Chapter 23

Machining Processes Used to Produce Round Shapes: Turning and Hole Making
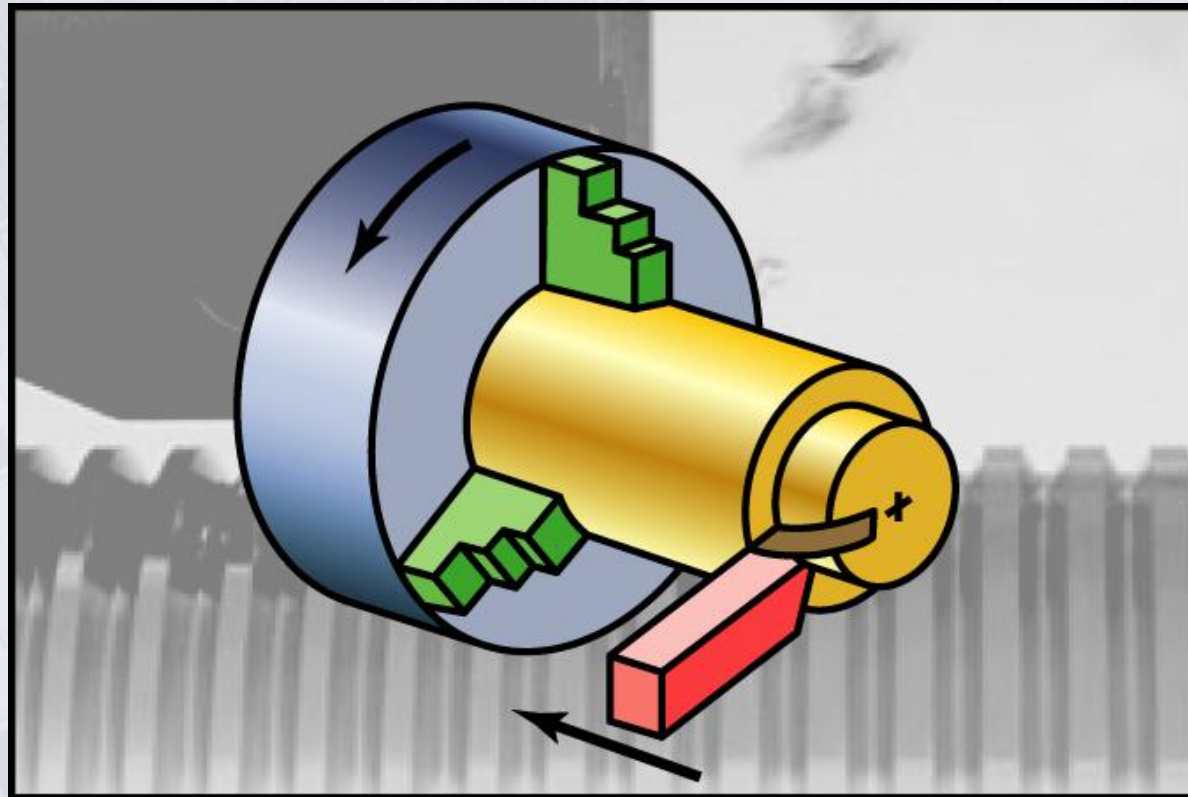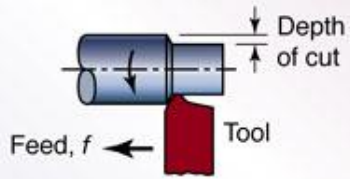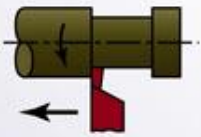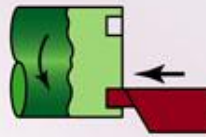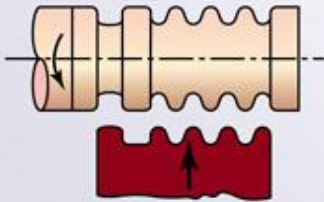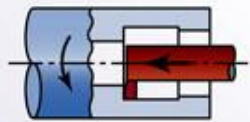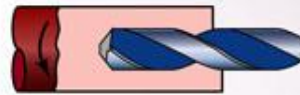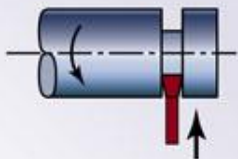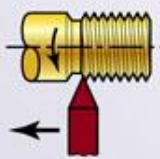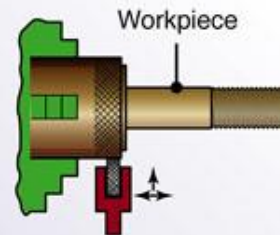
Lathe Cutting Operations

Figure 23.1 Miscellaneous cutting operations that can be performed on a lathe. Note that all parts are circular – a property known as axisymmetry. The tools used, their shape, and the processing parameters are described throughout this chapter.

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Characteristics of Machining Processes and Typical Dimensional Tolerances

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-quanity 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
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

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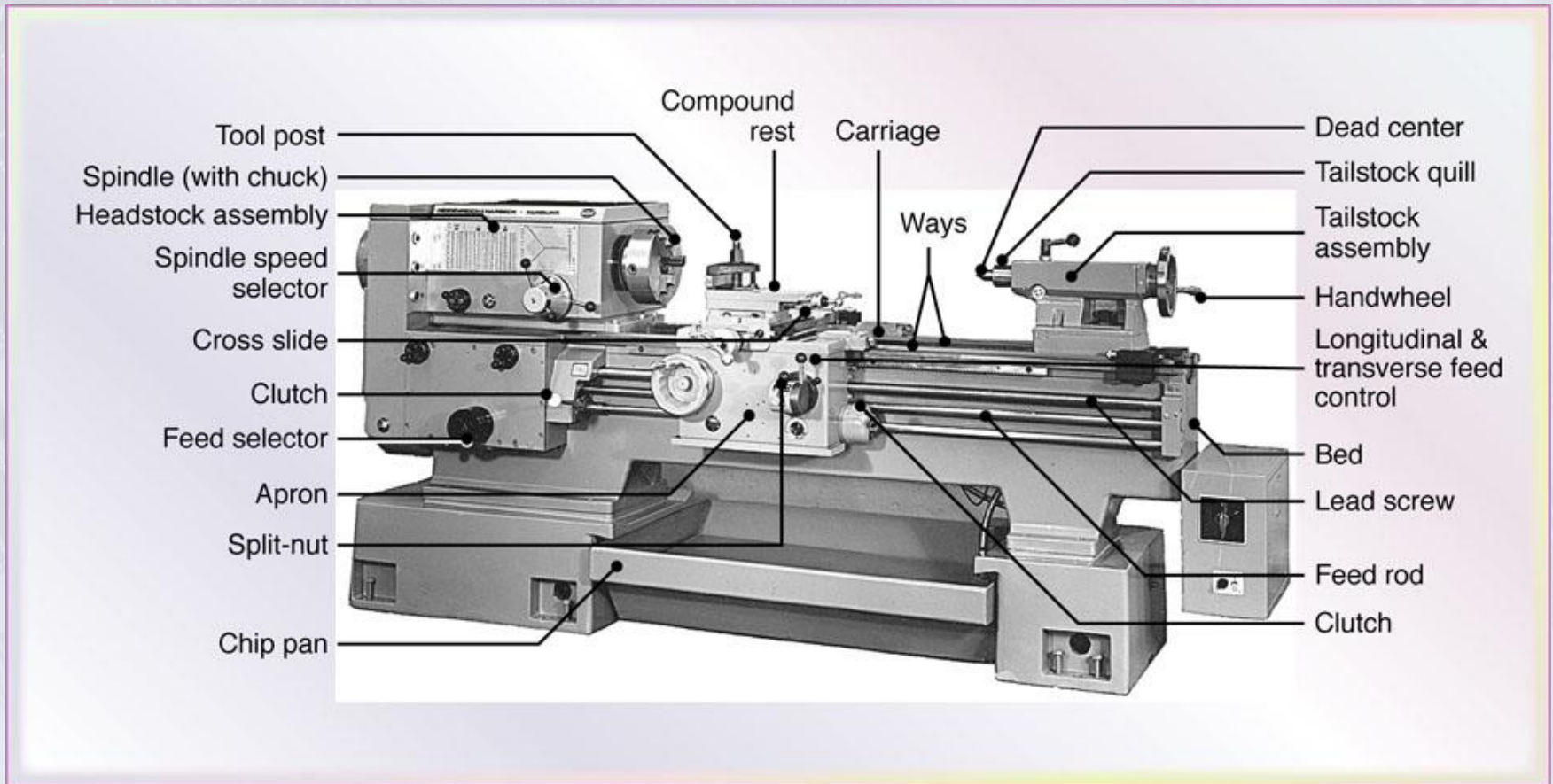
Lathe

Figure 23.2 General view of a typical lathe, showing various components.
Source: Courtesy of Heidenreich & Harbeck.

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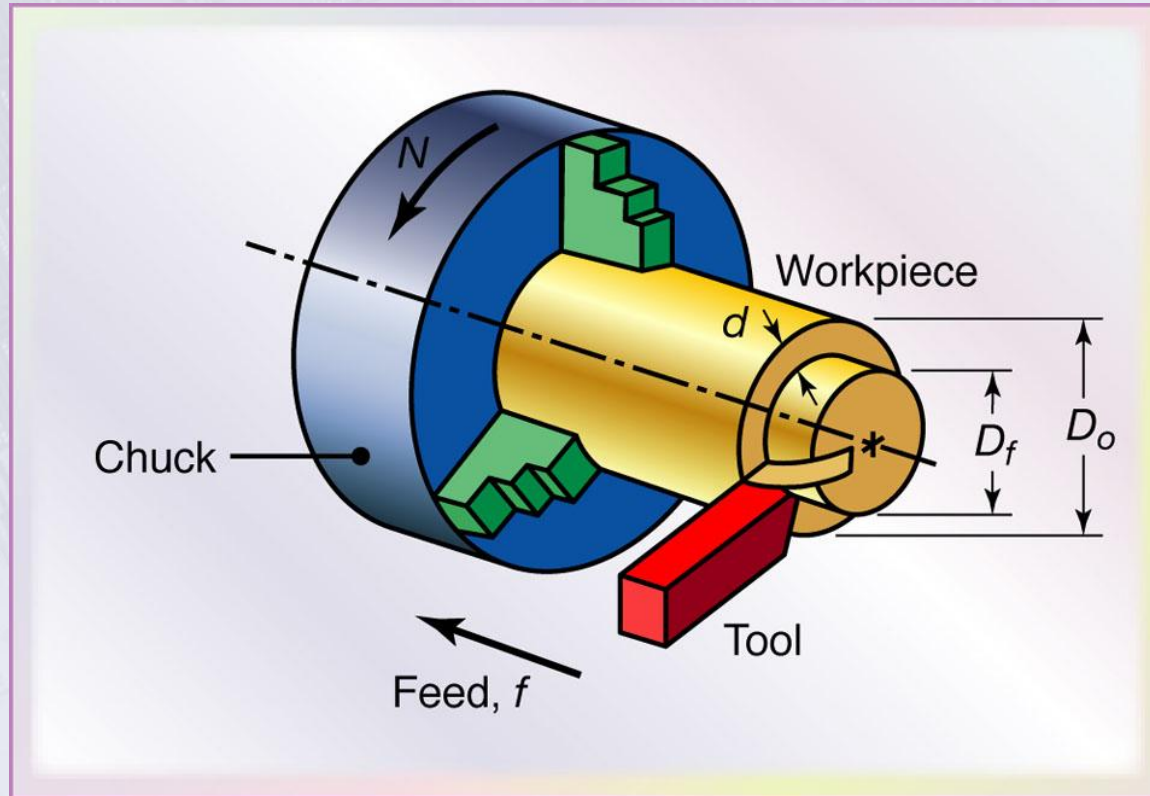
Turning Operation

Figure 23.3 Schematic illustration of the basic turning operation, showing depth-of-cut, d; feed, f; and spindle rotational speed, N in rev/min. Cutting speed is the surface speed of the workpiece at the tool tip.

