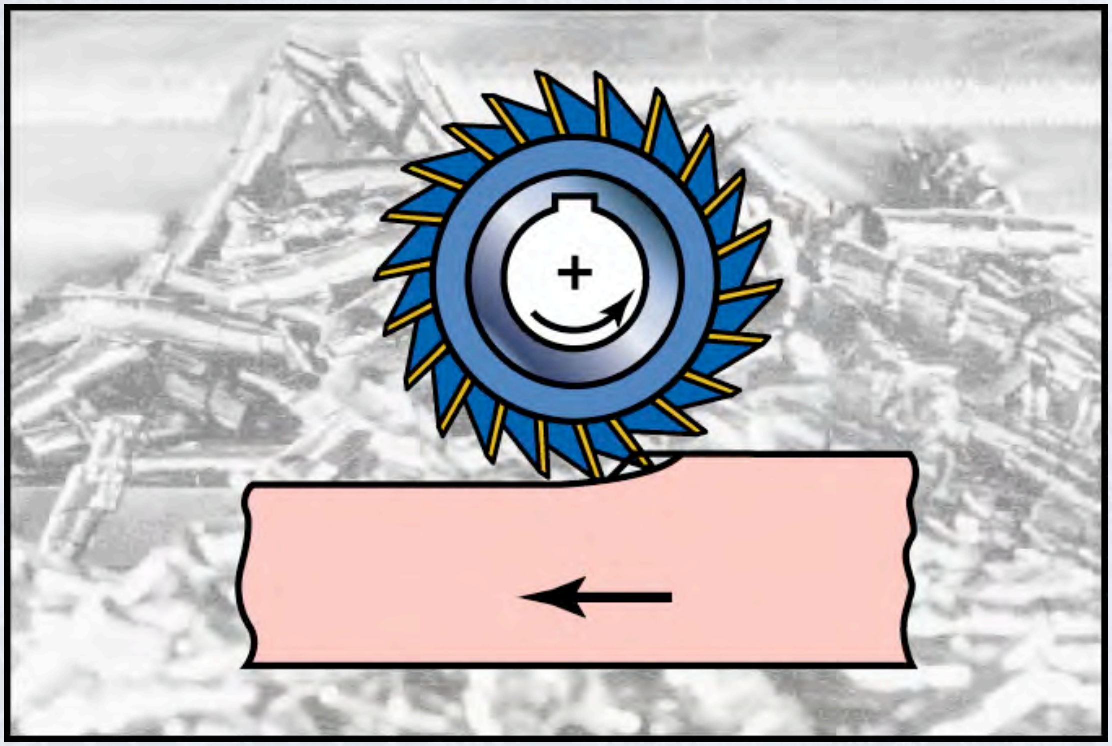
Chapter 24

Machining Processes Used to Produce Various Shapes: Milling, Broaching, Sawing, and Filing; Gear Manufacturing



Parts Made with Machining Processes of Chapter 24

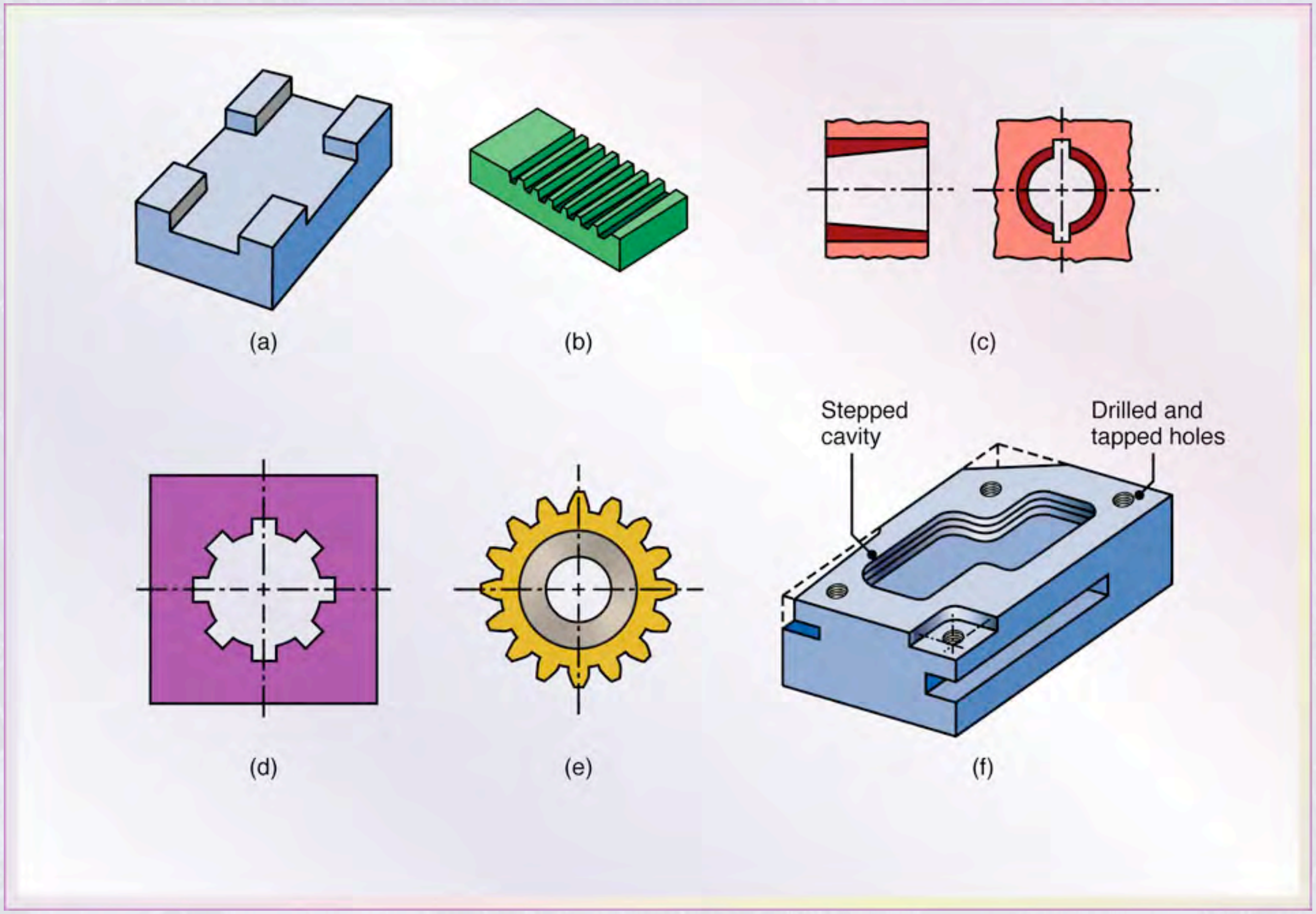


Figure 24.1 Typical parts and shapes that can be produced with the machining processes described in this chapter.

Milling Cutters and Milling Operations

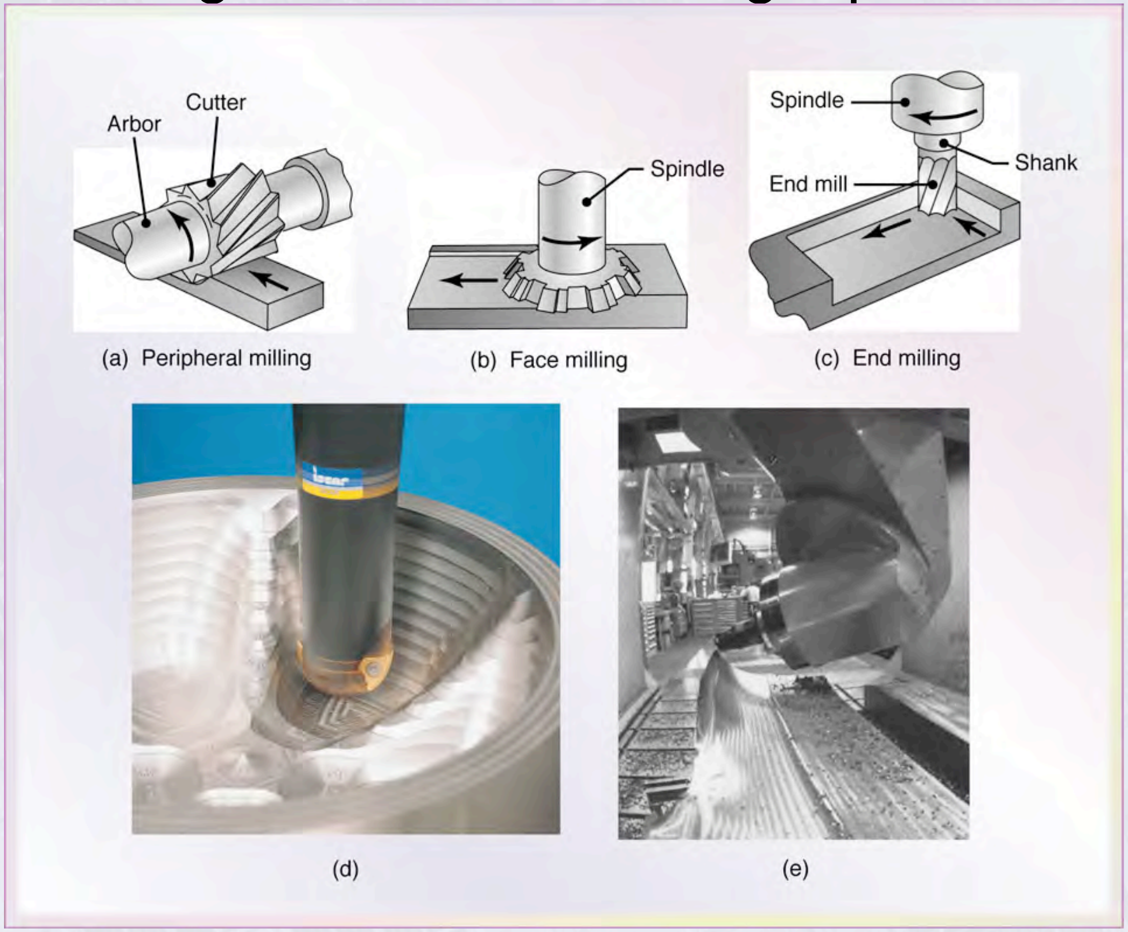


Figure 24.2 Some basic types of milling cutters and milling operations. (a) Peripheral milling. (b) Face milling. (c) End milling. (d) Ball-end mill with indexable coated-carbide inserts machining a cavity in a die block. (e) Milling a sculptured surface with an end mill, using a five-axis numerical control machine. *Source*: (d) Courtesy of Iscar. (e) Courtesy of The Ingersoll Milling Machine Co.

Milling Operations

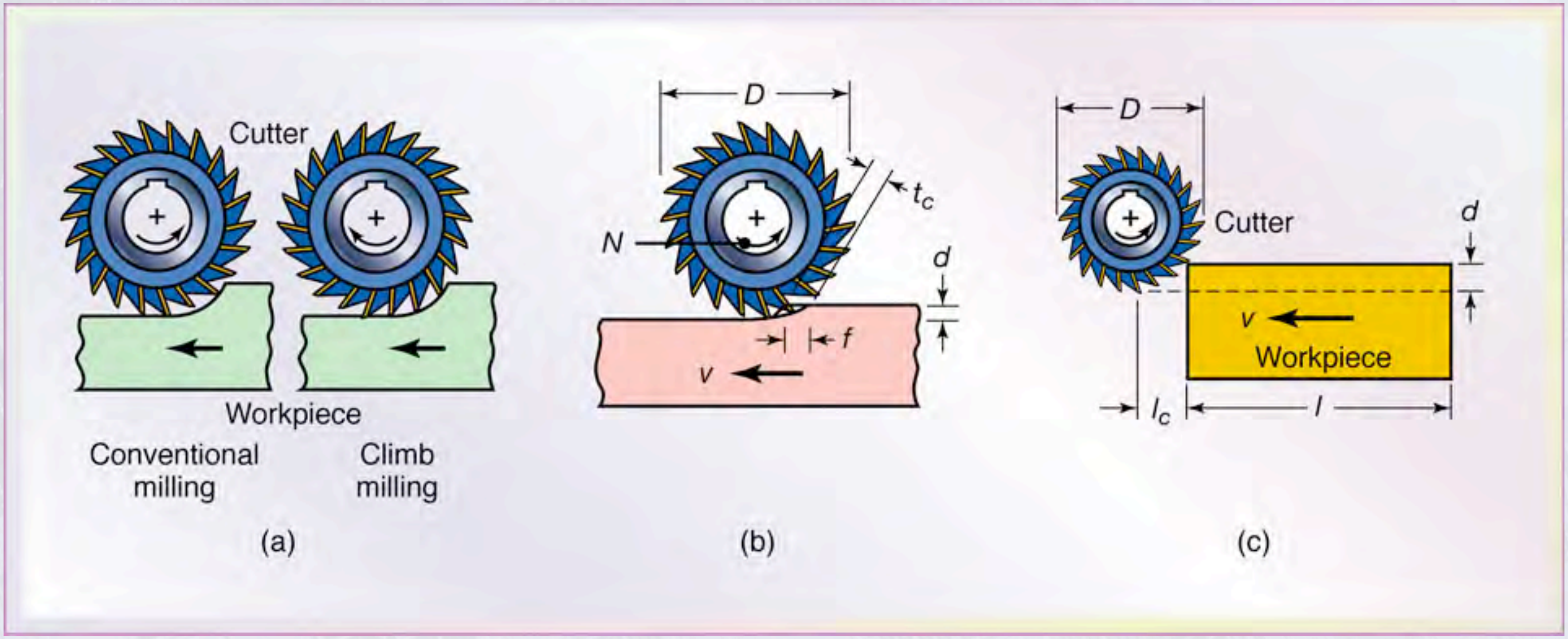


Figure 24.3 (a) Schematic illustration of conventional milling and climb milling. (b) lab-milling operation showing depth-of-cut, *d*; feed per tooth, *f*; chip depth-of-cut, t_c; and workpiece speed, *v*. (c) Schematic illustration of cutter travel distance, l_c, to reach full depth-of-cut.

