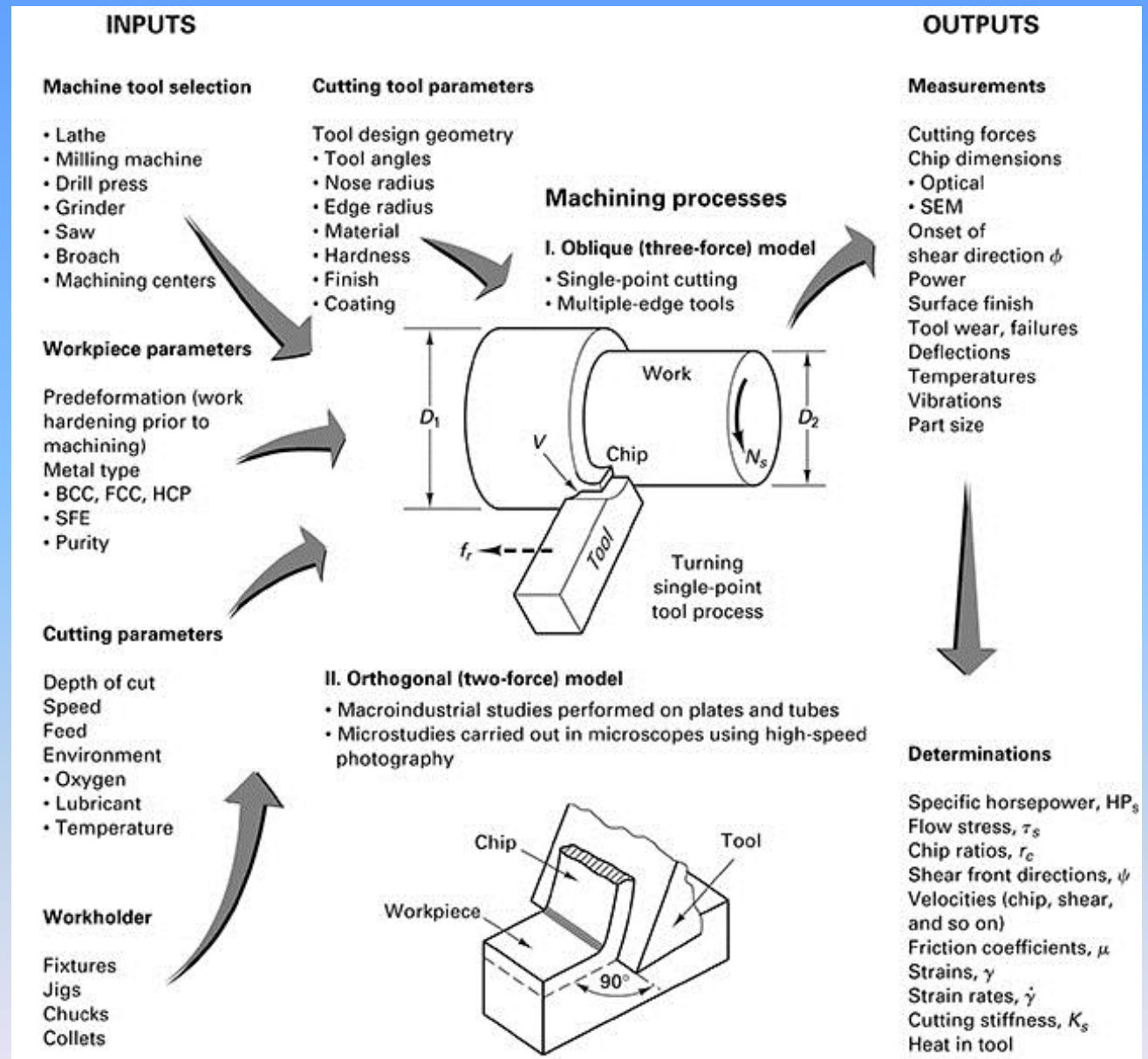


# Fundamentals of Machining/Orthogonal Machining

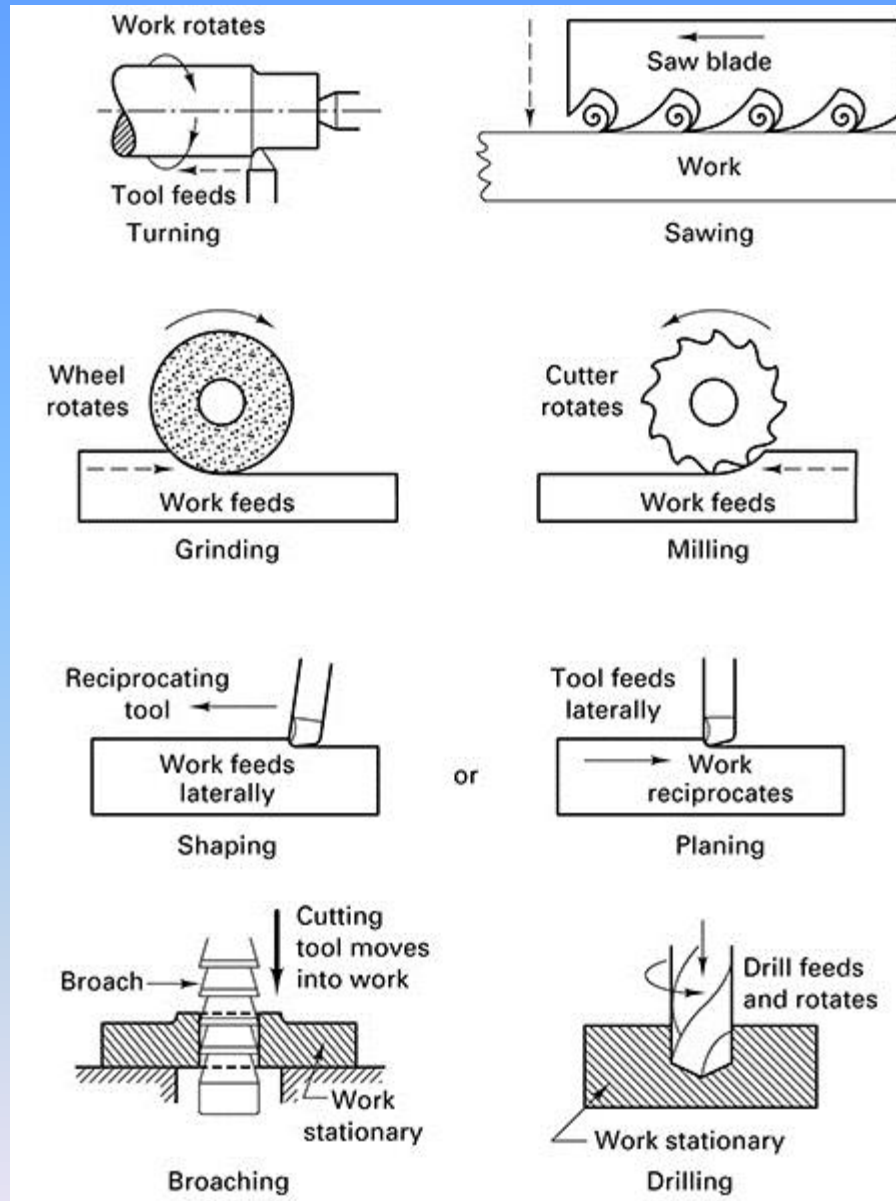