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Designations for a Right-Hand Cutting Tool
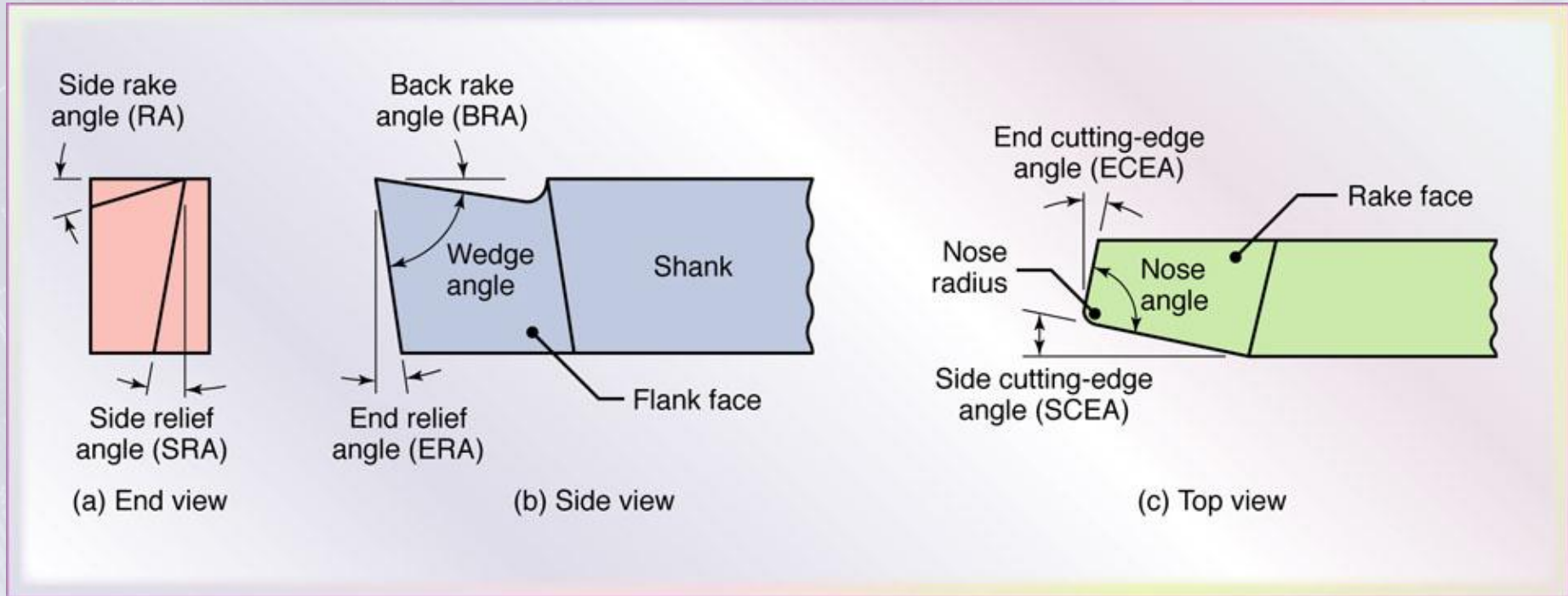
Figure 23.4 Designations for a right-hand cutting tool. Right-hand means the tool travels form right to left, as shown in Fig. 23.3.

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General Recommendations for Tool Angles in Turning

TABLE 23.2

General Recommendations for Tool Angles 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

TABLE 23.3

Summary of Turning Parameters and Formulas

N = Rotational speed of the workpiece, rpm

f = Feed, mm/rev or in./rev

v = Feed rate, or linear speed of the tool along workpiece length, mm/min or in./min

$\quad = fN$

V = Surface speed of workpiece, m/min or ft/min

$\quad = \pi D_o N$ (for maximum speed)

$\quad = \pi D_{avg} N$ (for average speed)

l = Length of cut, mm or in.

D_o = Original diameter of workpiece, mm or in.

D_f = Final diameter of workpiece, mm or in.

D_{avg} = Average diameter of workpiece, mm or in.

$\quad = (D_o + D_f)/2$

d = Depth of cut, mm or in.

$\quad = (D_o - D_f)/2$

t = Cutting time, s or min

$\quad = l/fN$

MRR = mm^3/min or in^3/min

$\quad = \pi D_{avg} df N$

Torque = N•m or lb•ft

$\quad = F_c D_{avg}/2$

Power = kW or hp

$\quad = $ (Torque)(ω), where $\omega = 2\pi N$ rad/min

Note: The units given are those that are used commonly; however, appropriate units must be used and checked in the formulas.

Summary of Turning Parameters and Formulas

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Forces Acting on a Cutting Tool in Turning
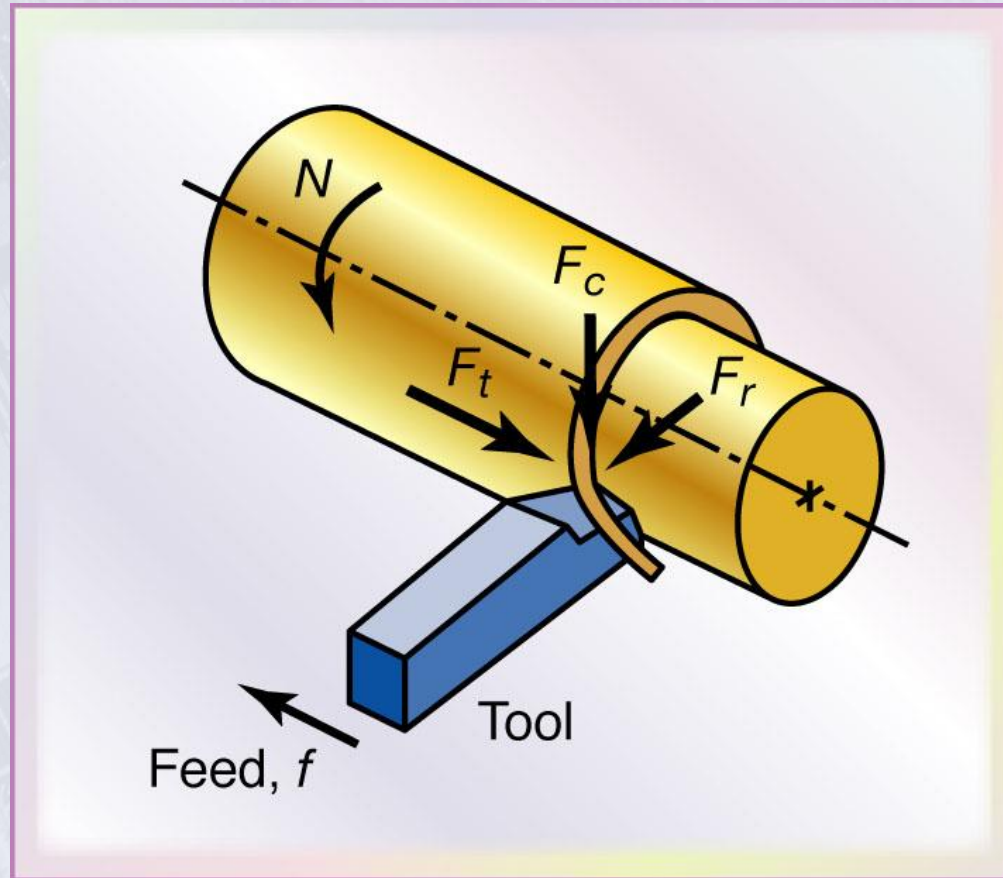
Figure 23.5 Forces acting on a cuttin tool in turning, F_c is the cutting force, F_t is the thrust of feed force (in the direction of feed), and F_r is the radial force that tends to push the tool away from the workpiece being machined.

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Range of Applicable Cutting Speeds and Feeds for Tool Materials
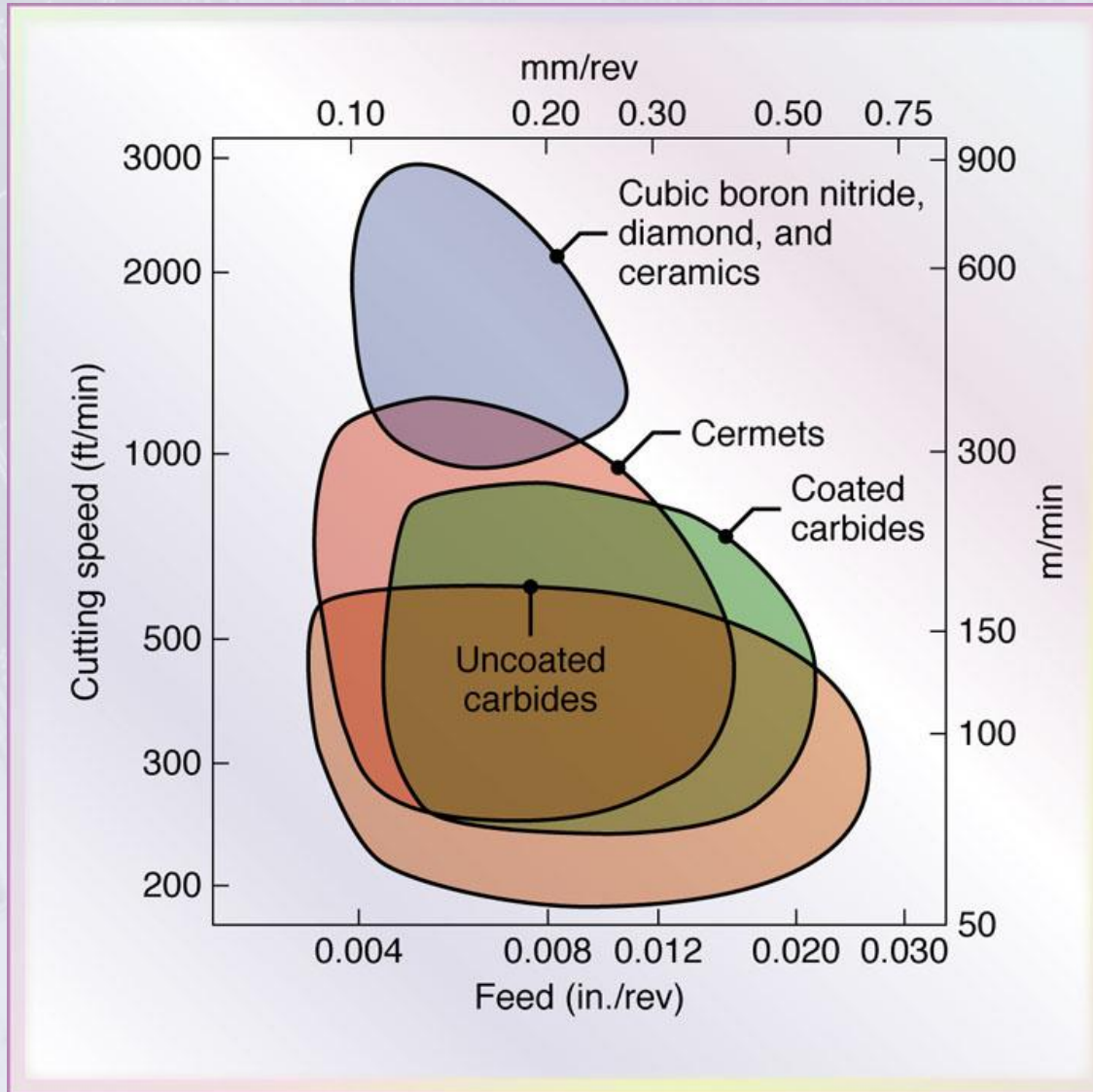
Figure 23.6 The range of applicable cutting speeds and feeds for a variety of tool materials.

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TABLE 23.4 # General Recommendations for Turning Operations

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions			Range for roughing and finishing		
		Depth of cut, mm (in.)	Feed, mm/rev (in./rev)	Cutting speed, m/min (ft/min)	Depth of cut, mm (in.)	Feed, mm/rev (in./rev)	Cutting speed, m/min (ft/min)
Low-C and free machining steels	Uncoated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	90 (300)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	60–135 (200–450)
	Ceramic-coated carbide	"	"	245–275 (800–900)	"	"	120–425 (400–1400)
	Triple-coated carbide	"	"	185–200 (600–650)	"	"	90–245 (300–800)
	TiN-coated carbide	"	"	105–150 (350–500)	"	"	60–230 (200–750)
	Al_2O_3 ceramic	"	0.25 (0.010)	395–440 (1300–1450)	"	"	365–550 (1200–1800)
	Cermet	"	0.30 (0.012)	215–290 (700–950)	"	"	105–455 (350–1500)
Medium and high-C steels	Uncoated carbide	1.2–4.0 (0.05–0.20)	0.30 (0.012)	75 (250)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	45–120 (150–400)
	Ceramic-coated carbide	"	"	185–230 (600–750)	"	"	120–410 (400–1350)
	Triple-coated carbide	"	"	120–150 (400–500)	"	"	75–215 (250–700)
	TiN-coated carbide	"	"	90–200 (300–650)	"	"	45–215 (150–700)
	Al_2O_3 ceramic	"	0.25 (0.010)	335 (1100)	"	"	245–455 (800–1500)
	Cermet	"	0.25 (0.010)	170–245 (550–800)	"	"	105–305 (350–1000)
Cast iron, gray	Uncoated carbide	1.25–6.3 (0.05–0.25)	0.32 (0.013)	90 (300)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	75–185 (250–600)
	Ceramic-coated carbide	"	"	200 (650)	"	"	120–365 (400–1200)
	TiN-coated carbide	"	"	90–135 (300–450)	"	"	60–215 (200–700)
	Al_2O_3 ceramic	"	0.25 (0.010)	455–490 (1500–1600)	"	"	365–855 (1200–2800)
	SiN ceramic	"	0.32 (0.013)	730 (2400)	"	"	200–990 (650–3250

(Continued)

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Stainless steel, austenitic	Triple-coated carbide	1.5–4.4 (0.06–0.175)	0.35 (0.014)	150 (500)	0.5–12.7 (0.02–0.5)	0.08–0.75 (0.003–0.03)	75–230 (250–750)
	TiN-coated carbide	"	"	85–160 (275–525)	"	"	55–200 (175–650)
	Cermet	"	0.30 (0.012)	185–215 (600–700)	"	"	105–290 (350–950)
High-temperature alloys, nickel based	Uncoated carbide	2.5 (0.10)	0.15 (0.006)	25–45 (75–150)	0.25–6.3 (0.01–0.25)	0.1–0.3 (0.004–0.012)	15–30 (50–100)
	Ceramic-coated carbide	"	"	45 (150)			20–60 (65–200)
	TiN-coated carbide	"	"	30–55 (95–175)			20–85 (60–275)
	Al_2O_3 ceramic	"	"	260 (850)	"	"	185–395 (600–1300)
	SiN ceramic	"	"	215 (700)	"	"	90–215 (300–700)
	Polycrystalline cBN	"	"	150 (500)	"	"	120–185 (400–600)
Titanium alloys	Uncoated carbide	1.0–3.8 (0.04–0.15)	0.15 (0.006)	35–60 (120–200)	0.25–6.3 (0.01–0.25)	0.1–0.4 (0.004–0.015)	10–75 (30–250)
	TiN-coated carbide	"	"	30–60 (100–200)			10–100 (30–325)
Aluminum alloys Free machining	Uncoated carbide	1.5–5.0 (0.06–0.20)	0.45 (0.018)	490 (1600)	0.25–8.8 (0.01–0.35)	0.08–0.62 (0.003–0.025)	200–670 (650–2000)
	TiN-coated carbide	"	"	550 (1800)	"	"	60–915 (200–3000)
	Cermet	"	"	490 (1600)	"	"	215–795 (700–2600)
	Polycrystalline diamond	"	"	760 (2500)	"	"	305–3050 (1000–10,000)
High silicon	Polycrystalline diamond	"	"	530 (1700)	"	"	365–915 (1200–3000)

