Fundamentals of Machining/Orthogonal Machining

Chapter 20

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20.1 Introduction

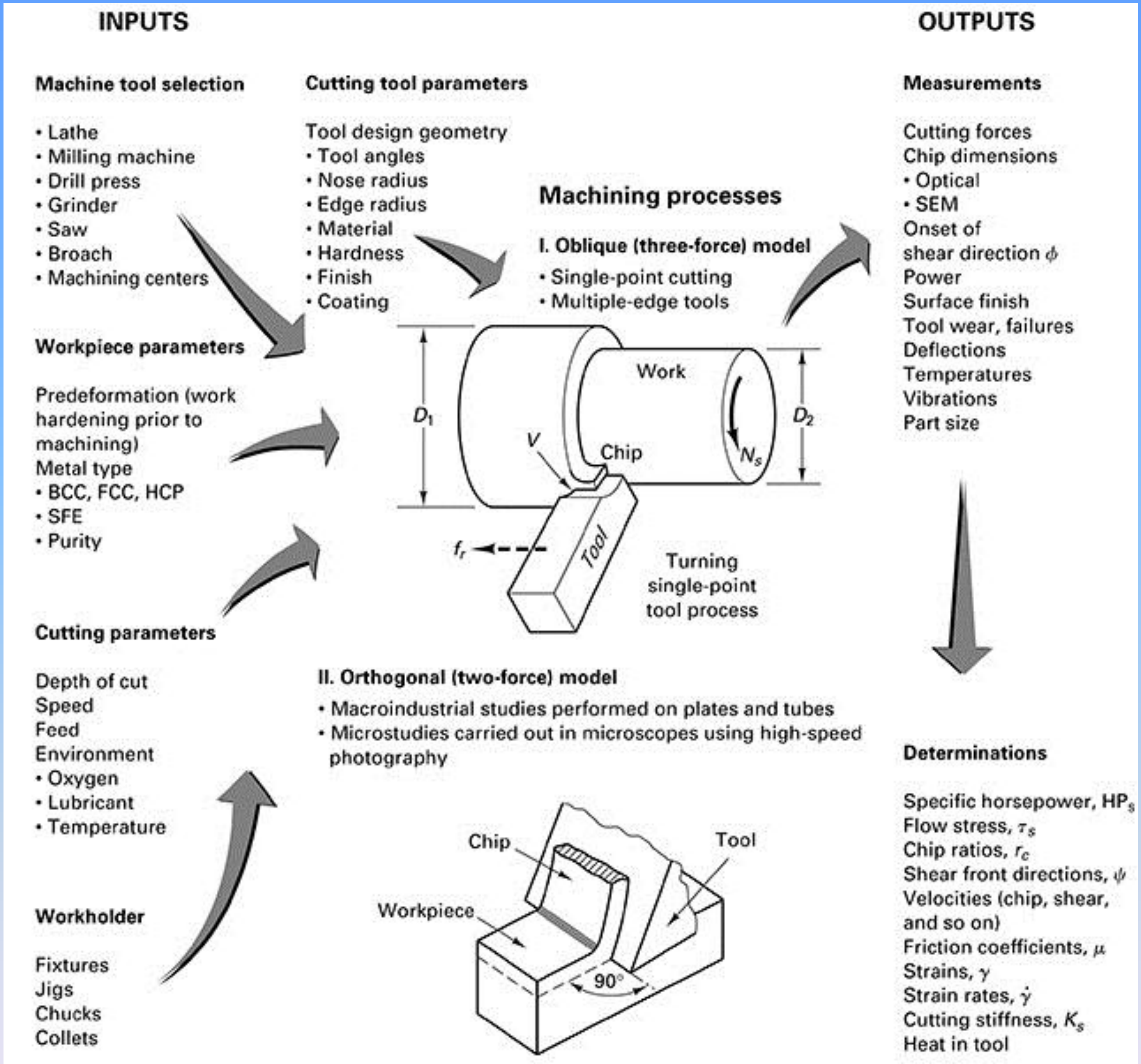


FIGURE 20-1 The fundamental inputs and outputs to machining processes.

20.2 Fundementals

FIGURE 20-2 The seven basic machining processes used in chip formation.

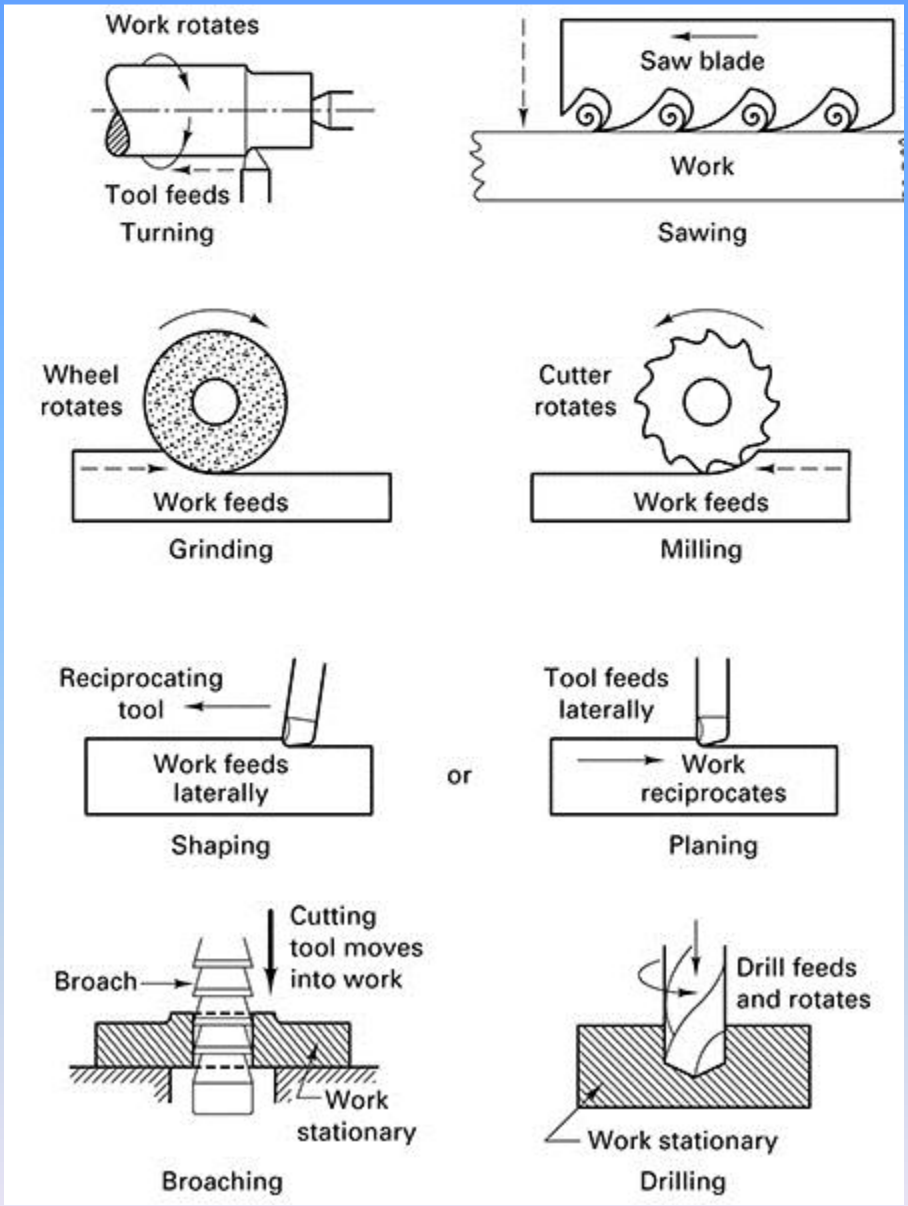
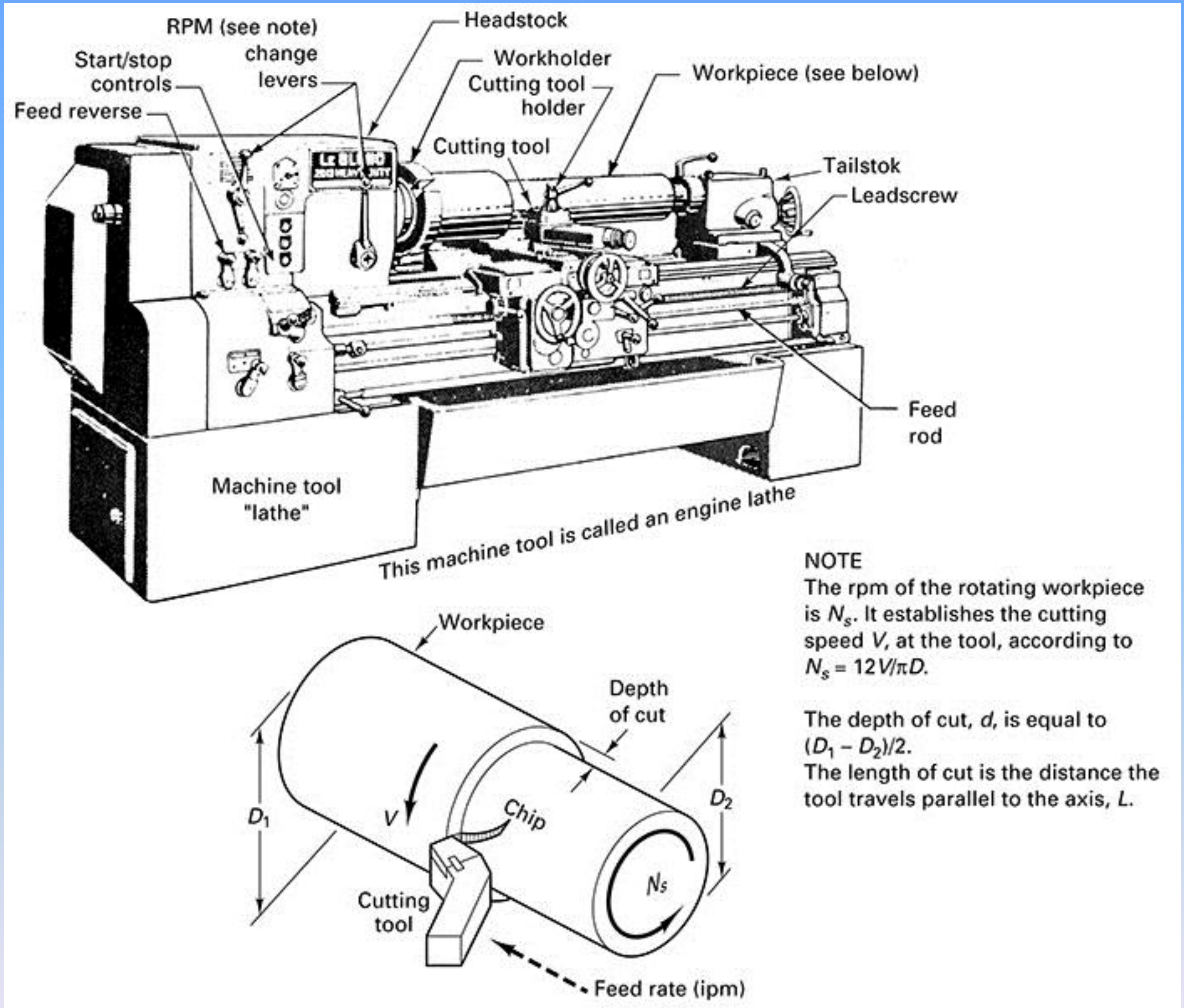


FIGURE 20-3 Turning a cylindrical workpiece on a lathe requires you to select the cutting speed, feed, and depth of cut.



Turning, Single Point and Box Tools

Material	Hardness Bhn	Condition	Depth of Cut* in mm	High Speed Steel Tool: Speed fpm m/min	High Speed Steel Tool: Feed ipr mm/r	High Speed Steel Tool: Tool Material AISI ISO	Carbide Tool, Uncoated: Speed Brazed fpm m/min	Carbide Tool, Uncoated: Speed Indexable fpm m/min	Carbide Tool, Uncoated: Feed ipr mm/r	Carbide Tool, Uncoated: Tool Material Grade C ISO	Carbide Tool, Coated: Speed fpm m/min	Carbide Tool, Coated: Feed ipr mm/r	Carbide Tool, Coated: Tool Material Grade C ISO
1. FREE MACHINING		Hot Rolled,	.040	160	.008	M2, M3	500	650	.007	C-7	925	.007	CC-7
CARBON STEELS,		Normalized,	.150	125	.015	M2, M3	390	480	.020	C-6	600	.015	CC-6
WROUGHT (cont.)		Annealed,	.300	100	.020	M2, M3	310	375	.030	C-6	500	.020	CC-6
Medium Carbon	225	Cold Drawn	.625	80	.030	M2, M3	240	290	.040	C-6	—	—	—
Leaded	to	or	**1**	**49**	**.20**	**S4, S5**	**150**	**185**	**.18**	**P10**	**230**	**.18**	**CP10**
(cont.)	275	Quenched	**4**	**38**	**.40**	**S4, S5**	**120**	**145**	**.50**	**P20**	**185**	**.40**	**CP20**
(materials listed		and	**8**	**30**	**.50**	**S4, S5**	**95**	**115**	**.75**	**P30**	**150**	**.50**	**CP30**
on preceding page)		Tempered	**16**	**24**	**.75**	**S4, S5**	**73**	**88**	**1.0**	**P40**	—	—	—
		Hot	.040	135	.007	T15, M42	460	545	.007	C-7	825	.007	CC-7
		Rolled,	.150	105	.015	T15, M42	350	425	.020	C-6	525	.015	CC-6
		Normalized,	.300	85	.020	T15, M42	275	380	.030	C-6	425	.020	CC-6
	275	Annealed	.625	—	—	—	—	—	—	—	—	—	—
	to	or	**1**	**41**	**.18**	**S9, S11**	**140**	**165**	**.18**	**P10**	**250**	**.18**	**CP10**
	325	Quenched	**4**	**32**	**.40**	**S9, S11**	**105**	**130**	**.50**	**P20**	**160**	**.40**	**CP20**
		and	**8**	**26**	**.50**	**S9, S11**	**84**	**100**	**.75**	**P30**	**130**	**.50**	**CP30**
		Tempered	**16**	—	—	—	—	—	—	—	—	—	—
			.040	100	.007	T15, M42	390	480	.007	C-7	725	.007	CC-7
			.150	80	.015	T15, M42	300	375	.020	C-6	475	.015	CC-6
	325	Quenched	.300	65	.020	T15, M42	230	290	.030	C-6	375	.020	CC-6
	to	and	.625	—	—	—	—	—	—	—	—	—	—
	375	Tempered	**1**	**30**	**.18**	**S9, S11**	**120**	**145**	**.18**	**P10**	**220**	**.18**	**CP10**
			4	**24**	**.40**	**S9, S11**	**90**	**115**	**.50**	**P20**	**145**	**.40**	**CP20**
			8	**20**	**.50**	**S9, S11**	**70**	**88**	**.75**	**P30**	**115**	**.50**	**CP30**
			16	—	—	—	—	—	—	—	—	—	—
			.040	70	.007	T15, M42	325	400	.007	C-7	600	.007	CC-7
			.150	55	.015	T15, M42	250	310	.020	C-6	400	.015	CC-6
	375	Quenched	.300	45	.020	T15, M42	200	240	.030	C-6	325	.020	CC-6
	to	and	.625	—	—	—	—	—	—	—	—	—	—
	425	Tempered	**1**	**21**	**.18**	**S9, S11**	**100**	**120**	**.18**	**P10**	**185**	**.18**	**CP10**
			4	**17**	**.40**	**S9, S11**	**76**	**95**	**.50**	**P20**	**120**	**.40**	**CP20**
			8	**14**	**.50**	**S9, S11**	**60**	**73**	**.75**	**P30**	**100**	**.50**	**CP30**
			16	—	—	—	—	—	—	—	—	—	—

FIGURE 20-4 Examples of a table for selection of speed and feed for turning. *(Source:* Metcut's Machinability Data Handbook.*)*