## Chapter 20

# 20.1 Introduction



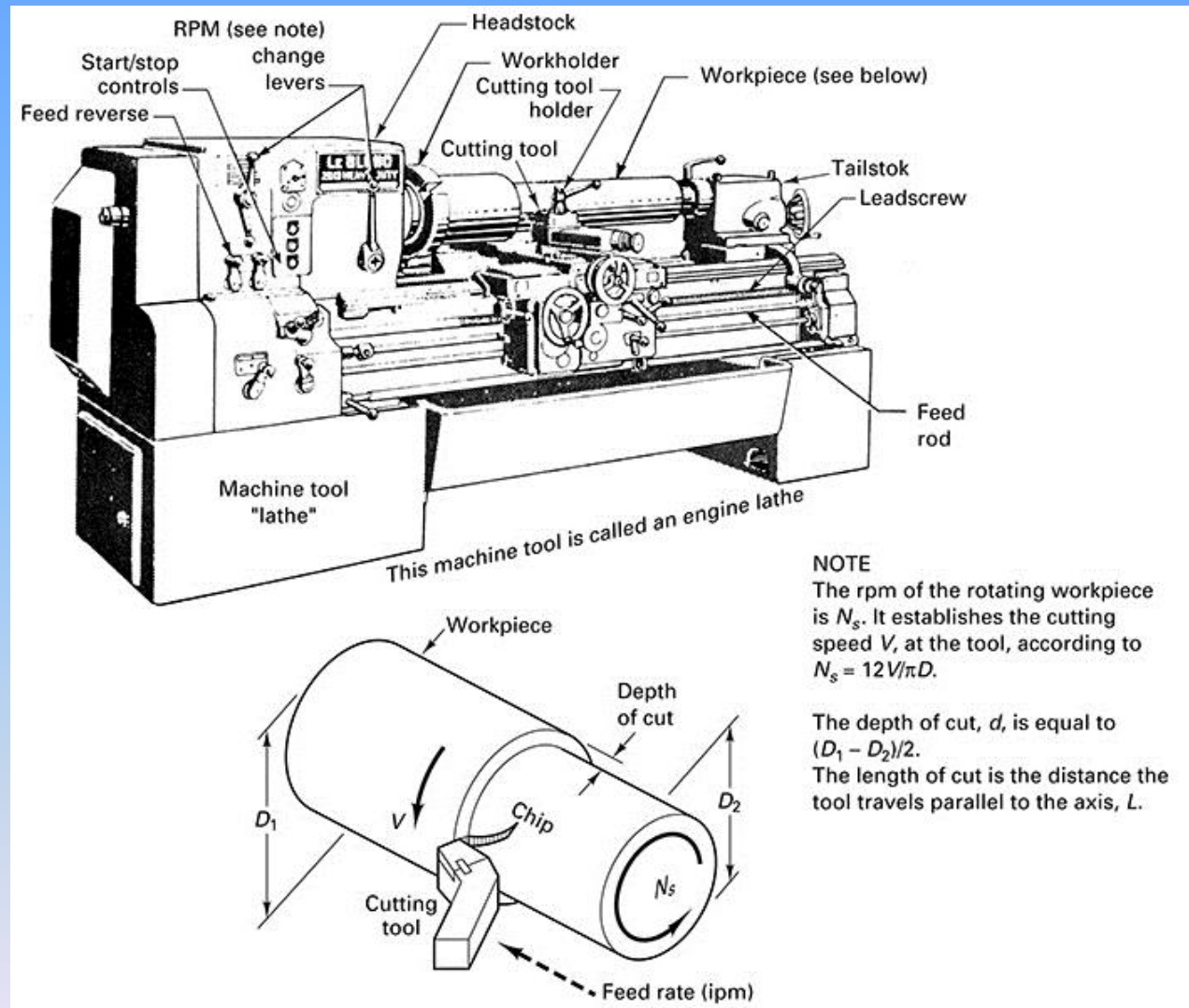
**FIGURE 20-1** The fundamental inputs and outputs to machining processes.

