Manufacturing Processes (2), IE-352

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Chapter 23:

Machining Processes: Turning and Hole Making – Part A (Turning)

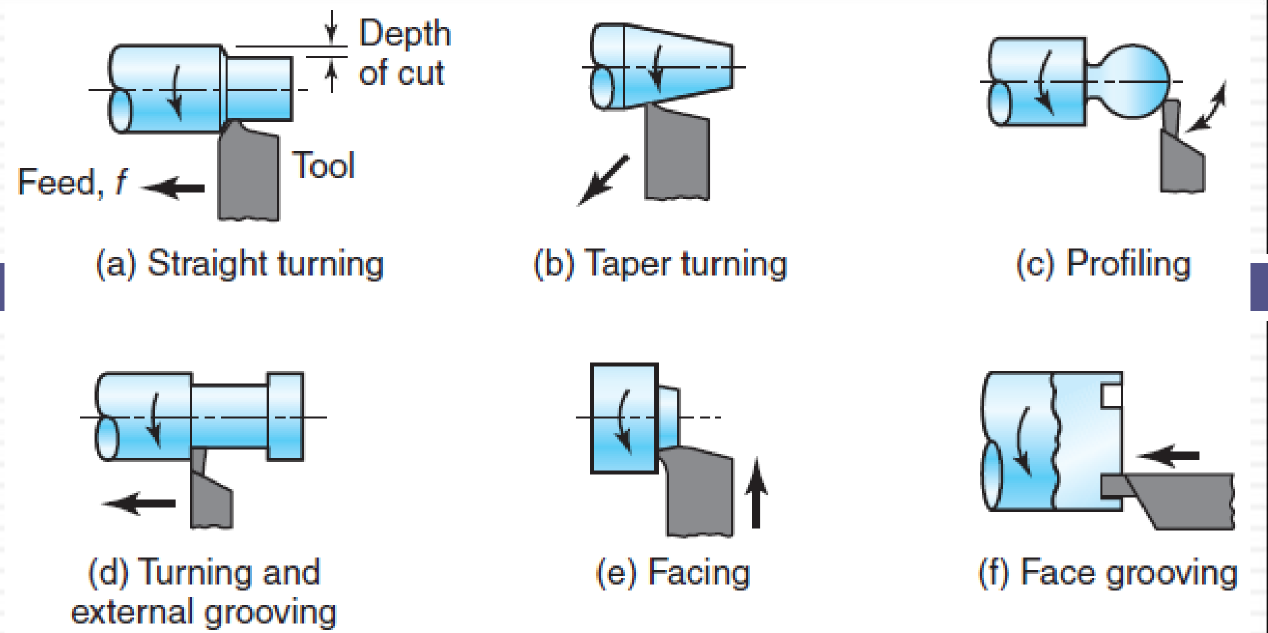
Chapter Outline

1. **Introduction**
2. **The Turning Process**
3. *Lathes and Lathe Operations*
4. *Boring and Boring Machines*
5. *Drilling, Drills, and Drilling Machines*
6. *Reaming and Reamers*
7. *Tapping and Taps*

Introduction

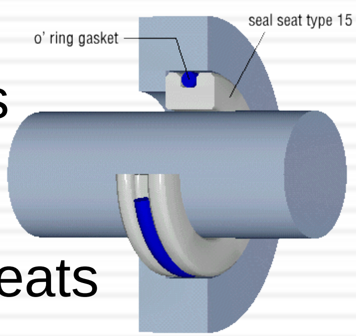
- Machining processes discussed here:
  - With capability of producing parts that are round in shape
  - Most basic is turning: part is rotated while it is being machined
- Lathe (or by similar machine tools):
  - Considered to be the oldest machine tools
  - Carry out turning processes (*see next 4 slides*):
  - Highly simple, versatile machines
  - Requires a skilled machinist
  - Inefficient for repetitive operations and for large production
  - All parts are circular (property known as *axisymmetry**)
  - Processes produce a wide variety of shapes
  - Speeds range from moderate to high speed machining

Introduction



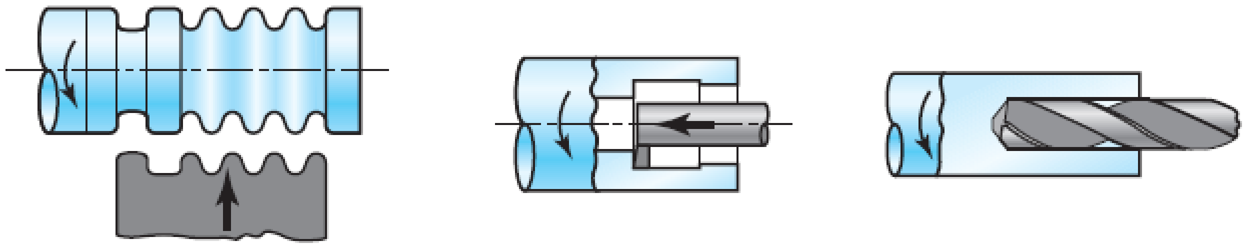
Processes carried out on a lathe:

- **Turning** (figures a-d):
  - Produce straight, conical, curved, or grooved workpieces
  - Examples: shafts, spindles, pins
- **Facing** (figure e):
  - Produce flat surface at end of part and ⊥ to its axis
- **Face grooving** (figure f):
  - Produce grooves for applications such as O-ring seats



cross-section of an installed seal seat type 15

Introduction

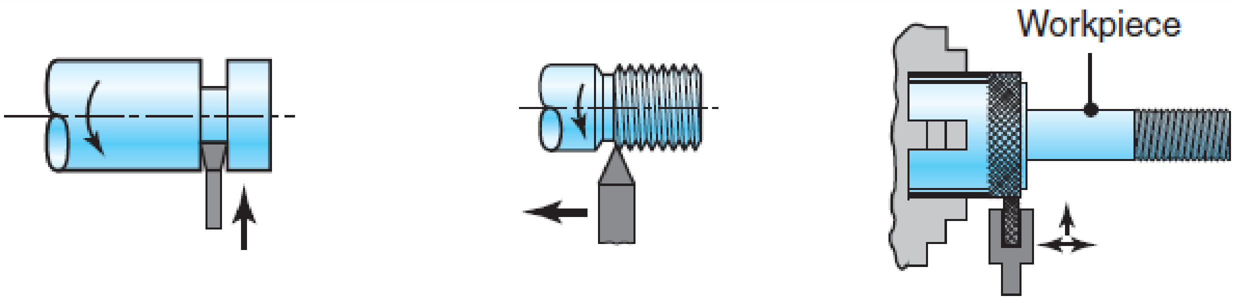


(g) Cutting with a form tool (h) Boring and internal grooving (i) Drilling

Cont. Processes carried out on a lathe:

- **Cutting with forms tools** (figure g):
  - Produce axisymmetric shapes (functional, aesthetic purposes)
- **Boring** (figure h):
  - Enlarge hole/cylindrical cavity made by previous process:
  - Produce circular internal grooves (figure h)
- **Drilling** (figure i):
  - Produce a hole
  - May be followed by boring to improve dim. acc./ surface finish

Introduction



(j) Cutting off (k) Threading (l) Knurling

Cont. Processes carried out on a lathe:

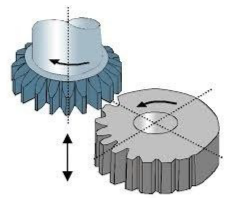
- **Parting** (figure j): AKA **cutting off**
  - Cut a piece from the end of a part
  - Used with production of blanks for additional processing/parts
- **Threading** (figure k):
  - Produce external or internal threads

- **Knurling** (figure l):
  - Produce regularly shaped roughness on cylindrical surfaces
  - Example: making knobs, handles (remember micrometer?)

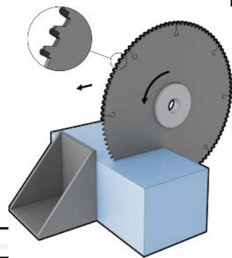
Introduction

General Characteristics of Machining Processes and Typical Dimensional Tolerances

Process	Characteristics	Typical dimensional tolerances, ± mm
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 Rough: 0.13
Boring	Internal surfaces or profiles with characteristics similar to turning; stiffness of boring bar important to avoid chatter	0.025
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
Milling	Wide variety of shapes involving contours, flat surfaces, and slots; versatile; low-to-medium production rate; requires skilled labor	0.013–0.025
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
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; low-quantity production; labor skill required depends on part shape	0.05–0.08
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