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Face-Milling Operation

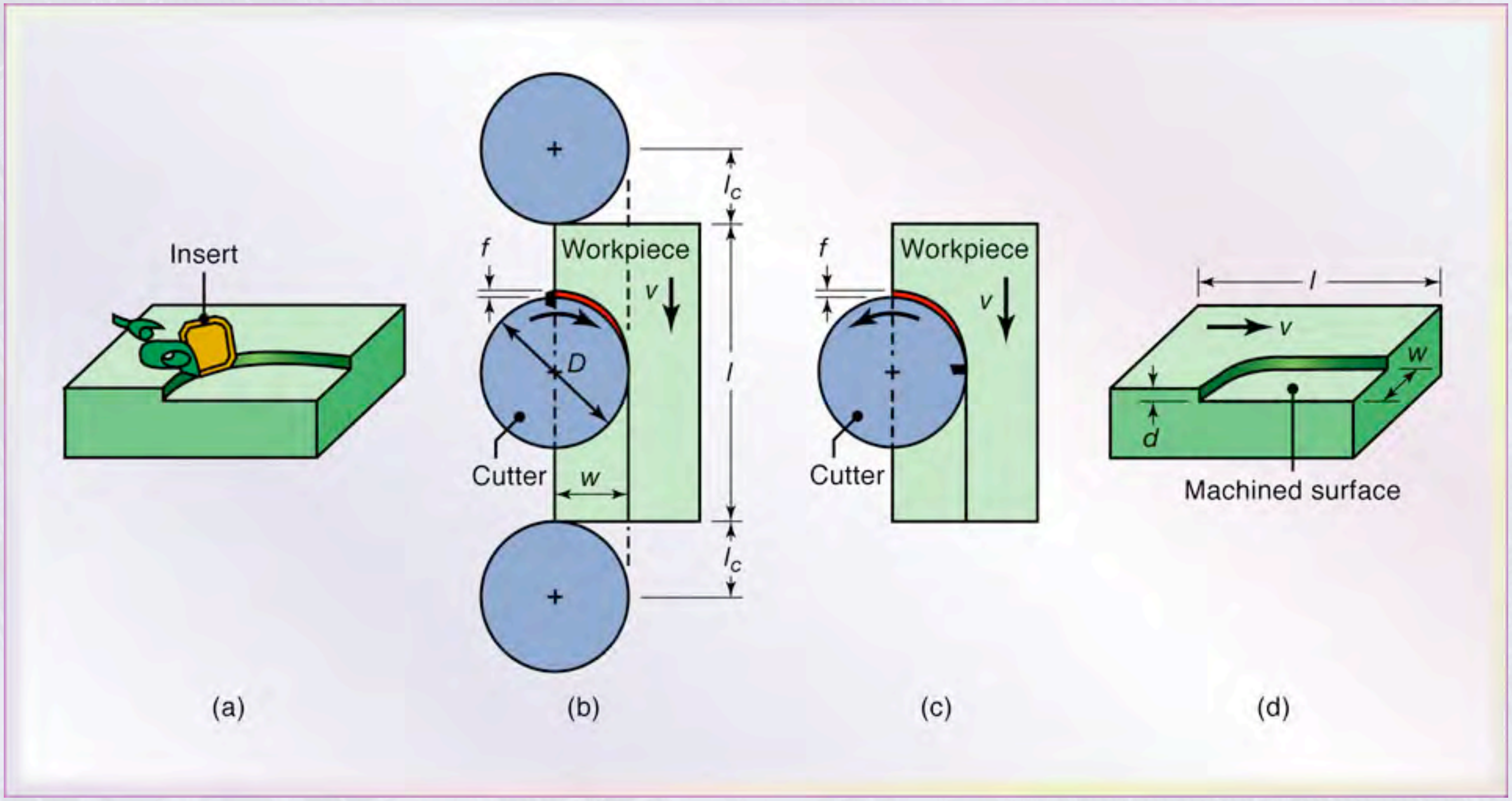

Figure 24.4 Face-milling operation showing (a) action of an insert in face milling; (b) climb milling; (c) conventional milling; (d) dimensions in face milling. The width of cut, *w,* is not necessarily the same as the cutter radius.

Summary of Peripheral Milling Parameters and Formulas

TABLE 24.1

Summary of Peripheral Milling Parameters and Formulas

N	=	Rotational speed of the milling cutter, rpm
F	=	Feed, mm/tooth or in./tooth
D	=	Cutter diameter, mm or in.
n	=	Number of teeth on cutter
v	=	Linear speed of the workpiece or feed rate, mm/min or in./min
V	=	Surface speed of cutter, m/min or ft/min
	=	DN
f	=	Feed per tooth, mm/tooth or in./tooth
	=	v/Nn
l	=	Length of cut, mm or in.
t	=	Cutting time, s or min
	=	$(l + l_c)/v$, where l_c = extent of the cutter's first contact with workpiece
MRR	=	mm^3/min or in^3/min
	=	wdv, where w is the width of cut
Torque	=	N•m or lb•ft
	=	$F_c D/2$
Power	=	kW or hp
	=	(Torque)(ω), where $\omega = 2\pi N$ radians/min

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Face-Milling Cutter with Indexable Inserts

Figure 24.5 A face-milling cutter with indexable inserts.
Source: Courtesy of Ingersoll Cutting Tool Company.

Effect of Insert Shape on Feed Marks on a Face-Milled Surface

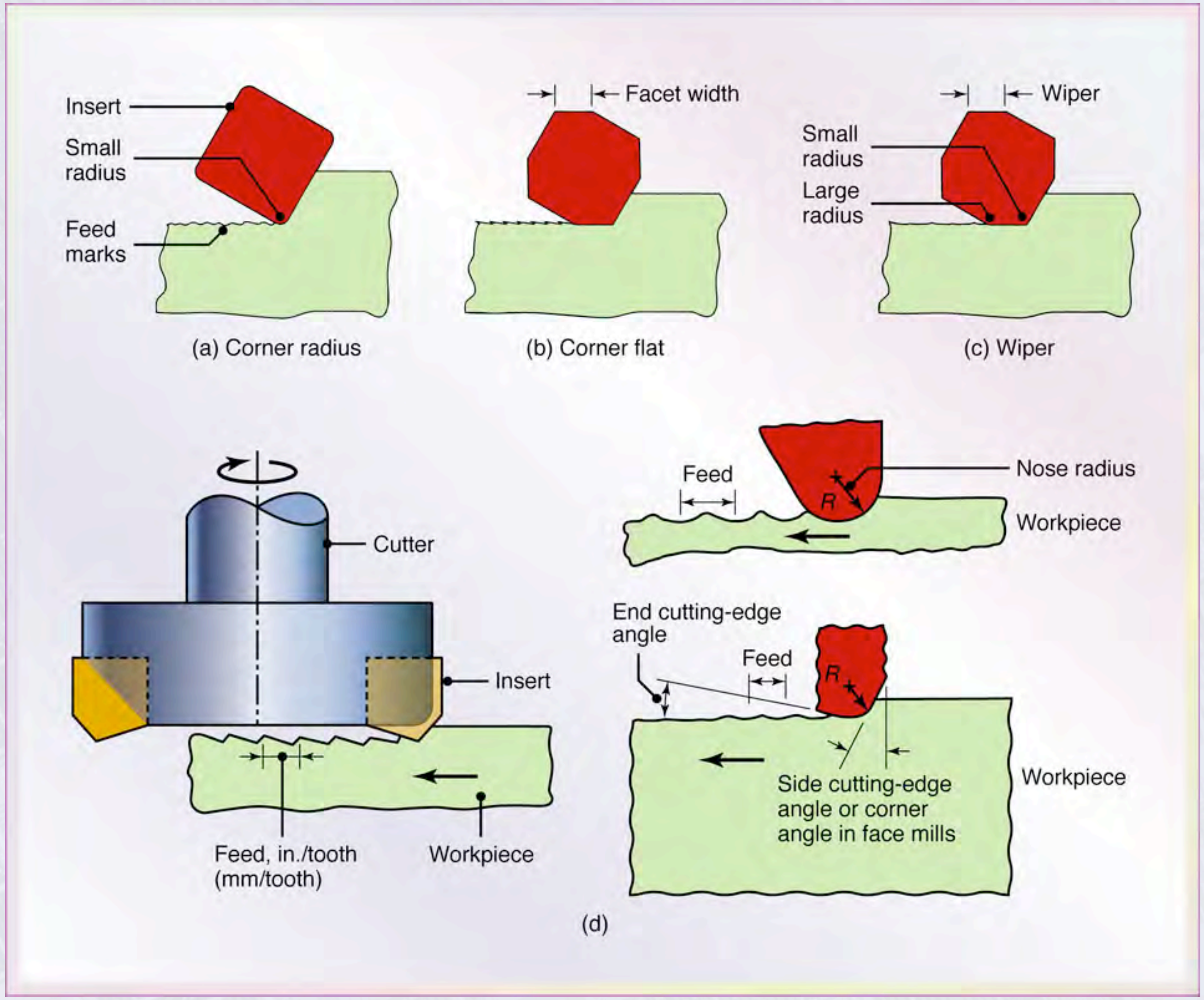

Figure 24.6 Schematic illustration of the effect of insert shape on feed marks on a face-milled surface: (a) small corner radius, (b) corner flat on insert, and (c) wiper, consisting of small radius followed by a large radius which leaves smoother feed marks. (d) Feed marks due to various insert shapes.

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Face-Milling Cutter

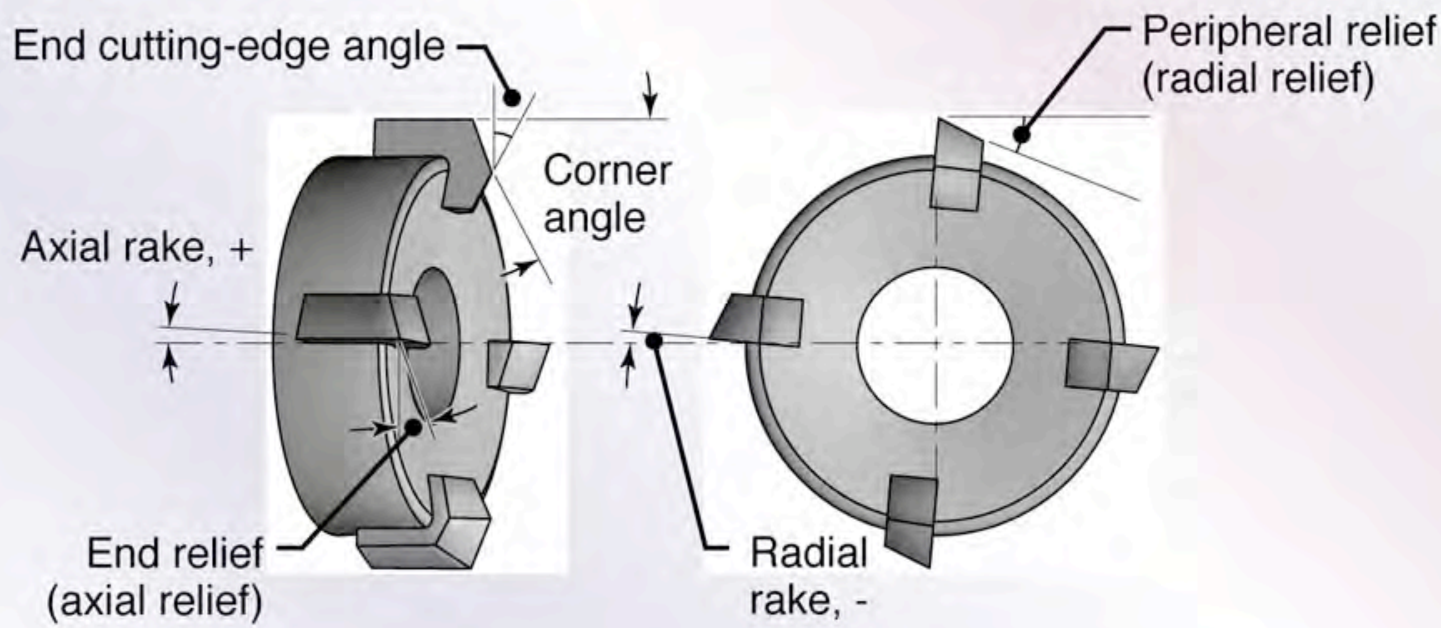

Figure 24.7 Terminology for a face-milling cutter.