# 20.2 Fundamentals



**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   | Hard-<br>ness    | Condition                  | Depth<br>of<br>Cut*<br>in<br>mm | High Speed Steel<br>Tool   |                      |                                 | Carbide Tool          |                |      |                                       |        |      |                                       |       |
|--|------------------|----------------------------|---------------------------------|----------------------------|----------------------|---------------------------------|-----------------------|----------------|------|---------------------------------------|--------|------|---------------------------------------|-------|
|  |                  |                            |                                 | Speed                      | Feed                 | Tool<br>Material<br>AISI<br>ISO | Uncoated              |                | Feed | Tool<br>Material<br>Grade<br>C<br>ISO | Coated |      | Tool<br>Material<br>Grade<br>C<br>ISO |       |
|  |                  |                            |                                 |                            |                      |                                 | Speed                 |                |      |                                       | Speed  | Feed |                                       |       |
|  |                  |                            |                                 |                            |                      |                                 | Brazed                | Index-<br>able |      |                                       |        |      |                                       | Speed |
| lpm<br>m <sub>3</sub> /min   | ipr<br>mm/r      | lpm<br>m <sub>3</sub> /min | ipr<br>mm/r                     | lpm<br>m <sub>3</sub> /min | ipr<br>mm/r          | lpm<br>m <sub>3</sub> /min      | ipr<br>mm/r           |                |      |                                       |        |      |                                       |       |
| <b>L FREE MACHINING<br/>CARBON STEELS,<br/>WROUGHT (cont.)<br/>Medium Carbon<br/>Leaded<br/>(cont.)<br/>(materials listed<br/>on preceding page)</b> | 225              | Hot Rolled,                | .040                            | 160                        | .008                 | M2, M3                          | 500                   | 600            | .007 | C-7                                   | 925    | .007 | CC-7                                  |       |
|  |                  | Normalized,                | .150                            | 125                        | .015                 | M2, M3                          | 390                   | 480            | .020 | C-6                                   | 600    | .015 | CC-6                                  |       |
|  |                  | Annealed,                  | .300                            | 100                        | .020                 | M2, M3                          | 310                   | 375            | .030 | C-6                                   | 500    | .020 | CC-6                                  |       |
|  |                  | Cold Drawn                 | .625                            | 80                         | .030                 | M2, M3                          | 240                   | 290            | .040 | C-6                                   | —      | —    | —                                     |       |
|  |                  | or                         | 1                               | 49                         | .20                  | S4, S5                          | 150                   | 185            | .18  | P10                                   | 250    | .18  | CP10                                  |       |
|  |                  | Quenched                   | 4                               | 38                         | .40                  | S4, S5                          | 120                   | 145            | .50  | P20                                   | 185    | .40  | CP20                                  |       |
|  | 275              | and                        | 8                               | 30                         | .50                  | S4, S5                          | 95                    | 115            | .75  | P30                                   | 150    | .50  | CP30                                  |       |
|  |                  | Tempered                   | 16                              | 24                         | .75                  | S4, S5                          | 75                    | 88             | 1.0  | P40                                   | —      | —    | —                                     |       |
|  |                  | 275<br>to<br>325           | Hot<br>Rolled,                  | .040                       | 135                  | .007                            | T15, M42 <sup>†</sup> | 460            | 545  | .007                                  | C-7    | 825  | .007                                  | CC-7  |
|  |                  |                            | Normalized,                     | .150                       | 105                  | .015                            | T15, M42 <sup>†</sup> | 350            | 425  | .020                                  | C-6    | 525  | .015                                  | CC-6  |
|  |                  |                            | Normalized,                     | .300                       | 85                   | .020                            | T15, M42 <sup>†</sup> | 275            | 380  | .030                                  | C-6    | 425  | .020                                  | CC-6  |
|  |                  |                            | Annealed                        | .625                       | —                    | —                               | —                     | —              | —    | —                                     | —      | —    | —                                     | —     |
|  | or               |                            | 1                               | 41                         | .18                  | S9, S11 <sup>†</sup>            | 140                   | 165            | .18  | P10                                   | 250    | .18  | CP10                                  |       |