(Continued)

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General Recommendations for Turning Operations, con't

TABLE 23.4 (*Continued*)

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions			Range for roughing and finishing		
		Depth of cut, mm (in.)	Feed, mm/rev (in./rev)	Cutting speed, m/min (ft/min)	Depth of cut, mm (in.)	Feed, mm/rev (in./rev)	Cutting speed, m/min (ft/min)
Copper alloys	Uncoated carbide	1.5–5.0 (0.06–0.20)	0.25 (0.010)	260 (850)	0.4–7.51 (0.015–0.3)	0.15–0.75 (0.006–0.03)	105–535 (350–1750)
	Ceramic-coated carbide	"	"	365 (1200)	"	"	215–670 (700–2200)
	Triple-coated carbide	"	"	215 (700)	"	"	90–305 (300–1000)
	TiN-coated carbide	"	"	90–275 (300–900)	"	"	45–455 (150–1500)
	Cermet	"	"	245–425 (800–1400)	"	"	200–610 (650–2000)
	Polycrystalline diamond	"	"	520 (1700)	"	"	275–915 (900–3000)
Tungsten alloys	Uncoated carbide	2.5 (0.10)	0.2 (0.008)	75 (250)	0.25–5.0 (0.01–0.2)	0.12–0.45 (0.005–0.018)	55–120 (175–400)
	TiN-coated carbide	"	"	85 (275)	"	"	60–150 (200–500)
Thermoplastics and thermosets	TiN-coated carbide	1.2 (0.05)	0.12 (0.005)	170 (550)	0.12–5.0 (0.005–0.20)	0.08–0.35 (0.003–0.015)	90–230 (300–750)
	Polycrystalline diamond	"	"	395 (1300)	"	"	150–730 (500–2400)
Composites graphite reinforced	TiN-coated carbide	1.9 (0.075)	0.2 (0.008)	200 (650)	0.12–6.3 (0.005–0.25)	0.12–1.5 (0.005–0.06)	105–290 (350–950)
	Polycrystalline diamond	"	"	760 (2500)	"	"	550–1310 (1800–4300)

Source: Based on data from Kennametal, Inc.
Note: Cutting speeds for high-speed-steel tools are about one-half those for uncoated carbides.

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General Recommendations for Cutting Fluids for Machining

TABLE 23.5

General Recommendations for Cutting Fluids for Machining (see also Chapter 33)

Material	Type of fluid
Aluminum	D, MO, E, MO+FO, CSN
Beryllium	MO, E, CSN
Copper	D, E, CSN, MO+FO
Magnesium	D, MO, MO+FO
Nickel	MO, E, CSN
Refractory metals	MO, E, EP
Steels	
carbon and low-alloy	D, MO, E, CSN, EP
stainless	D, MO, E, CSN
Titanium	CSN, EP, MO
Zinc	C, MO, E, CSN
Zirconium	D, E, CSN

Note: CSN = chemicals and synthetics; D = dry; E = emulsion; EP = extreme pressure; FO = fatty oil; and MO = mineral oil.

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Typical Capacities and Maximum Workpiece Dimensions for Machine Tools

TABLE 23.6

Typical Capacities and Maximum Workpiece Dimensions for Machine Tools

Machine tool	Maximum dimension (m)	Power (kW)	Maximum rpm
Lathes (swing.length)			
Bench	0.3/1	61	3000
Engine	3/5	70	4000
Turret	0.5/1.5	60	3000
Automatic screw	0.1/0.3	20	10,000
Boring machines (work diameter/length)			
Vertical spindle	4/3	200	300
Horizontal spindle	1.5/2	70	1000
Drilling machines			
Bench and column (drill diameter)	0.1	10	12,000
Radial (column to spindle distance)	3	-	-
Numerical control (table travel)	4	-	-

Note : Larger capacities are available for special applications.

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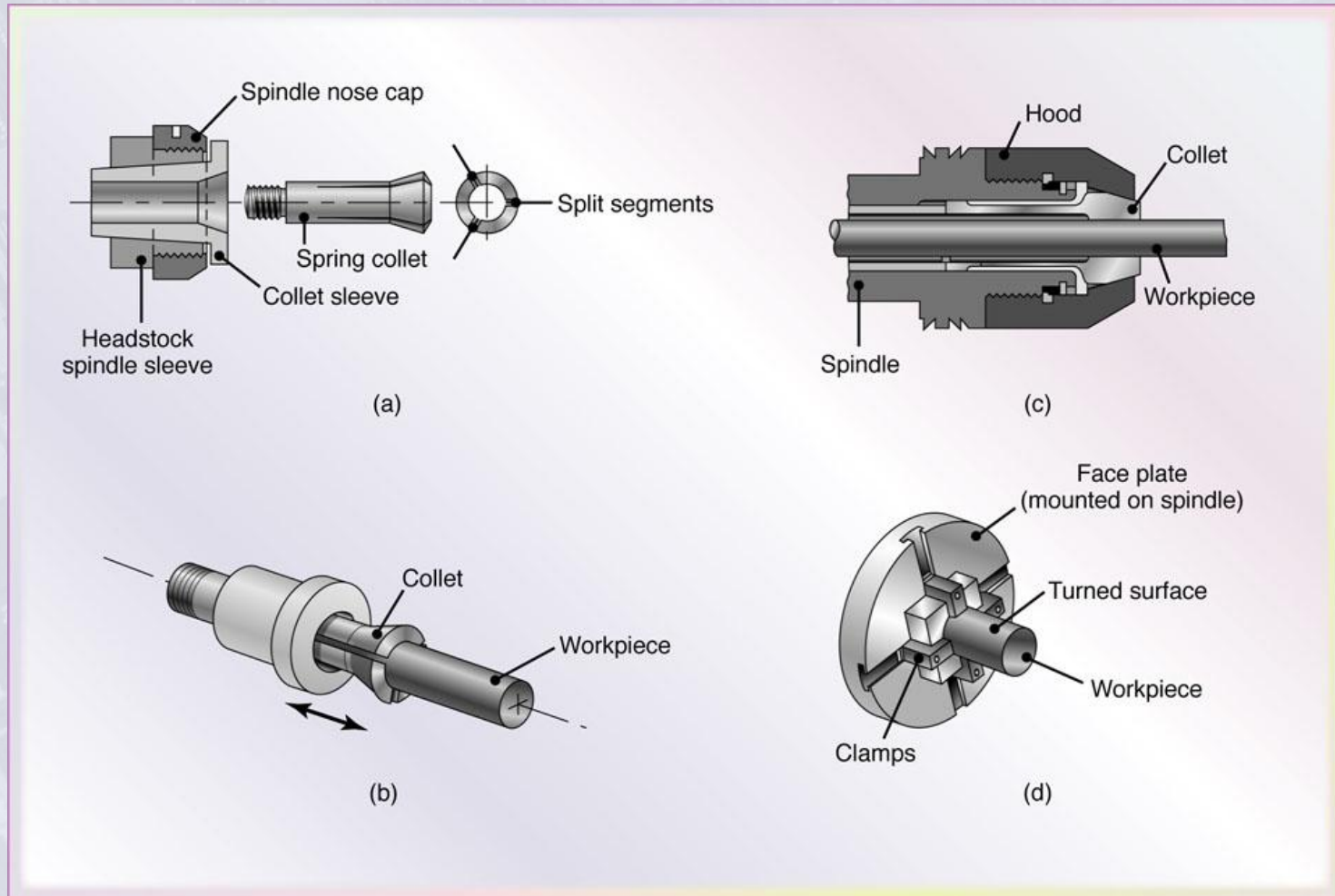Kalpakjian and Steven R. Schmid

Collets

Figure 23.7 (a) and (b) Schematic illustrations of a draw-in type collet. The workpiece is placed in the collet hole, and the conical surfaces of the collet are forced inwards by pulling it with a draw bar into the sleeve. (c) A push-out type collet. (d) Workholding of a workpiece on a face plate.

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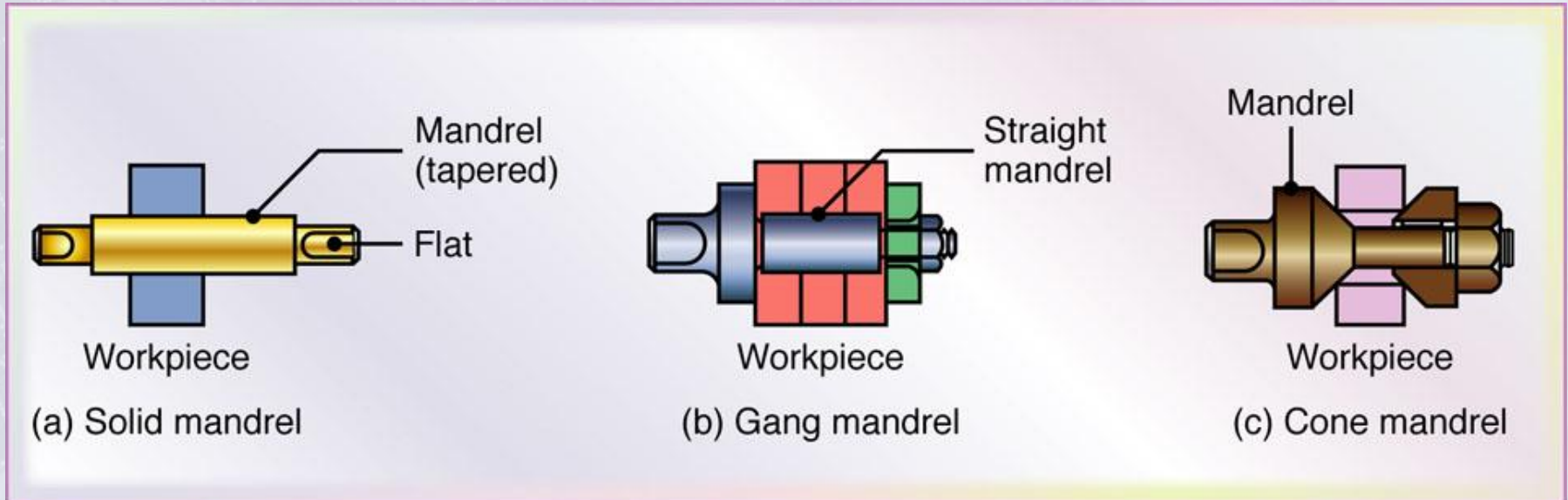
Mandrels to Hold Workpieces for Turning

Figure 23.8 Various types of mandrels to hold workpieces for turning. These mandrels usually are mounted between centers on a lathe. Note that in (a), both the cylindrical and the end faces of the workpiece can be machined, whereas in (b) and (c), only the cylindrical surfaces can be machined.
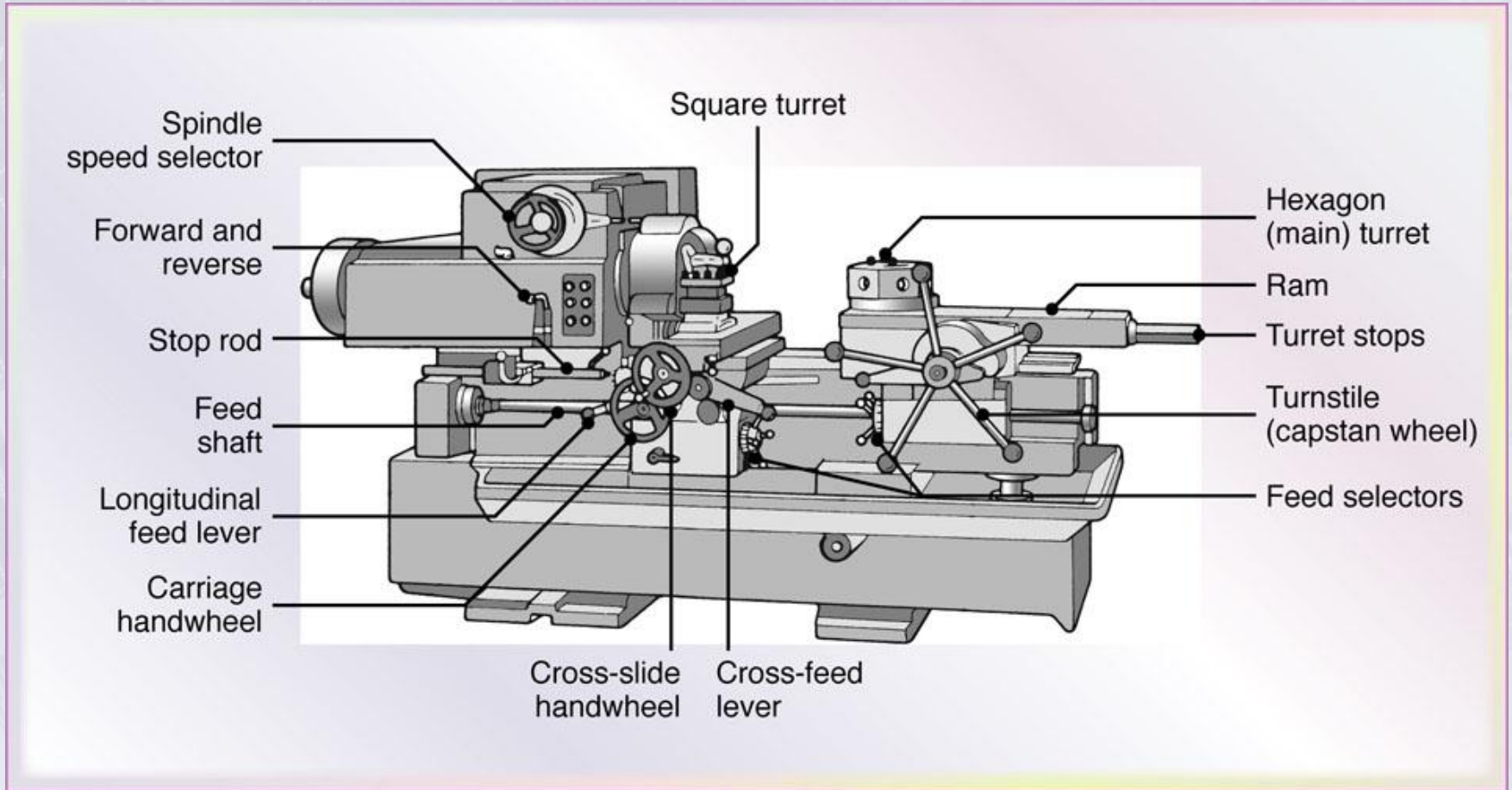
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Turret Lathe

Figure 23.9 Schematic illustration of the components of a turret lathe. Note the two turrets: square and hexagonal (main).