			16	—	—	—	—	—	—	—	—	—	—
2. CARBON STEELS, WROUGHT Low Carbon 1005 1006 1008 1009 1010 1012 1015 1017 1020 1023 1025	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	185	.007	M2, M3	535	700	.007	C-7	1050	.007	CC-7
			.150	145	.015	M2, M3	435	540	.020	C-6	700	.015	CC-6
			.300	115	.020	M2, M3	340	420	.030	C-6	550	.020	CC-6
			.625	90	.030	M2, M3	265	330	.040	C-6	—	—	—
			1	**56**	**.18**	**S4, S5**	**165**	**215**	**.18**	**P10**	**320**	**.18**	**CP10**
			4	**44**	**.40**	**S4, S5**	**135**	**165**	**.50**	**P20**	**215**	**.40**	**CP20**
			8	**35**	**.50**	**S4, S5**	**105**	**130**	**.75**	**P30**	**170**	**.50**	**CP30**
			16	**27**	**.75**	**S4, S5**	**81**	**100**	**1.0**	**P40**	—	—	—
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	150	.007	M2, M3	485	640	.007	C-7	950	.007	CC-7
			.150	125	.015	M2, M3	410	500	.020	C-6	625	.015	CC-6
			.300	100	.020	M2, M3	320	390	.030	C-6	500	.020	CC-6
			.625	80	.030	M2, M3	245	305	.040	C-6	—	—	—
			1	**46**	**.18**	**S4, S5**	**150**	**195**	**.18**	**P10**	**290**	**.18**	**CP10**
			4	**38**	**.40**	**S4, S5**	**125**	**150**	**.50**	**P20**	**190**	**.40**	**CP20**
			8	**30**	**.50**	**S4, S5**	**100**	**120**	**.75**	**P30**	**150**	**.50**	**CP30**
			16	**24**	**.75**	**S4, S5**	**75**	**95**	**1.0**	**P40**	—	—	—
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	145	.007	M2, M3	460	570	.007	C-7	850	.007	CC-7
			.150	115	.015	M2, M3	385	450	.020	C-6	550	.015	CC-6
			.300	95	.020	M2, M3	300	350	.030	C-6	450	.020	CC-6
			.625	75	.030	M2, M3	235	265	.040	C-6	—	—	—
			1	**44**	**.18**	**S4, S5**	**140**	**175**	**.18**	**P10**	**260**	**.18**	**CP10**
			4	**35**	**.40**	**S4, S5**	**115**	**135**	**.50**	**P20**	**170**	**.40**	**CP20**
			8	**29**	**.50**	**S4, S5**	**90**	**105**	**.75**	**P30**	**135**	**.50**	**CP30**
			16	**23**	**.75**	**S4, S5**	**72**	**81**	**1.0**	**P40**	—	—	—
	225 to 275	Annealed or Cold Drawn	.040	125	.007	M2, M3	410	510	.007	C-7	750	.007	CC-7
			.150	95	.015	M2, M3	360	400	.020	C-6	500	.015	CC-6
			.300	75	.020	M2, M3	285	315	.030	C-6	400	.020	CC-6
			.625	60	.030	M2, M3	220	240	.040	C-6	—	—	—
			1	**38**	**.18**	**S4, S5**	**125**	**155**	**.18**	**P10**	**230**	**.18**	**CP10**
			4	**29**	**.40**	**S4, S5**	**110**	**120**	**.50**	**P20**	**150**	**.40**	**CP20**
			8	**23**	**.50**	**S4, S5**	**87**	**95**	**.75**	**P30**	**120**	**.50**	**CP30**
			16	**18**	**.75**	**S4, S5**	**67**	**73**	**1.0**	**P40**	—	—	—

See section 15.1 for Tool Geometry.
*Caution: Check Horsepower requirements on heavier depths of cut.

See section 16 for Cutting Fluid Recommendations.
†Any premium HSS (T15, M33, M41–M47) or (S9, S10, S11, S12).

FIGURE 20-4 Examples of a table for selection of speed and feed for turning. *(Source:* Metcut's Machinability Data Handbook.*)*

FIGURE 20-5 Relationship of speed, feed, and depth of cut in turning, boring, facing, and cutoff operations typically done on a lathe.

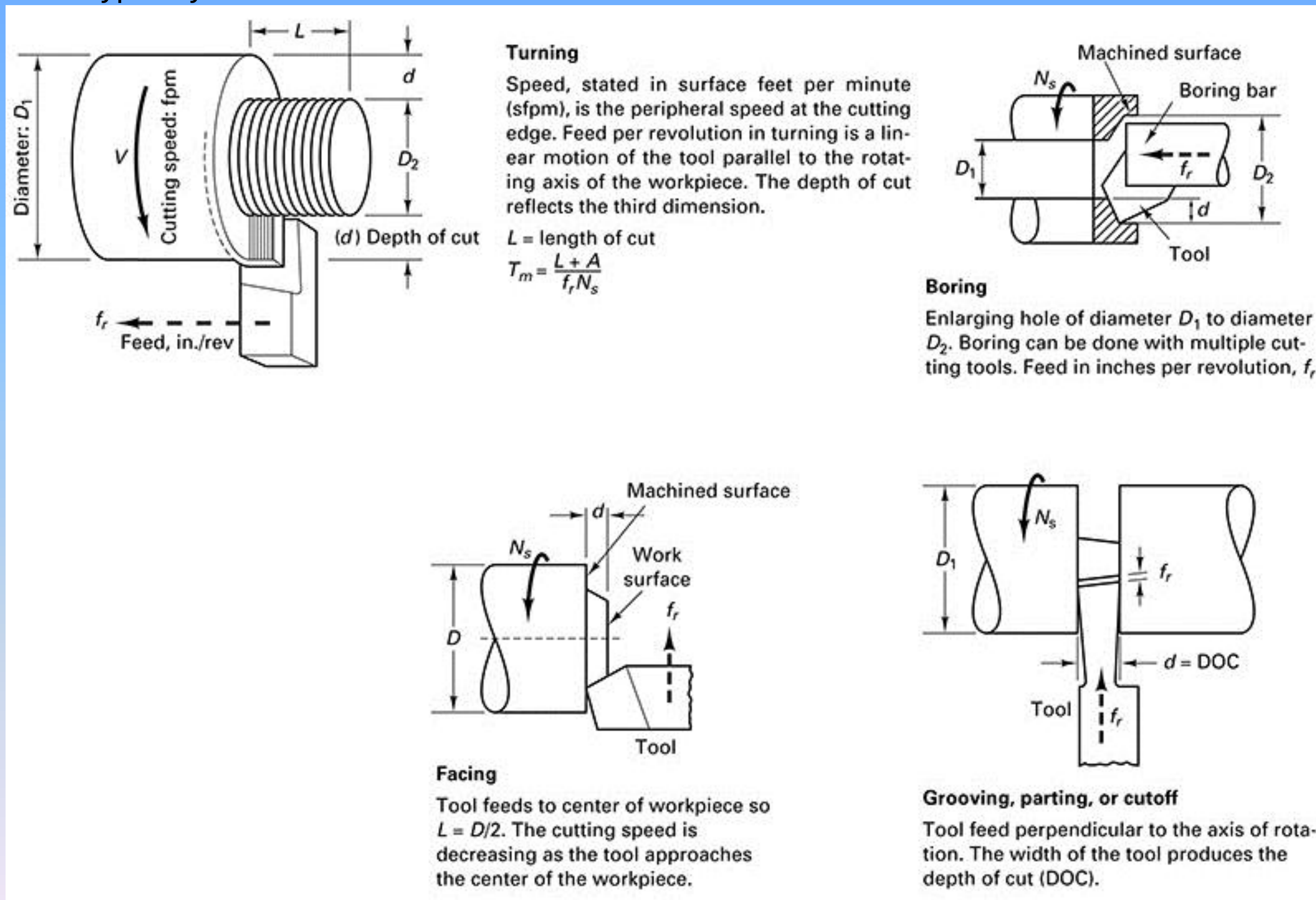


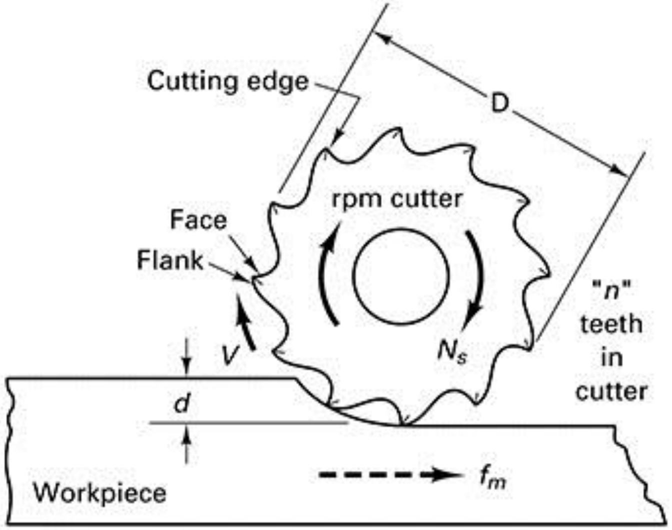
TABLE 20-1 Shop Formulas for Turning, Milling, Drilling, and Broaching (English Units)

Parameter	Turning	Milling	Drilling	Broaching
Cutting speed, fpm	$V = 0.262 \times D_t \times$ rpm	$V = 0.262 \times D_m \times$ rpm	$V = 0.262 \times D_d \times$ rpm	V
Revolutions per minute, N_s	rpm $= 3.82 \times V_c/D_t$	rpm $= 3.82 \times V_c/D_m$	rpm $= 3.82 \times V_c/D_d$	—
Feed rate, in./min	$f_m = f_r \times$ rpm	$f_m = f_r \times$ rpm	$f_m = f_r \times$ rpm	—
Feed per rev tooth pass, in./rev	f_r	f_t	f_r	—
Cutting time, min, T_m	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/12V$
Rate of metal removal, in.^{3}/min	MRR $= 12 \times d \times f_r \times V_c$	MRR $= w \times d \times f_m$	MRR $= \pi D^2 d/4 \times f_m$	MRR $= 12 \times w \times d \times V$
Horsepower required at spindle	hp $=$ MRR $\times$ HP$_s$	hp $=$ MRR $\times$ HP$_s$	hp $=$ MRR $\times$ HP$_s$	—
Horsepower required at motor	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$
Torque at spindle	$t_s = 63{,}030$ hp/rpm	$t_s = 63{,}030$ hp/rpm	$t_s = 63{,}030$ hp/rpm	—

Symbols

D_t = Diameter of workpiece in turning, inches
D_m = Diameter of milling cutter, inches
D_d = Diameter of drill, inches
d = Depth of cut, inches
E = Efficiency of spindle drive
f_m = Feed rate, inches per minute
f_r = Feed, inches per revolution
f_t = Feed, inches per tooth
hp$_m$ = Horsepower at motor
MRR = Metal removal rate, in.^{3}/min
hp = horsepower at spindle
L = Length of cut, inches
n = Number of teeth in cutter
HP$_s$ = Unit power, horsepower per cubic inch per minute, specific horsepower
N_s = Revolution per minute of work or cutter
t_s = Torque at spindle, inch-pound
T_m = Cutting time, minutes
V = Cutting speed, feet per minute
w = Width of cut, inches

Values for specific horsepower (unit power) are given in Table 20-4.



Slab milling – multiple tooth

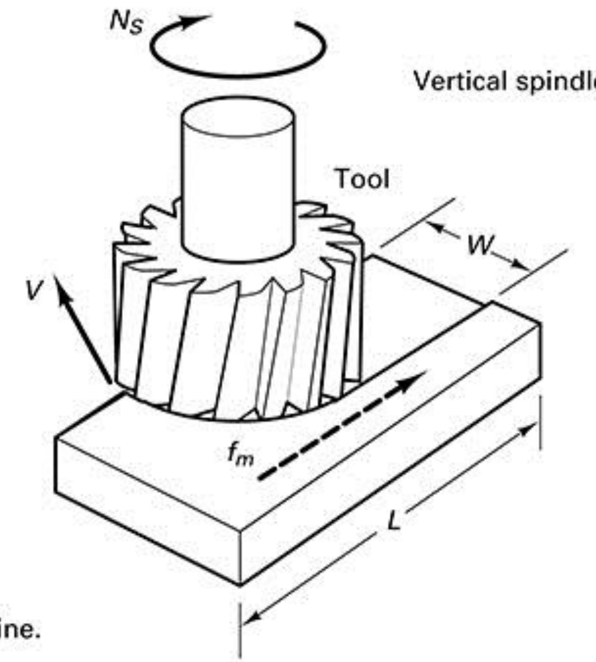
Slab milling is usually performed on a horizontal milling machine. Equations for T_m and MRR derived in Chapter 25.

The tool rotates at rpm N_s. The workpiece translates past the cutter at feed rate f_m, the table feed. The length of cut, L, is the length of workpiece plus allowance, L_A,

$$L_A = \sqrt{\frac{D^2}{4} - \left(\frac{D}{2} - d\right)^2} = \sqrt{d(D-d)} \text{ inches}$$

$$T_m = (L + L_A)/f_m$$

The MRR = Wdf_m where W = width of the cut and d = depth of cut.



Face milling
Multiple-tooth cutting

Given a selected cutting speed V and a feed per tooth f_t, the rpm of the cutter is $N_s = 12V/\pi D$ for a cutting of diameter D. The table feed rate is $f_m = f_t n N_s$ for a cutter with n teeth.

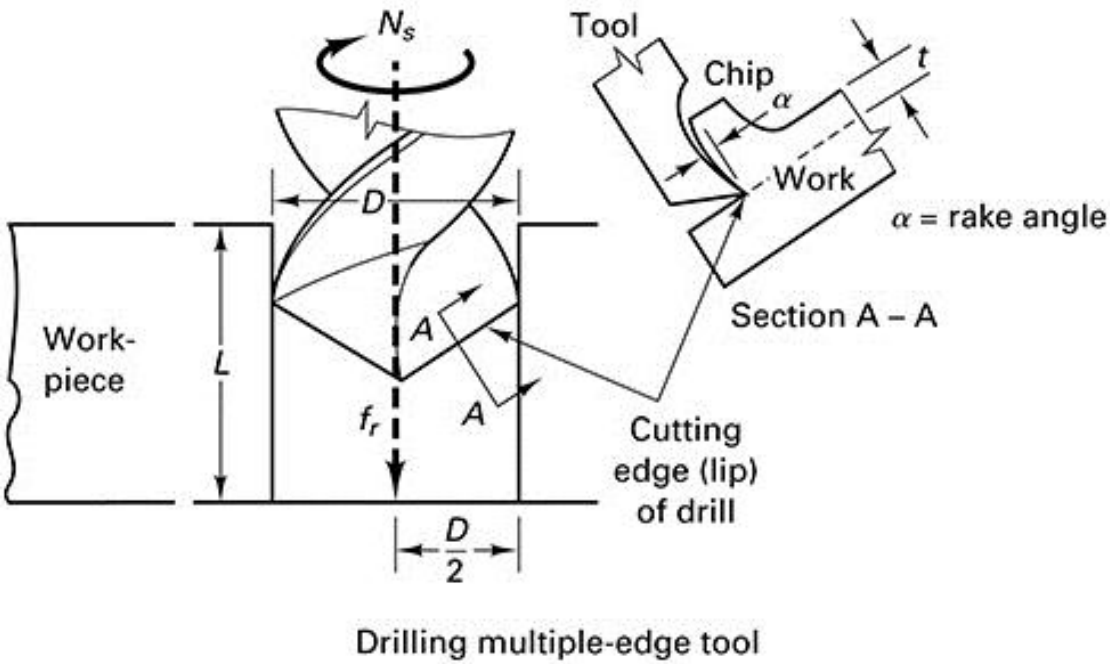
The cutting time, $T_m = (L + L_A + L_o)/f_m$

where $L_o = L_A = \sqrt{W(D-W)}$ for $W < D/2$

or $L_o = L_A = D/2$ for $W \geq D/2$.

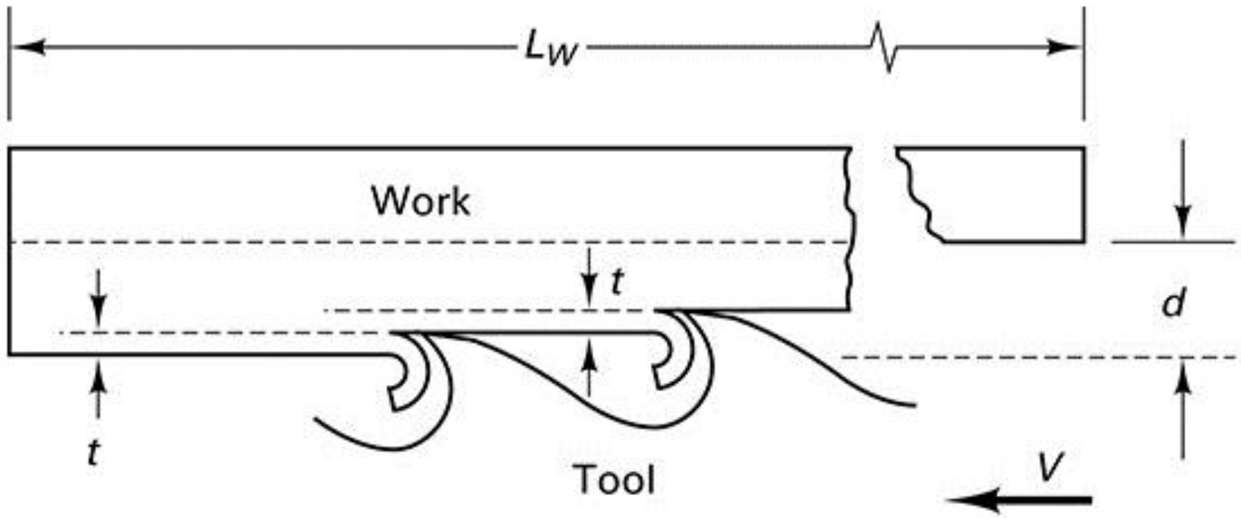
The MRR = Wdf_m where d = depth of cut.

FIGURE 20-6 Basics of milling processes (slab, face, and end milling) including equations for cutting time and metal removal rate (MRR).