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Effect of Lead Angle on Undeformed Chip Thickness in Face Milling

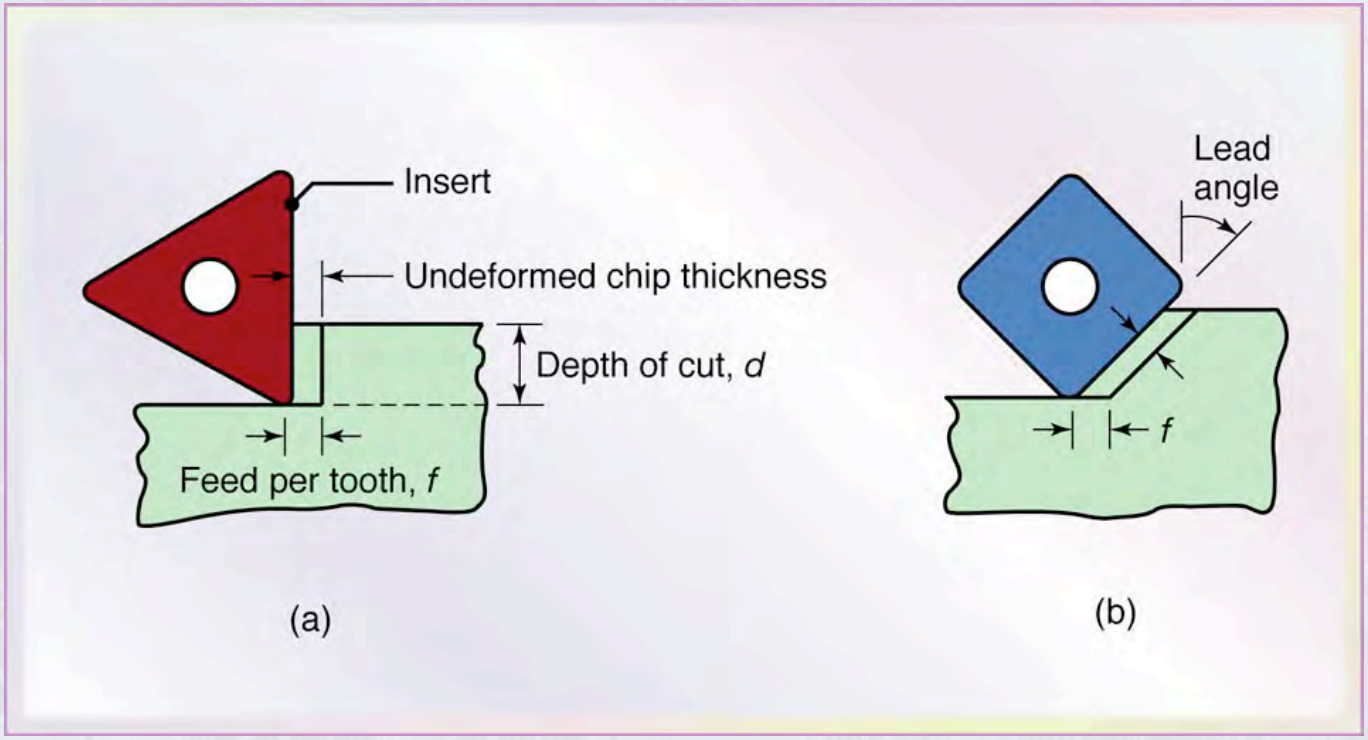

Figure 24.8 The effect of the lead angle on the undeformed chip thickness in face milling. Note that as the lead angle increases, the chip thickness decreases, but the length of contact (i.e., chip width) increases. The edges of the insert must be sufficiently large to accommodate the contact length increase.

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Position of Cutter and Insert in Face Milling

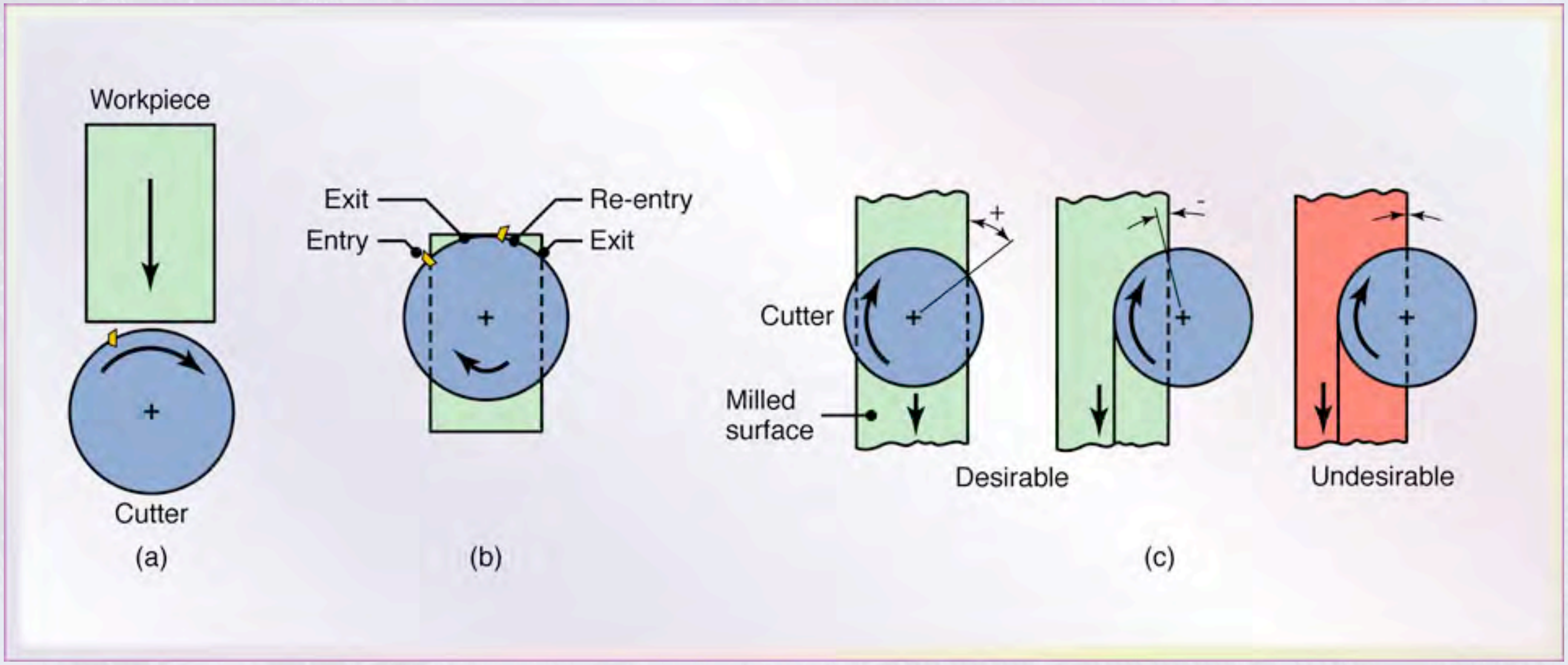

Figure 24.9 (a) Relative position of the cutter and insert as it first engages the workpiece in face milling. (b) Insert positions towards the end of cut. (c) Examples of exit angles of insert, showing desirable (positive or negative angle) and undesirable (zero angle) positions. In all figures, the cutter spindle is perpendicular to the page and rotates clockwise.

Ball Nose End Mills

Figure 24.10 Ball nose end mills. These cutters are able to produce elaborate contours and are often used in the machining of dies and molds. (See also Fig. 24.2d.) *Source:* Courtesy of Dijet, Inc.

Cutters

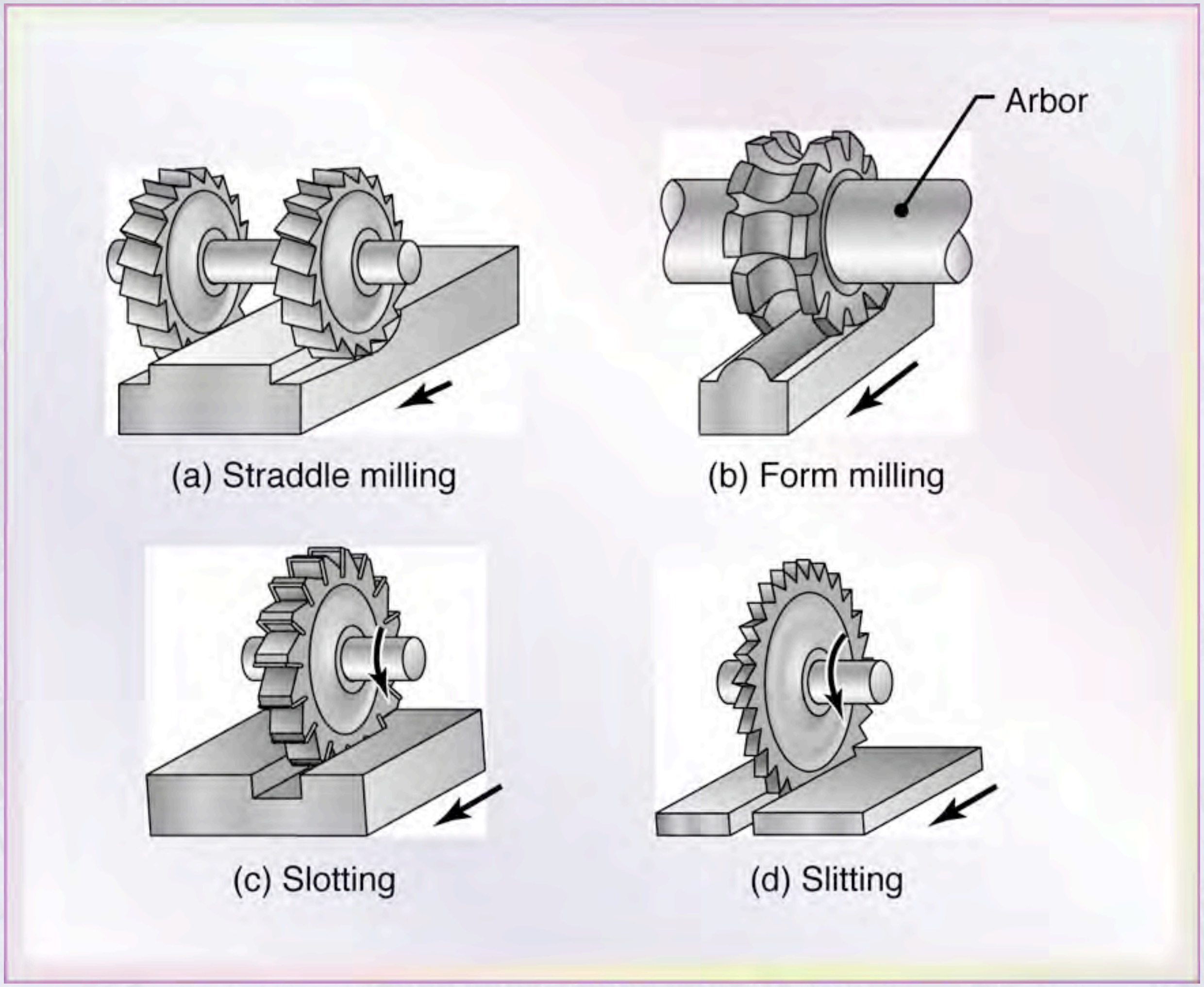

Figure 24.11 Cutters for (a) straddle milling, (b) form milling, (c) slotting, and (d) slitting with a milling cutter.

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T-Slot Cutting and Shell Mill

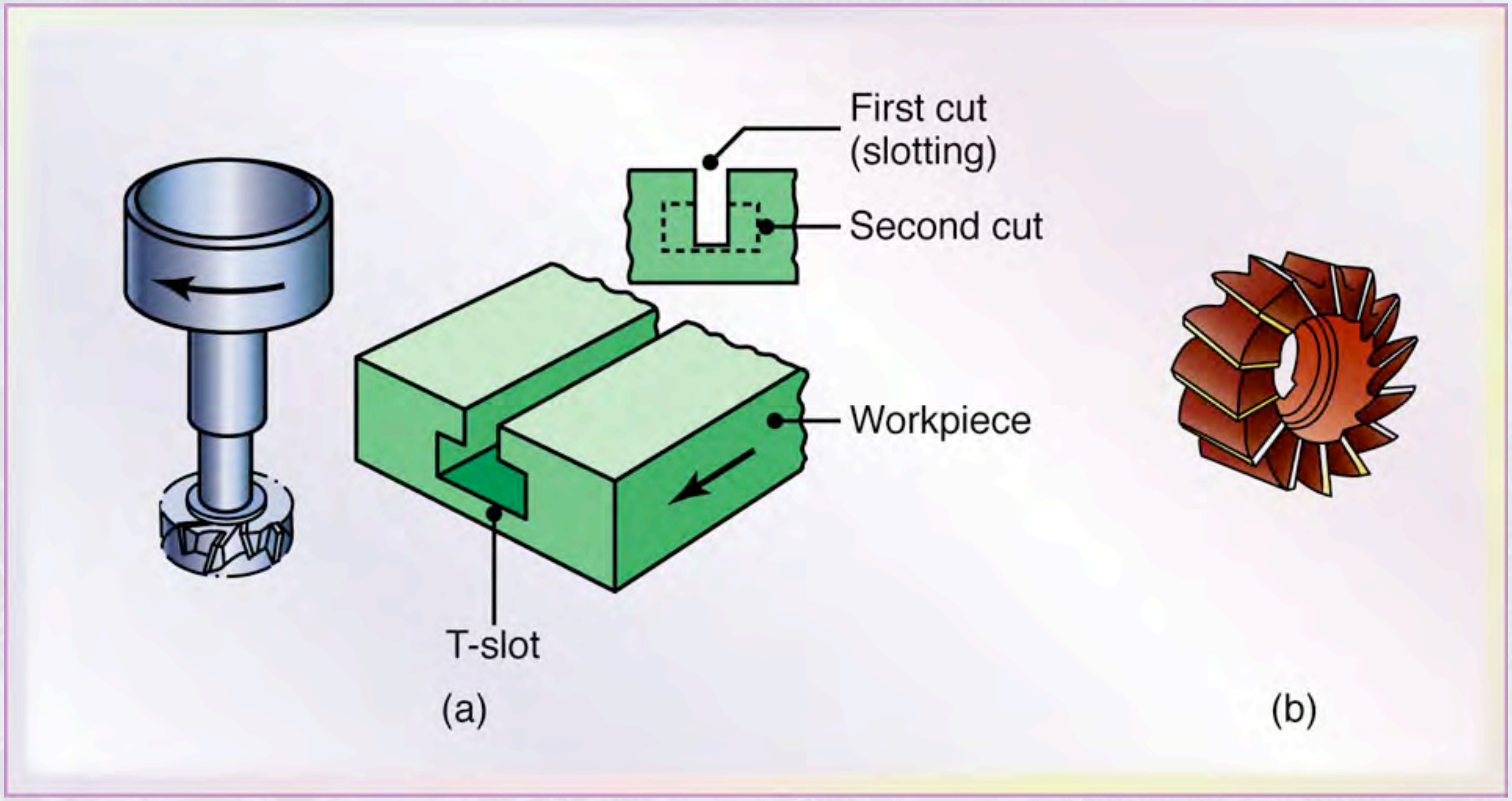

Figure 24.12 (a) T-slot cutting with a milling cutter. (b) A shell mill.