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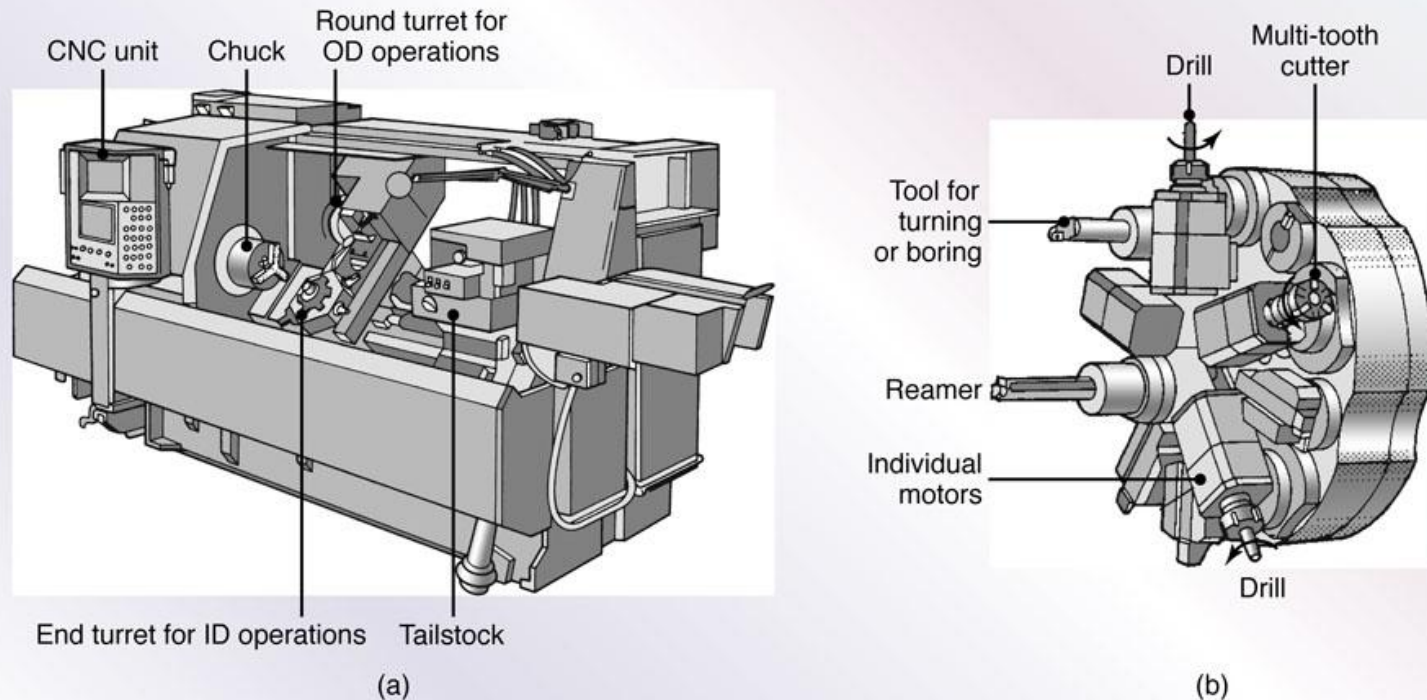
Numerical Control Lathe and Turret

Figure 23.10 (a) A computer numerical-control lathe. Note the two turrets on this machine. These machines have higher power and spindle speed than other lathes in order to take advantage of new cutting tools with enhanced properties. (b) A typical turret equipped with ten tools, some of which are powered.
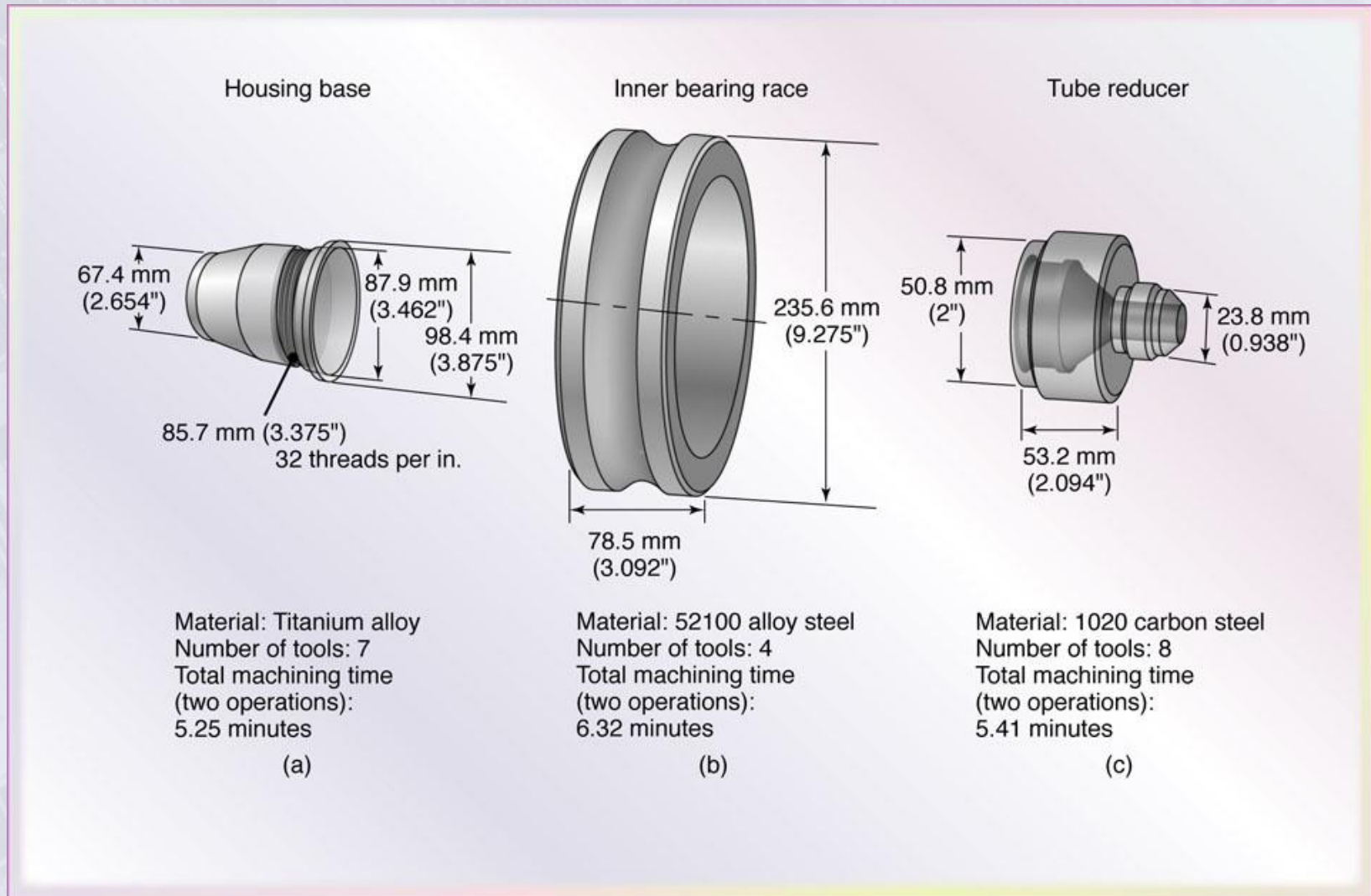
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Parts Made on CNC Lathes

Figure 23.11 Typical parts made on CNC lathes.

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Example 23.3: Machining of Complex Shapes
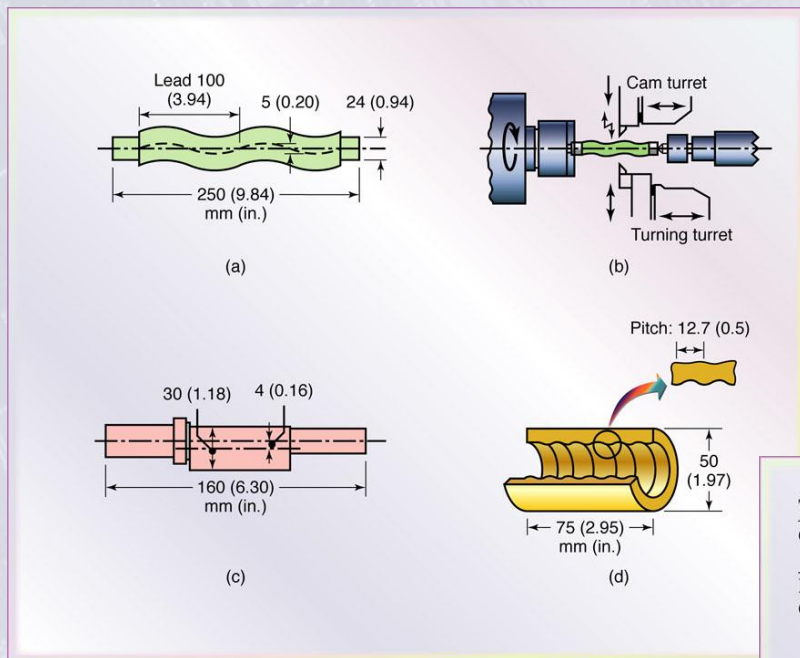
Figure 23.12 Examples of more complex shapes that can be produced on a CNC lathe.

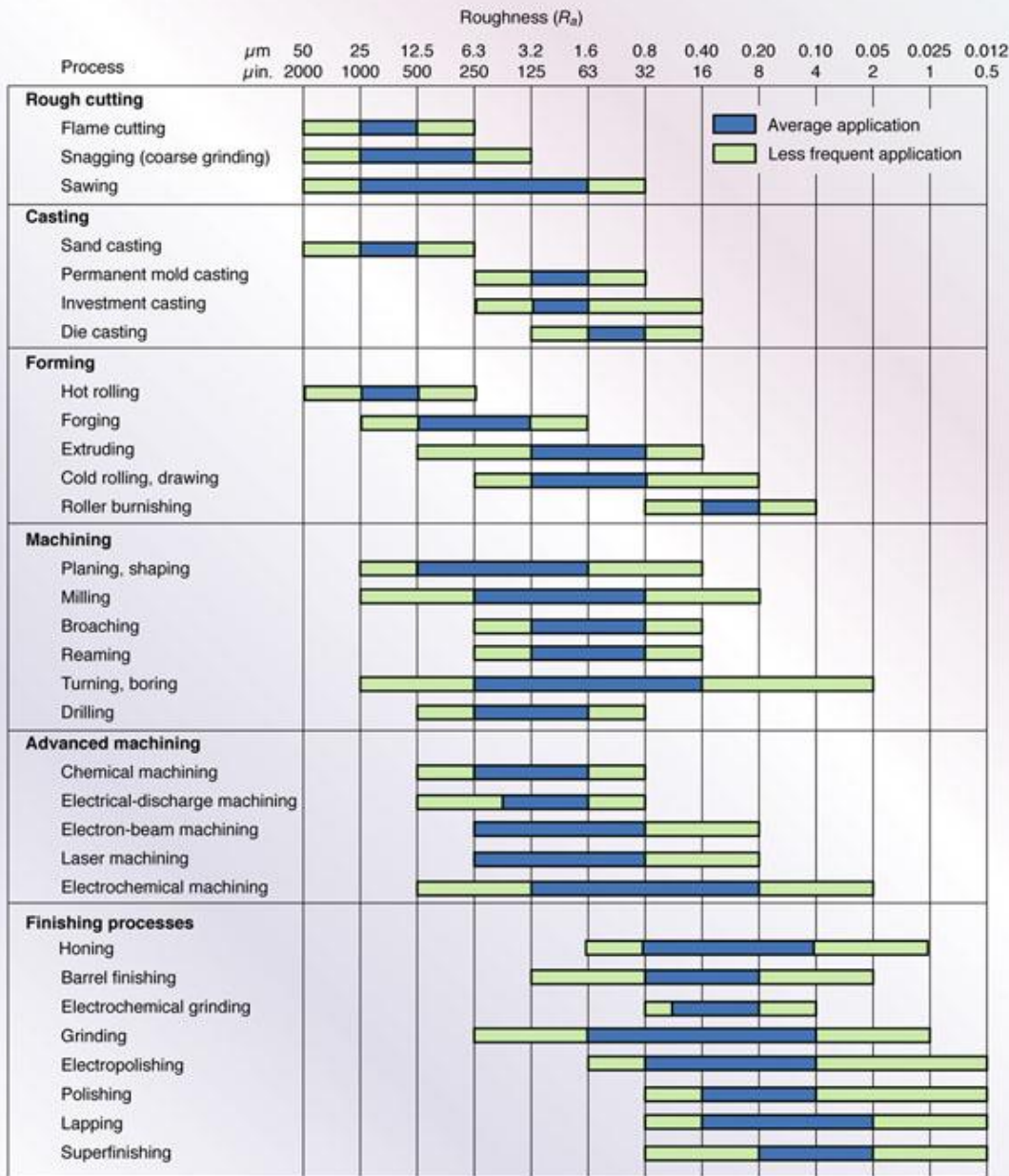| TABLE 23.7					
Operation	Speed/ rpm	Cutting speed	Depth of	Feed	Tool
Part a and b:					
OD					
Roughing	1150	160 m/min (525 fpm)	3 mm (0.12 in.)	0.3 mm/rev (0.012 in./rev)	K10 (C3)
Finishing	1750	250 (820)	0.2 (0.008)	0.15 (0.006)	K10 (C3)
Lead					
Roughing	300 (148)	45 (0.12)	3 (0.006)	0.15	K10 (C3)
Finishing	300 (148)	45 (0.004)	0.1 (0.006)	0.15	Diamond compact
Part c: Eccentric shaft					
Roughing	200	5–11 (16–136)	1.5 (0.059)	0.2 (0.008)	K10 (C3)
Finishing	200	5–11 (16–36)	0.1 (0.004)	0.05 (0.0020)	K10 (C3)
Part d: Internal thread					
Roughing	800	70 (230)	1.6 (0.063)	0.15 (0.0059)	Coated carbide
Finishing	800	70 (230)	0.1 (0.004)	0.15 (0.0059)	Cermet