Select cutting speed V, fpm and feed, f_r, in./rev. Select drill.
D = diameter of the drill which rotates 2 cutting edges at rpm N_s. V = velocity of outer edge of the lip of the drill.
$N_s = 12V/\pi D$. T_m = cutting time = $(L + A)/f_r N_s$ where f_r is the feed rate in in. per rev. The allowance $A = D/2$.
The MRR = $(\pi D^2/4) f_r N_s$ in.^{3} /min which is approximately $3DVf_r$.

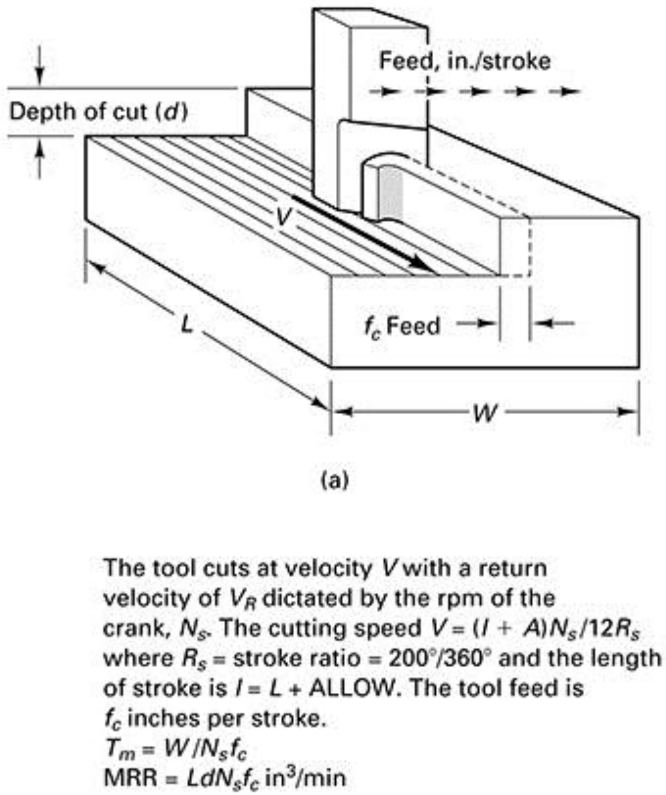
FIGURE 20-7 Basics of the drilling (hole-making) processes, including equations for cutting time and metal removal rate (MRR).

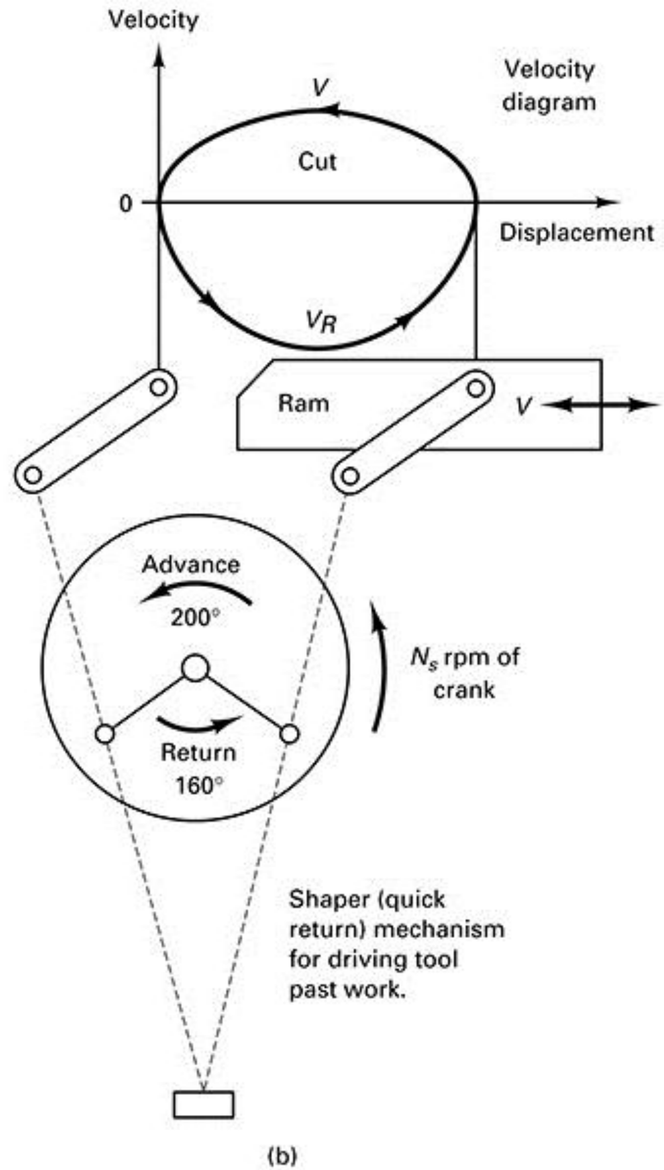


The T_m for broaching is $T_m = L/12V$. The MRR (per tooth) is $12tWV$ in.^{3}/min where V = cutting velocity in fpm, W is the width of cut, t = rise per tooth.

FIGURE 20-8 Process basics of broaching. Equations for cutting time and metal removal rate (MRR) are developed in Chapter 26

FIGURE 20-9 (a) Basics of the shaping process, including equations for cutting time (*Tm*) and metal removal rate (MRR). (b) The relationship of the crank rpm *Ns* to the cutting velocity *V*.





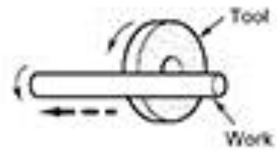
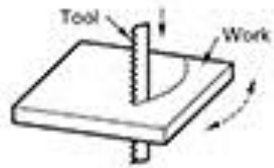
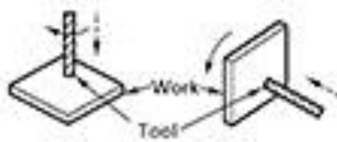
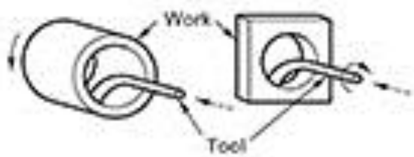
Operation	Block diagram	Most commonly used machines	Machines less frequently used	Machines seldom used
Turning		Lathe NC lathe machining center	Boring mill	Turret lathe
Grinding		Cylindrical grinder		Lathe (with special attachment)
Sawing (of plates and sheets)		Contour or band saw	Laser Flame cutting Plasma arc	
Drilling		Drill press Machining center (nc) Vert. milling machine	Lathe Horizontal boring machine	Horizontal milling machine Boring mill
Boring		Lathe Boring mill Horizontal boring machine Machining center		Milling machine Drill press

FIGURE 20-10 Operations and machines used for machining cylindrical surfaces.

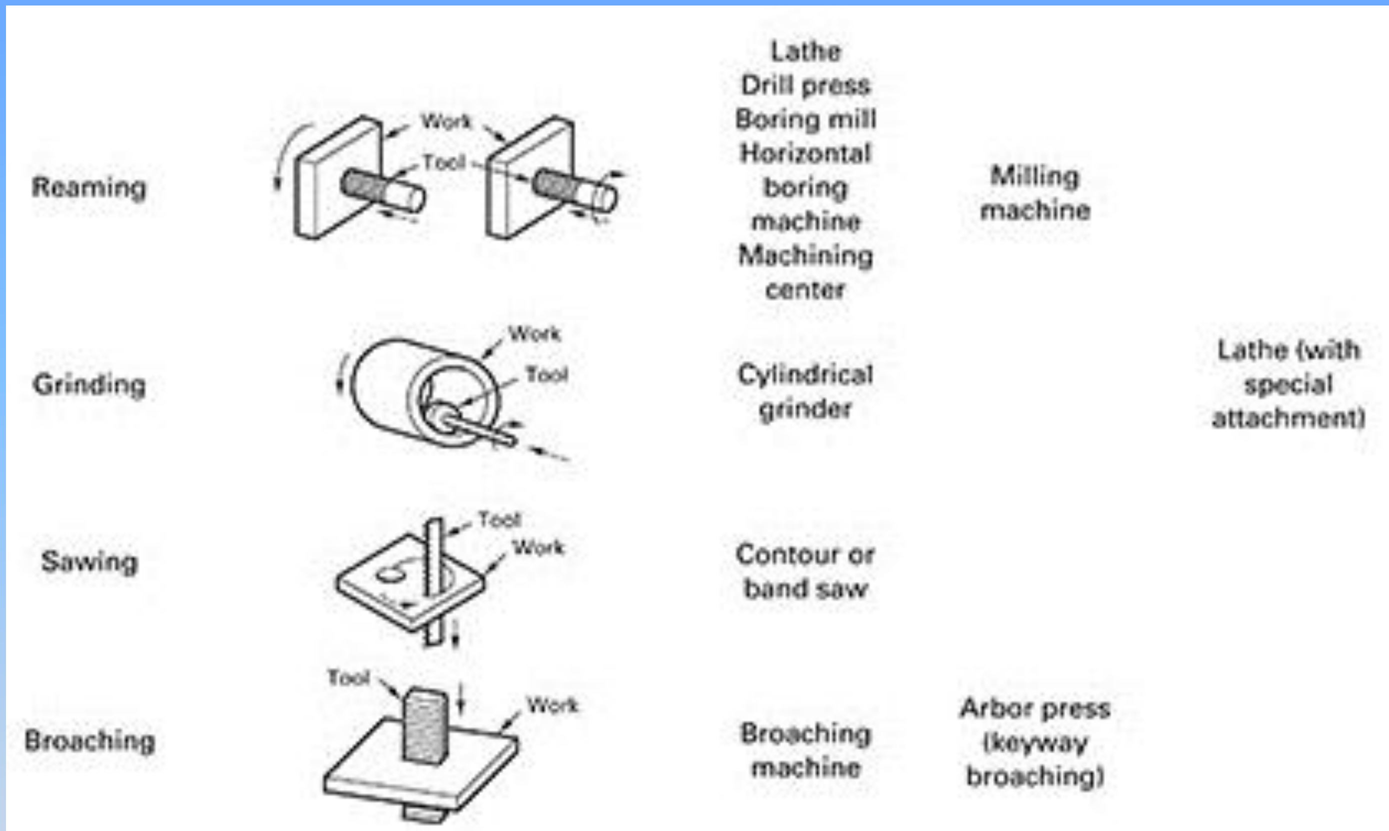


FIGURE 20-10 Operations and machines used for machining cylindrical surfaces.

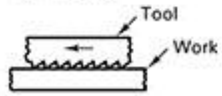
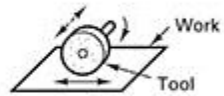
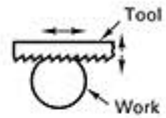
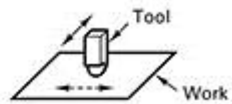
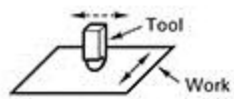
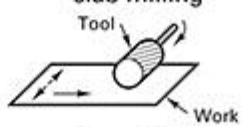
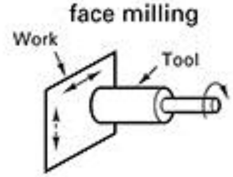
Operation	Block diagram	Most commonly used machines	Machines less frequently used	Machines seldom used
Facing		Lathe	Boring mill	
Broaching		Broaching machine		Turret broach
Grinding		Surface grinder		Lathe (with special attachment)
Sawing		Cutoff saw	Contour saw	
Shaping		Horizontal shaper	Vertical shaper	
Planing		Planer		
Milling	slab milling 	Milling machine	Lathe with special milling tools	
	face milling 	Milling machine Machining center	Lathe with special milling tools	Drill press (light cuts)

FIGURE 20-11 Operations and machines used to generate flat surfaces.

20.3 Energy and Power in Machining

TABLE 20-2 Basic Machining Process

Applicable Process	Raw Material Form	Size: Maximum	Size: Minimum	Typical Production Rate	Material Choice	Typical Tolerance	Typical Surface Roughness
Turning (engine lathes)	Cylinders, preforms, castings, forgings	78 in. dia. × 73 in. long	[illegible] in. typical	1–10 parts/hour	All ferrous and nonferrous material considered machinable	±0.002 in. on dia. common; ±0.001 in. obtainable	125–250
Turning (CNC)	Bar, rod, tube, preforms	36 in. dia. × 93 in. long	[illegible] in. dia.	1–2 parts/minute to 1–4 parts/hour	Any material with good machinability rating	±0.001 in. on dia. where needed; ±0.0005 in. possible	63 or better
Turning (automatic screw machine)	Bar, rod	Generally 2 in. dia. × 6 in. long	[illegible] in. dia. and less, weight less than 1 ounce	10–30 parts/minute	Any material with good machinability rating ±0.001 to ±0.003 in.	±0.0005 in. possible ±0.001 to ±0.003 in. common	63 average
Turning (Swiss automatic machining)	Rod	Collets adapt to [illegible] in. dia.	Collets adapt to less than [illegible] in.	12–30 parts/minute	Any material with good machinability rating	±0.0002 in. to ±0.001 in. common	63 and better
Boring (vertical)	Casting, preforms	98 in. × 72 in.	2 in. × 12 in.	2–20 hours/piece	All ferrous and nonferrous	±0.0005 in.	90–250
Milling	Bar, plate, rod, tube	4–6 ft long	Limited usually by ability to hold part	1–100 parts/hour	Any material with good machinability rating	±0.0005 in. possible; ±0.001 in. common	63–250
Hobbing (milling gears)	Blanks, preforms, rods	10-ft-dia. gears 14-in. face width	0.100 in. dia.	1 part/minute	Any material with good machinability rating	±0.001 in. or better	63
Drilling	Plate, bar, preforms	3[illegible]-in.-dia. drills (1-in.-dia. normal)	0.002-in. drill dia.	2-20 second/hole after setup	Any unhardened material; carbides needed for some case-hardened parts	±0.002–±0.010 in. common; ±0.001 in. possible	63–250
Sawing	Bar, plate, sheet	2-in. armor plate [illegible] in. is preferred)	0.010 in. thick	3–30 parts/hour	Any nonhardened material;	±0.015 in. possible	250–1000
Broaching	Tube, rod, bar, plate	74 in. long	1 in.	300–400 parts/minute	Any material with good machinability rating	±0.0005–±0.001 in.	32–125
Grinding	Plate, rod, bars	36 in. wide × 7 in. dia.	0.020 in. dia.	1–1000 pieces/hour	Nearly all metallic materials plus many nonmetallic	0.0001 in. and less	16
Shaping	Bar, plate, casting	3 ft × 6 ft	Limited usually by ability to hold part	1–4 parts/hour	Low-to medium-carbon steels and nonferrous metals best; no hardened parts	±0.001–±0.002 in. (larger parts) ±0.0001–±0.0005 in. (small-medium parts)	63–250
Planing	Bar, plate, casting	42 ft wide × 18 ft high × 76 ft long	Parts too large for shaper work	1 part/hour	Low- to medium-carbon steels or nonferrous materials best	±0.001–±0.005 in.	63–125
Gear shaping	Blanks	120-in.-dia. gears 6-in. face width	1 in. dia.	1–60 parts/hour	Any material with good machinability rating	±0.001 in. or better at 200 D.P. to 0.0065 in. at 30 D.P.	63

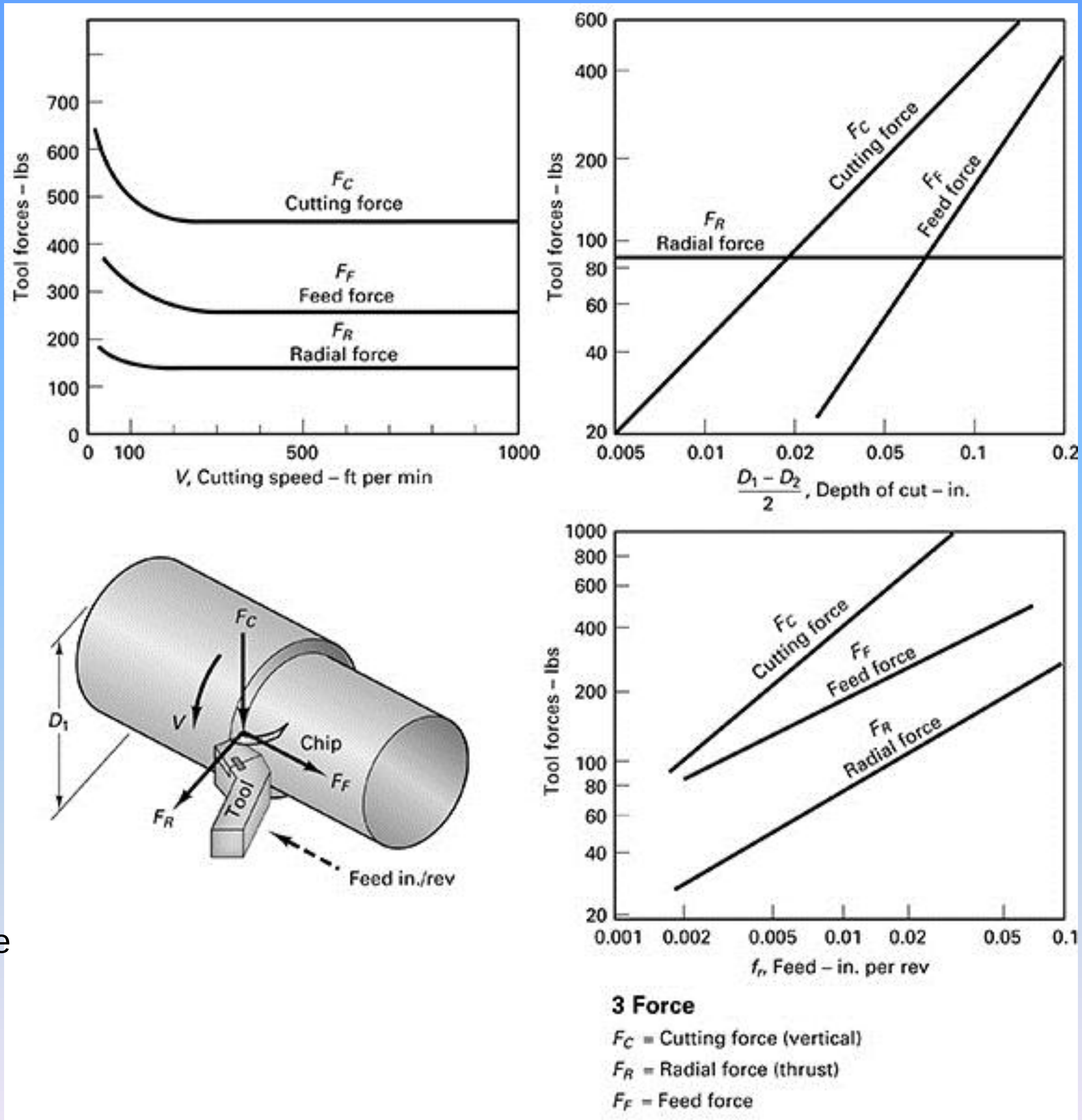


FIGURE 20-12 Oblique machining has three measurable components of forces acting on the tool. The forces vary with speed, depth of cut, and feed.

