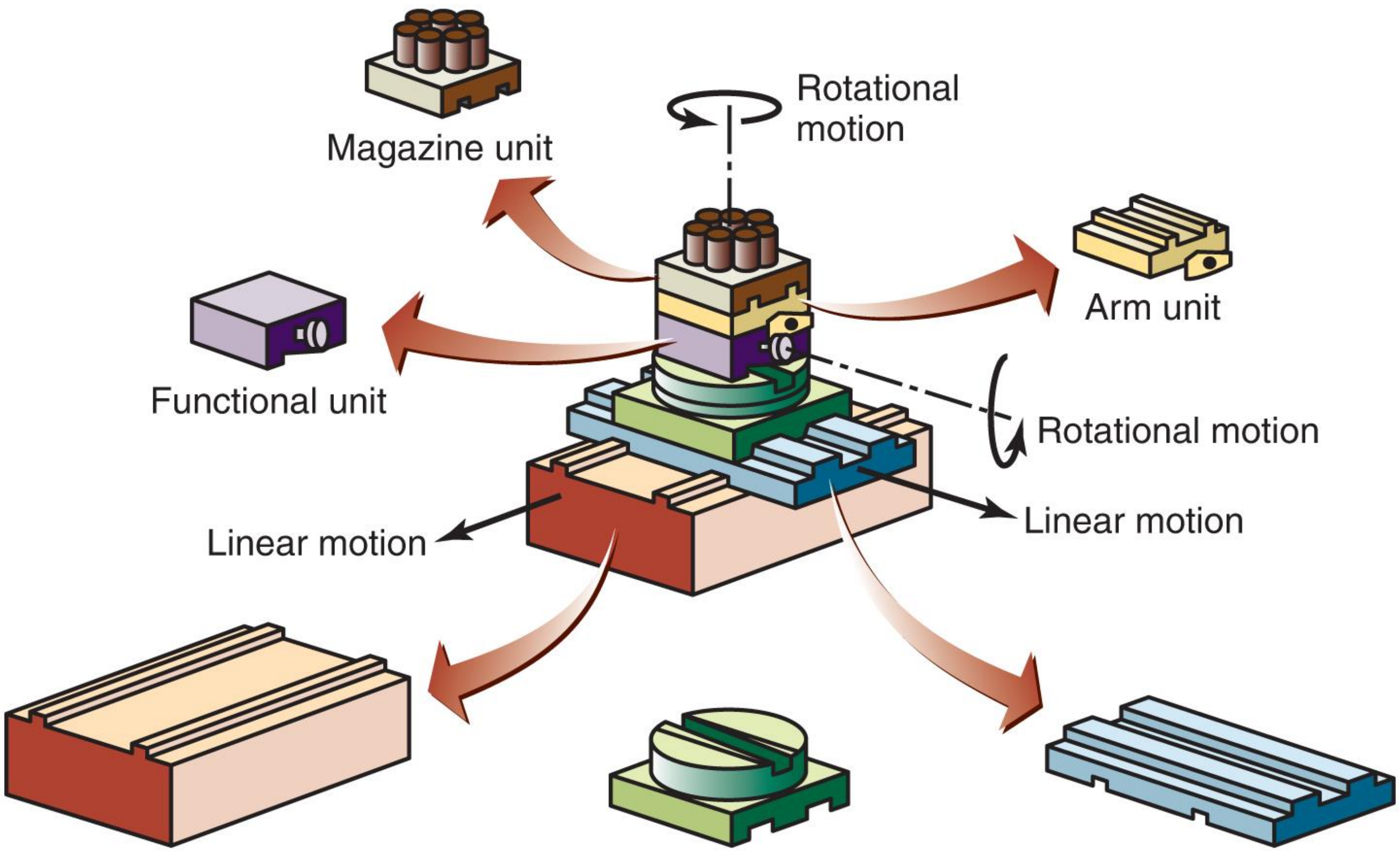
Schematic illustration of a reconfigurable modular machining center capable of accommodating workpieces of different shapes and sizes and requiring different machining operations on their various surfaces.