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TABLE 23.8

Typical Production Rates for Various Machining Operations

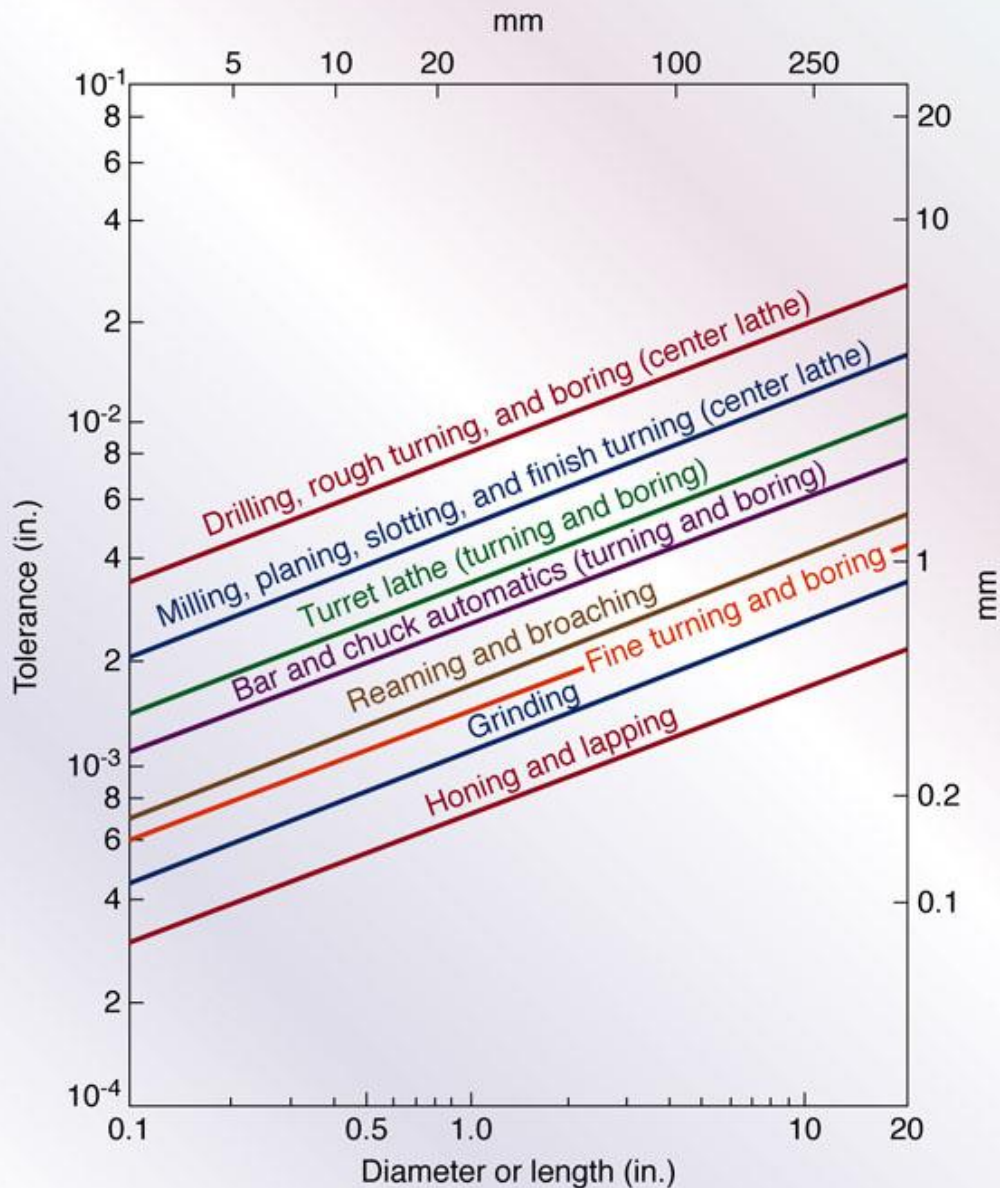| Operation	Rate
Turning	
Engine lathe	Very low to low
Tracer lathe	Low to medium
Turret lathe	Low to medium
Computer-controlled lathe	Low to medium
Single-spindle chuckers	Medium to high
Multiple-spindle chuckers	High to very high
Boring	Very low
Drilling	Low to medium
Milling	Low to medium
Planing	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 one or more parts per hour; *medium* is approximately 100 parts per hour; and *very high* is 1000 or more parts per hour.

Typical Production Rates for Various Machining Operations

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Range of Surface Roughnesses in Machining Processes

Figure 23.13 The range of surface roughnesses obtained in various machining processes. Note the wide range within each group, especially in turning and boring.

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Range of Dimensional Tolerances in Machining as a Function of Workpiece Size

Figure 23.14 Range of dimensional tolerances obtained in various machining processes as a function of workpiece size. Note that there is an order os magnitude difference between small and large workpieces.

Troubleshooting Guide for Turning

TABLE 23.9

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 workholding devices, excessive temperature rise, tool wear
Tool chatter	Lack of stiffness of machine tool and workholding devices, excessive tool overhang, machining parameters not set properly

Cutting Screw Threads
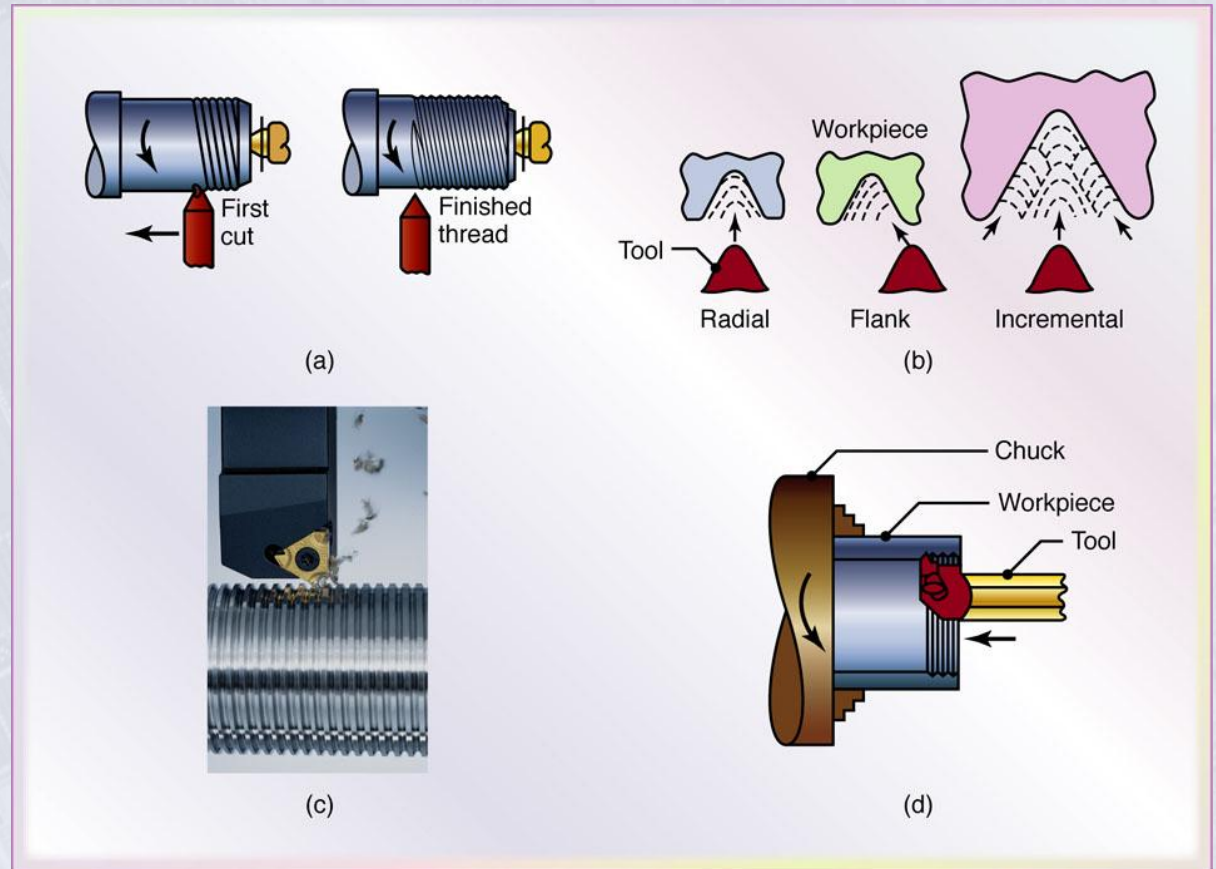
Figure 23.15 (a) Cutting screw threads on a lathe with a single-point cutting tool. (b) Cutting screw threads with a single-point tool in several passes, normally utilized for large threads. The small arrows in the figures show the direction of the feed, and the broken lines show the position of the cutting tool as time progresses. Note that in *radial cutting*, the tool is fed directly into the workpiece. In *flank cutting*, the tool is fed inot the piece along the right face of the thread. In *incremental cutting*, the tool is first fed directly into the piece at the center of the thread, then at its sides, and finally into the root. (c) A typical coated-carbide insert in the process of cutting screw threads on a round shaft. (d) Cutting internal screw threads with a carbide insert. *Source*: (c): Courtesy of Iscar Metals Inc.
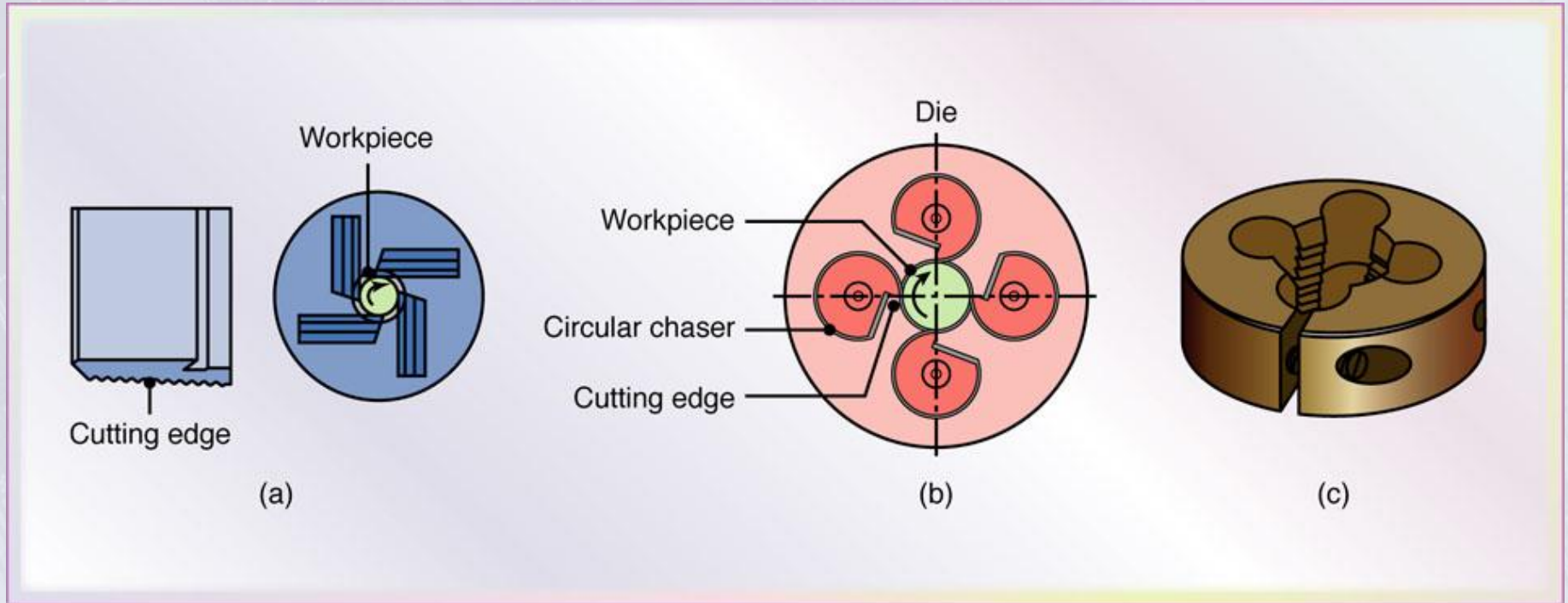
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Chasers and Die for Thread Cutting

Figure 23.16 (a) Straight chasers for cutting threads on a lathe. (b) Circular chasers. (c) A solid threading die.