TABLE 20-3 Values for Unit Power and Specific Energy (cutting stiffness)

Material		Unit Power (hp-min. in.^{3}) HP_s	Specific Energy (in.-lb/in.^{3}) K_s or U	Hardness Brinell HB
Nonalloy carbon steel	C 0.15%	.58	268,000	125
	C 0.35%	.58	302,400	150
	C 0.60%	.75	324,800	200
Alloy steel	Annealed	.50	302,400	180
	Hardened and tempered	0.83	358,400	275
	Hardened and tempered	0.87	392,000	300
	Hardened and tempered	1.0	425,000	350
High-alloy steel	Annealed	0.83	369,000	200
	Hardened	1.2	560,000	325
Stainless steel, annealed	Martensitic/ferritic	0.75	324,800	200
Steel castings	Nonalloy	0.62	257,000	180
	Low-alloy	0.67	302,000	200
	High-alloy	0.80	336,000	225
Stainless steel, annealed	Austenitic	0.73	369,600	180
Heat-resistant alloys	Annealed	0.78		200
	Aged—Iron based	—		280
	Annealed—Nickel or cobalt	1.10		250
	Aged	1.20		350
Hard steel	Hardened steel	1.4	638,400	55 HRC
	Manganese steel 12%	1.0	515,200	250
Malleable iron	Ferritic	0.42	156,800	130
	Pearlitic	—	257,600	230
Cast iron, low tensile		0.62	156,800	180
Cast iron, high tensile		0.80	212,800	260
Nodular SG iron	Ferritic	0.55	156,800	160
	Pearlitic	0.76	257,600	250
Chilled cast iron		—	492,800	400
Aluminum alloys	Non-heat-treatable	.25	67,200	60
	Heat-treatable	.33	100,800	100
Aluminum alloys (cast)	Non-heat-treatable	.25	112,000	75
	Heat-treatable	.33	123,200	90
Bronze-brass alloys	Lead alloys, Pb>1%	.25	100,800	110
	Brass, cartridge brass	1.8–2.0	112,000	90
	Bronze and lead-free copper	0.33–0.83		
	Includes Electrolytic copper	0.90	246,400	100
Zinc alloy	Diecast	0.25	—	—
Titanium		.034	250-275	

Values assume normal feed ranges and sharp tools. Multiply values by 1.25 for a dull tool.

Calculation of unit power (HP_s)

$HP = F_c V/33000$

$HP_s = HP/MRR$ Where

$MRR = 12 V t w c$ for tube turning

$HP_s = F_c V/12 V t w c \times 33000 = F_c/t w c \times 396000$

Calculation of specific energy (U)

$U = F_c V/V t w c = F_c/t w c$ for tube turning

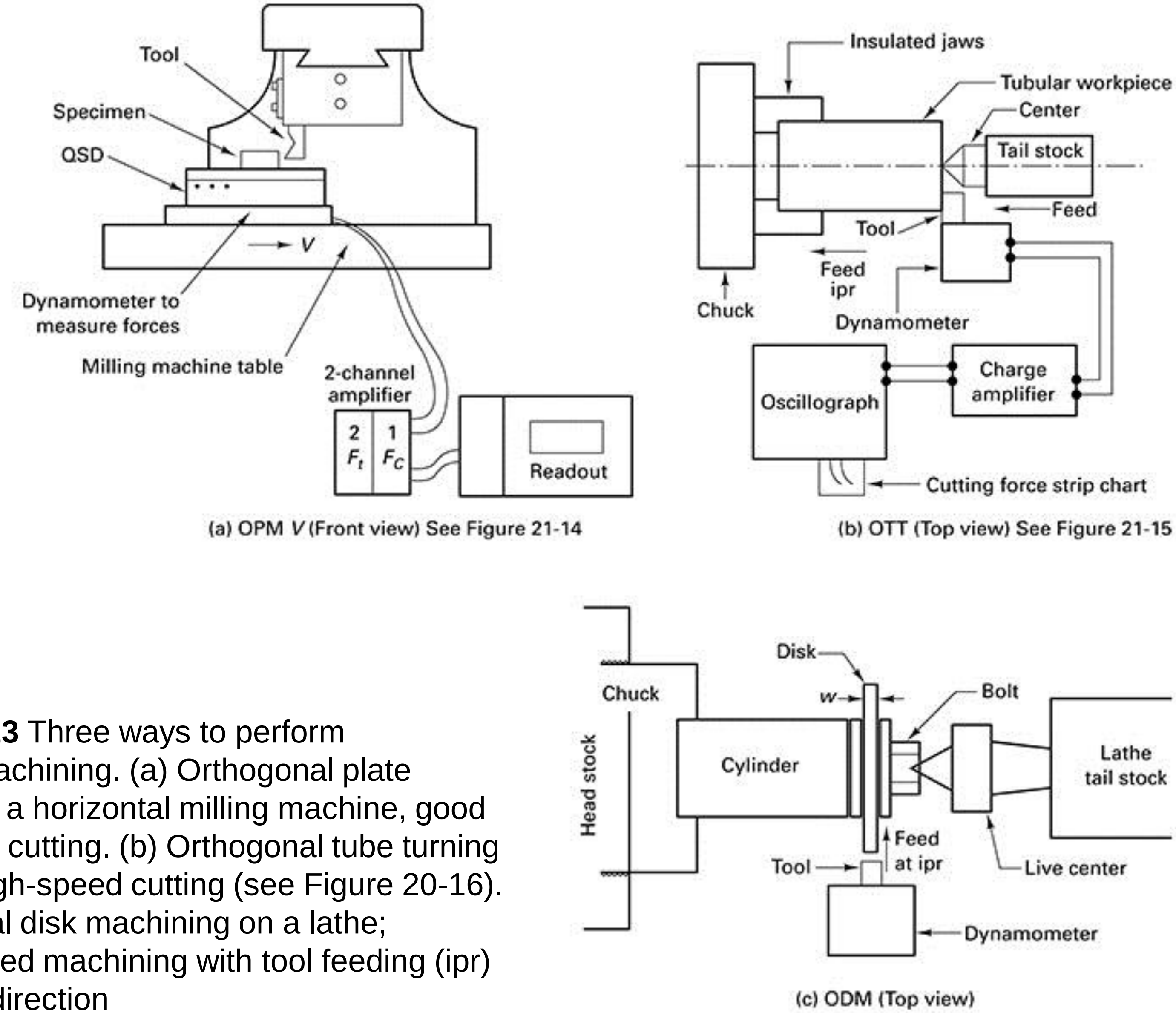


FIGURE 20-13 Three ways to perform orthogonal machining. (a) Orthogonal plate machining on a horizontal milling machine, good for low-speed cutting. (b) Orthogonal tube turning on a lathe; high-speed cutting (see Figure 20-16). (c) Orthogonal disk machining on a lathe; very high-speed machining with tool feeding (ipr) in the facing direction

20.4 Orthogonal Machining (Two Forces)

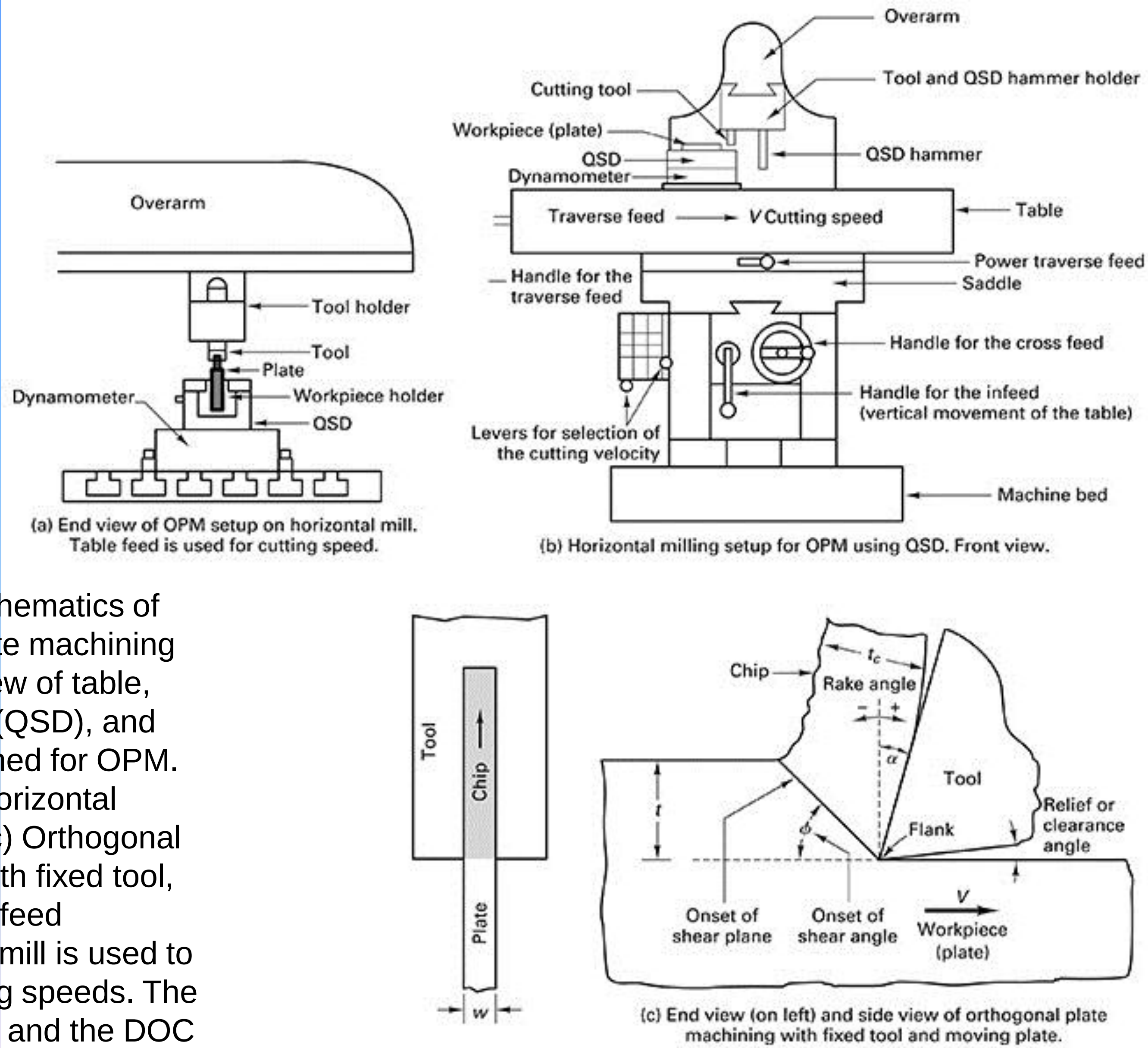


FIGURE 20-14 Schematics of the orthogonal plate machining setups. (a) End view of table, quick-stop device (QSD), and plate being machined for OPM. (b) Front view of horizontal milling machine. (c) Orthogonal plate machining with fixed tool, moving plate. The feed mechanism of the mill is used to produce low cutting speeds. The feed of the tool is *t* and the DOC is *w*, the width of the plate.

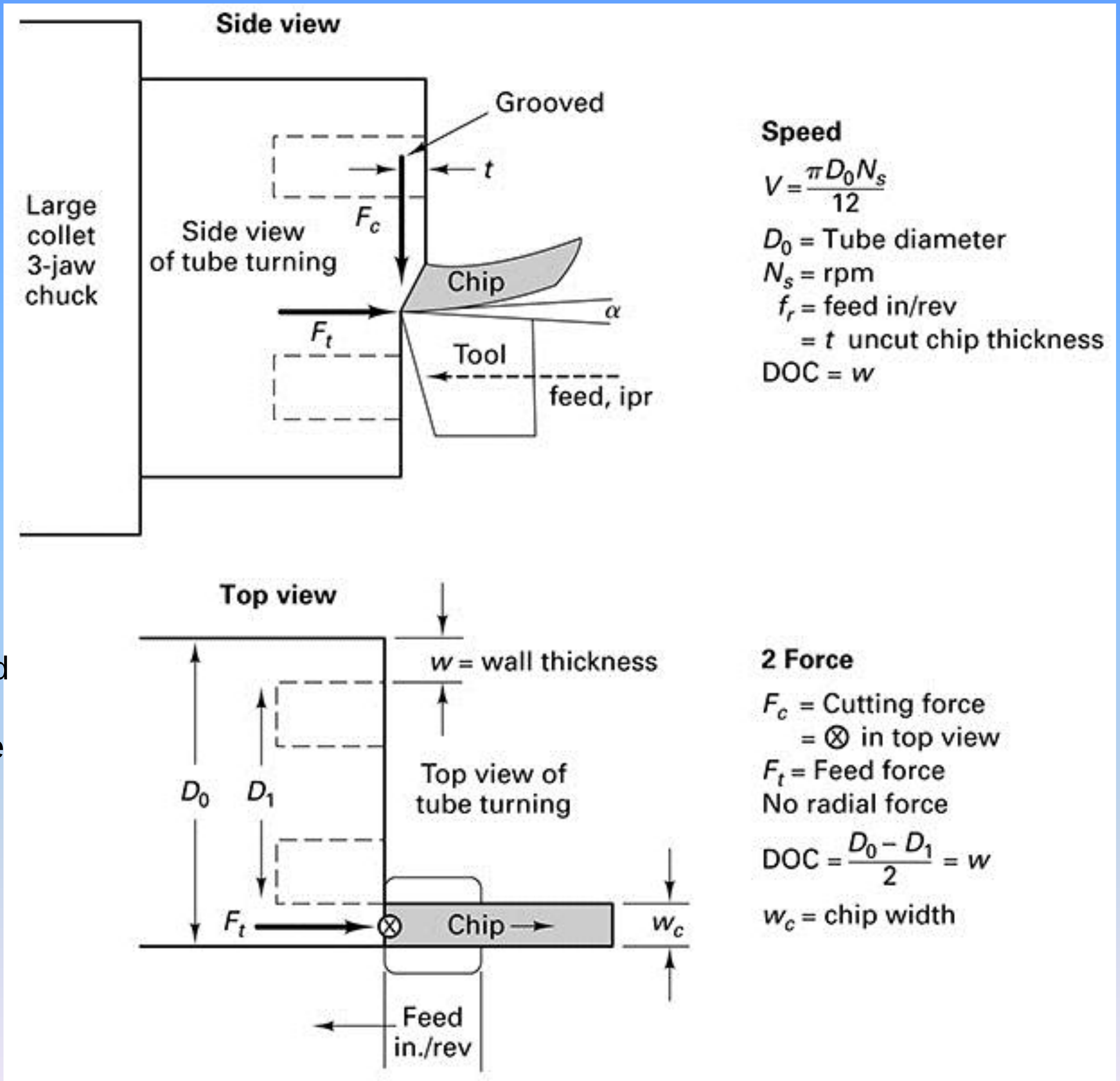


FIGURE 20-15 Orthogonal tube turning (OTT) produces a two-force cutting operation at speeds equivalent to those used in most oblique machining operations. The slight difference in cutting speed between the inside and outside edge of the chip can be neglected.

FIGURE 20-16 Videograph made from the orthogonal plate machining process.