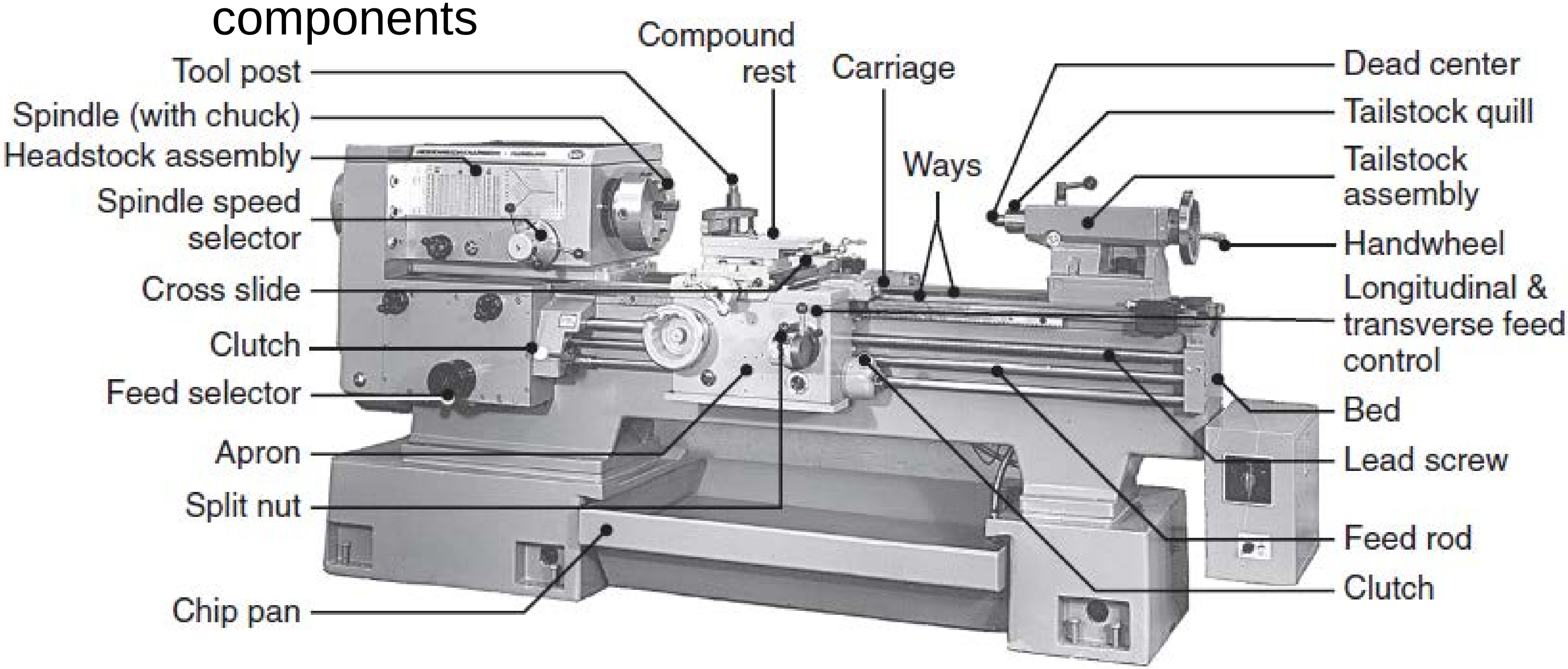


GEAR SHAPING PROCESS



Introduction

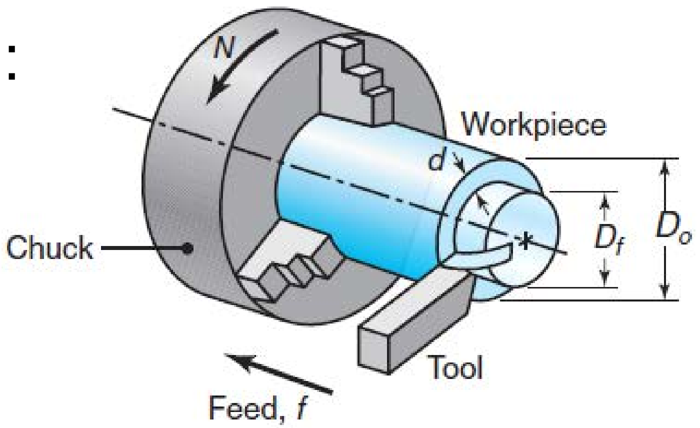
- Lathes:
  - Available in different designs, sizes, capacities, computer-controlled features
  - Below: general view of typical lathe, showing various components



Introduction

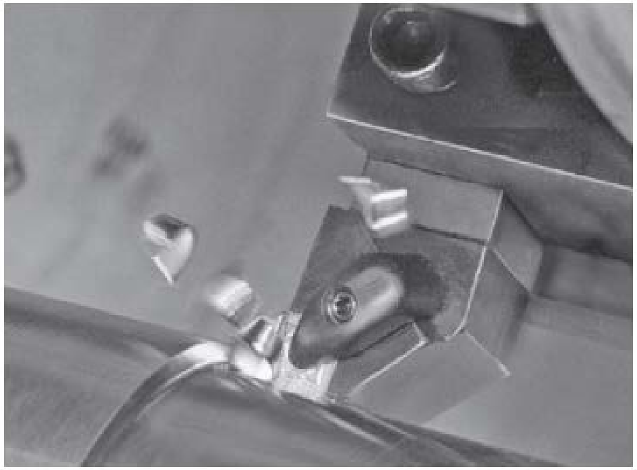
- Turning (see below) is performed at various:
  1. Rotational speeds, N, of workpiece clamped in a spindle
  2. Depths of cut, d
  3. Feeds, f

- Change in parameters depends on:
  - workpiece materials
  - cutting-tool materials
  - surface finish
  - dimensional accuracy
  - characteristics of the machine tool

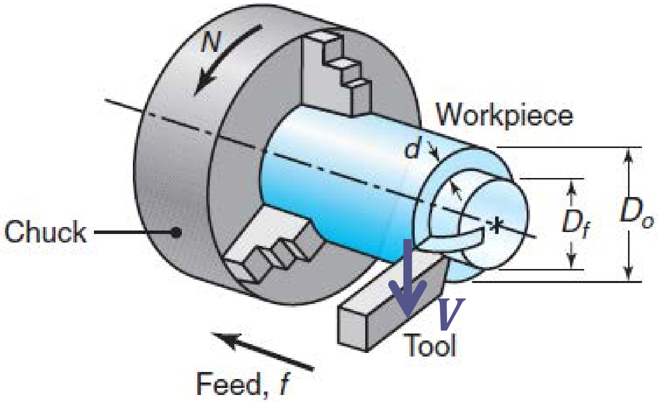


Basic turning operation

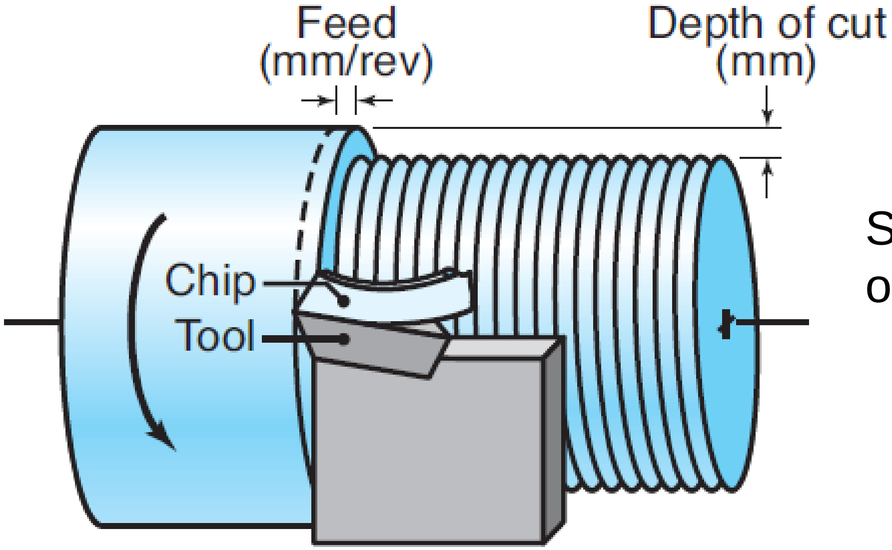
Introduction



a) Turning operation
(showing insert and chip removal)



b) Basic turning operation showing: N (rev/min), d, f; Note, V is surface speed of workpiece at tool tip



Schematic of the turning operation

The Turning Process

- Turning operations:
  - Majority: simple single-point cutting tools (right-hand cutting tool)
  - Each group of workpiece materials has optimum tool angles
  - Process parameters $\Rightarrow$ direct influence on machining processes & optimized productivity (Chapter 21)
- Topics discussed here:
  - Tool geometry
  - Material removal rate (MRR)
  - Forces in turning
  - Approximating turning using the orthogonal model
  - Roughing and finishing cuts
  - Tool materials, feeds, and cutting speeds
  - Cutting Fluids