|  | Quenched         |                            | 4                               | 32                         | .40                  | S9, S11 <sup>†</sup>            | 105                   | 130            | .50  | P20                                   | 160    | .40  | CP20                                  |       |
|  | 325<br>to<br>375 | and                        | 8                               | 26                         | .50                  | S9, S11 <sup>†</sup>            | 84                    | 100            | .75  | P30                                   | 130    | .50  | CP30                                  |       |
|  |                  | Tempered                   | 16                              | —                          | —                    | —                               | —                     | —              | —    | —                                     | —      | —    | —                                     |       |
|  |                  | 325<br>to<br>375           | Quenched                        | .040                       | 100                  | .007                            | T15, M42 <sup>†</sup> | 390            | 480  | .007                                  | C-7    | 725  | .007                                  | CC-7  |
|  |                  |                            | and                             | .150                       | 80                   | .015                            | T15, M42 <sup>†</sup> | 300            | 375  | .020                                  | C-6    | 475  | .015                                  | CC-6  |
|  |                  |                            | and                             | .300                       | 65                   | .020                            | T15, M42 <sup>†</sup> | 230            | 290  | .030                                  | C-6    | 375  | .020                                  | CC-6  |
|  |                  |                            | and                             | .625                       | —                    | —                               | —                     | —              | —    | —                                     | —      | —    | —                                     | —     |
|  | Tempered         |                            | 1                               | 30                         | .18                  | S9, S11 <sup>†</sup>            | 120                   | 145            | .18  | P10                                   | 220    | .18  | CP10                                  |       |
|  | Tempered         |                            | 4                               | 24                         | .40                  | S9, S11 <sup>†</sup>            | 90                    | 115            | .50  | P20                                   | 145    | .40  | CP20                                  |       |
|  | 375<br>to<br>425 | and                        | 8                               | 20                         | .50                  | S9, S11 <sup>†</sup>            | 70                    | 88             | .75  | P30                                   | 115    | .50  | CP30                                  |       |
|  |                  | and                        | 16                              | —                          | —                    | —                               | —                     | —              | —    | —                                     | —      | —    | —                                     |       |
| 375<br>to<br>425   |                  | Quenched                   | .040                            | 70                         | .007                 | T15, M42 <sup>†</sup>           | 325                   | 400            | .007 | C-7                                   | 600    | .007 | CC-7                                  |       |
|  |                  | and                        | .150                            | 55                         | .015                 | T15, M42 <sup>†</sup>           | 250                   | 310            | .020 | C-6                                   | 400    | .015 | CC-6                                  |       |
|  |                  | and                        | .300                            | 45                         | .020                 | T15, M42 <sup>†</sup>           | 200                   | 240            | .030 | C-6                                   | 325    | .020 | CC-6                                  |       |
|  |                  | and                        | .625                            | —                          | —                    | —                               | —                     | —              | —    | —                                     | —      | —    | —                                     |       |
|  | Tempered         | 1                          | 21                              | .18                        | S9, S11 <sup>†</sup> | 100                             | 120                   | .18            | P10  | 185                                   | .18    | CP10 |                                       |       |
|  | Tempered         | 4                          | 17                              | .40                        | S9, S11 <sup>†</sup> | 76                              | 95                    | .50            | P20  | 120                                   | .40    | CP20 |                                       |       |
| 425  | and              | 8                          | 14                              | .50                        | S9, S11 <sup>†</sup> | 60                              | 75                    | .75            | P30  | 100                                   | .50    | CP30 |                                       |       |
|  | and              | 16                         | —                               | —                          | —                    | —                               | —                     | —              | —    | —                                     | —      | —    |                                       |       |