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General Recommendations for Milling Operations

TABLE 24.2

General Recommendations for Milling Operations

Material	Cutting tool	General-purpose starting conditions		Range of conditions	
		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)	120–180 (400–600)	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)	90–170 (300–550)	0.08–0.30 (0.003–0.012)	60–370 (200–1200)
Hard	Cermets, PcBN	0.10–0.15 (0.004–0.006)	180–210 (600–700)	0.08–0.25 (0.003–0.010)	75–460 (250–1500)
Cast iron, gray					
Soft	Uncoated, coated, cermets, SiN	0.10–10.20 (0.004–0.008)	120–760 (400–2500)	0.08–0.38 (0.003–0.015)	90–1370 (300–4500)
Hard	Cermets, SiN, PcBN	0.10–0.20 (0.004–0.008)	120–210 (400–700)	0.08–0.38 (0.003–0.015)	90–460 (300–1500)
Stainless steel, Austenitic	Uncoated, coated, cermets	0.13–0.18 (0.005–0.007)	120–370 (400–1200)	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)	610–900 (2000–3000)	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	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	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 to 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.

Troubleshooting Guide for Milling Operations

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 workholding 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
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

Machined Surface Features in Face Milling

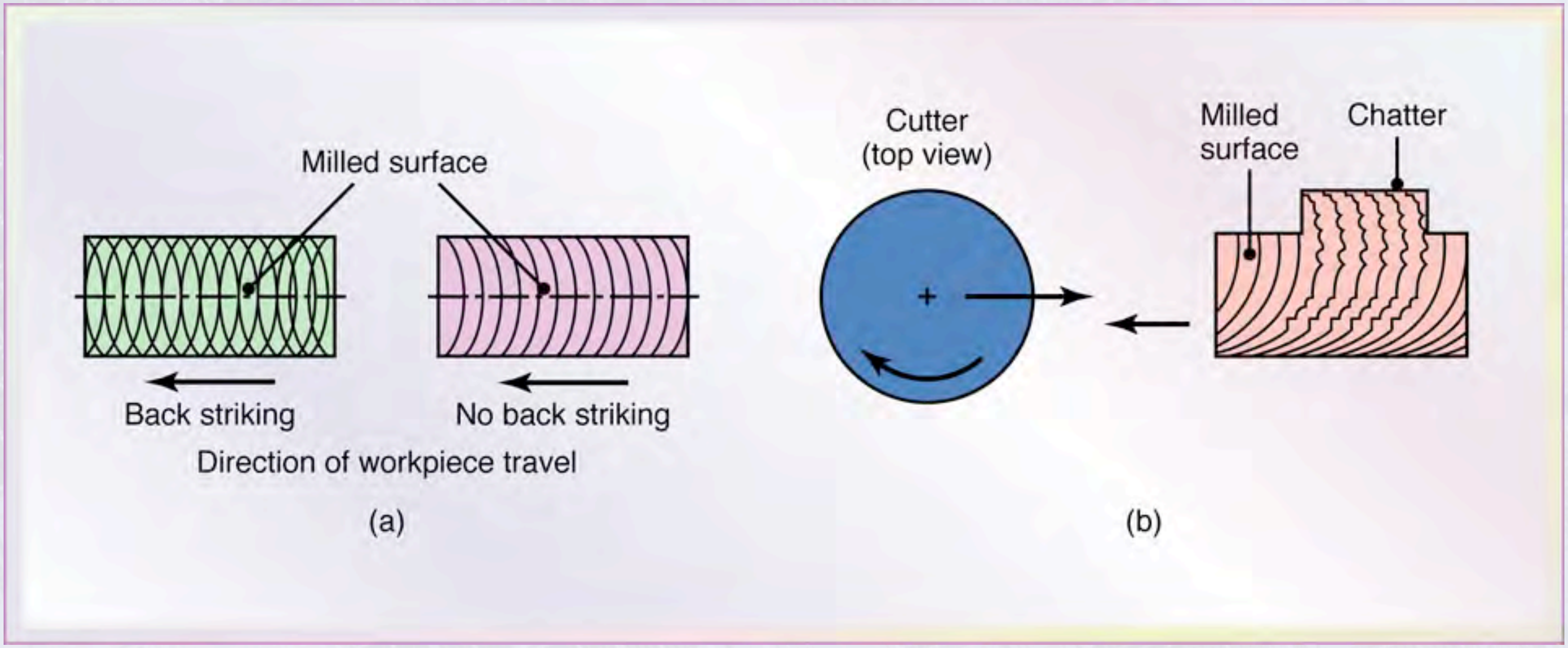

Figure 24.13 Machined surface features in face milling. See also Fig. 24.6.

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Edge Defects in Face Milling

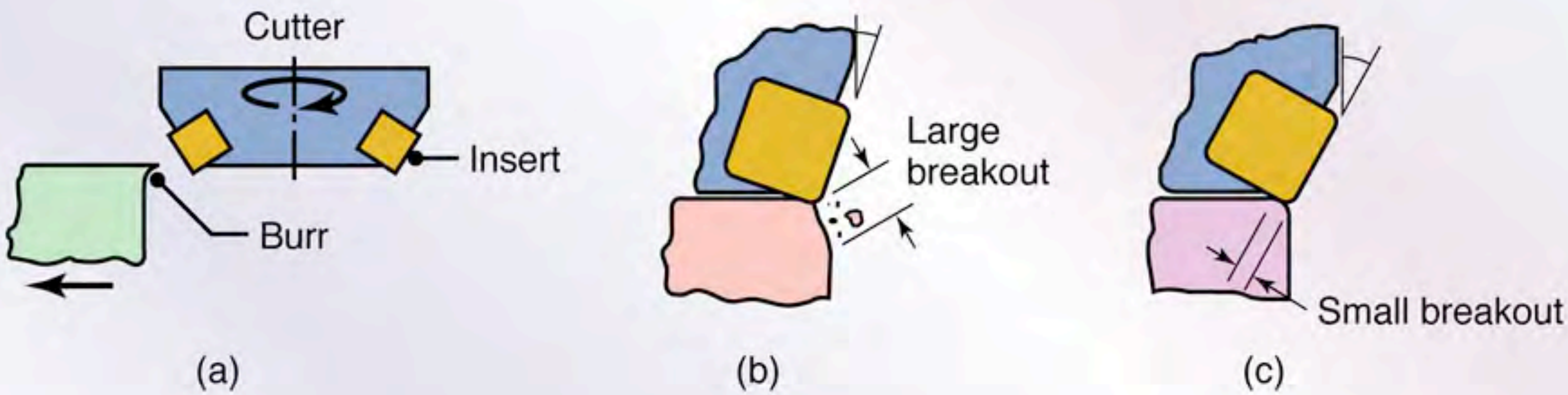

Figure 24.14 Edge defects in face milling: (a) burr formation along workpiece edge, (b) breakout along workpiece edge, and (c) how it can be avoided by increasing the lead angle (see also last row in Table 24.4).

Column-and-Knee Type Milling Machines

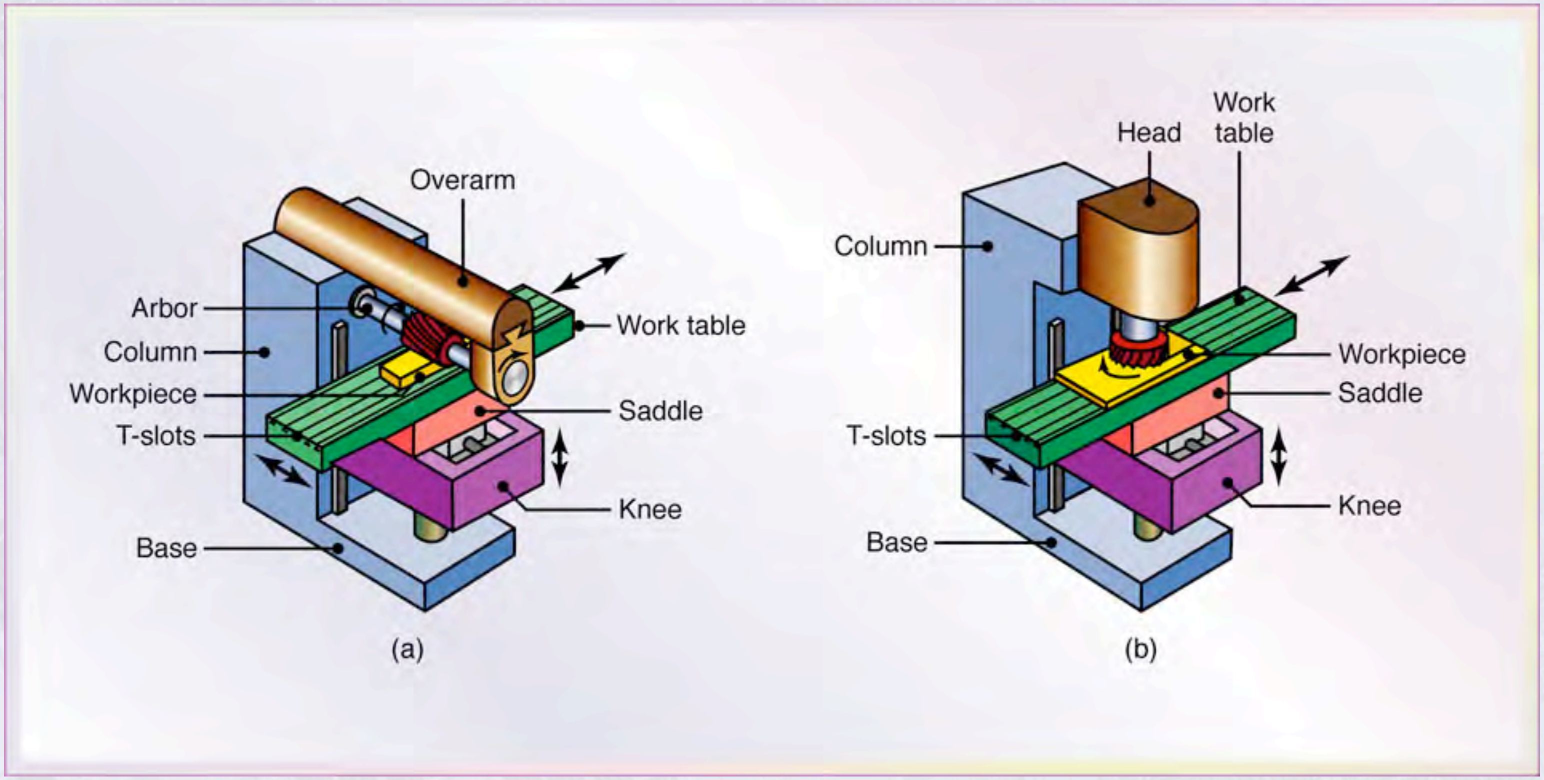

Figure 24.15 Schematic illustration of (a) a horizontal-spindle column-and-knee type milling machine and (b) vertical-spindle column-and-knee type milling machine. *Source*: After G. Boothroyd.

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CNC Vertical-Spindle Milling Machine

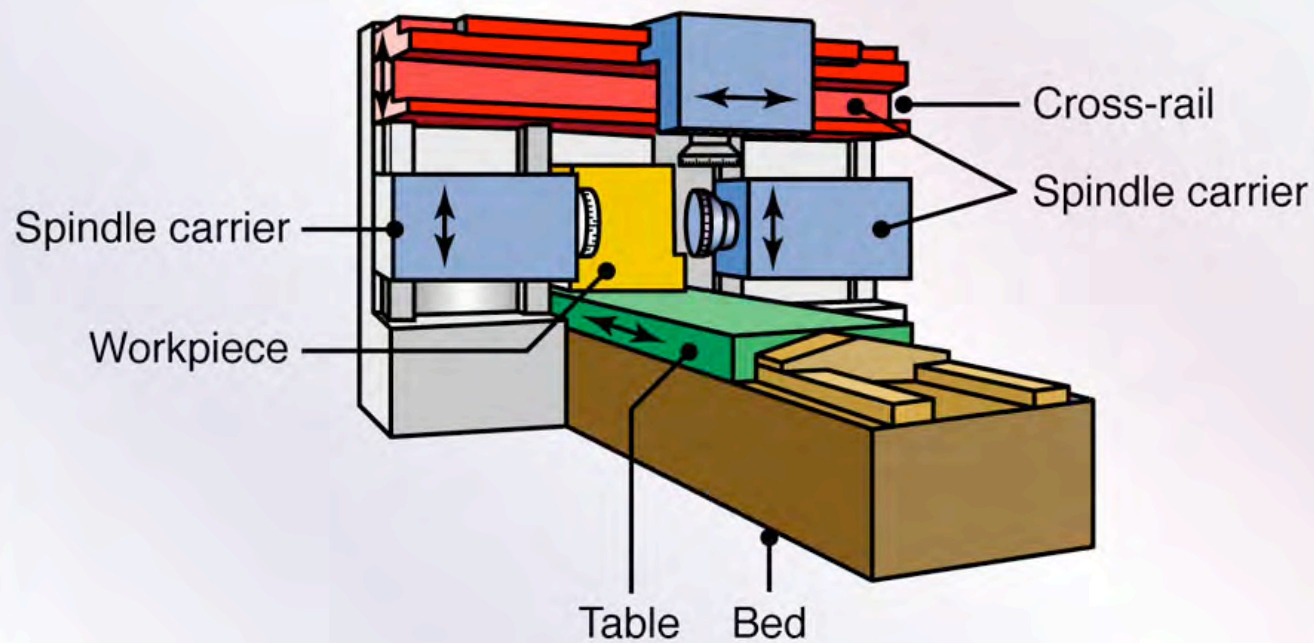

Figure 24.17 A computer numerical-control (CNC) vertical-spindle milling machine. This machine is one of the most versatile machine tools. The original vertical-spindle milling machine iused in job shops is still referred to as a “Bridgeport”, after its manufacturer in Bridgeport, Connecticut. *Source*: Courtesy of Bridgeport Machines Dibision, Textron Inc.