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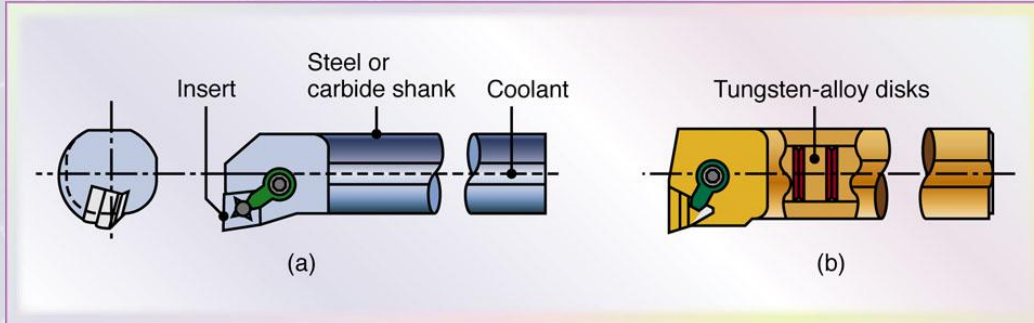Kalpakijan and Steven R. Schmid

Boring and Boring Mill

Figure 23.17 (a) Schematic illustration of a steel boring bar with a carbide insert. Note the passageway in the bar for cutting fluid application. (b) Schematic illustration of a boring bar with tungsten-alloy "inertia disks" sealed in the bar to counteract vibration and chatter during boring. This system is effective for boring bar length-to-diameter ratios of up to 6.

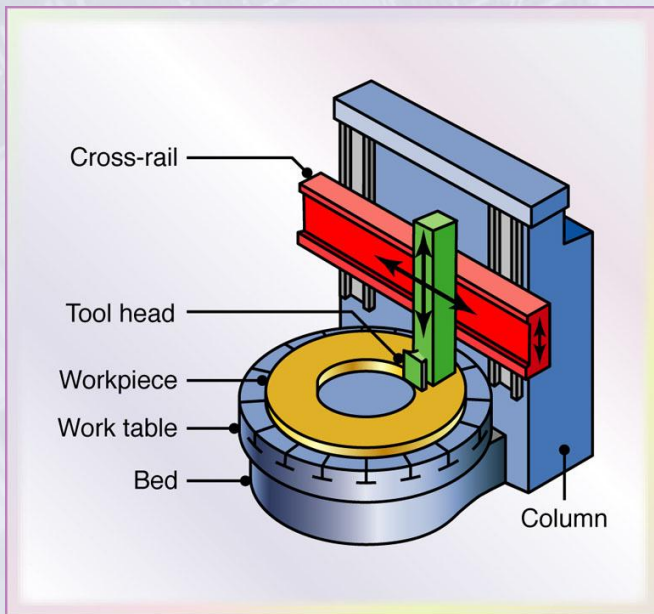Figure 23.18 Schematic illustration of a vertical boring mill. Such a machine can accommodate workpiece sizes as large as 2.5m (98 in.) in diameter.

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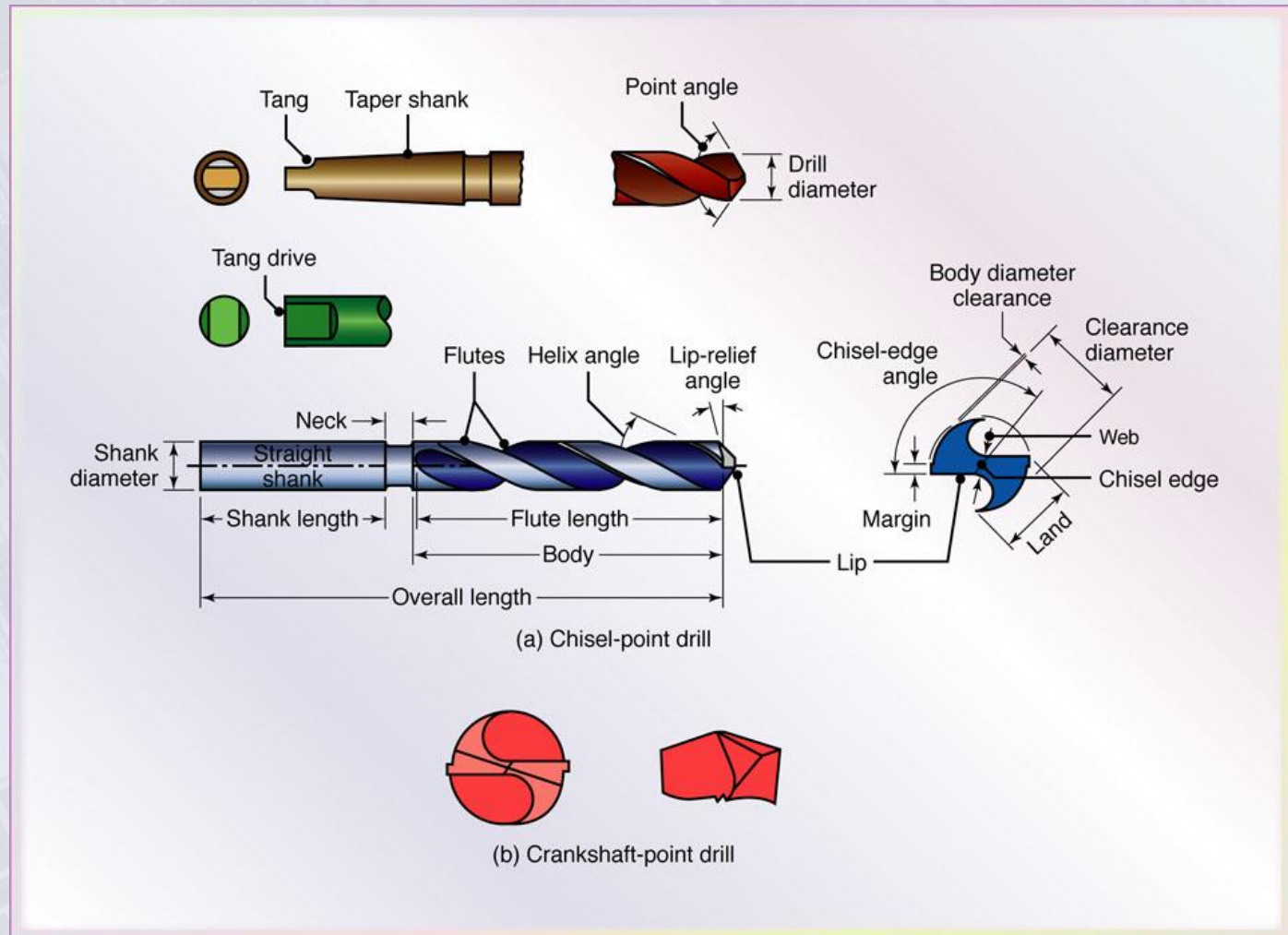## Chisel-Point Drill and Crankshaft Drill

Figure 23.19 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 also are available. (b) Crankshaft drills. These drills have good centering ability, and because chips tend to break up easily, these drills are suitable for producing deep holes.

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General Capabilities of Drilling

TABLE 23.10

General Capabilities of Drilling and Boring Operations			
Cutting tool type	Diameter range (mm)	Hole depth/diameter	
		Typical	Maximum
Twist	0.5-150	8	50
Spade	25-150	30	100
Gun	2-50	100	300
Trepanning	40-250	10	100
Boring	3-1200	5	8

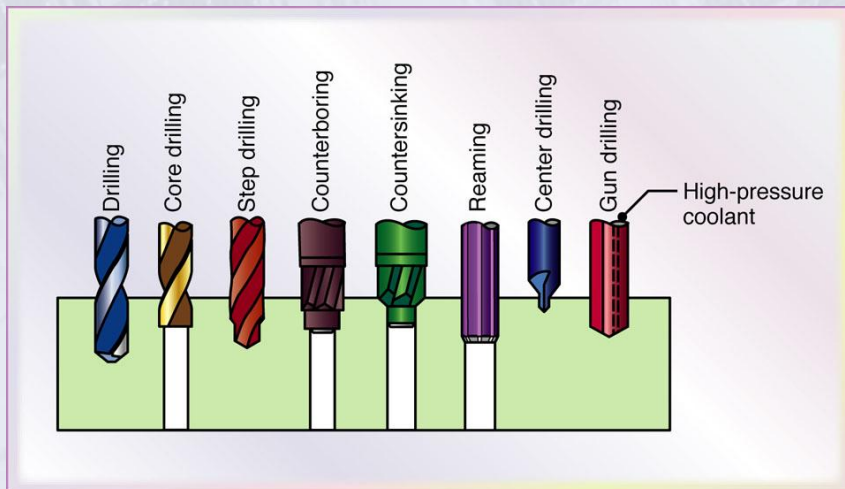
Figure 23.20 Various types of drills and drilling and reaming operations.
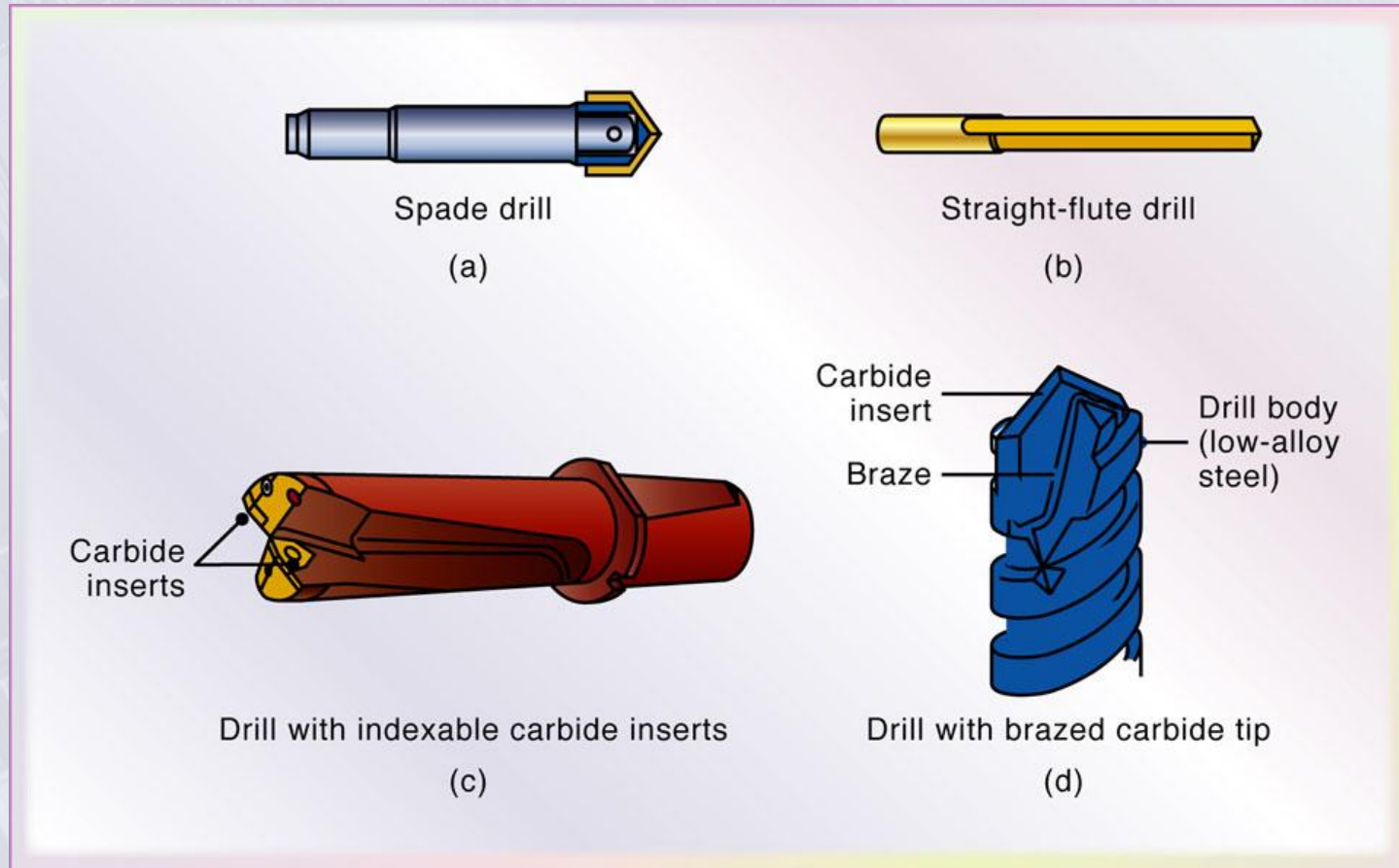
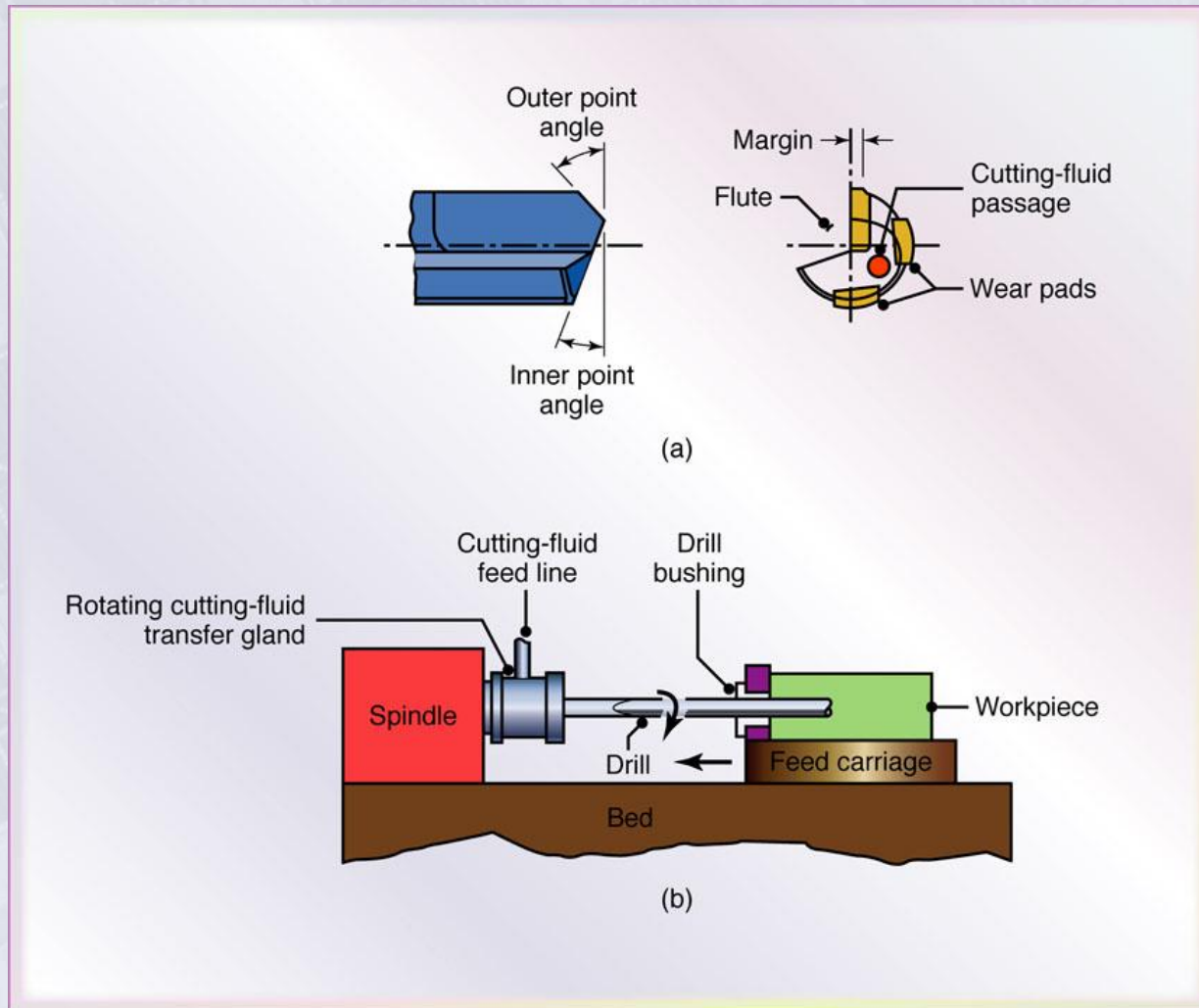# Types of Drills