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

|   |   |                           | 10                        | —    | —    | —      | —      | —   | —    | —    | —    | —    |      |      |
|---|---|---------------------------|---------------------------|------|------|--------|--------|-----|------|------|------|------|------|------|
| <b>2. CARBON STEELS,<br/>WROUGHT<br/>Low Carbon</b> | 85<br>to<br>125   | Hot Rolled,               | .040                      | 185  | .007 | M2, M3 | 535    | 700 | .007 | C-7  | 1080 | .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 |      |
|   |   | Normalized,               | .625                      | 90   | .030 | M2, M3 | 265    | 330 | .040 | C-6  | —    | —    | —    |      |
|   | 1005 1010 1020<br>1006 1012 1023<br>1008 1015 1025<br>1009 1017 | 125<br>to<br>175          | to Annealed or Cold Drawn | 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<br>to<br>175  | 175<br>to<br>225          | Hot Rolled,               | .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 |
|   |   |                           | Normalized,               | .625 | 80   | .030   | M2, M3 | 245 | 305  | .040 | C-6  | —    | —    | —    |
|   | 175<br>to<br>225  | 225<br>to<br>275          | to Annealed or Cold Drawn | 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<br>to<br>225                                    | 225<br>to<br>275  | Hot Rolled,               | .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 |      |
|   |   | Normalized,               | .625                      | 75   | .030 | M2, M3 | 235    | 265 | .040 | C-6  | —    | —    | —    |      |
| 225<br>to<br>275                                    | 275   | to Annealed or Cold Drawn | 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<br>to<br>275                                    | 275   | to 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 |      |
|   |   | Normalized,               | .625                      | 60   | .030 | M2, M3 | 220    | 240 | .040 | C-6  | —    | —    | —    |      |
| 225<br>to<br>275                                    | 275   | to Annealed or Cold Drawn | 1                         | 38   | .18  | S4, S5 | 125    | 155 | .18  | P10  | 250  | .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.

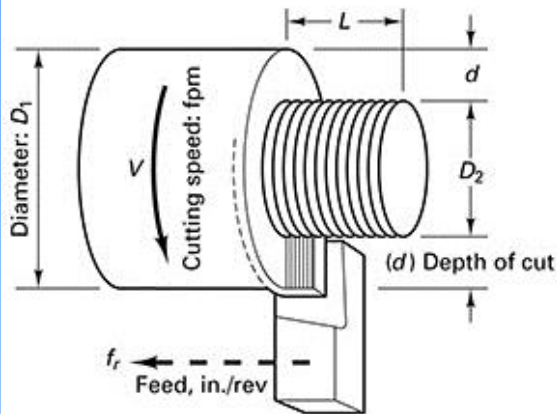
\*Caution: Check Horsepower requirements on heavier depths of cut.

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.)