Five-Axis Profile Milling Machine

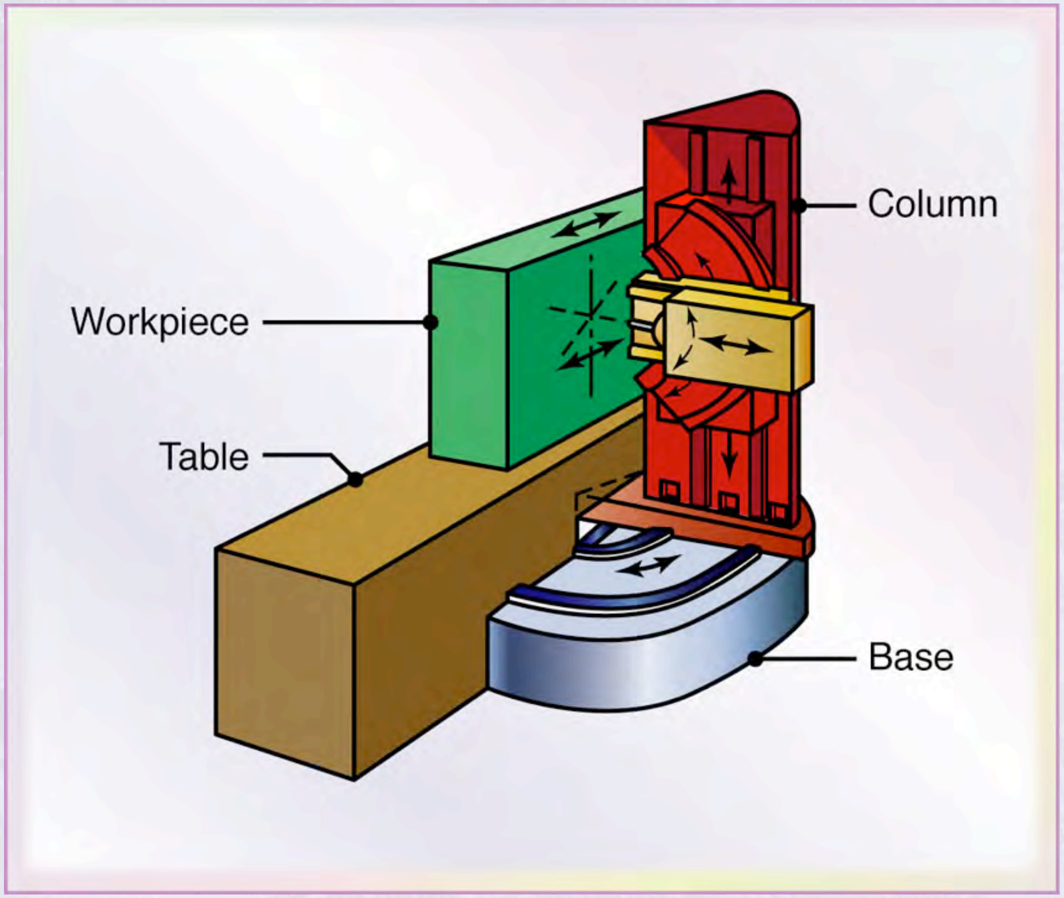

Figure 24.18 Schematic illustration of a five-axis profile milling machine. Note that there are three principal linear and two angular movements of machine components.

Parts Made on a Planer

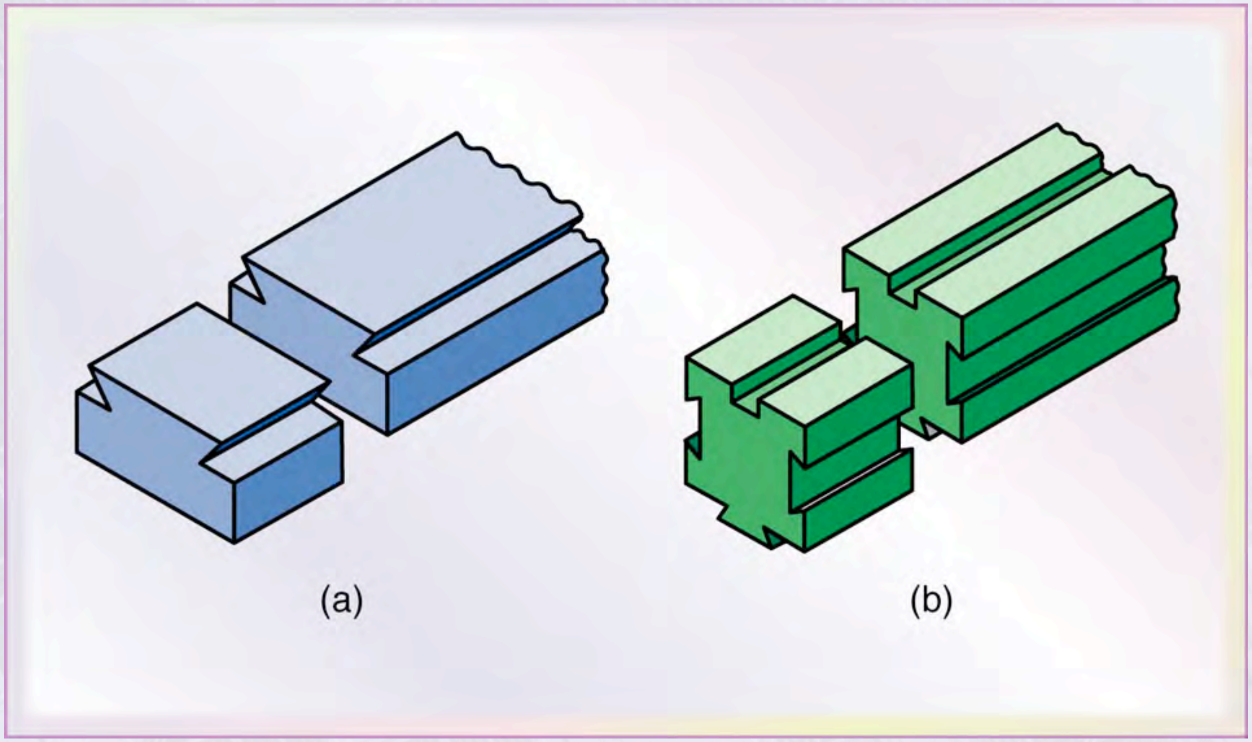

Figure 24,19 Typical parts that can be made on a planer.

Broaching

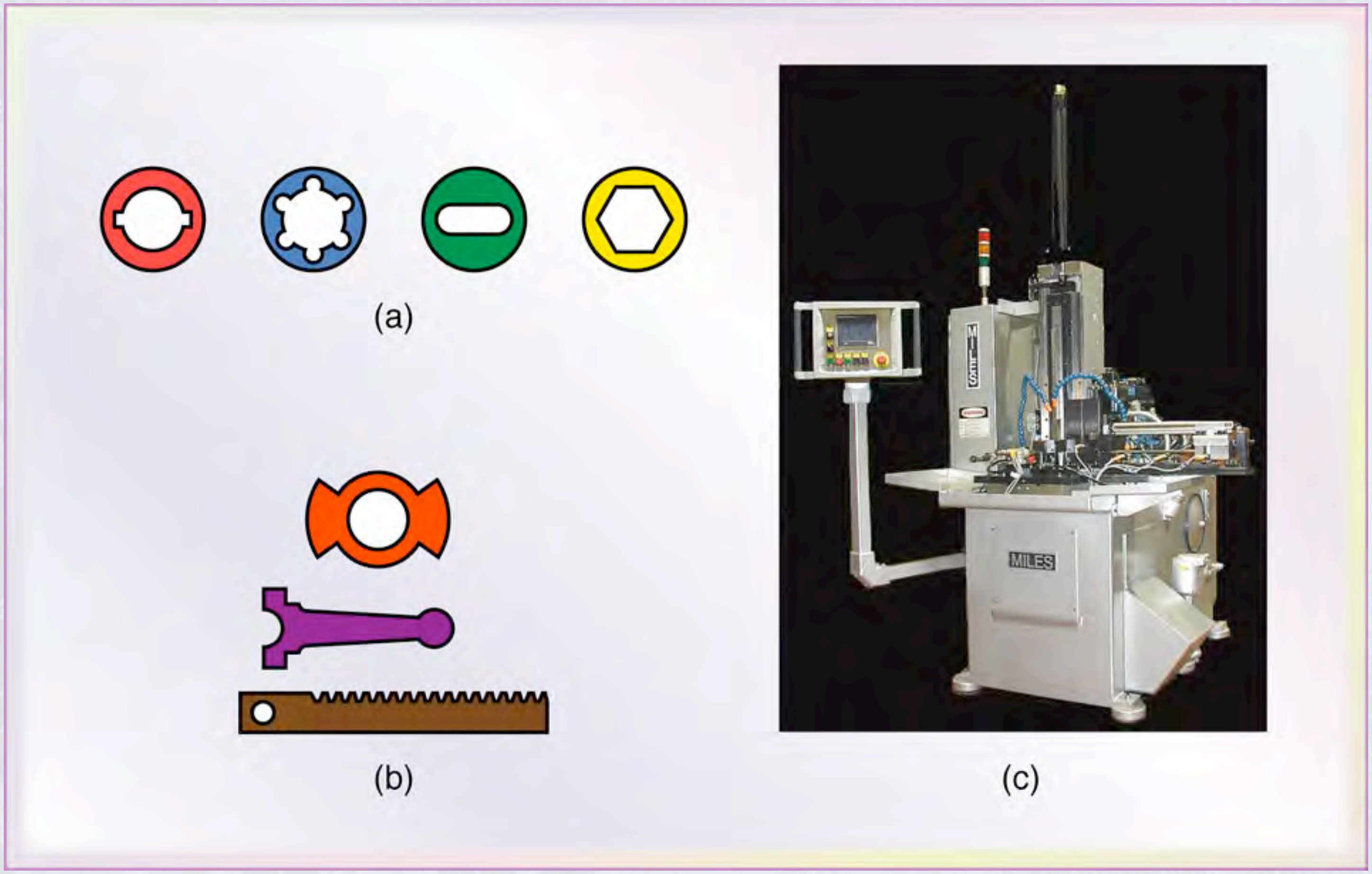

Figure 24.20 (a) Typical parts made by internal broaching. (b) Parts made by surface broaching. Heavy lines indicate broached surfaces. (c) Vertical broaching machine. *Source*: (a) and (b) Courtesy of General Broach and Engineering Company. (c) Courtesy of Ty Miles, Inc.

Broach Geometry

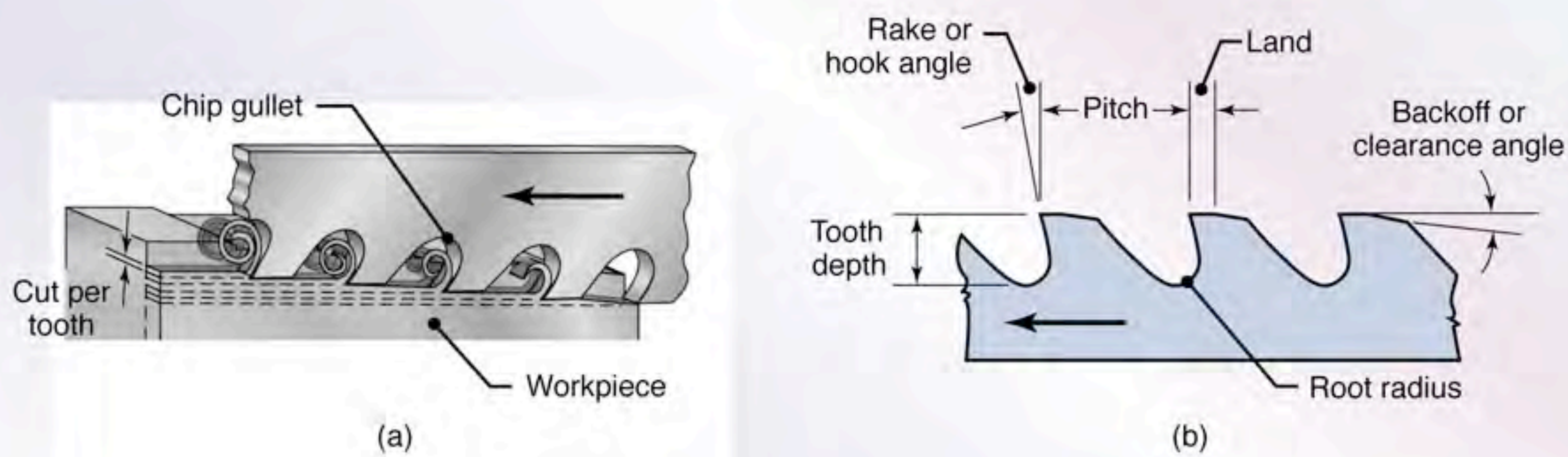

Figure 24.21 (a) Cutting action of a broach showing various features.
(b) Terminology for a broach.