The Turning Process

Tool Geometry

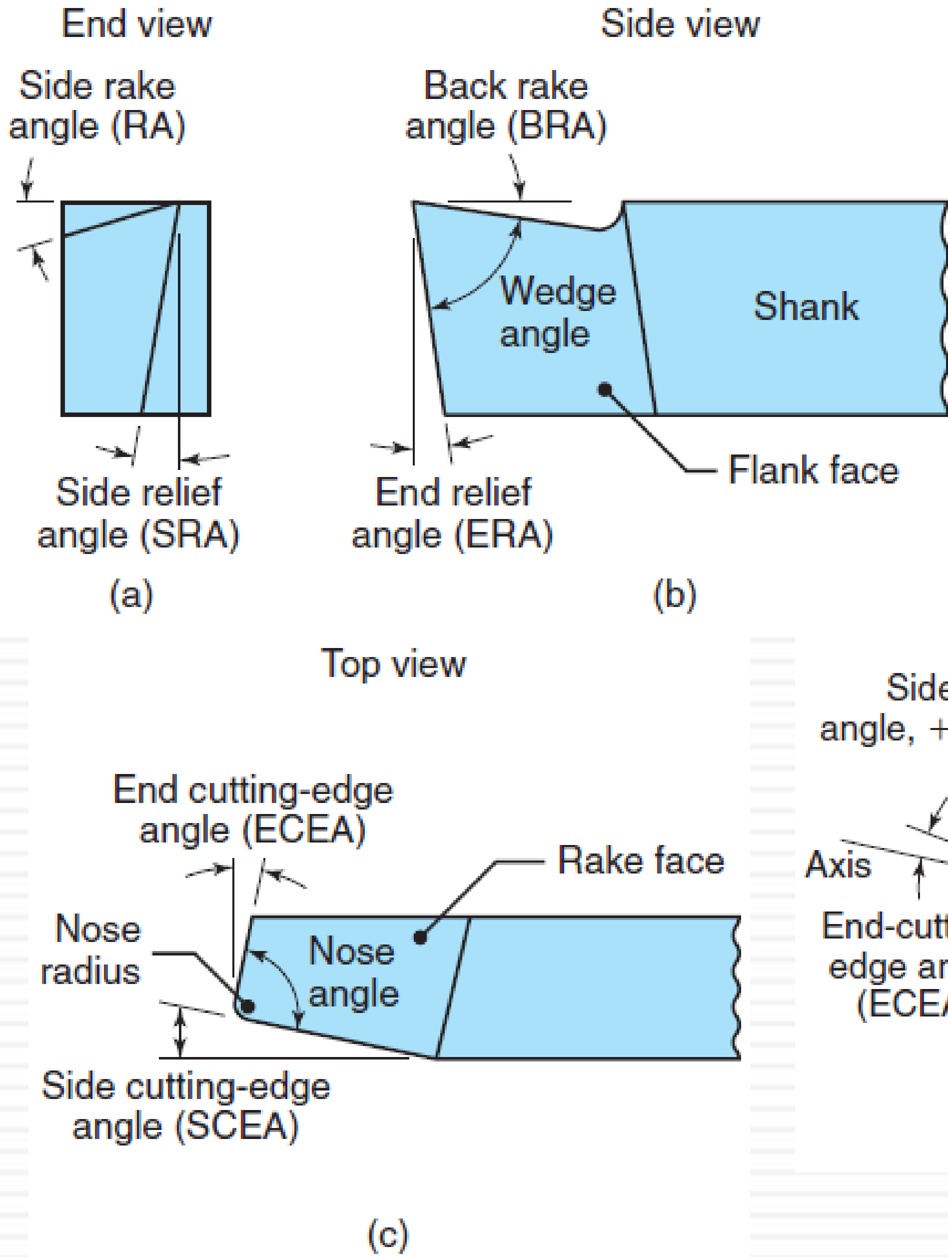
- **Rake angle** (aka back rake angle, BRA):
  - controls both direction of chip flow and strength of tool tip
  - +ve RA improves cutting operation (reduced forces, temperature),
  - but result in small angle @ tool tip ⇒ premature chipping + failure (depending on tool toughness; compare carbide vs HSS)
- **Side rake angle**: typically from -5° to 5°
- **Cutting-edge angle**:
  - affects chip formation, tool strength and cutting forces
  - typically: around 15°