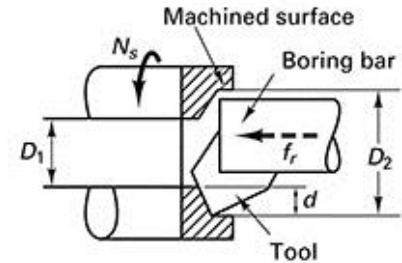
**FIGURE 20-5** Relationship of speed, feed, and depth of cut in turning, boring, facing, and cutoff operations typically done on a lathe.



**Turning**

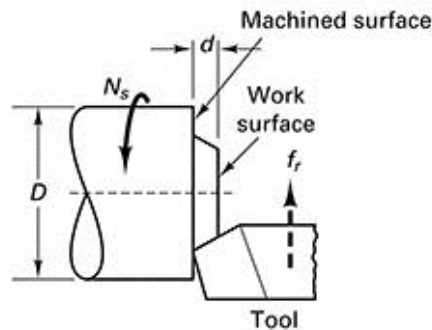
Speed, stated in surface feet per minute (sfpm), is the peripheral speed at the cutting edge. Feed per revolution in turning is a linear motion of the tool parallel to the rotating axis of the workpiece. The depth of cut reflects the third dimension.

$L = \text{length of cut}$   
 $T_m = \frac{L + A}{f_r N_s}$



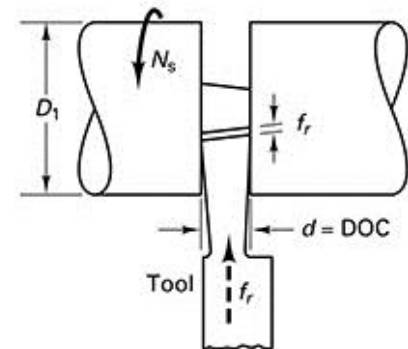
**Boring**

Enlarging hole of diameter  $D_1$  to diameter  $D_2$ . Boring can be done with multiple cutting tools. Feed in inches per revolution,  $f_r$ .



**Facing**

Tool feeds to center of workpiece so  $L = D/2$ . The cutting speed is decreasing as the tool approaches the center of the workpiece.



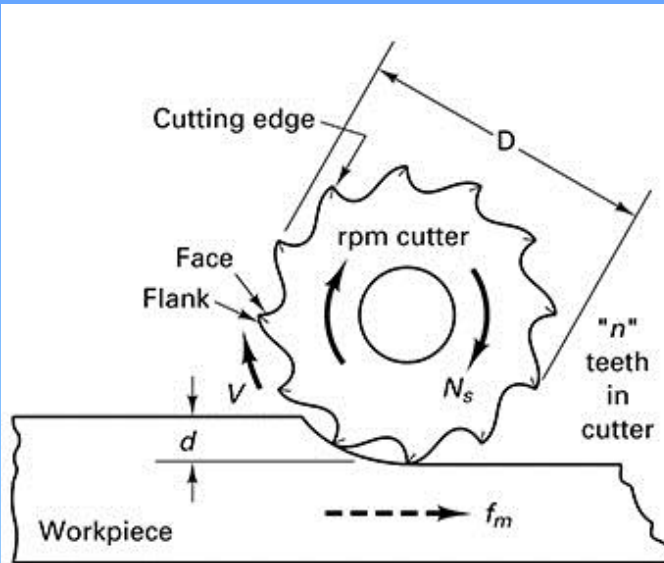
**Grooving, parting, or cutoff**

Tool feed perpendicular to the axis of rotation. The width of the tool produces the depth of cut (DOC).