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Chipbreaker Features on Broaches

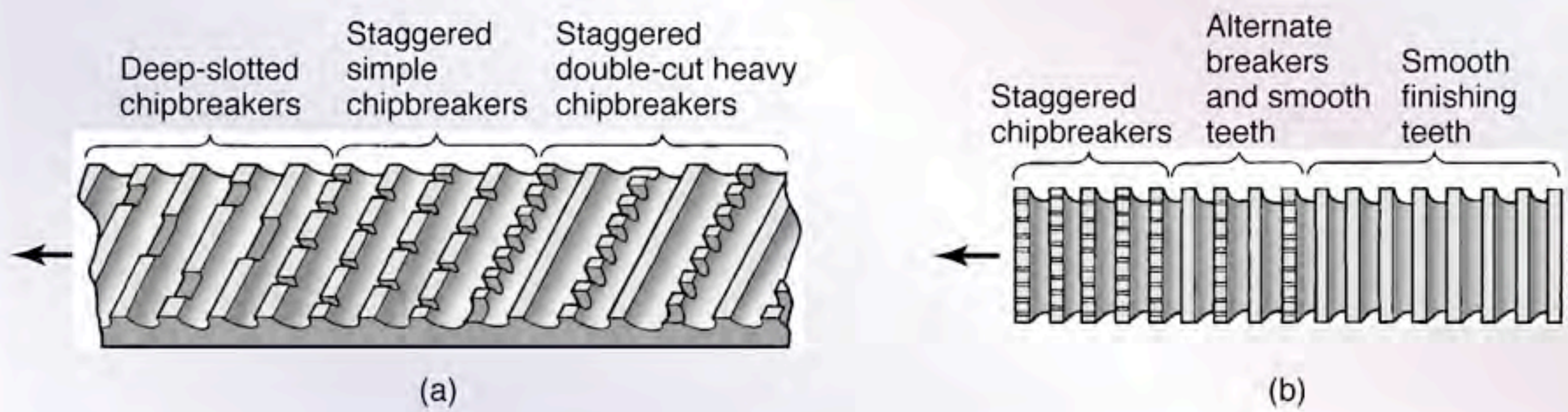


Figure 24.22 Chipbreaker features on (a) a flat broach and (b) a round broach.

Pull-Types Internal Broach

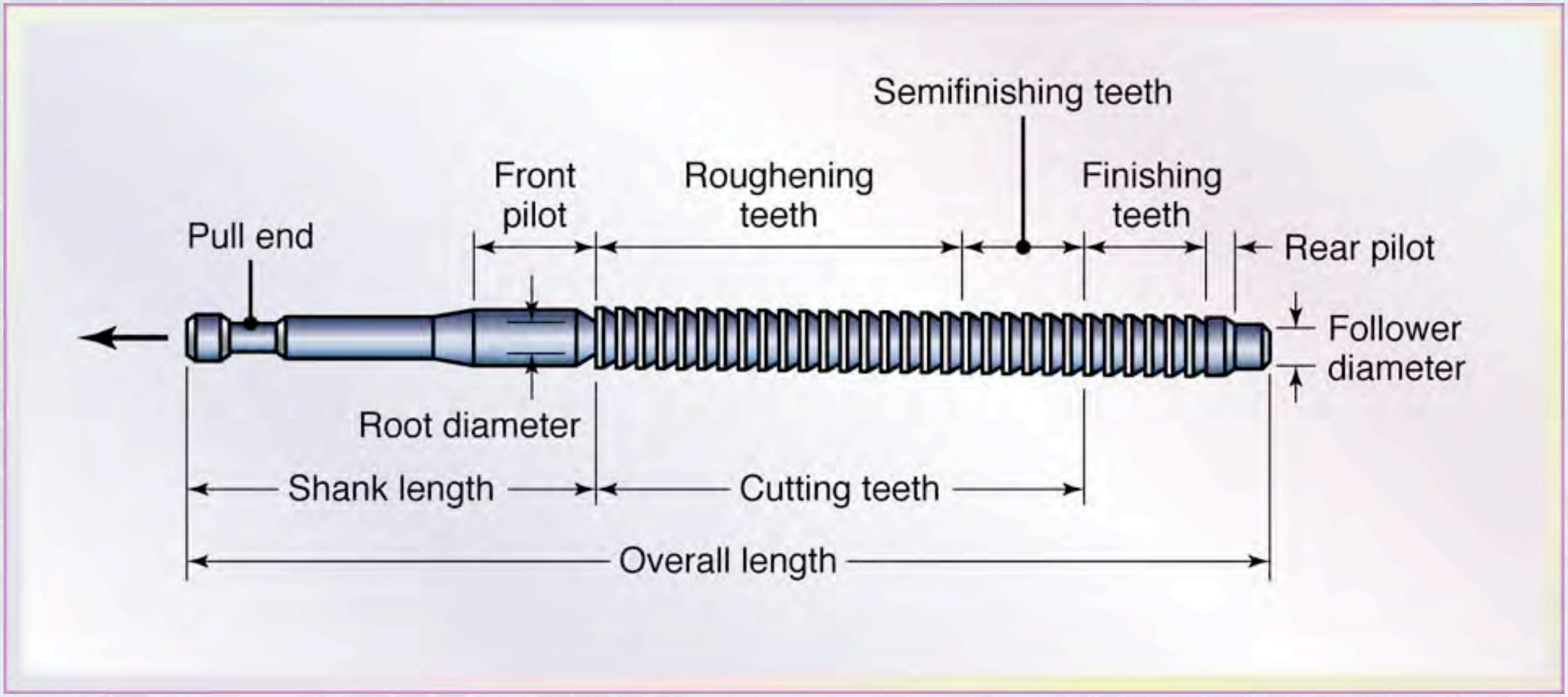


Figure 24.23 Terminology for a pull-type internal broach used for enlarging long holes.

Part with Internal Splines Made by Broaching

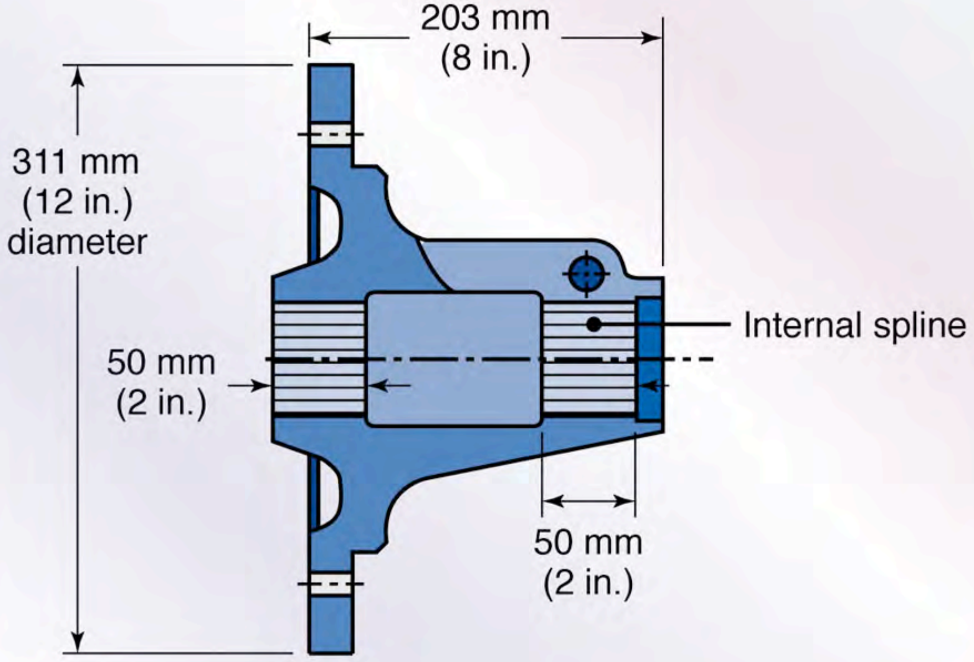


Figure 24.24 Example of a part with internal splines produced by broaching.

Sawing Operations

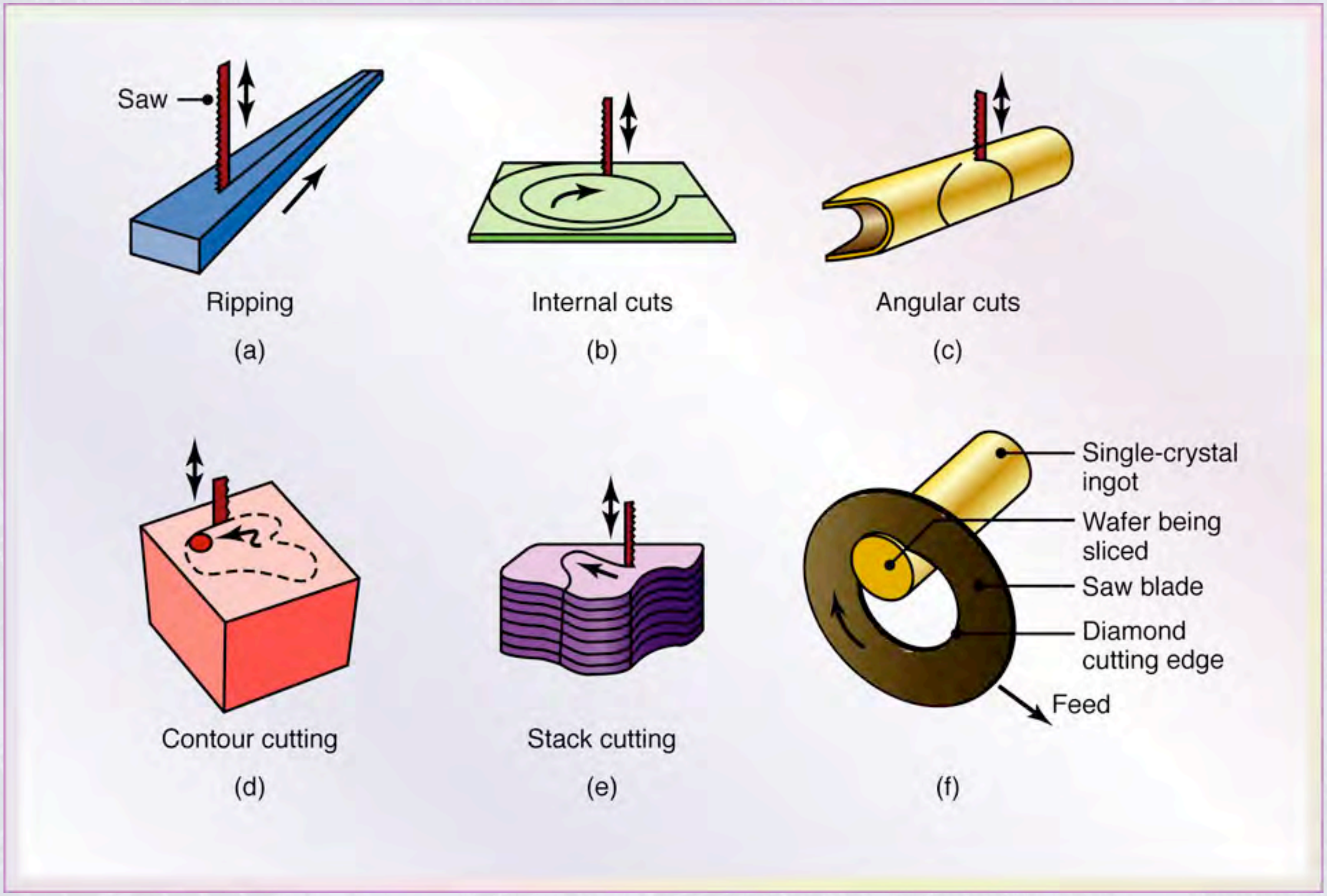


Figure 24.25 Examples of various sawing operations.