Figure 23.21 Various types of drills.

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Gun Drill

Figure 23.22 (a) A gun drill showing various features.
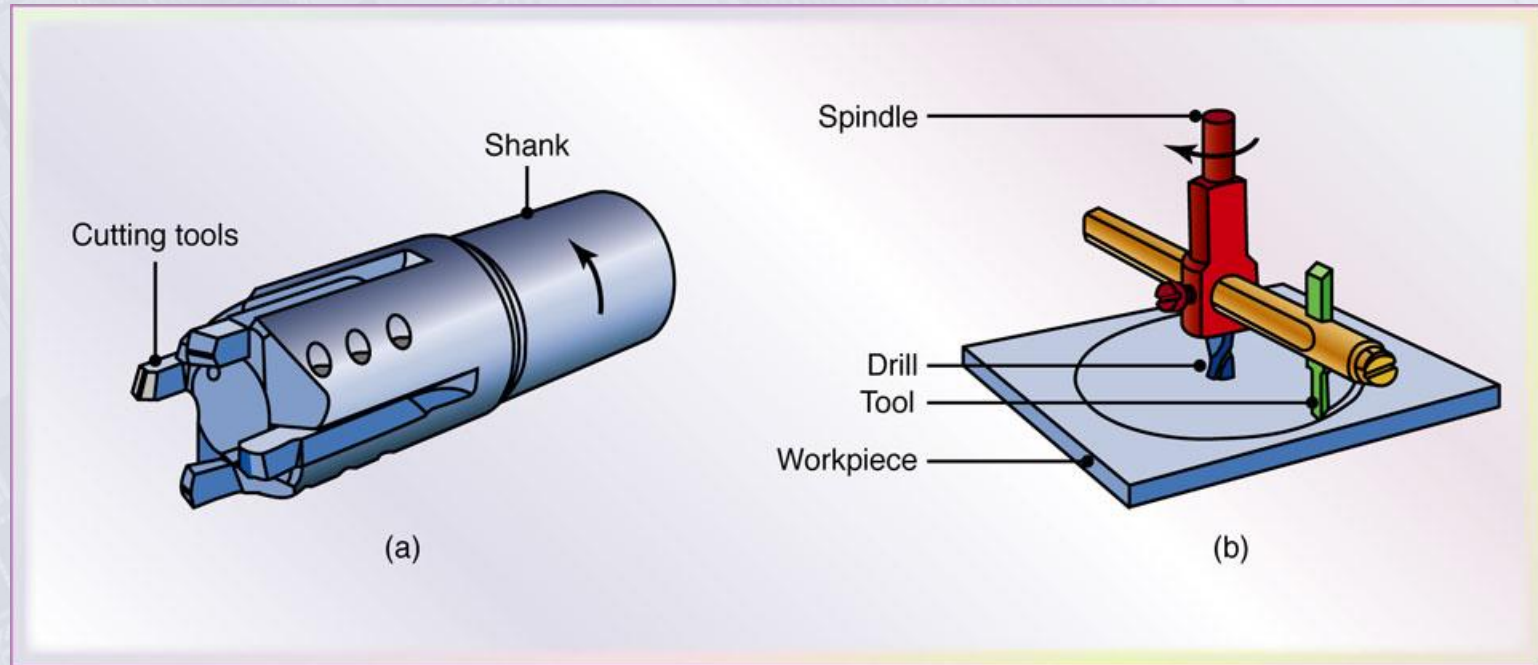(b) Schematic illustration of the gun-drilling operation.

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Trepanning

Figure 23.23 (a) Trepanning tool. (b) Trepanning with a drill-mounted single cutter.

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General Recommendations for Speeds and Feeds in Drilling

TABLE 23.11

General Recommendations for Speeds and Feeds in Drilling

Workpiece material	Surface speed		Feed, mm/rev (in./rev)		Drill diameter rpm	
	m/min	ft/min	1.5 mm (0.060 in.)	12.5 mm (0.5 in.)	1.5 mm	12.5 mm
Aluminum alloys	30-120	100-400	0.025 (0.001)	0.30 (0.012)	6400-25,000	800-3000
Magnesium alloys	45-120	150-400	0.025 (0.001)	0.30 (0.012)	9600-25,000	1100-3000
Copper alloys	15-60	50-200	0.025 (0.001)	0.25 (0.010)	3200-12,000	400-1500
Steels	20-30	60-100	0.025 (0.001)	0.30 (0.012)	4300-6400	500-800
Stainless steels	10-20	40-60	0.025 (0.001)	0.18 (0.007)	2100-4300	250-500
Titanium alloys	6-20	20-60	0.010 (0.0004)	0.15 (0.006)	1300-4300	150-500
Cast irons	20-60	60-200	0.025 (0.001)	0.30 (0.012)	4300-12,000	500-1500
Thermoplastics	30-60	100-200	0.025 (0.001)	0.13 (0.005)	6400-12,000	800-1500
Thermosets	20-60	60-200	0.025 (0.001)	0.10 (0.004)	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.

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Troubleshooting Guide for Drilling

TABLE 23.12

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 sharpened
Tapered hole	Drill misaligned or bent, lips not equal, web not central
Oversize hole	Same as above, 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

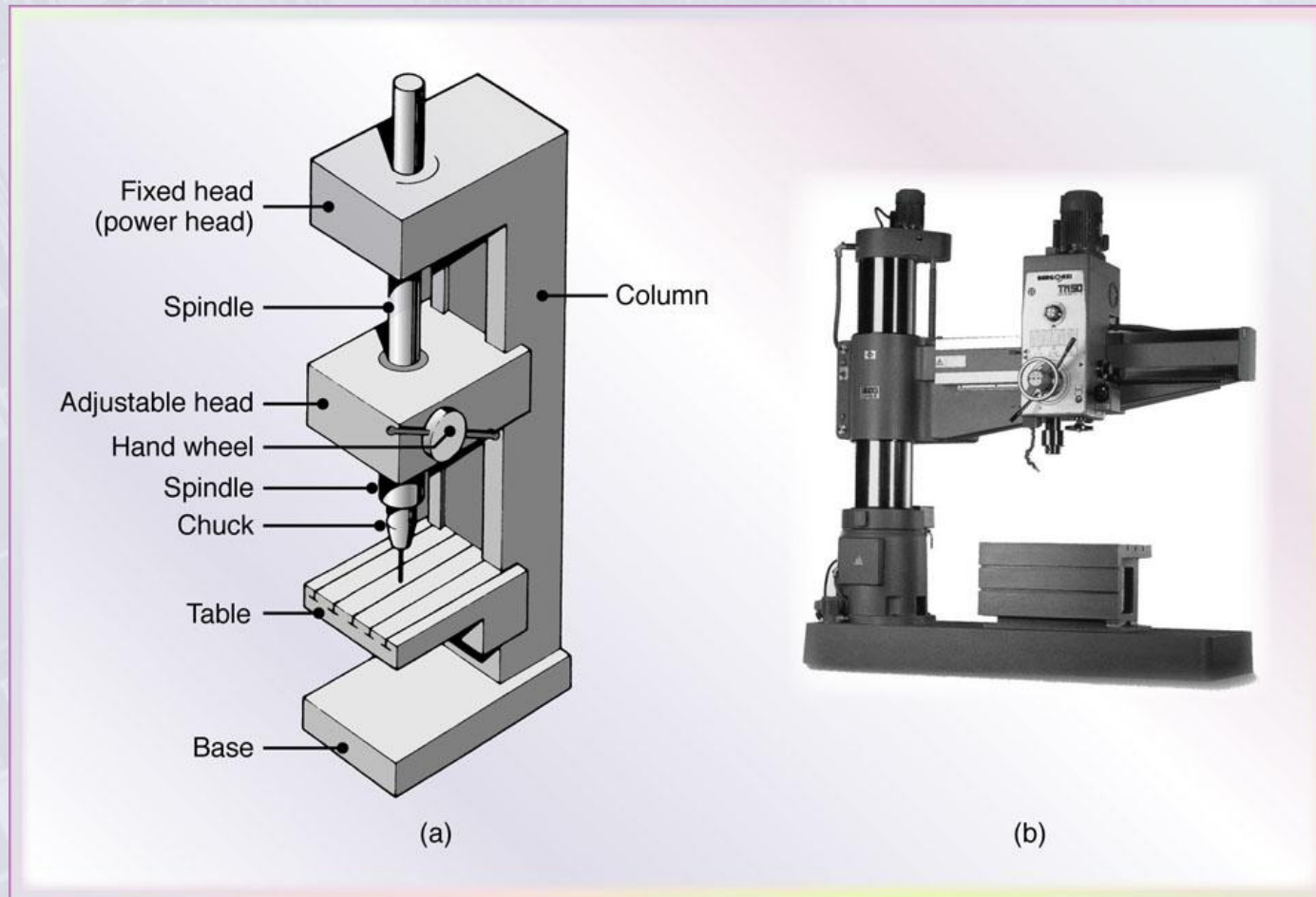# Vertical Drill Press and Radial Drilling Machine

Figure 23.24 (a) Schematic illustration of the components of a vertical drill press.
(b) A radial drilling machine. *Source*: (b) Courtesy of Willis Machinery and Tools.