(a) (b) (c)

Figure 25.11

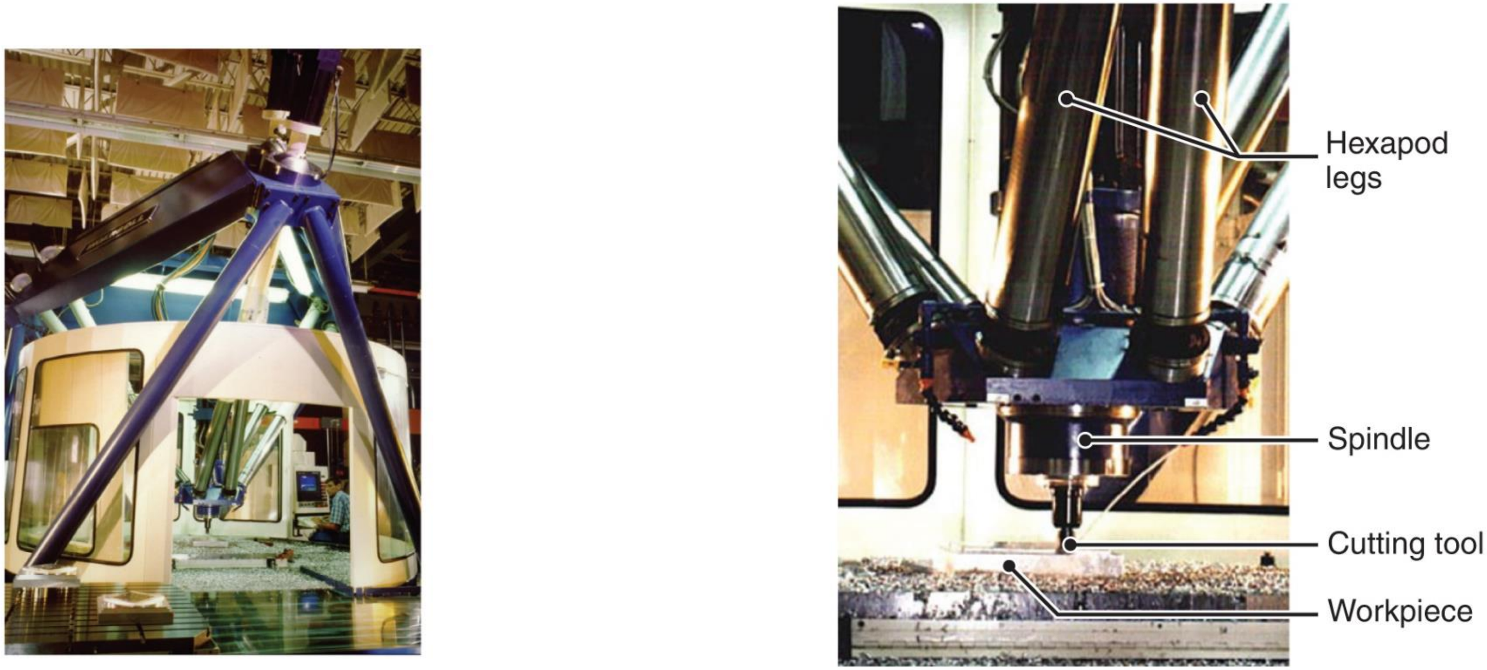
Schematic illustration of the assembly of different components of a reconfigurable machining center.



Source: After Y. Koren.