Saw Teeth

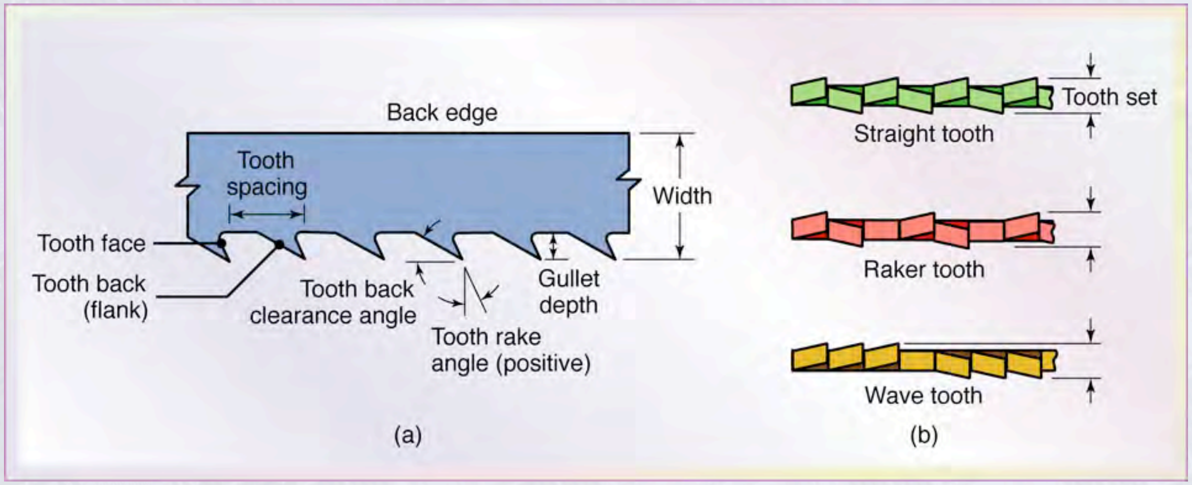
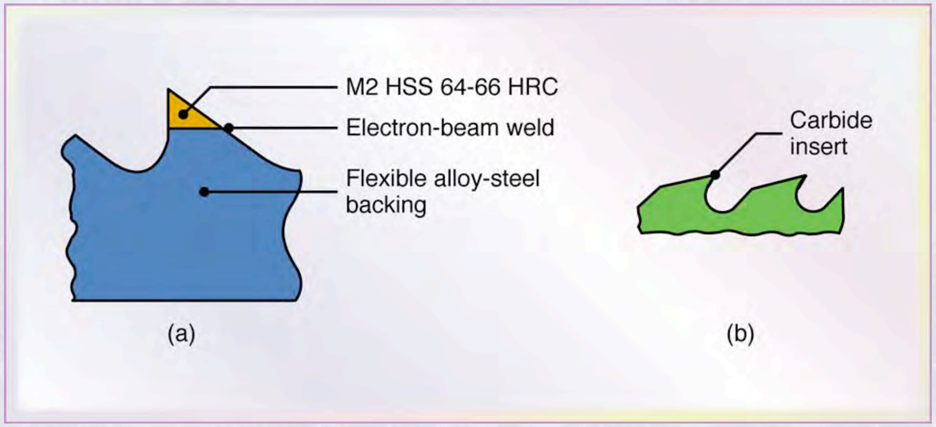


Figure 24.26 (a) Terminology for saw teeth. (b) Types of tooth sets on saw teeth staggered to provide clearance for the saw blade to prevent binding during sawing.

Figure 24.27 (a) High-speed-steel teeth welded on a steel blade. (b) Carbide inserts brazed to blade teeth.



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Types of Burs

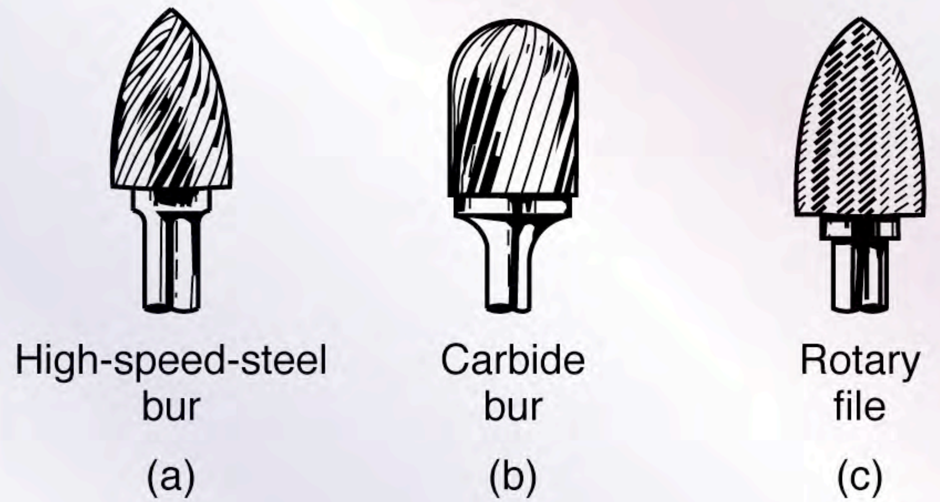

Figure 24.28 Types of burs used in burring operations.

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Involute Spur Gear

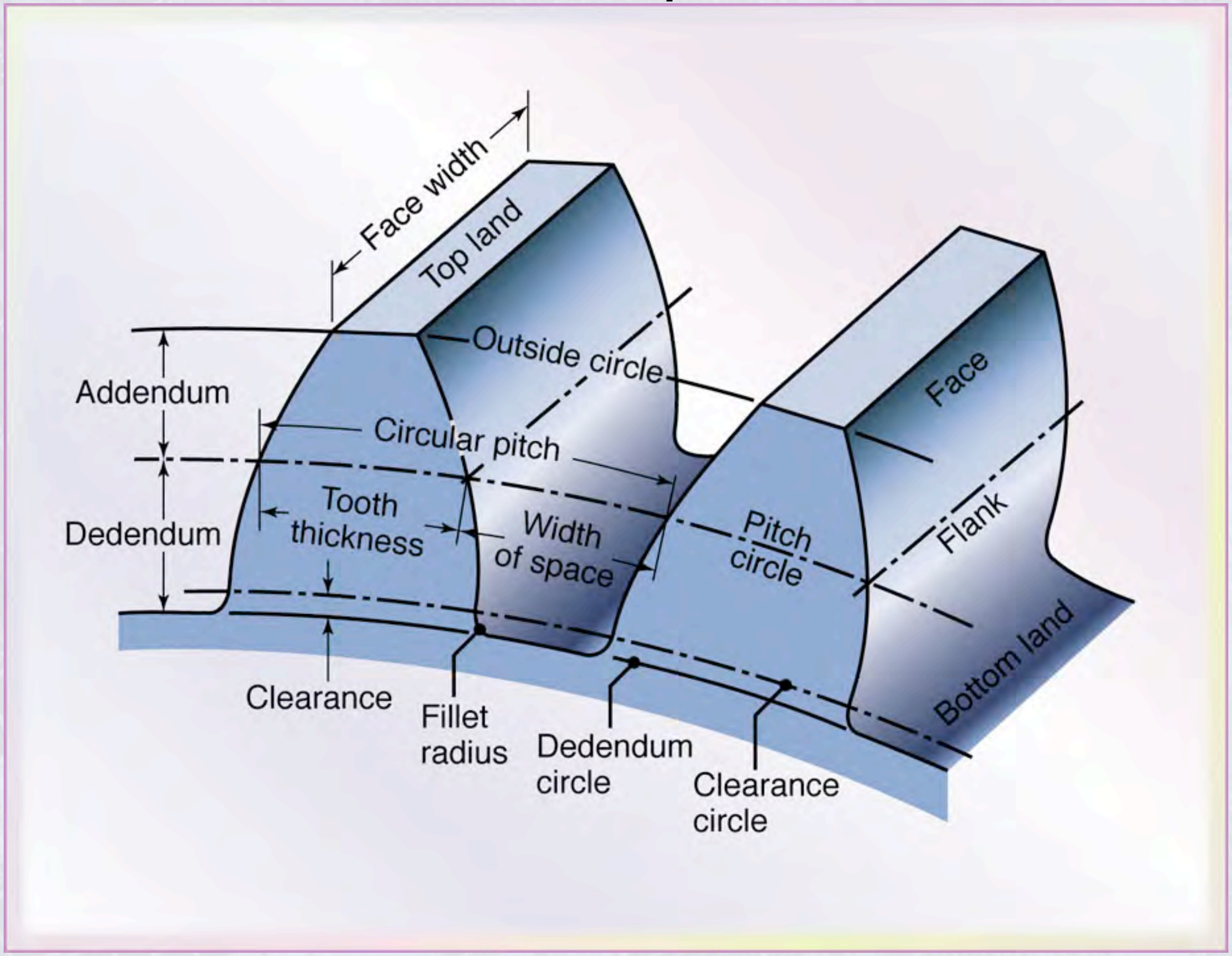

Figure 24.29 Nomenclature for an involute spur gear.

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Gear Generating with Various Cutters

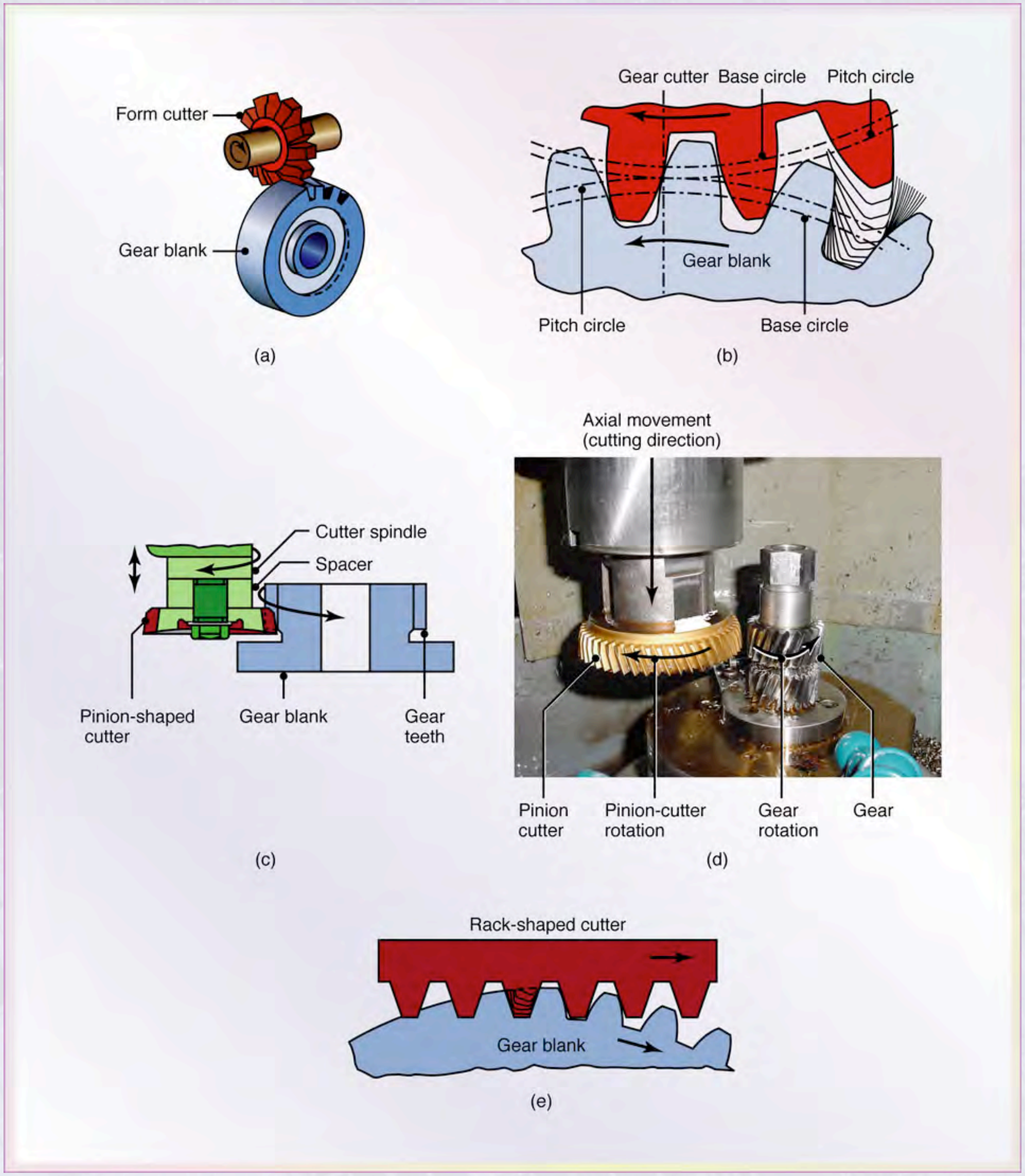

Figure 24.30 (a) Producing gear teeth on a blank by form cutting. (b) Schematic illustration of gear generating with a pinion-shaped gear cutter. (c) and (d) Gear generating on a gear shaper using a pinion-shaped cutter. Note that the cutter reciprocates vertically. (e) Gear generating with rack-shaped cutter. *Source*: (d) Schafer Gear Works, Inc.

Hobbing

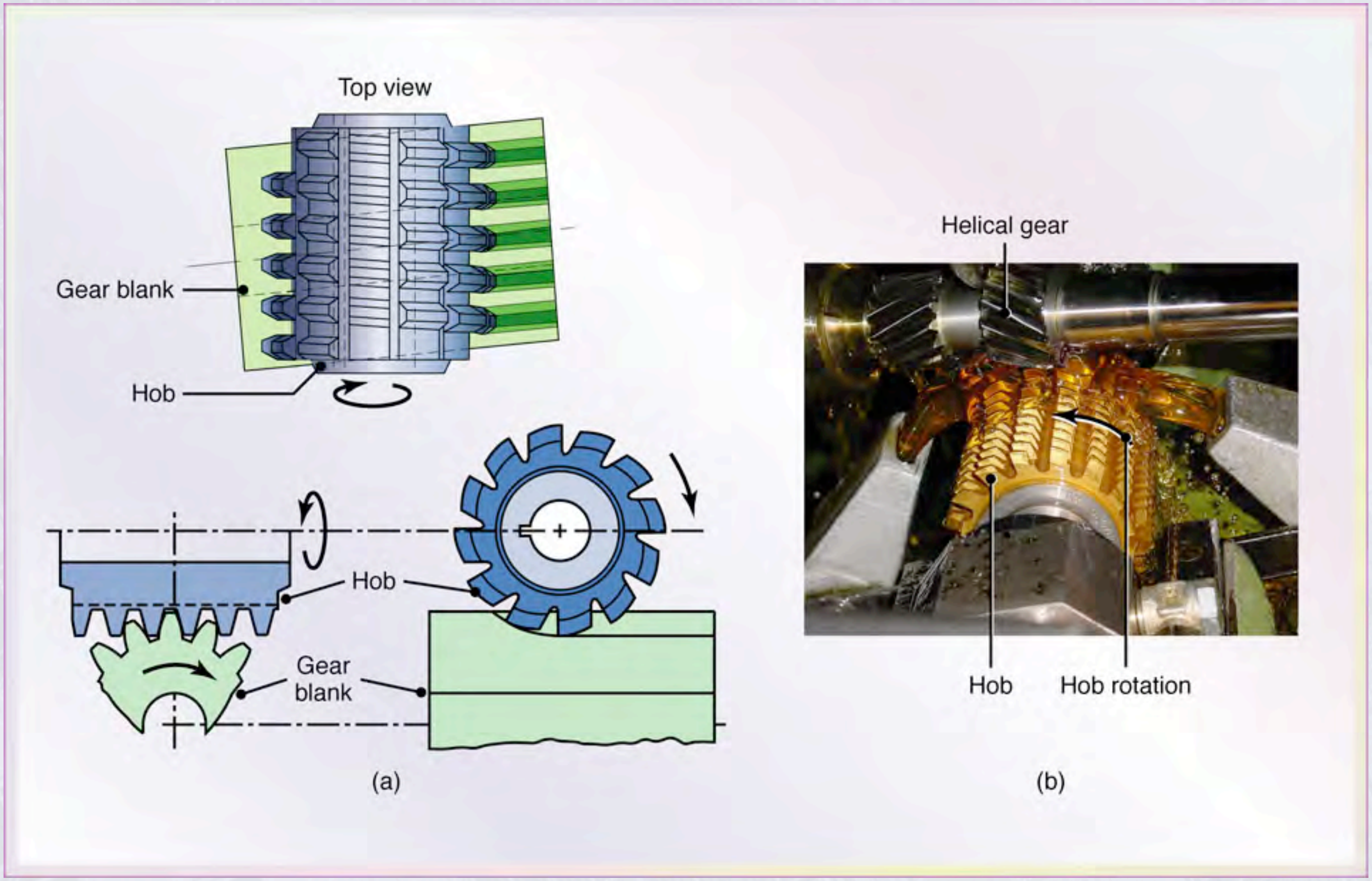

Figure 24.31 (a) Schematic illustration of gear cutting with a hob. (b) Production of worm gear through hobbing. *Source*: Courtesy of Schafer Gear Works, Inc.