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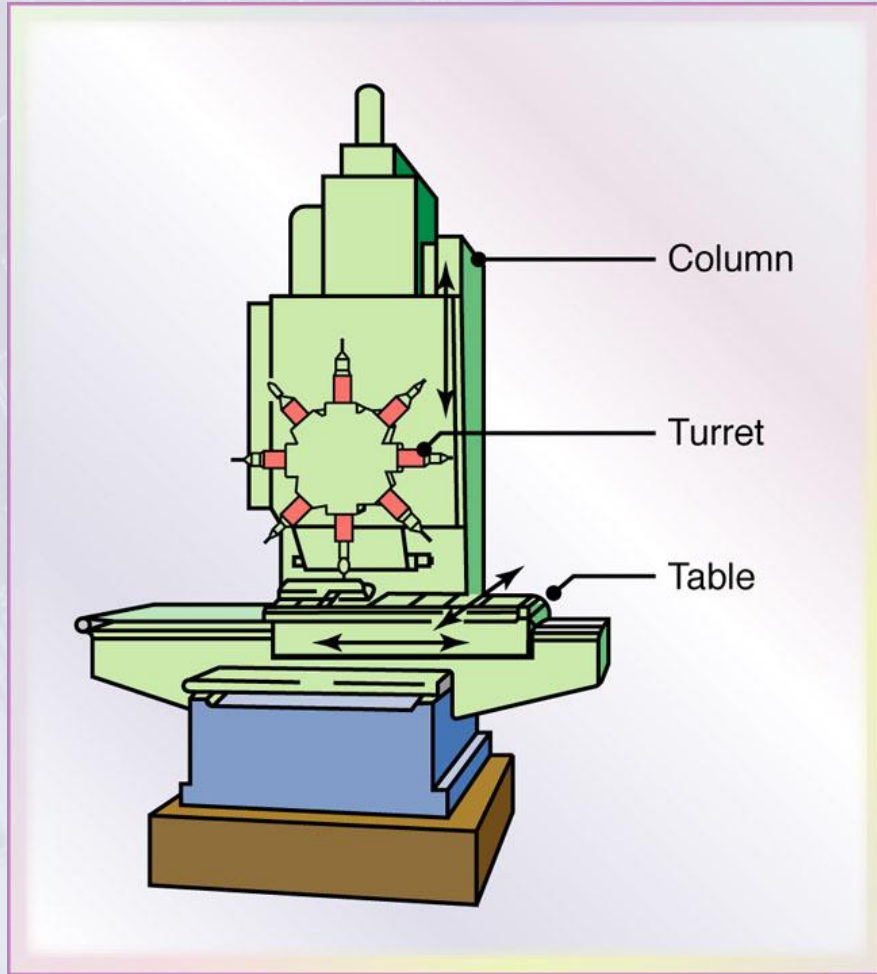# Three-Axis Computer Numerical-Control Drilling Machine

Figure 23.25 A three-axis computer numerical-control drilling machine. The turret holds as many as eight different tools, such as drills, taps, and reamers.

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Helical Reamer and Inserted-Blade Adjustable Reamer
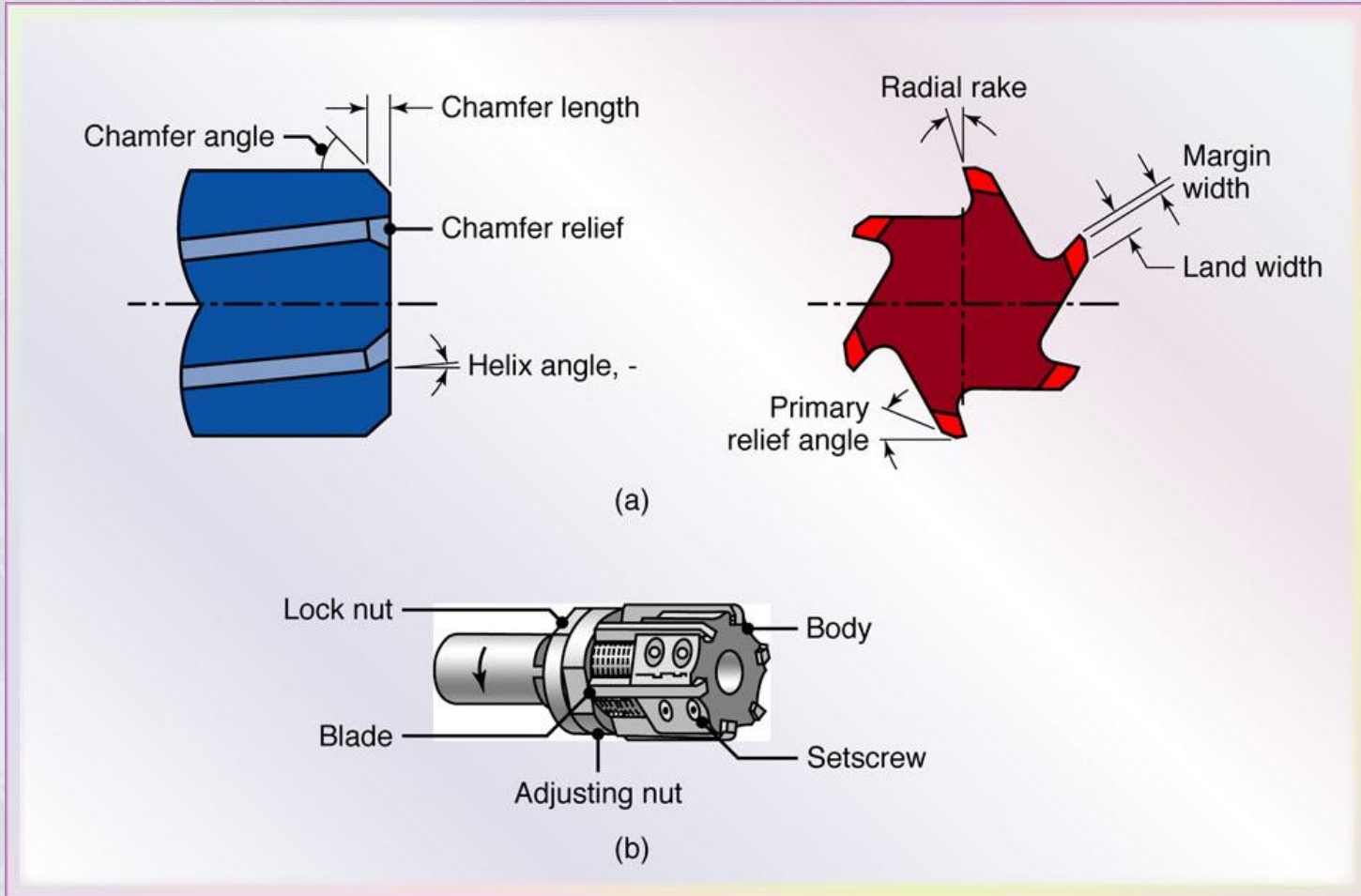
Figure 23.26 (a) Terminology for a helical reamer.
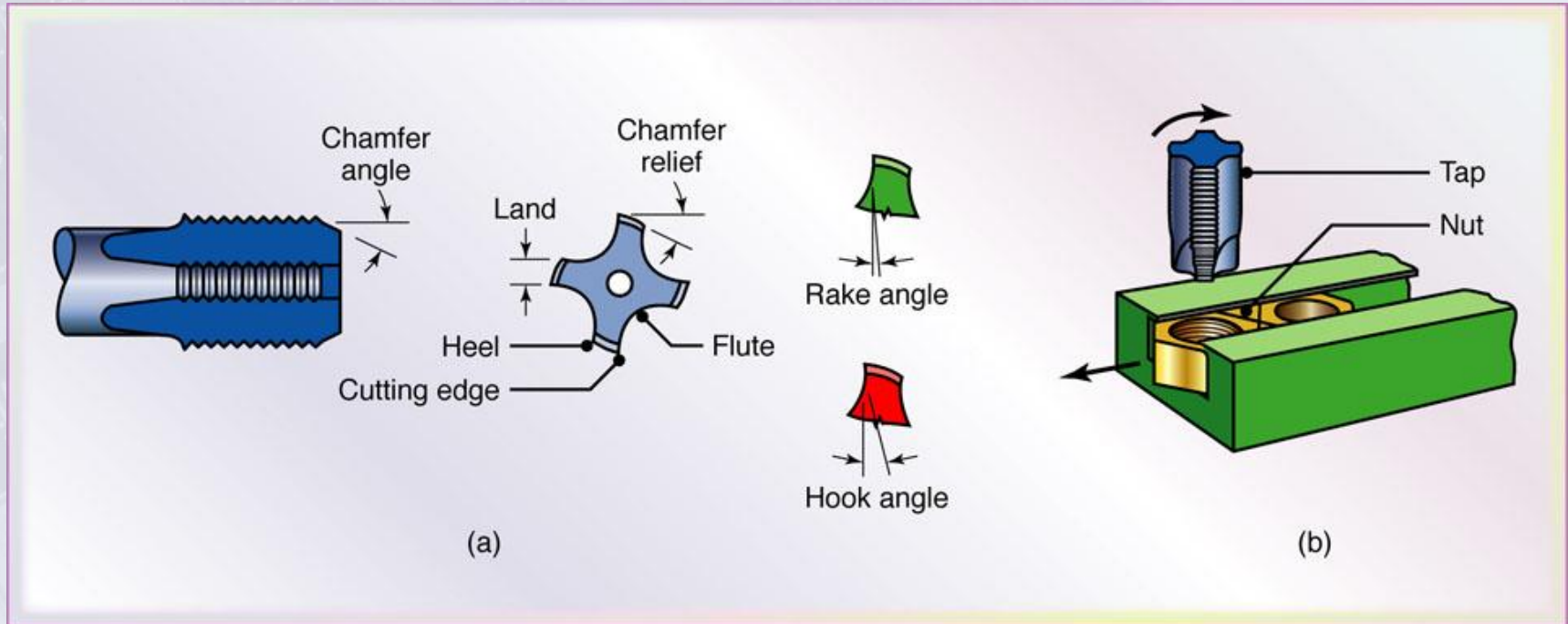(b) Inserted-blade adjustable reamer.

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Tapping

Figure 23.27 (a) Terminology for a tap. (b) Tapping of steel nuts in production.

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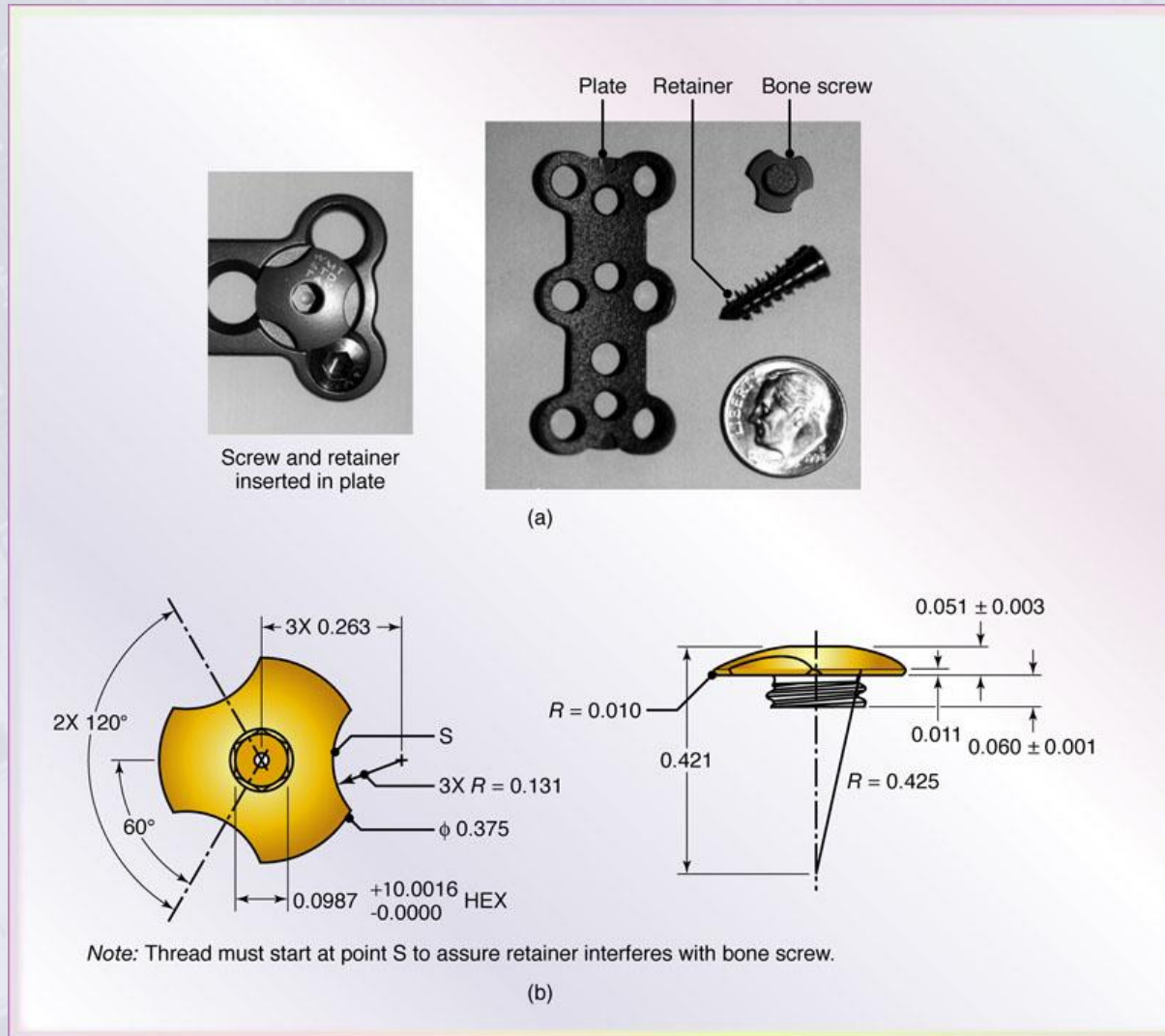Kalpakjian and Steven R. Schmid

Cervical Spine Implant

Figure 23.28 A cervical spine implant.

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