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

| Parameter                                    | Turning  | Milling  | Drilling  | Broaching  |
|--|--|--|---|--|
| Cutting speed, fpm                           | $V = 0.262 \times D_1 \times$<br>rpm   | $V = 0.262 \times D_m \times$<br>rpm                 | $V = 0.262 \times D_d \times$<br>rpm  | $V$  |
| Revolutions per minute, $N_s$                | $\text{rpm} = 3.82 \times V_c/D_1$   | $\text{rpm} = 3.82 \times V_c/D_m$                   | $\text{rpm} = 3.82 \times$<br>$V_c/D_d$   | —  |
| Feed rate, in./min                           | $f_m = f_r \times \text{rpm}$  | $f_m = f_r \times \text{rpm}$                        | $f_m = f_r \times \text{rpm}$   | —  |
| 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. <sup>3</sup> /min | $\text{MRR} = 12 \times d \times f_r$<br>$\times V_c$  | $\text{MRR} = w \times d \times f_m$                 | $\text{MRR} = \pi D^2 d/4$<br>$\times f_m$  | $\text{MRR} = 12 \times w \times d$<br>$\times V$    |
| Horsepower required at spindle               | $\text{hp} = \text{MRR} \times \text{HP}_s$  | $\text{hp} = \text{MRR} \times \text{HP}_s$          | $\text{hp} = \text{MRR} \times$<br>$\text{HP}_s$  | —  |
| Horsepower required at motor                 | $\text{hp}_m = \text{MRR} \times$<br>$\text{HP}_s/E$   | $\text{hp}_m = \text{MRR} \times$<br>$\text{HP}_s/E$ | $\text{hp}_m = \text{MRR} \times$<br>$\text{HP}_s/E$  | $\text{hp}_m = \text{MRR} \times$<br>$\text{HP}_s/E$ |
| Torque at spindle                            | $t_s = 63,030$<br>hp/rpm   | $t_s = 63,030$<br>hp/rpm                             | $t_s = 63,030$<br>hp/rpm  | —  |
| Symbols                                      | $D_1$ = Diameter of workpiece in turning, inches<br>$D_m$ = Diameter of milling cutter, inches<br>$D_d$ = Diameter of drill, inches<br>$d$ = Depth of cut, inches<br>$E$ = Efficiency of spindle drive<br>$f_m$ = Feed rate, inches per minute<br>$f_r$ = Feed, inches per revolution<br>$f_t$ = Feed, inches per tooth<br>$\text{hp}_m$ = Horsepower at motor<br>$\text{MRR}$ = Metal removal rate, in. <sup>3</sup> /min |  | $\text{hp}$ = horsepower at spindle<br>$L$ = Length of cut, inches<br>$n$ = Number of teeth in cutter<br>$\text{HP}_s$ = Unit power, horsepower per cubic inch per minute, specific horsepower<br>$N_s$ = Revolution per minute of work or cutter<br>$t_s$ = Torque at spindle, inch-pound<br>$T_m$ = Cutting time, minutes<br>$V$ = Cutting speed, feet per minute<br>$w$ = Width of cut, inches |  |

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



Slab milling – multiple tooth

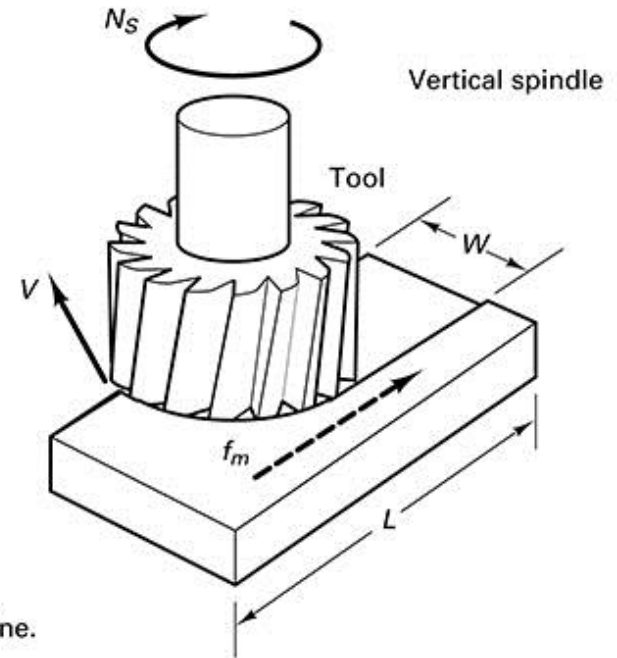
Slab milling is usually performed on a horizontal milling machine. Equations for  $T_m$  and MRR derived in Chapter 25.