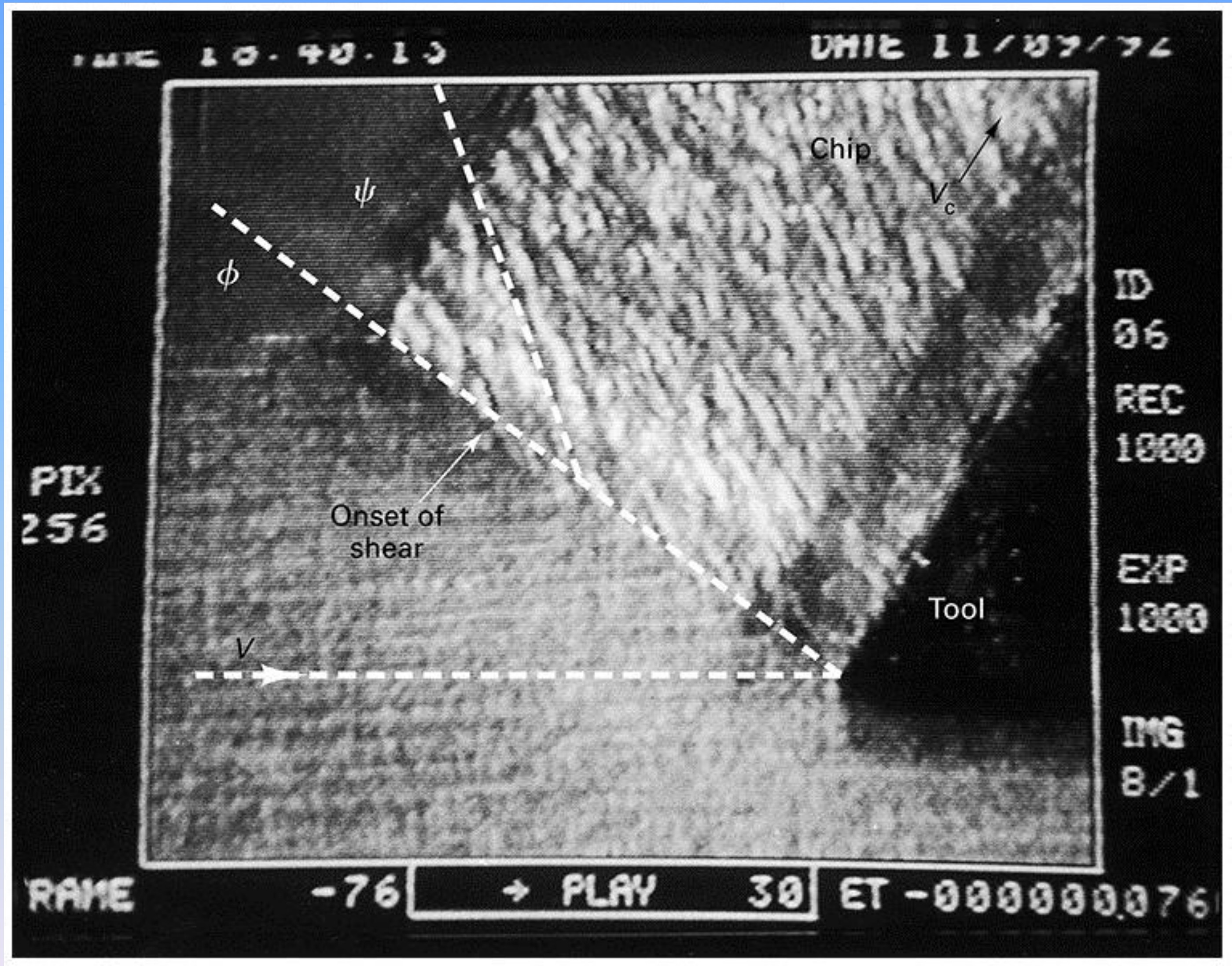
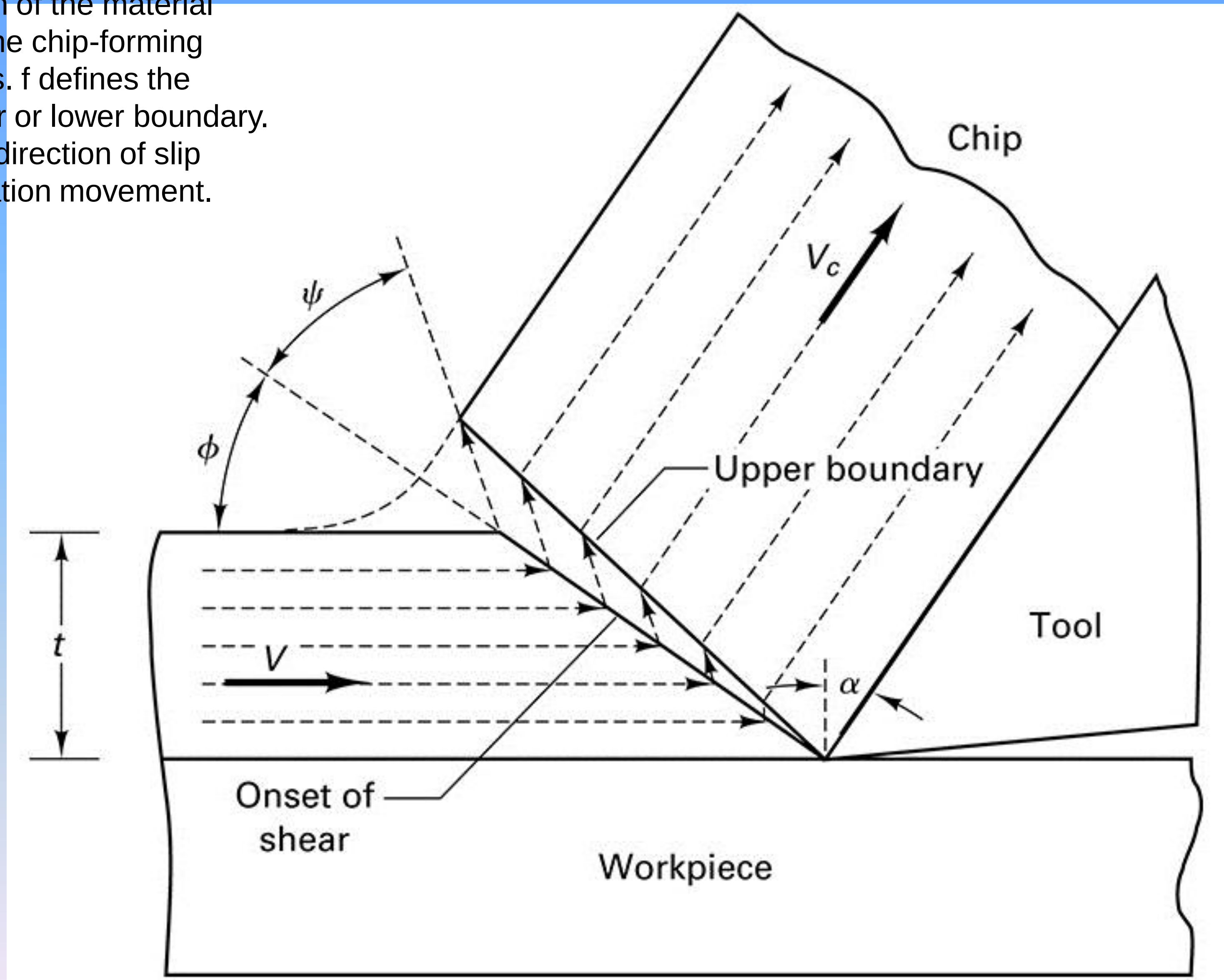


FIGURE 20-17 Schematic representation of the material flow, that is, the chip-forming shear process. f defines the onset of shear or lower boundary. c defines the direction of slip due to dislocation movement.



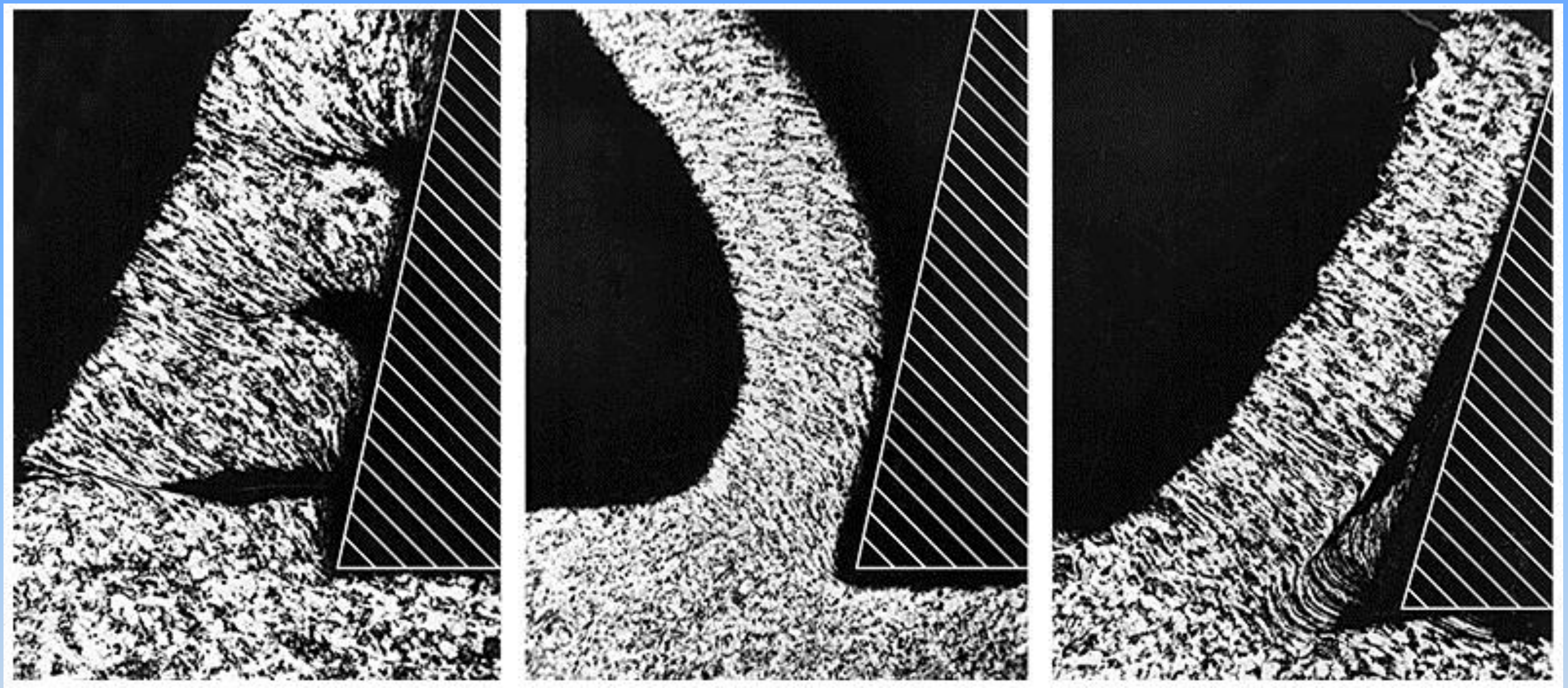


FIGURE 20-18 Three characteristic types of chips. (Left to right) Discontinuous, continuous, and continuous with built-up edge. Chip samples produced by quick-stop technique. *(Courtesy of Eugene Merchant (deceased) at Cincinnati Milacron, Inc., Ohio.)*

20.5 Merchant's Model

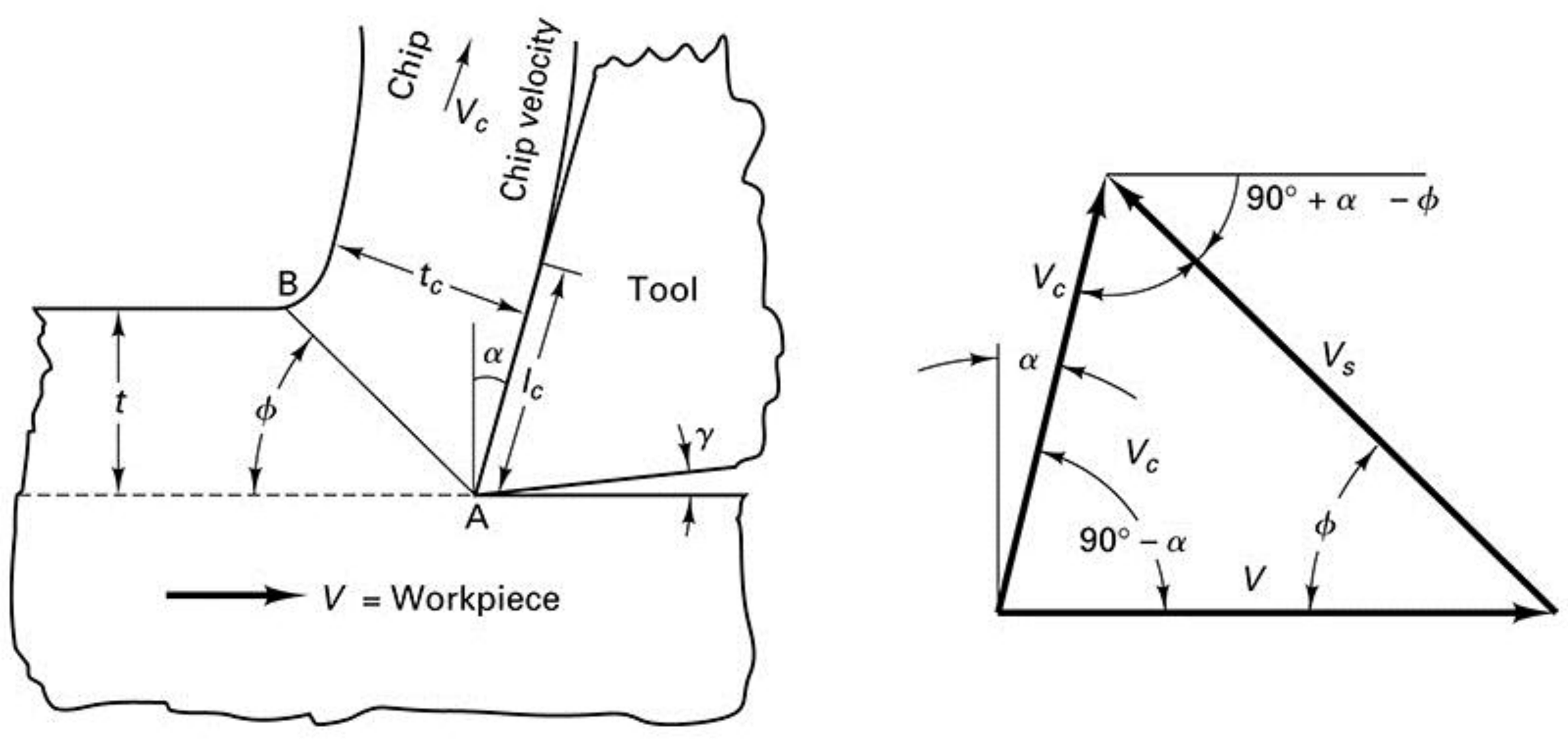


FIGURE 20-19 Velocity diagram associated with Merchant's orthogonal machining model.

20.6 Mechanics of Machining (Statics)

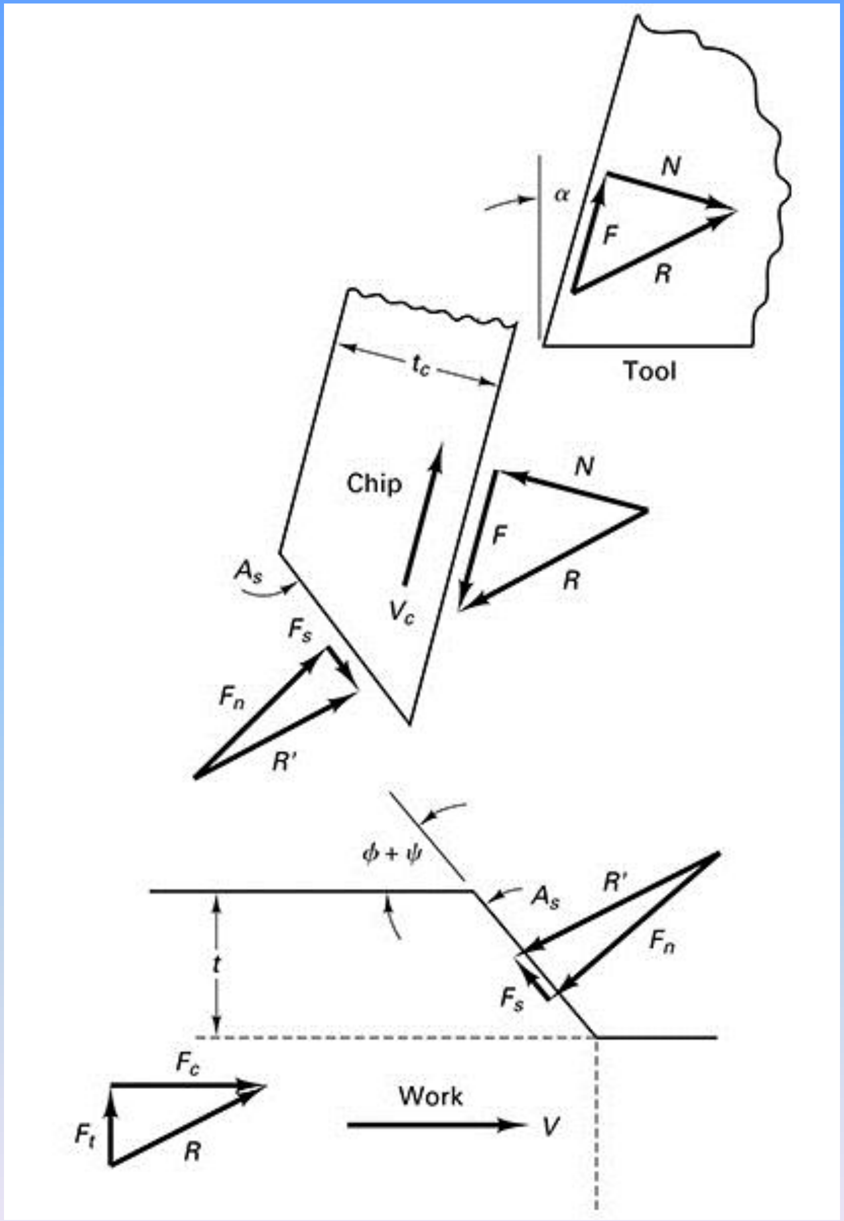


FIGURE 20-20 Free-body diagram of orthogonal chip formation process, showing equilibrium condition between resultant forces *R* and *R*.