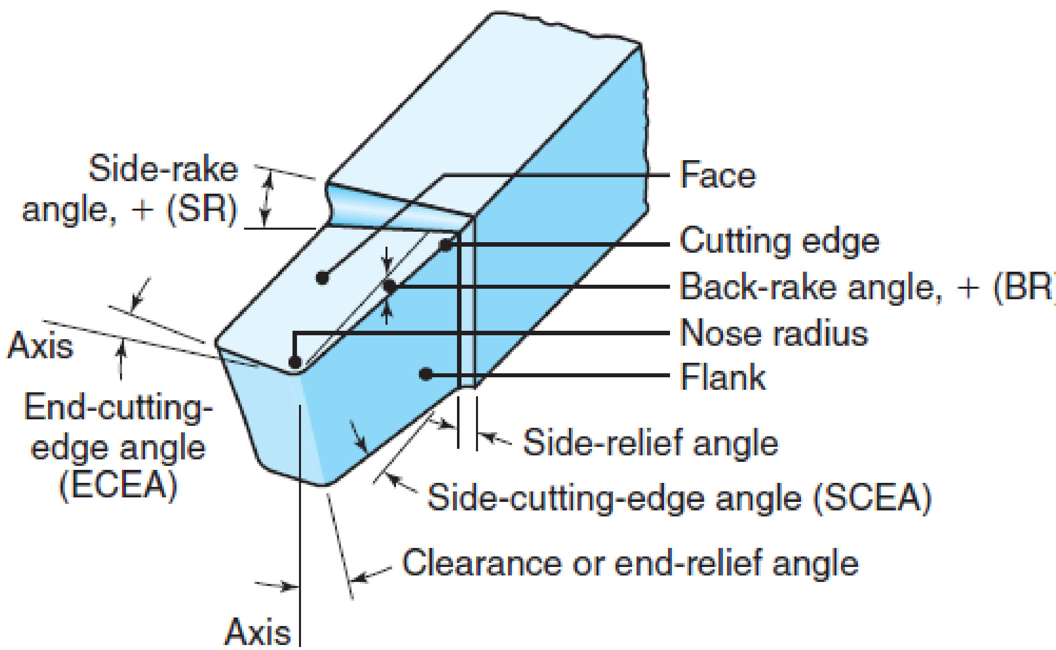
The Turning Process

Cont. Tool Geometry

- **Relief angle:**
  - controls interference and rubbing at tool–workpiece interface
  - if too large $\Rightarrow$ tool may chip off
  - if too small $\Rightarrow$ flank wear may be too large
  - typically: 5°
- **Nose radius:**
  - affects surface finish and tool-tip strength
  - smaller nose radius (i.e. sharp tool) $\Rightarrow$ rougher workpiece S.F. and lower tool strength
  - larger nose radius (i.e. dull tool) $\Rightarrow$ tool chatter

Designation for a right-hand cutting tool (i.e. tool travels from right to left)





The Turning Process

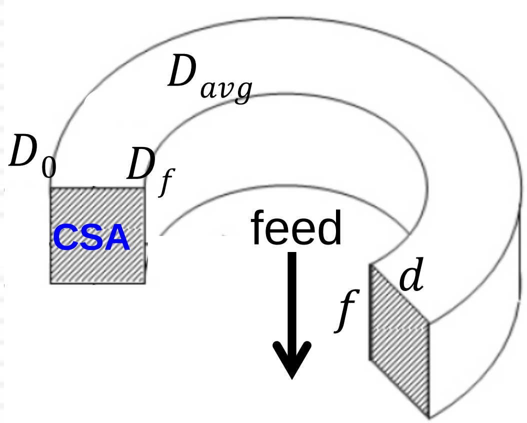
General Recommendations for Tool Angles in Turning

	High-speed steel					Carbide inserts				
Material	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

The Turning Process

Material-removal Rate

- This is vol. of material removed / unit time $[mm^3/min]$
- For each revolution:
  - Ring-shaped layer of material is removed
  - Cross section of layer (see right):
    - Distance tool travels in one revolution: feed, f
    - Depth of cut, d, where $d = (D_0 - D_f)/2$
    - $\Rightarrow CSA = f * d\ [mm^2/rev]$
  - Average diameter of the ring:
    - $D_{avg} = (D_0 + D_f)/2$
    - Note, for light cuts on large-D workpieces: $D_{avg} = D_0$
  - Average circumference of ring: $\pi D_{avg}\ [mm]$
  - $\Rightarrow Volume\ of\ ring\ = CSA\ * \pi D_{avg} = \pi D_{avg} d f\ [mm^3/rev]$



The Turning Process

Cont. Material-removal Rate

- Expression for MRR:
  - We established, one revolution: $Vol. removed\ = \pi D_{avg} df$
  - So given: N, rotational speed of workpiece $[rev/min]$ or $[rpm]$
  - $\Rightarrow \boldsymbol{MMR = \pi D_{avg} df N}$ ($[mm^3/\cancel{rev}]$ * $[\cancel{rev}/min]$ = $[mm^3/min]$)
  - Also, given: V, surface cutting speed
    - $V\ =\ (circumferential\ distance\ traveled\ /\ rev.) * (\#\ of\ rev\ /\ min)$
    - $\Rightarrow \boldsymbol{V\ = \pi D_{avg} N}$ $[mm/min]$
  - $\Rightarrow \boldsymbol{MMR = dfV}$ (Q: MMR has same units as above?)

The Turning Process

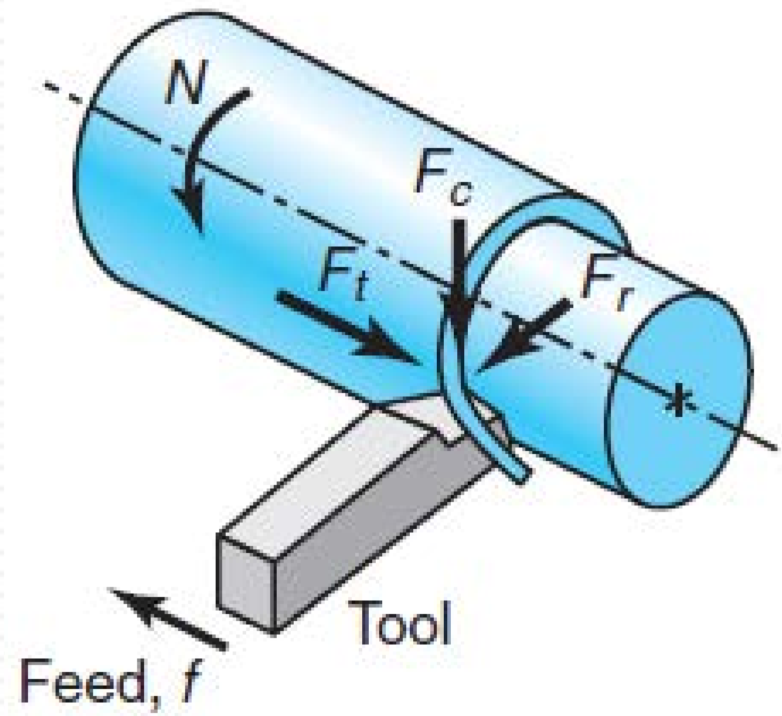
Cont. Material-removal Rate

- Expression for cutting time:
  - Given, l: distance traveled $[mm]$
  - Also, tool travels at feed rate
    - $\boldsymbol{v = fN}$ ($[mm/\cancel{rev}]$ * $[\cancel{rev}/min] = [mm/min]$)
    - But also: $speed\ =\ distance\ /\ time\ =\ l\ /\ t$; or: $t = l/v$
  - $\Rightarrow \boldsymbol{t = l/fN}$
  - Note,
    - t does not include time for *tool approach* and *retraction,*
    - Machine tools are designed/built to minimize these times
  - Equations/terminology mentioned: summarized in Table 23.3