Figure 25.12

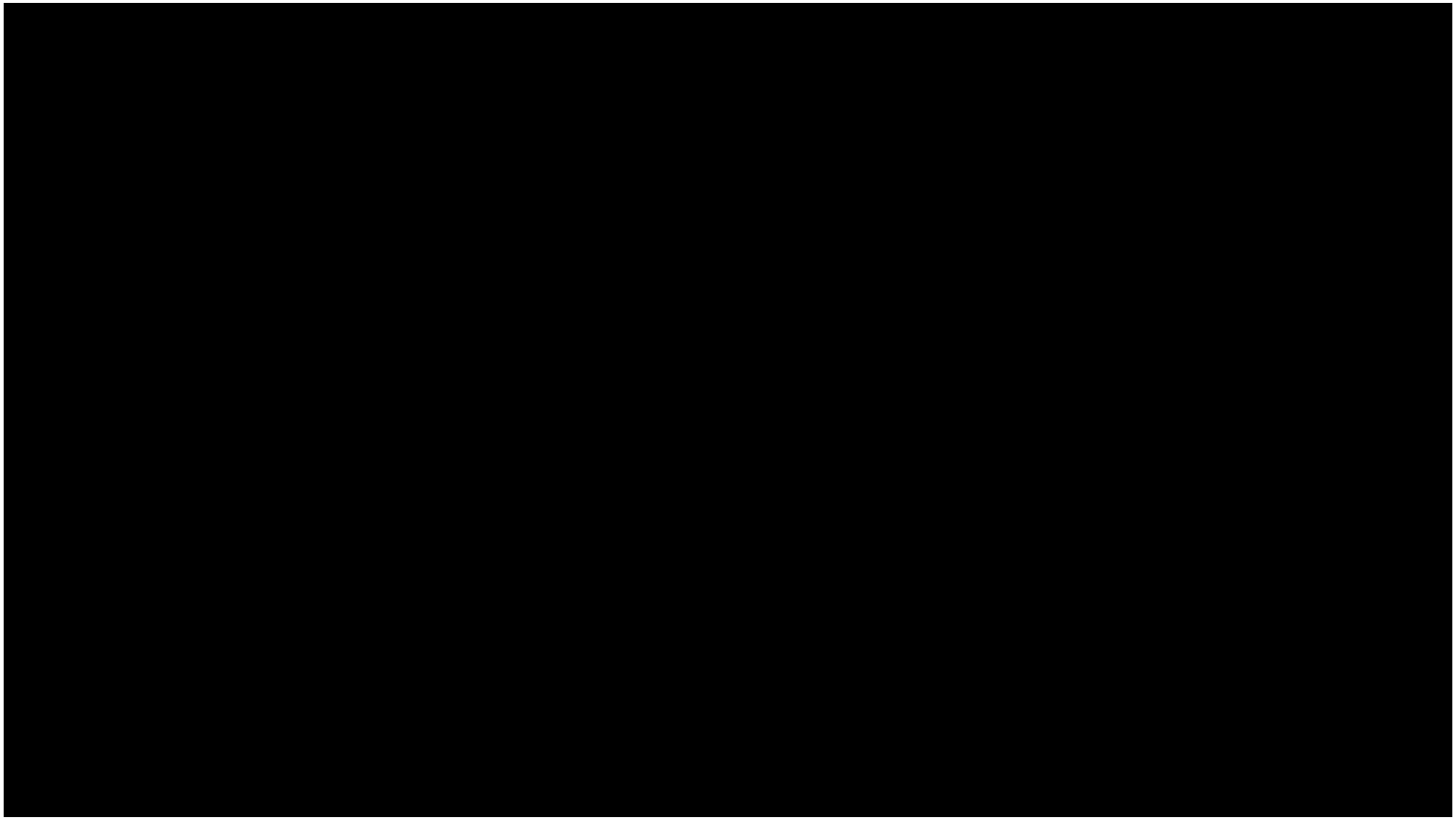
(a) A hexapod machine tool, showing its major components, (b) A detailed view of the cutting tool in a hexapod machining center.



(a) (b)

Source: National Institute of Standards and Technology.

Hexapod



https://youtu.be/nebJ59TcYlQ

Figure 25.14

The relative damping capacity of (a) gray cast iron, (b) an epoxy–granite composite material. The vertical scale is the amplitude of vibration and the horizontal scale is time.