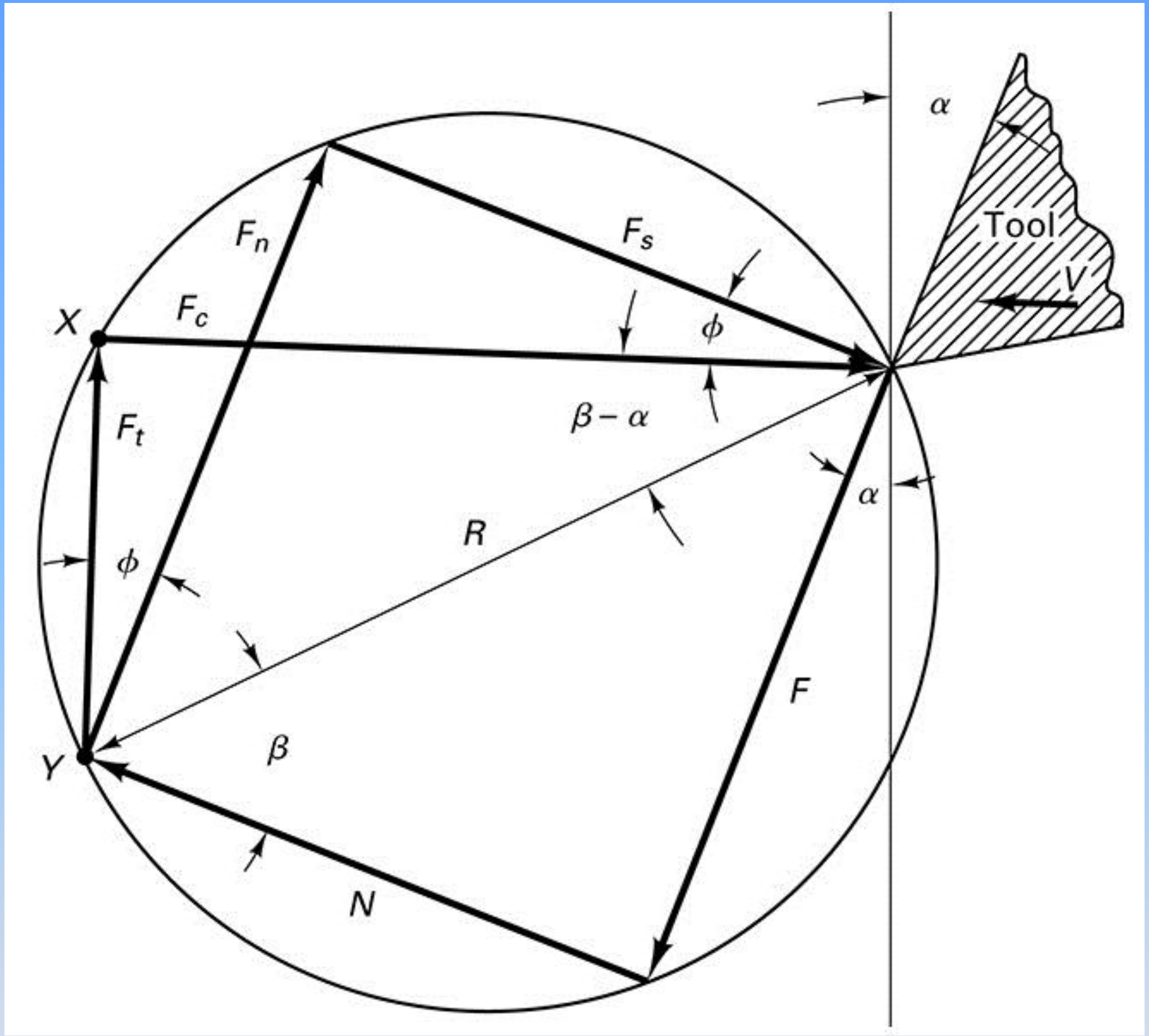


FIGURE 20-21 Merchant's circular force diagram used to derive equations for *Fs* , *Fr* , *Ft* , and *N* as functions of *Fc, Fr* , f, a, and b.

20.7 Shear Strain and Shear Front Angle

FIGURE 20-22 Shear stress ts variation with the Brinell hardness number for a group of steels and aerospace alloys. Data of some selected fcc metals are also included. *(Adapted with permission from S. Ramalingham and K. J. Trigger,* Advances in Machine Tool Design and Research, *1971, Pergamon Press.)*

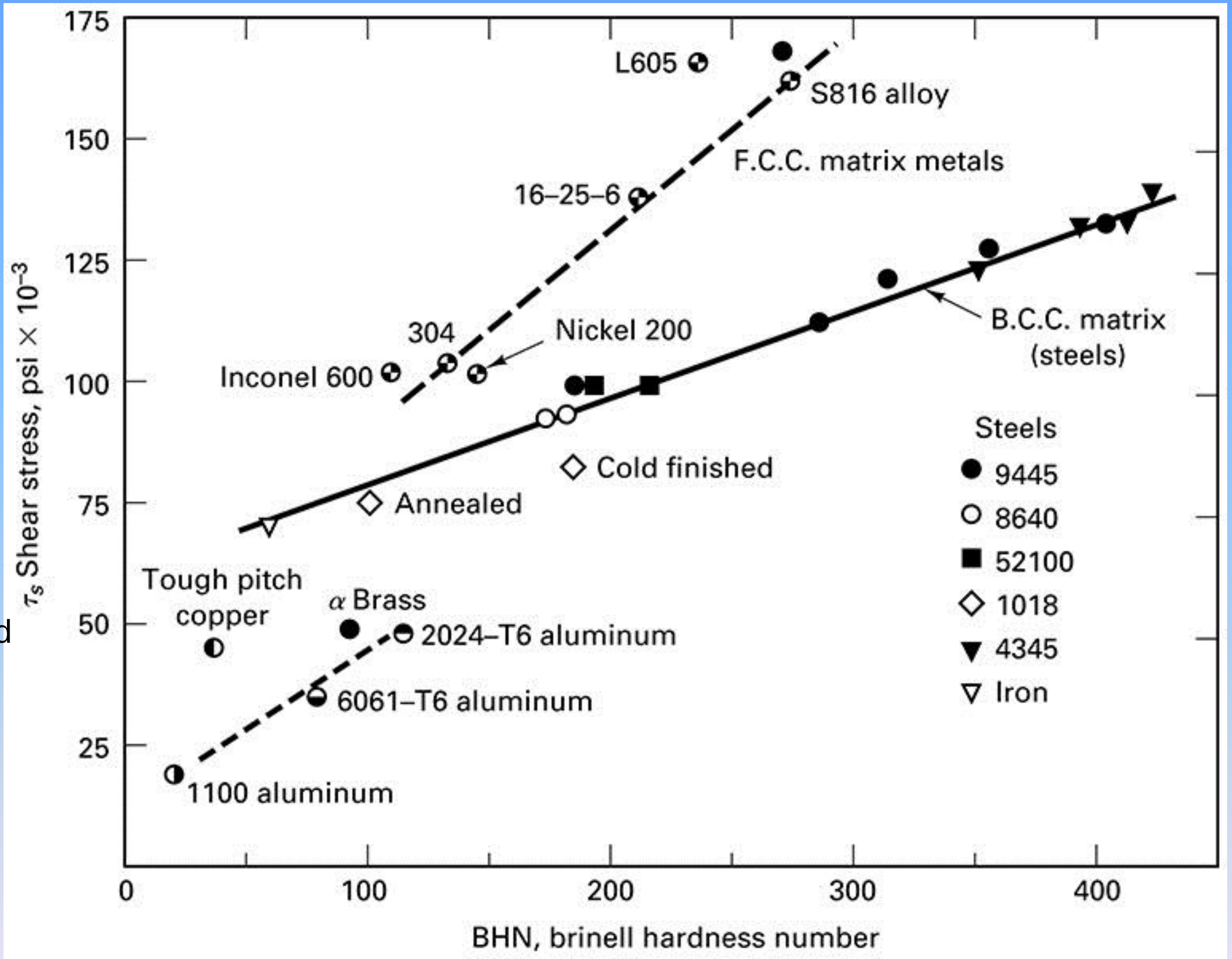
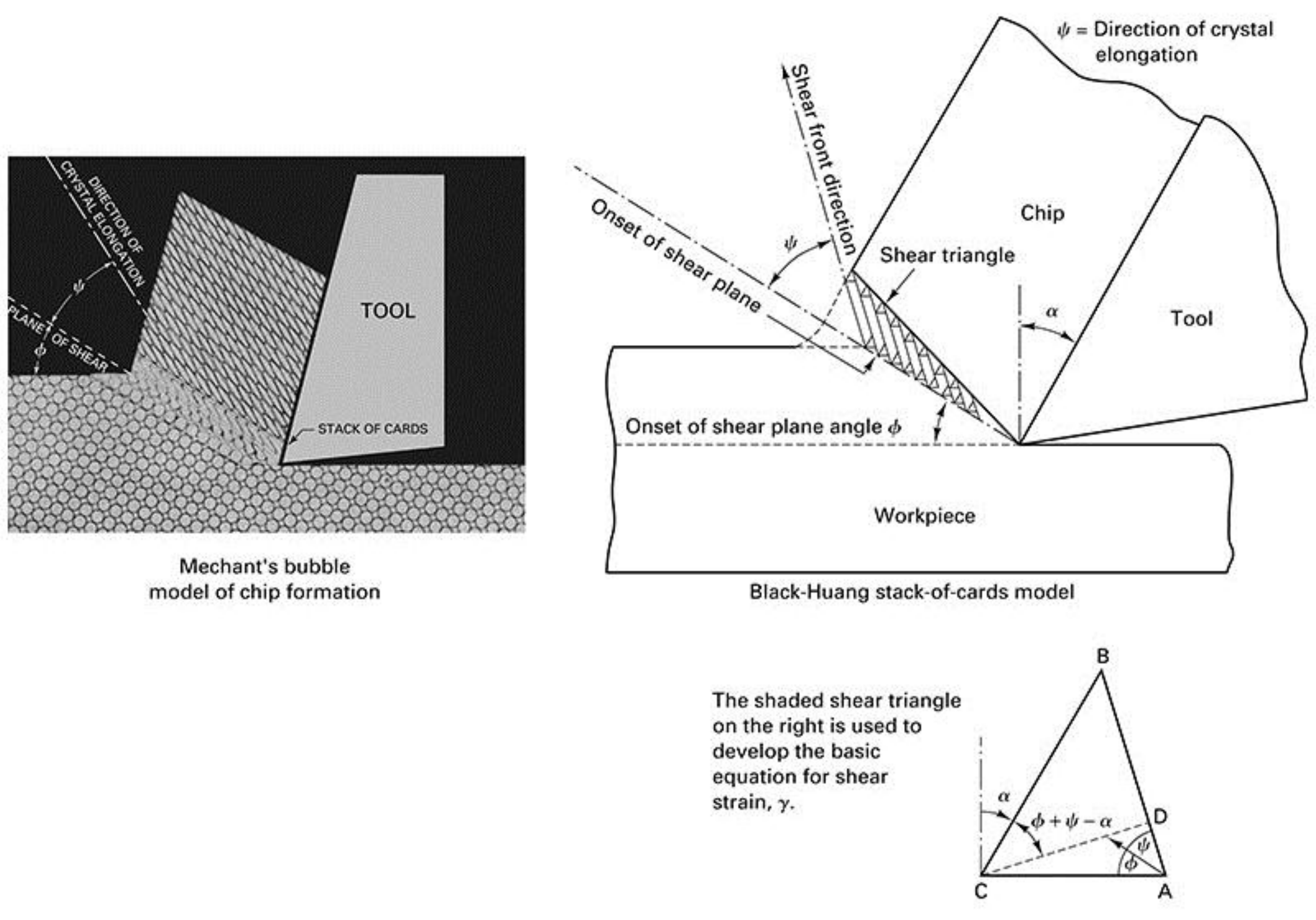


FIGURE 20-23 The Black–Huang “stack-of-cards” model for calculating shear strain in metal cutting is based on Merchant’s bubble model for chip formation, shown on the left.



Veljko Samardzic

20.8 Mechanics of Machining (Dynamics)

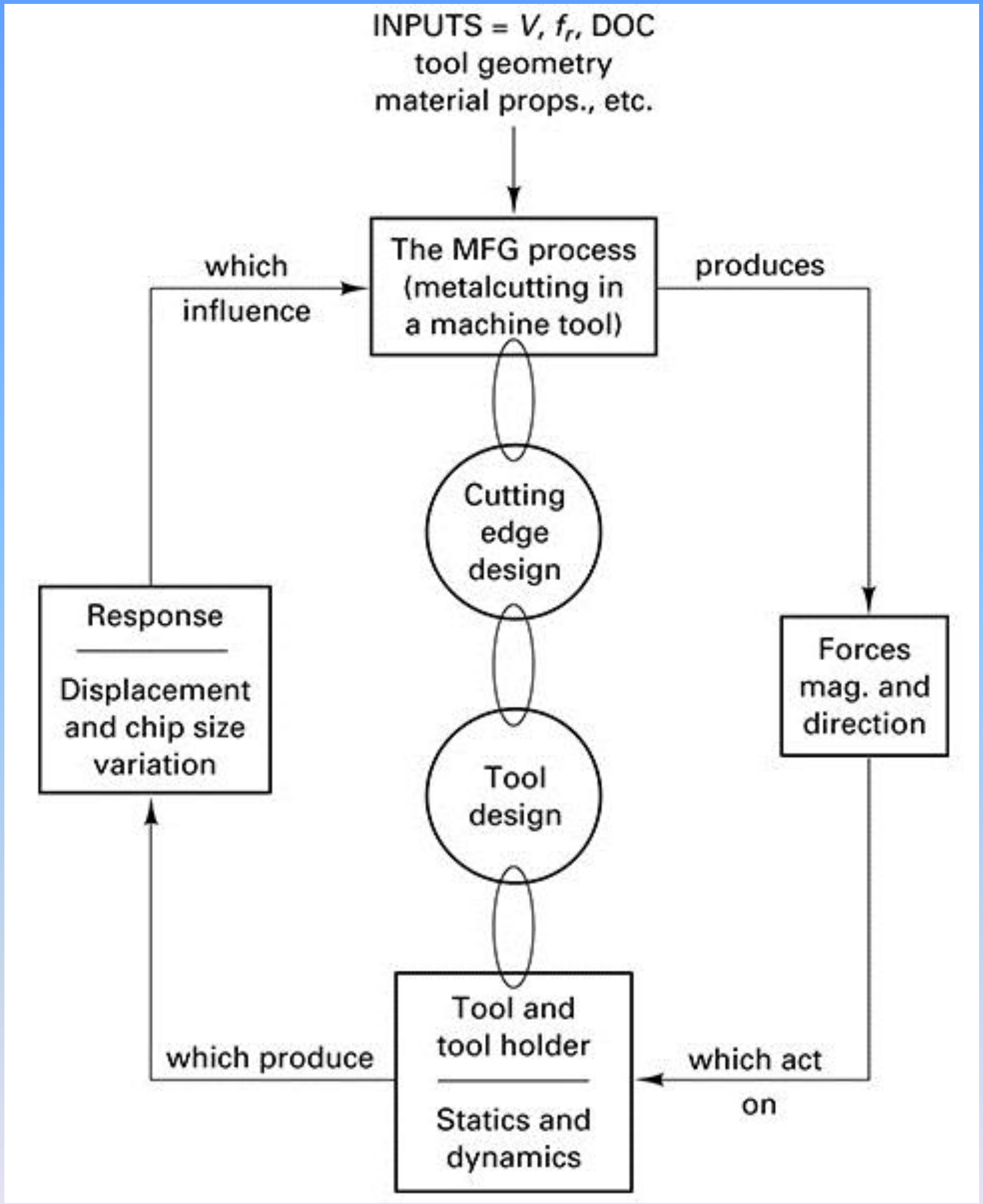
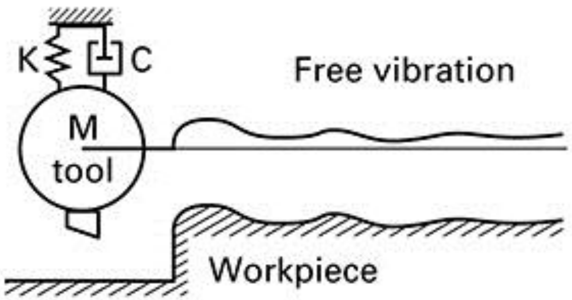
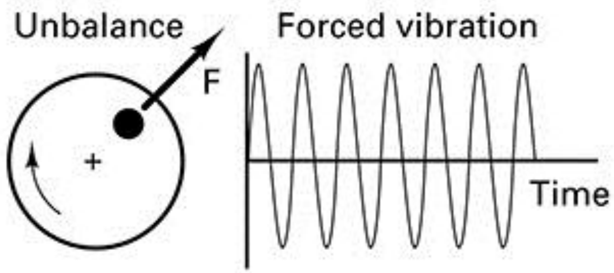


FIGURE 20-24 Machining dynamics is a closed-loop interactive process that creates a force-displacement response.