The Turning Process

Forces in Turning

- 3 principal forces acting on cutting tool:
  - **Cutting force, F_c**
  - **Thrust force, F_t**
  - **Radial force, F_r**
- Important for:
  - Design of machine tools
  - Precision-machining operations
  - Preventing deflection, vibrations, chatter of tools resulting from forces



The Turning Process

Cont. Forces in Turning

- Cutting force, F_c:
  - Acts downward on tool tip $\Rightarrow$
    - Deflects tool *downward*,
    - Deflects workpiece *upward*
  - Calculated using energy per unit volume (table)

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

Material	Specific energy $W \cdot s/mm^3$
Aluminum alloys	0.4–1
Cast irons	1.1–5.4
Copper alloys	1.4–3.2
High-temperature alloys	3.2–8
Magnesium alloys	0.3–0.6
Nickel alloys	4.8–6.7
Refractory alloys	3–9
Stainless steels	2–5
Steels	2–9
Titanium alloys	2–5

- Torque on the spindle:
  - $Torque = cutting\ force * its\ radius\ from\ workpiece$
  - $\Rightarrow \boldsymbol{Torque = F_c D_{avg}/2}\ [N \cdot m]$

The Turning Process

Cont. Forces in Turning

- Power required in the turning operation:
  - $Power = torque \; * spindle \; speed$
  - Given, spindle speed:$\omega = 2\pi N$ ([$rad/\cancel{rev}$]*[$\cancel{rev}/min$]=[rad/min])
  - $\Rightarrow Power = \left(F_c D_{avg}/\cancel{2}\right)(\cancel{2}\pi N)$
  - $\Rightarrow \boldsymbol{Power = (F_c) \cdot \left(\pi D_{avg} N\right)}$ [$N \cdot m/min$] or [$kW = kN \cdot m/s$]
  - Note how it is also easy to see that equation above reduces to:

$$\boldsymbol{Power = F_c \cdot V}$$

The Turning Process

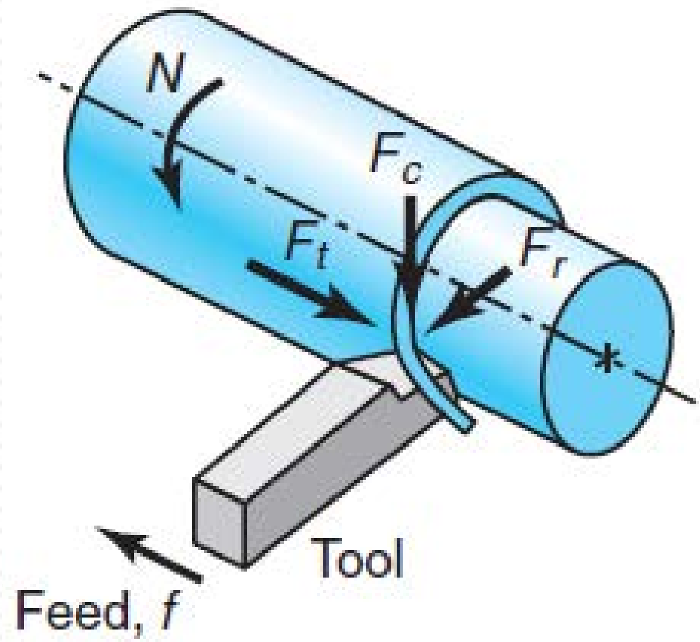
Summary of Turning Parameters and Formulas

N = Rotational speed of the workpiece, rpm
f = Feed, mm/rev
v = Feed rate, or linear speed of the tool along workpiece length, mm/min
$= fN$
V = Surface speed of workpiece, m/min
$= \pi D_o N$ (for maximum speed)
$= \pi D_{avg} N$ (for average speed)
l = Length of cut, mm
D_o = Original diameter of workpiece, mm
D_f = Final diameter of workpiece, mm
D_{avg} = Average diameter of workpiece, mm
$= (D_o + D_f)/2$
d = Depth of cut, mm
$= (D_0 - D_f)/2$
t = Cutting time, s or min
$= l/fN$
MRR = mm^3/min
$= \pi D_{avg} d f N$
Torque = N · m
$= F_c D_{avg}/2$
Power = kW or hp
= (Torque)(ω), where $\omega = 2\pi N$ rad/min

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

The Turning Process

Cont. Forces in Turning



- Thrust force F_t:
  - Acts in longitudinal direction
  - Also called feed force, F_f (since in same direction as feed)
  - Tends to push tool:
    - To the right
    - Away from the chuck
- Radial force, F_r:
  - Acts in radial direction
  - Tends to push tool away from workpiece
- Note, F_t and F_r are difficult to calculate (usu. determined experimentally)

The Turning Process

Approx. turning by orthogonal model:

a) Turning

b) Corresponding orthogonal cutting

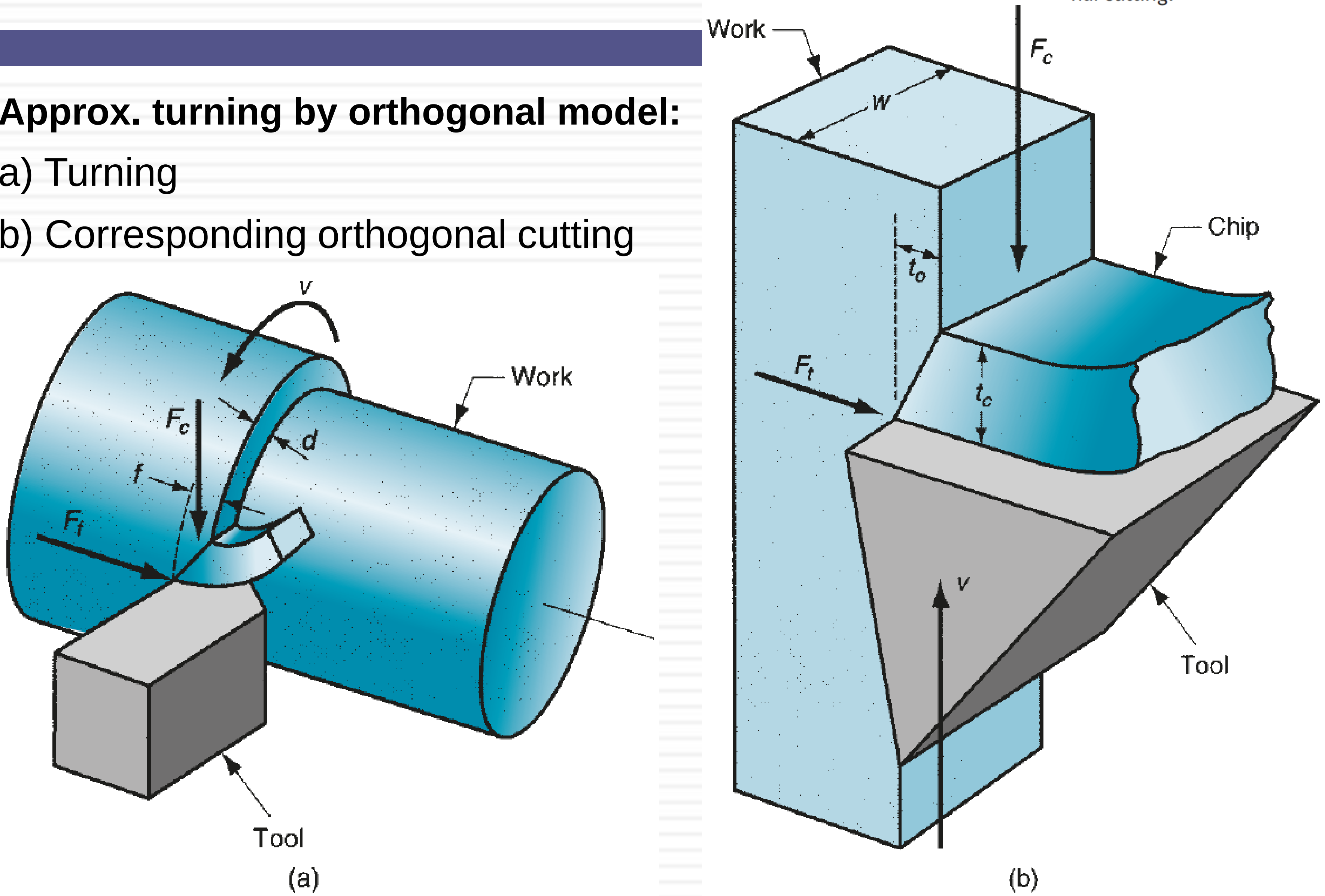


FIGURE 21.13 Approximation of turning by the orthogonal model: (a) turning; and (b) the corresponding orthogonal cutting.

The Turning Process

Approximating turning using the orthogonal model:

TABLE 21.1 Conversion key: turning operation vs. orthogonal cutting.

Turning Operation	Orthogonal Cutting Model
Feed f =	Chip thickness before cut t_o
Depth d =	Width of cut w
Cutting speed v =	Cutting speed v
Cutting force F_c =	Cutting force F_c
Feed force F_f =	Thrust force F_t

- Interpretation of cutting conditions is different in 2 cases:
  - Chip thickness before cut (t_o) in orthogonal cutting corresponds to feed (f) in turning
  - Width of cut (w) in orthogonal cutting corresponds to depth of cut (d) in turning
  - Thrust force (F_t) in orthogonal model corresponds to feed force (F_f) in turning
  - V and F_c have same meanings in both cases

The Turning Process

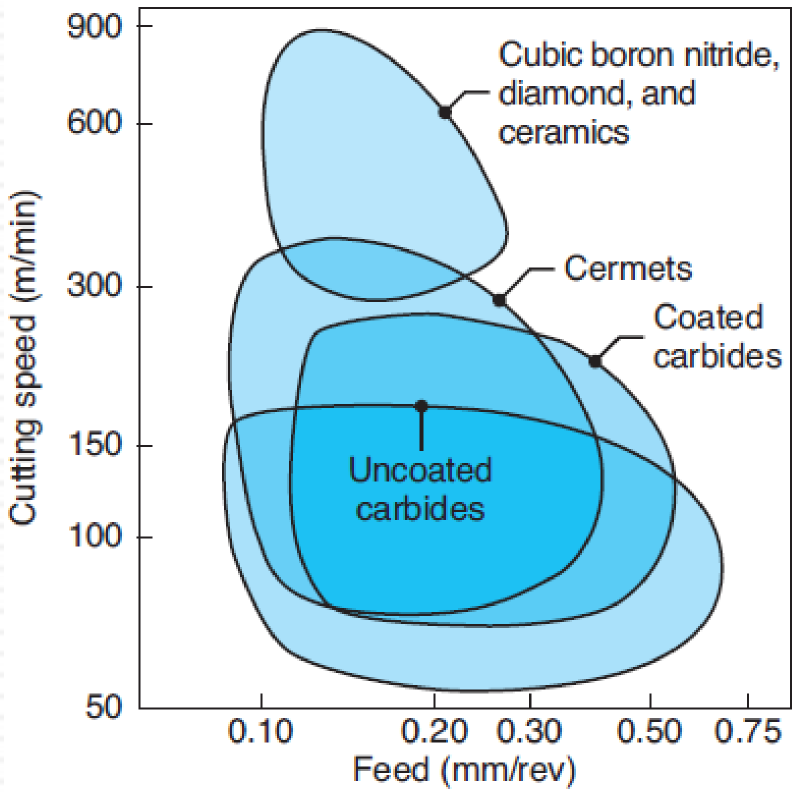
Roughing and Finishing Cuts

- Usual procedure:
  - one or more *roughing cuts*
  - at high feed rates,
  - large depths of cut (i.e. high MRR)
  - little consideration for dimensional tolerance and surface roughness
- This is followed by:
  - a *finishing cut*
  - at a lower feed,
  - lower depth of cut
  - $\Rightarrow$ good surface finish