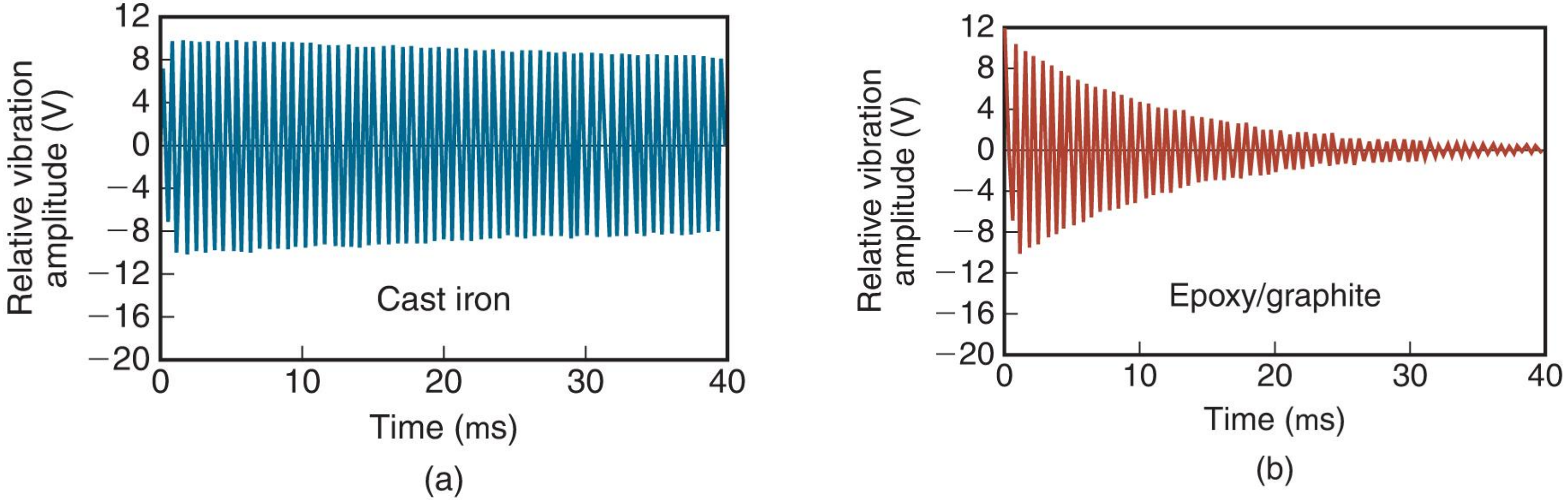
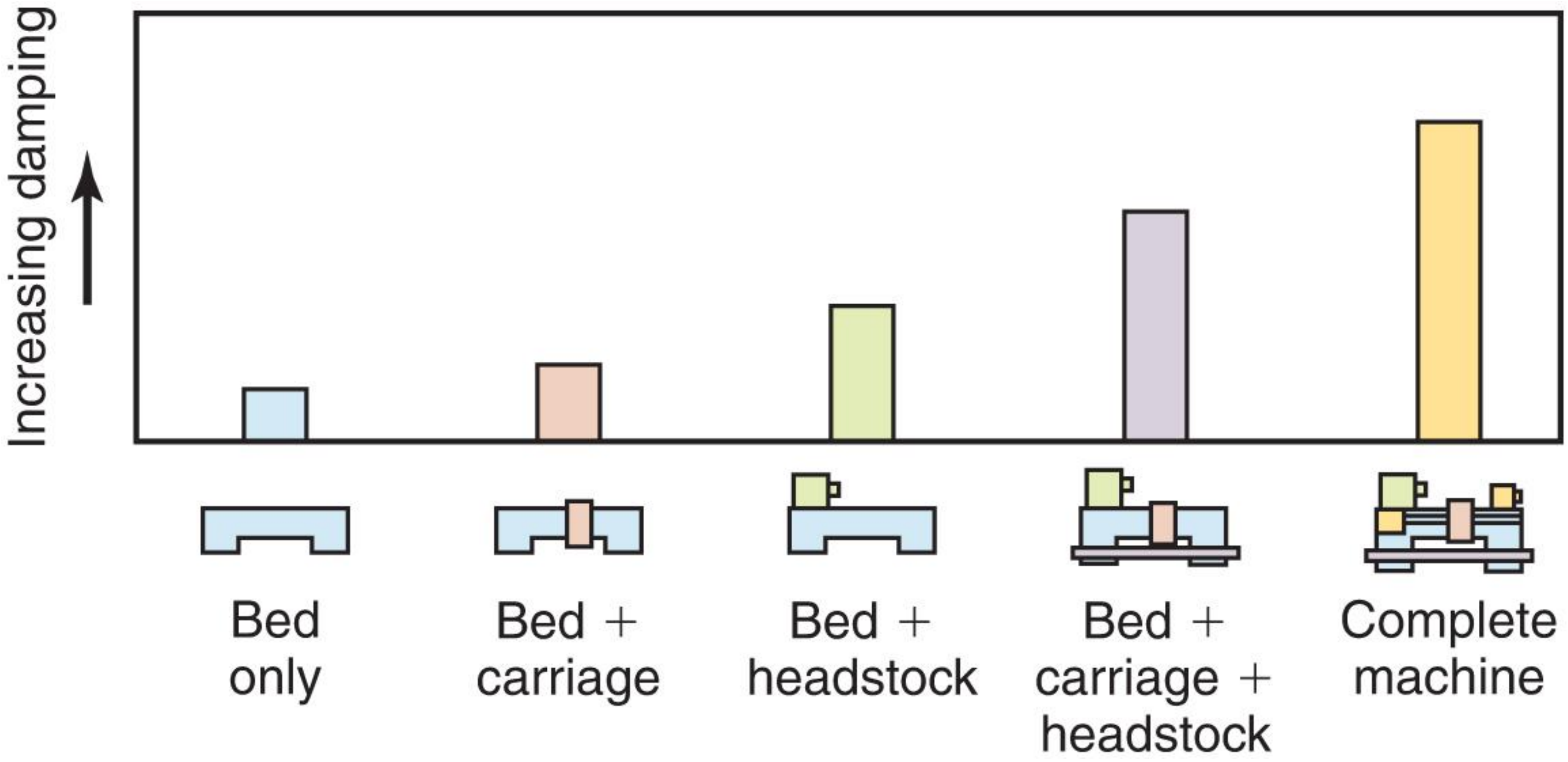