• **Free Vibration** The response to an initial condition or sudden change. The amplitude of the vibration decreases with time and occurs at the natural frequency of the system often produced by interrupted machining. Often appears as lines or shadows following a surface discontinuity.



• **Forced Vibration** The response to a periodic (repeating with time) input. The response and input occur at the same frequency. The amplitude of the vibration remains constant for a set input condition and is nonlinearly related to speed. Unbalance, misalignment, tooth impacts, and resonance of rotating systems are the most common examples.



• **Self-Excited Vibration** The periodic response of the system to a constant input. The vibration may grow in amplitude (unstable) and occurs near the natural frequency of the system regardless of the input. Chatter due to the regeneration of surface waviness is the most common metal cutting example.

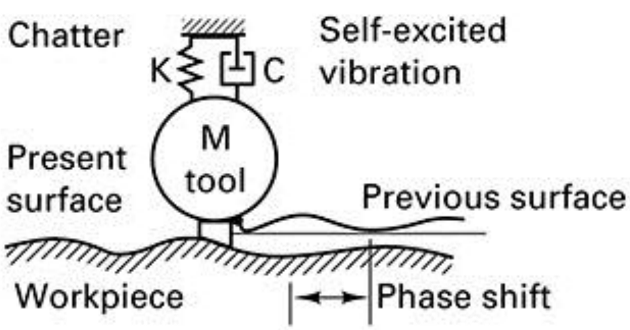


FIGURE 20-25 There are three types of vibration in machining.

FIGURE 20-26 Some examples of chatter that are visible on the surfaces of the workpiece.

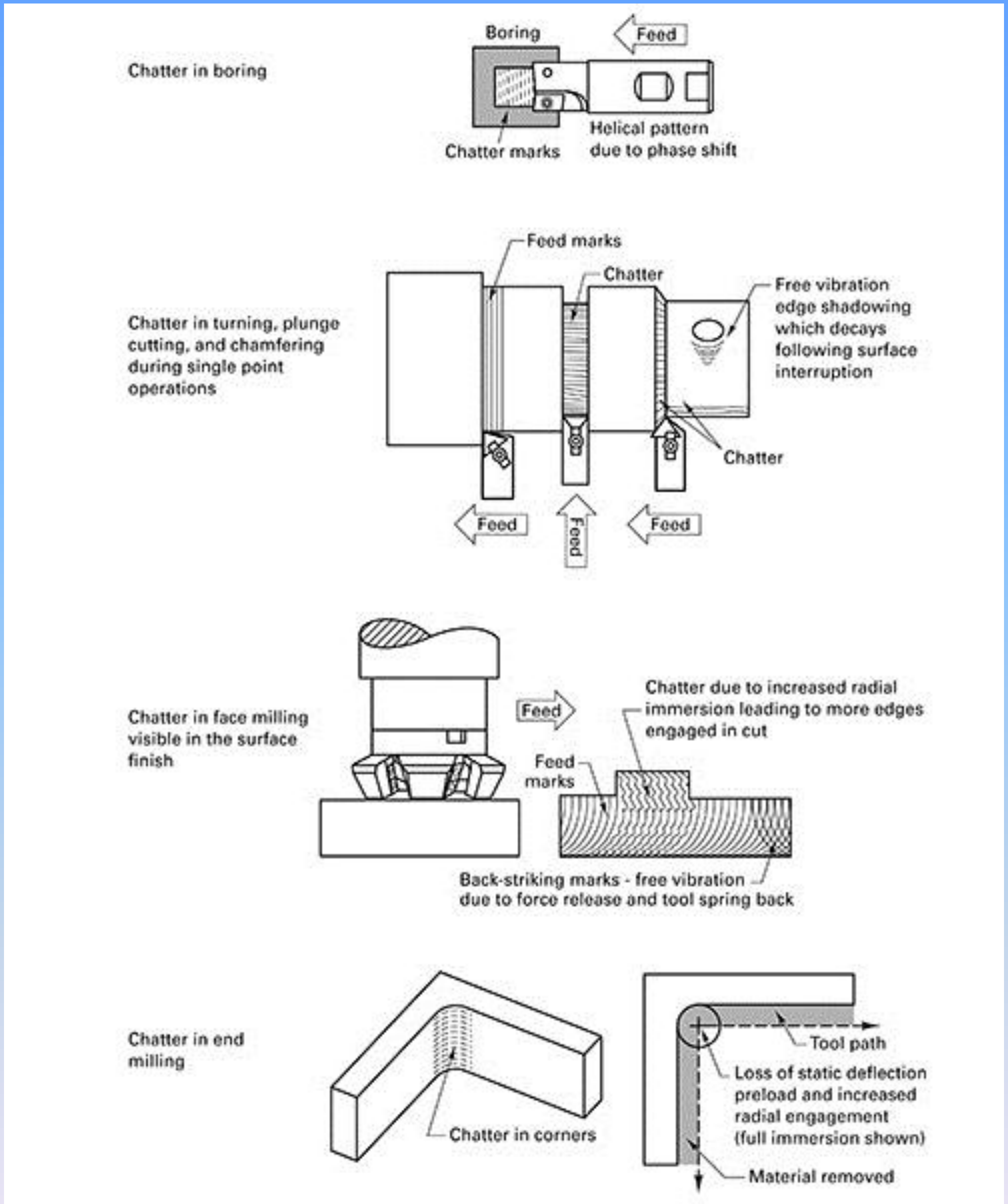
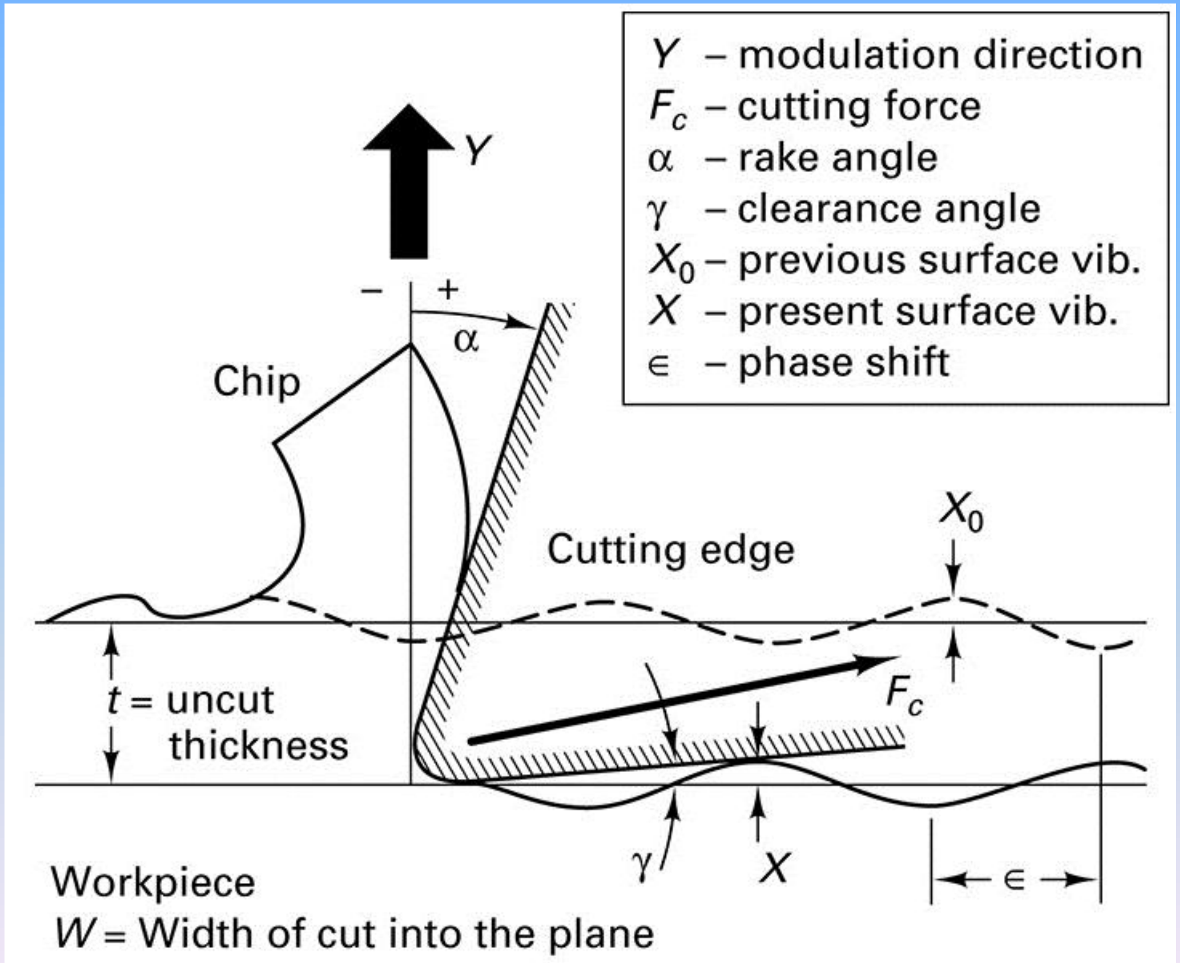


FIGURE 20-27 When the overlapping cuts get out of phase with each other, a variable chip thickness is produced, resulting in a change in *Fc* on the tool or workpiece.



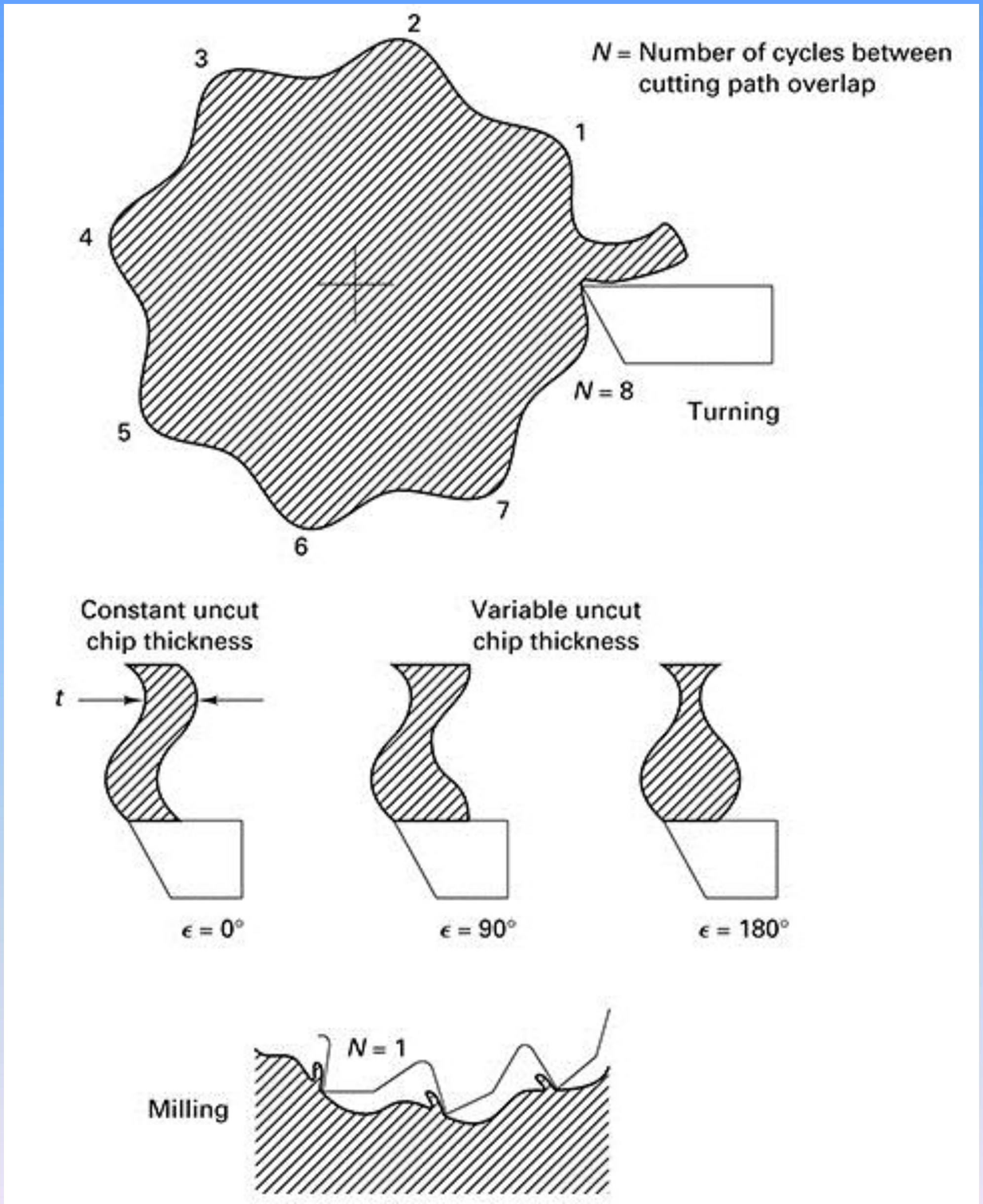


FIGURE 20-28 Regenerative chatter in turning and milling produced by variable uncut chip thickness.