The Turning Process

Tool Materials, Feeds, and Cutting Speeds

- Large range of applicable cutting speeds, feeds for a variety of tool materials (right)
- Used as general guideline in turning operations
- Specific parameters (d, f, V):
  - Various workpiece materials
  - Various tool materials
  - Different cutting conditions
  - See Table 23.4



The Turning Process

TABLE 23.4

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min	Range for roughing and finishing: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min
Low-C and free machining steels	Uncoated carbide	1.5–6.3	0.35	90	0.5–7.6	0.15–1.1	60–135
	Ceramic-coated carbide	"	"	245–275	"	"	120–425
	Triple-coated carbide	"	"	185–200	"	"	90–245
	TiN-coated carbide	"	"	105–150	"	"	60–230
	Al_2O_3 ceramic	"	0.25	395–440	"	"	365–550
	Cermet	"	0.30	215–290	"	"	105–455
Medium and high-C steels	Uncoated carbide	1.2–4.0	0.30	75	2.5–7.6	0.15–0.75	45–120
	Ceramic-coated carbide	"	"	185–230	"	"	120–410
	Triple-coated carbide	"	"	120–150	"	"	75–215
	TiN-coated carbide	"	"	90–200	"	"	45–215
	Al_2O_3 ceramic	"	0.25	335	"	"	245–455
	Cermet	"	0.25	170–245	"	"	105–305
Cast iron, gray	Uncoated carbide	1.25–6.3	0.32	90	0.4–12.7	0.1–0.75	75–185
	Ceramic-coated carbide	"	"	200	"	"	120–365
	TiN-coated carbide	"	"	90–135	"	"	60–215
	Al_2O_3 ceramic	"	0.25	455–490	"	"	365–855
	SiN ceramic	"	0.32	730	"	"	200–990

The Turning Process

TABLE 23.4

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min	Range for roughing and finishing: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min
Stainless steel, austenitic	Triple-coated carbide	1.5–4.4	0.35	150	0.5–12.7	0.08–0.75	75–230
	TiN-coated carbide	"	"	85–160	"	"	55–200
	Cermet	"	0.30	185–215	"	"	105–290
High-temperature alloys, nickel based	Uncoated carbide	2.5	0.15	25–45	0.25–6.3	0.1–0.3	15–30
	Ceramic-coated carbide	"	"	45	"	"	20–60
	TiN-coated carbide	"	"	30–55	"	"	20–85
	Al_2O_3 ceramic	"	"	260	"	"	185–395
	SiN ceramic	"	"	215	"	"	90–215
	Polycrystalline cBN	"	"	150	"	"	120–185
Titanium alloys	Uncoated car bide	1.0–3.8	0.15	35–60	0.25–6.3	0.1–0.4	10–75
	TiN-coated carbide	"	"	30–60	"	"	10–100
Aluminum alloys Free machining	Uncoated carbide	1.5–5.0	0.45	490	0.25–8.8	0.08–0.62	200–670
	TiN-coated carbide	"	"	550	"	"	60–915
	Cermet	"	"	490	"	"	215–795
	Polycrystalline diamond	"	"	760	"	"	305–3050
High silicon	Polycrystalline diamond	"	"	530	"	"	365–915

(continued)

The Turning Process

Cutting Fluids

- Recommendations for cutting fluids suitable for various workpiece materials
- Note:
  - Aluminum
  - Copper
  - Carbon/ low alloy steels
- Current trend: **DM/NDM**

General Recommendations for Cutting Fluids for Machining (see also Section 33.7)

Material	Type of fluid
Aluminum	D, MO, E, MO + FO, CSN
Beryllium	MC, E, CSN
Copper	D, E, CSN, MO + FO
Magnesium	D, MO, MO + FO
Nickel	MC, E, CSN
Refractory metals	MC, E, EP
Steels	
Carbon and low-alloy	D, MO, E, CSN, EP
Stainless	D, MO, E, CSN
Titanium	CSN, EP, MO
Zinc	C, MC, 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.

The Turning Process

EXAMPLE 23.1

Material-removal Rate and Cutting Force in Turning

A 150-mm-long, 12.5-mm-diameter 304 stainless steel rod is being reduced in diameter to 12.0 mm by turning on a lathe. The spindle rotates at N 400 rpm, and the tool is travelling at an axial speed of 200 mm/min. Calculate the cutting speed, material-removal rate, cutting time, power dissipated, and cutting force.

The Turning Process

Solution

Material-removal Rate and Cutting Force in Turning

The maximum cutting speed is

$$V = \pi D_0 N = \frac{\pi(12.5)(400)}{1000} = 15.7 \text{ m/min}$$

The cutting speed at the machined diameter is

$$V = \pi D_0 N = \frac{\pi(12.0)(400)}{1000} = 15.1 \text{ m/min}$$

The depth of cut is $d = \dfrac{12.5 - 12.0}{2} = 0.25 \text{ mm}$

The Turning Process

Solution

Material-removal Rate and Cutting Force in Turning

The feed is $f = \dfrac{200}{400} = 0.5\ \text{mm/rev}$

The material-removal rate is

$$MMR = (\pi)(12.25)(0.25)(0.5)(400) = 1924\ \text{mm}^3/\text{min} = 2 \times 10^{-6}\ \text{m}^3/\text{min}$$

The actual time to cut is

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

The Turning Process

Solution

Material-removal Rate and Cutting Force in Turning

The power dissipated is $Power = \frac{(4)(1924)}{60} = 128\text{ W}$

Since W=60 N•m/min, power dissipated is 7680 N m/min.

Also, power is the product of torque:

$$T = \frac{7680}{(2\pi)(400)} = 3.1\text{ Nm}$$

Since $T = F_c D_{avg}/2$, we have $F_c = \frac{(3.1)(1000)}{12.25/2} = 506\text{ N}$