Bevel Gears

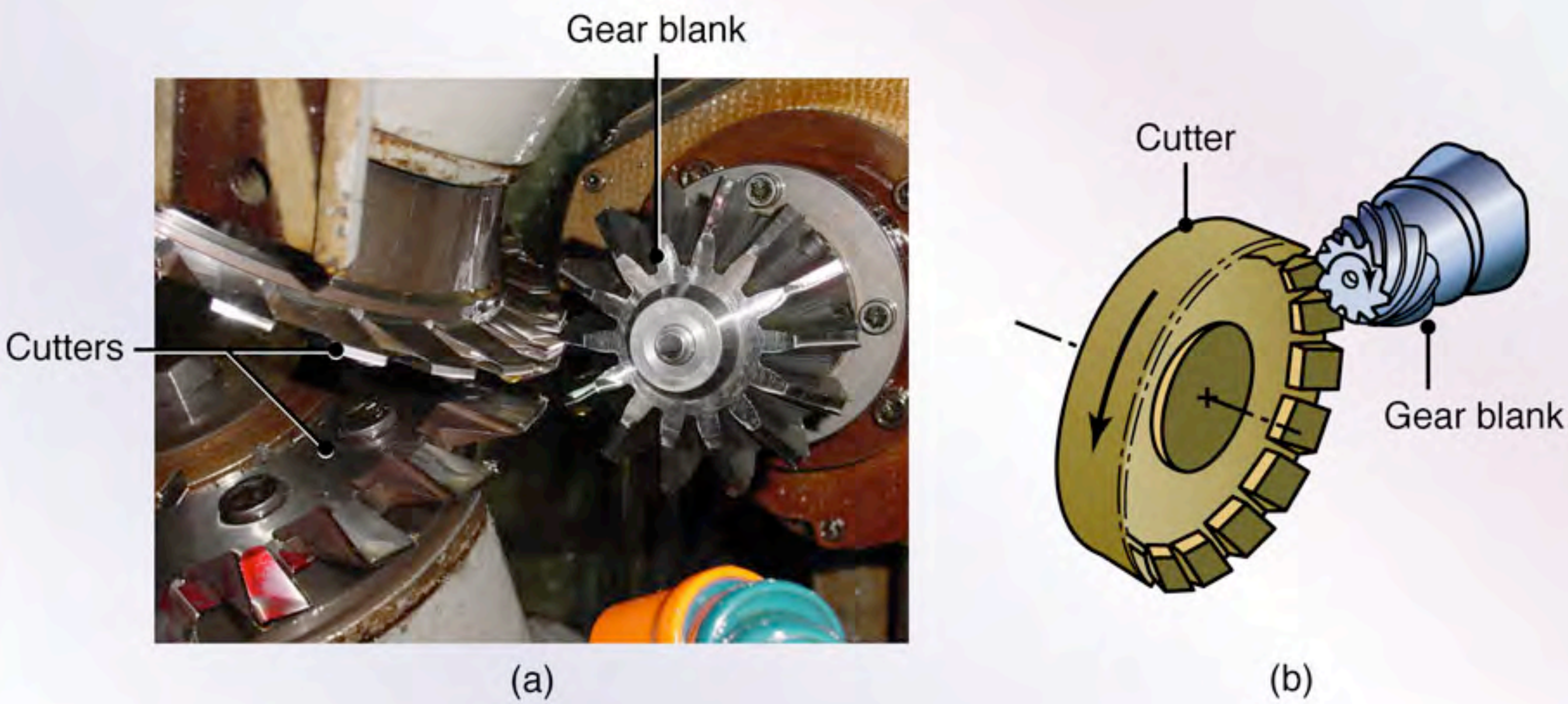

Figure 24.32 (a) Cutting a straight bevel-gear blank with two cutter. (b) Cutting a helical bevel gear. *Source*: Courtesy of Schafer Gear Works, Inc.

Finishing Gears by Grinding

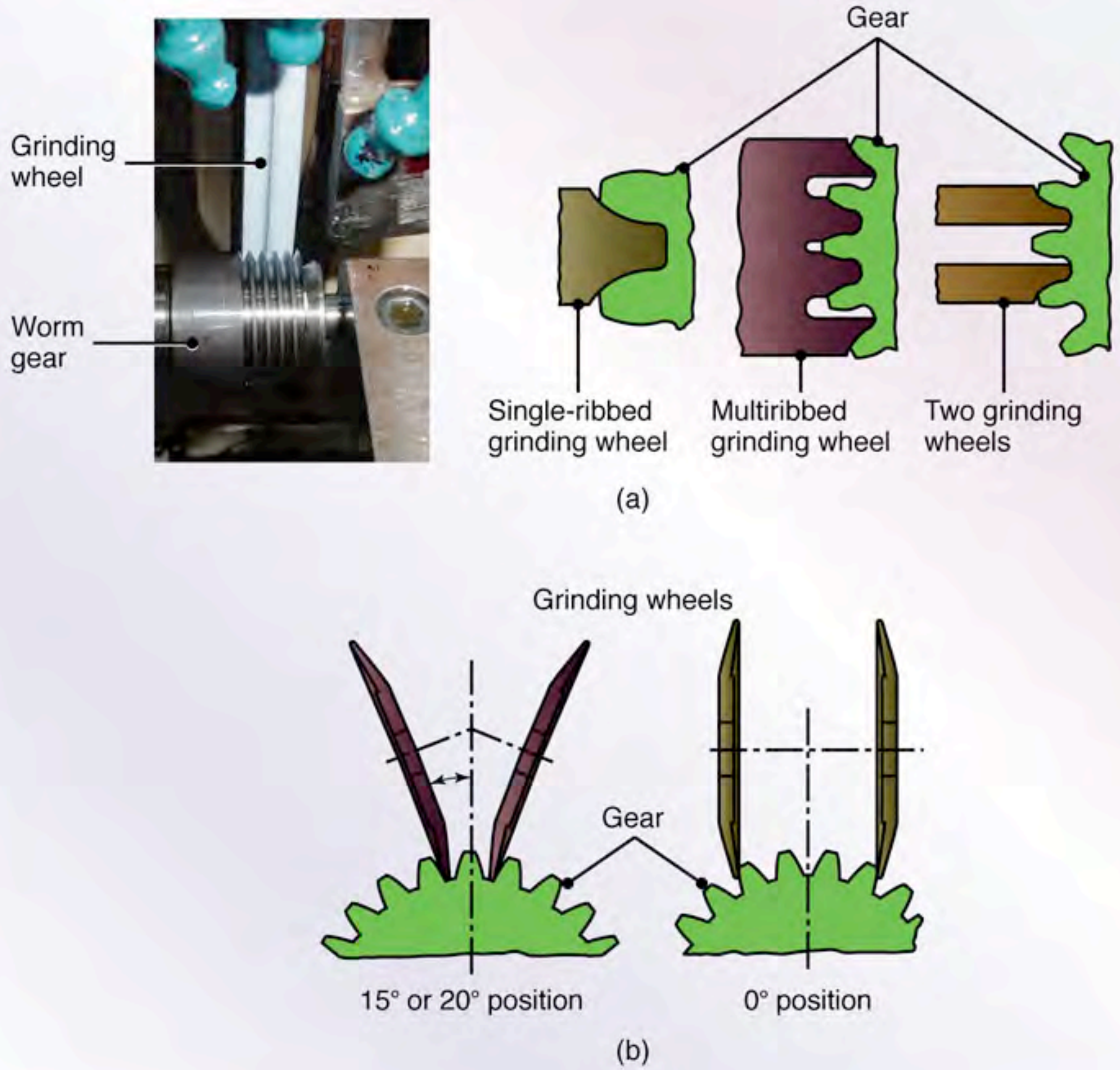

Figure 24.33 Finishing gears by grinding: (a) form grinding with shaped grinding wheels; (b) grinding by generating with two wheels.

Gear Manufacturing Cost as a Function of Gear Quantity

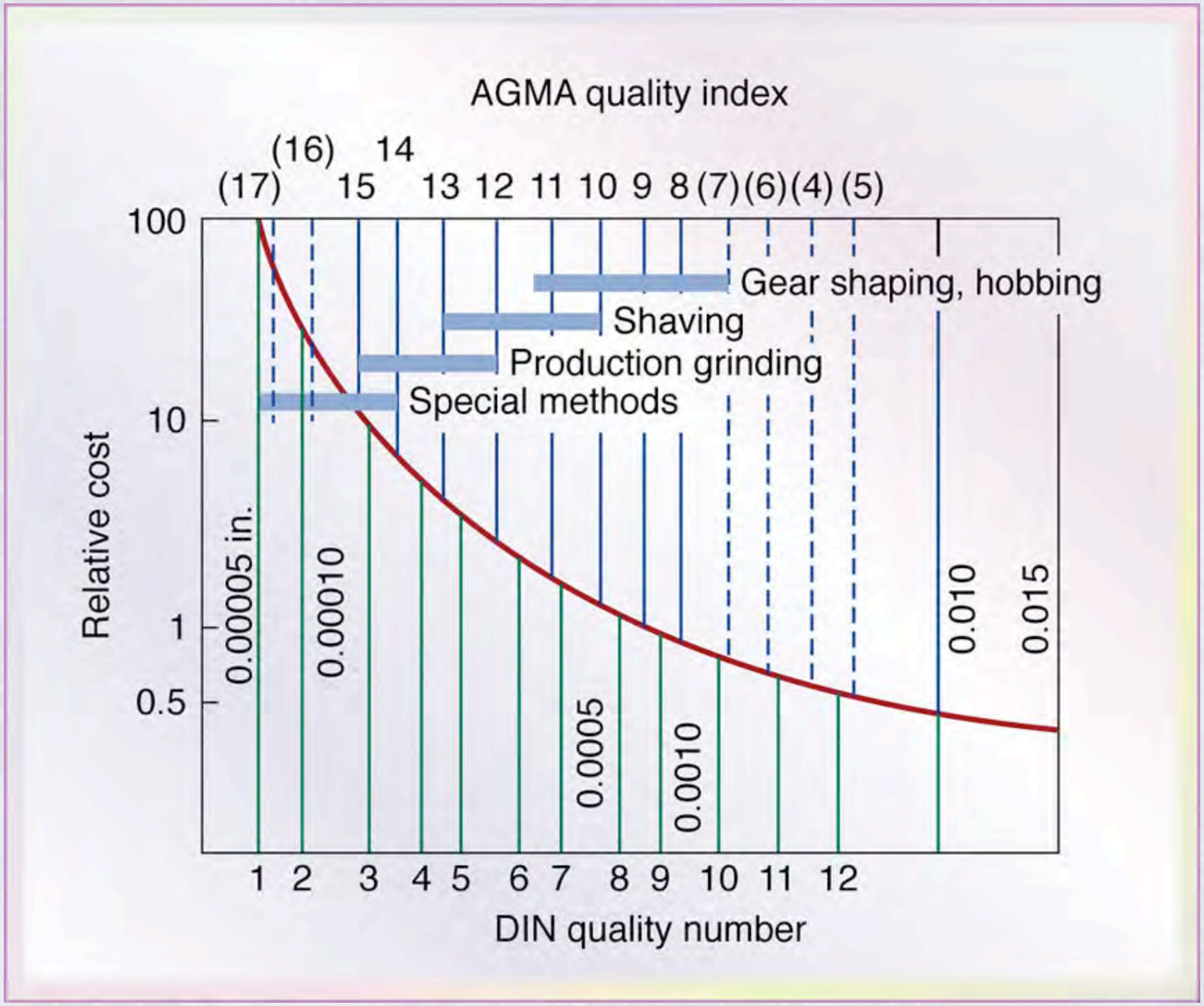

Figure 24.34 Gear manufacturing cost as a function of gear quality. The numbers along the vertical lines indicate tolerances.

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