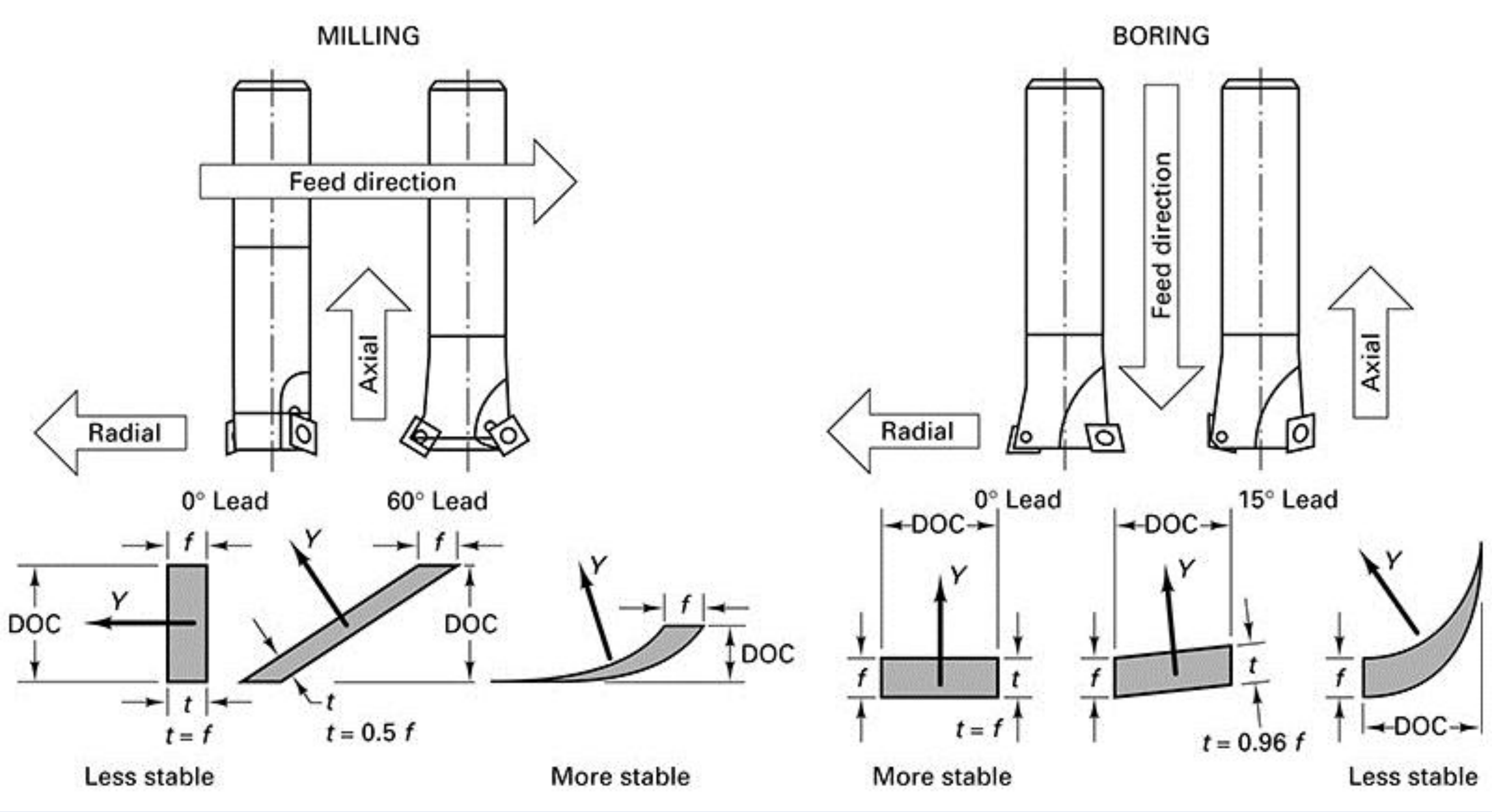
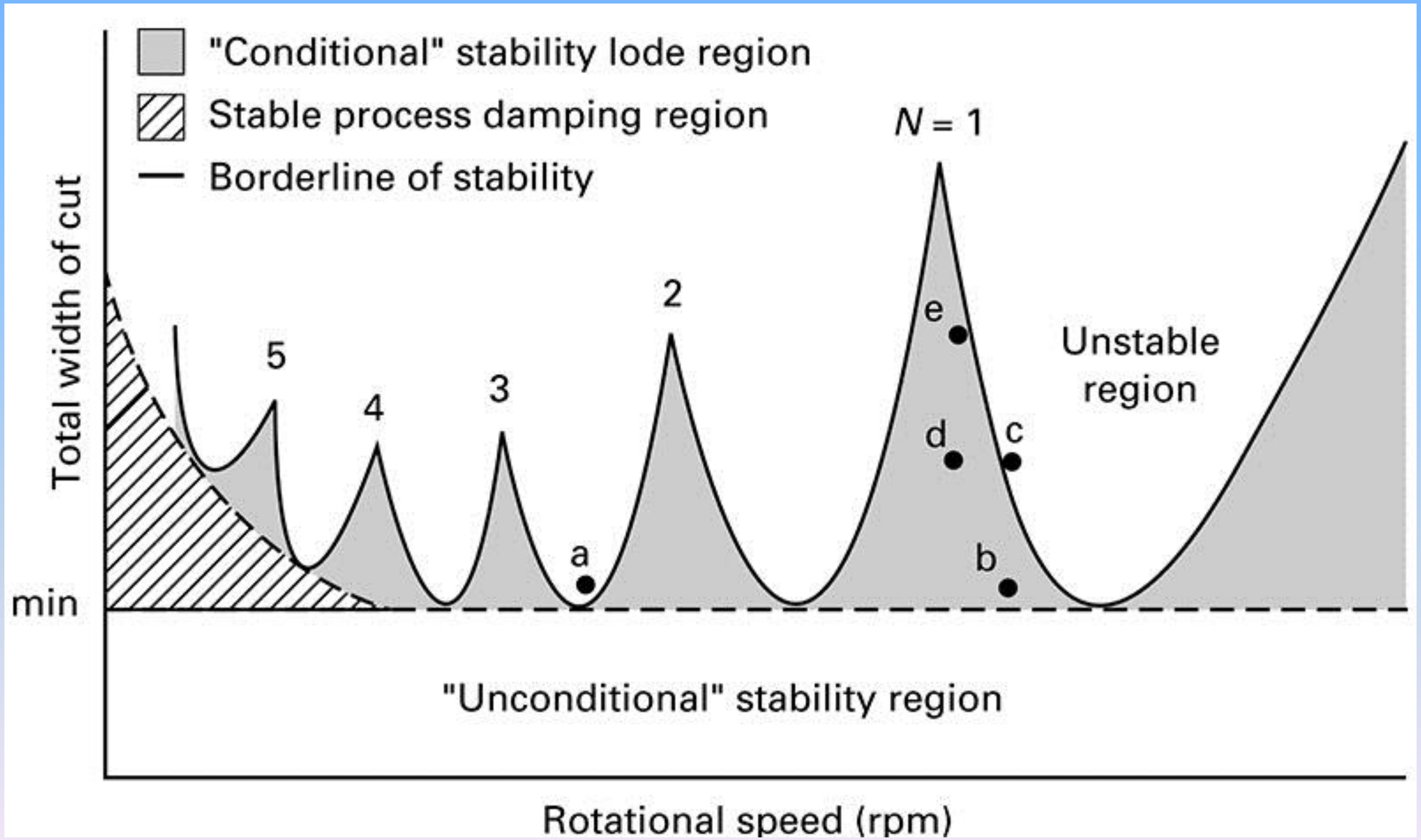


FIGURE 20-29 Milling and boring operations can be made more stable by correct selection of insert geometry.

FIGURE 20-30 Dynamic analysis of the cutting process produces a stability lobe diagram, which defines speeds that produce stable and unstable cutting conditions.



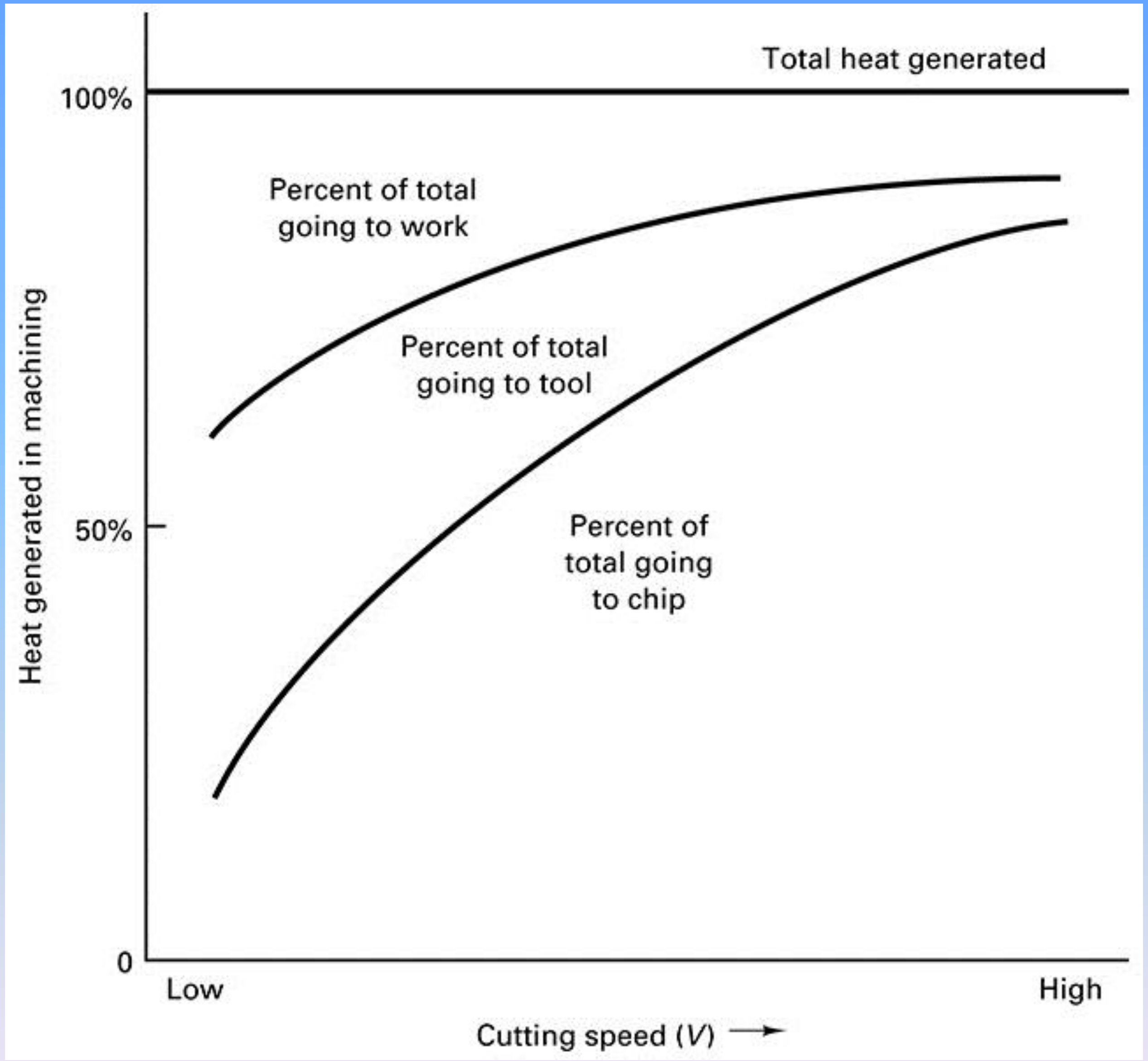


FIGURE 20-31 Distribution of heat generated in machining to the chip, tool, and workpiece. Heat going to the environment is not shown. Figure based on the work of A. O. Schmidt.

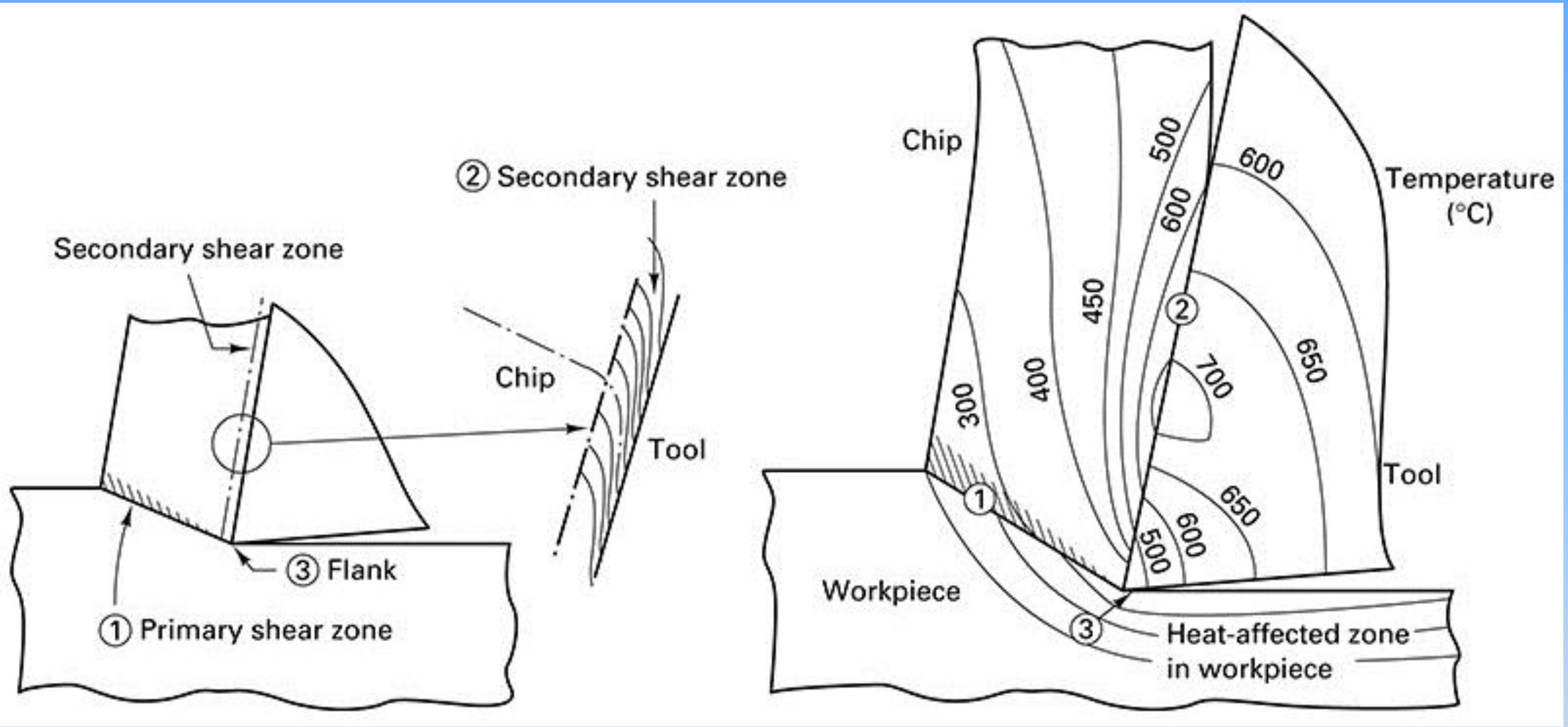


FIGURE 20-32 There are three main sources of heat in metal cutting. (1) Primary shear zone. (2) Secondary shear zone tool–chip (T–C) interface. (3) Tool flank. The peak temperature occurs at the center of the interface, in the shaded region.

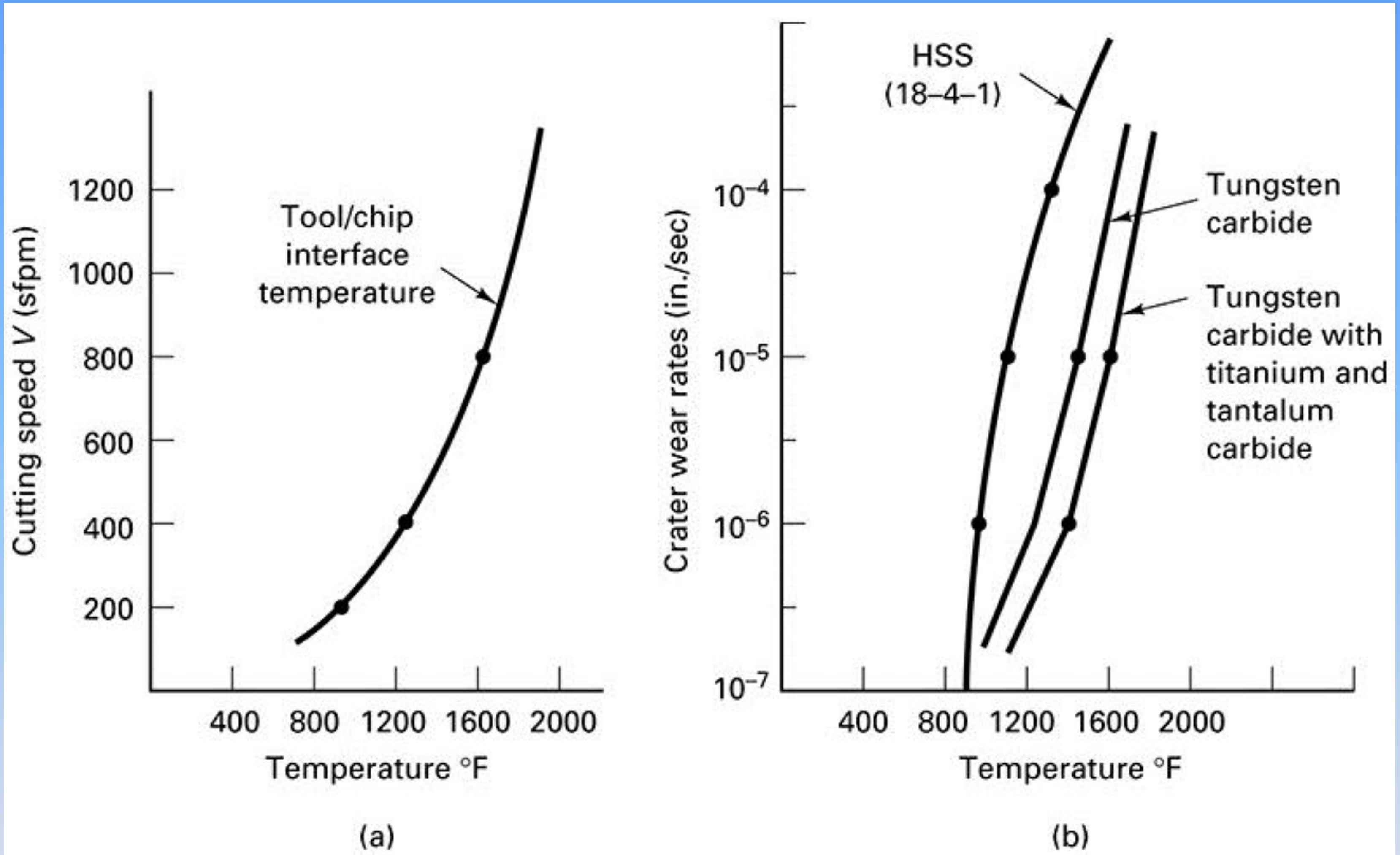


FIGURE 20-33 The typical relationship of temperature at the tool–chip interface to cutting speed shows a rapid increase. Correspondingly, the tool wears at the interface rapidly with increased temperature, often created by increased speed.

20.9 Summary