Figure 25.15

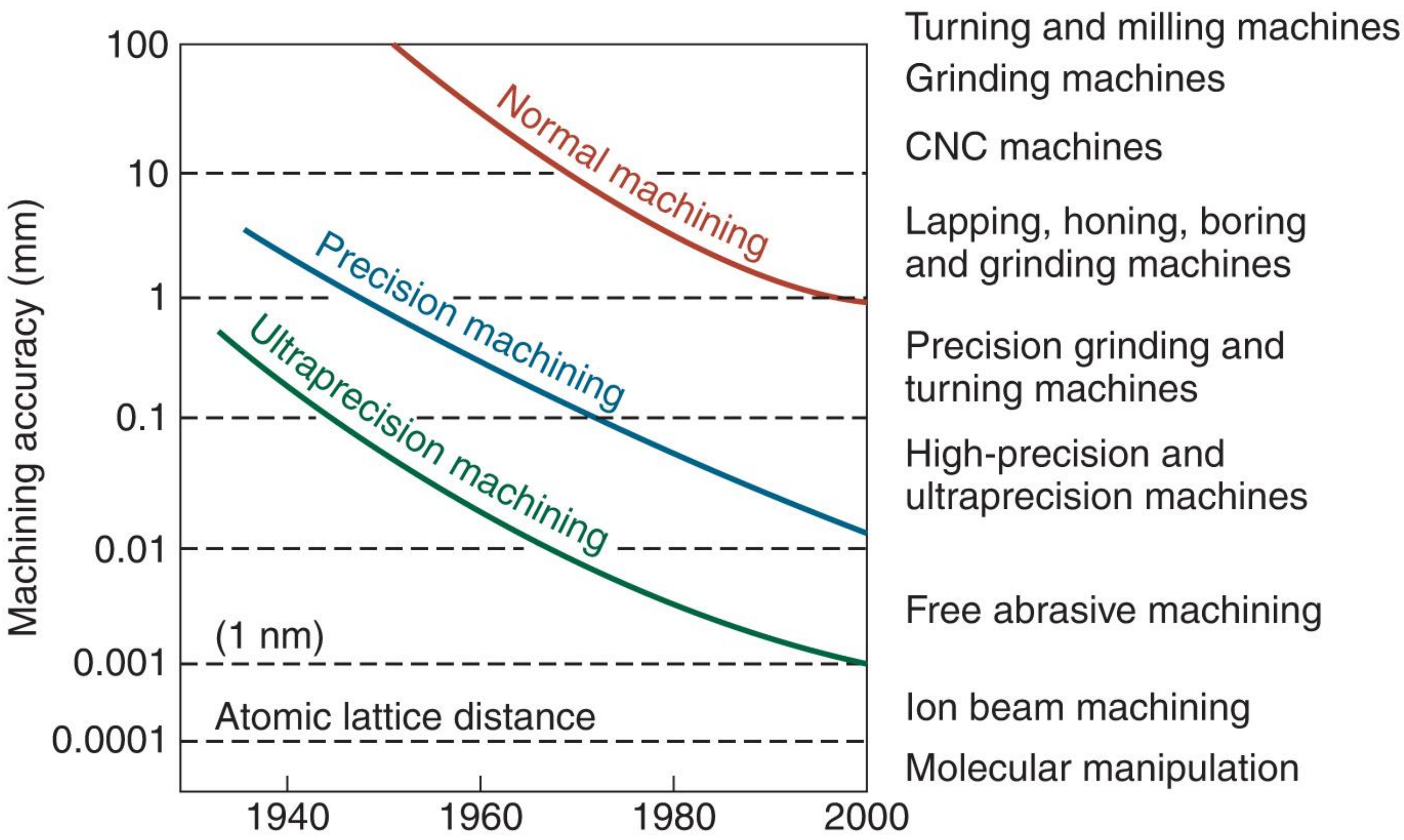
The damping of vibrations as a function of the number of components on a lathe. Joints dissipate energy; the greater the number of joints, the higher is the damping capacity of the machine.



Source: After J. Peters.

Figure 25.17

Improvements in machining accuracy over the years, using ultraprecision machining technologies.



Source: After C.J. McKeown, N. Taniguchi, G. Byrne, D. Dornfeld, and B. Denkena.

Figure 25.18

Graphs showing (a) cost per piece and (b) time per piece in machining. Note the optimum speeds for both cost and time. The range between the two is known as the *high-efficiency machining range.*