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

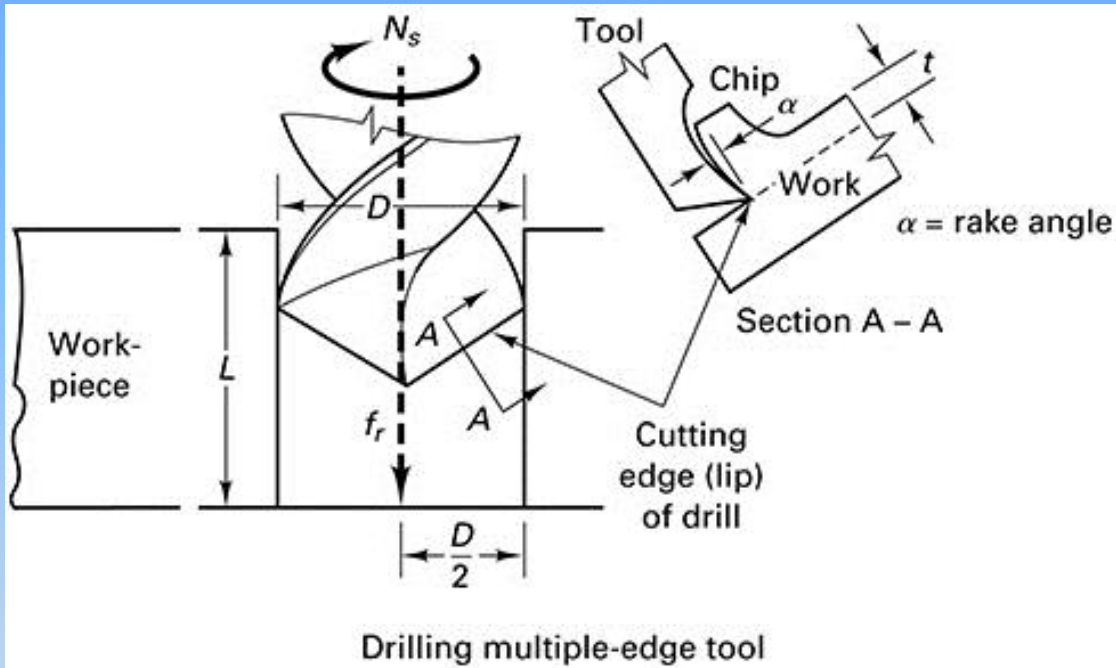
Given a selected cutting speed  $V$  and a feed per tooth  $f_t$ , the rpm of the cutter is  $N_s = 12V/\pi D$  for a cutting of diameter  $D$ . The table feed rate is  $f_m = f_t n N_s$  for a cutter with  $n$  teeth.

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  $W \geq D/2$ .

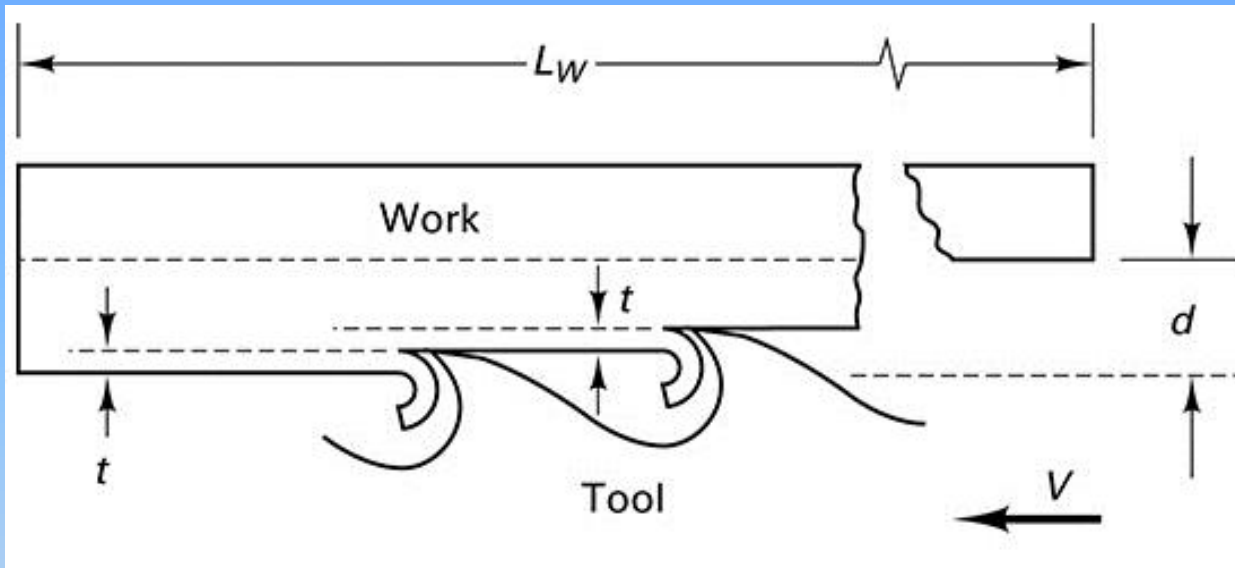
The MRR =  $Wdf_m$  where  $d$  = depth of cut.

**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.<sup>3</sup>/min which is approximately  $3DVf_r$ .

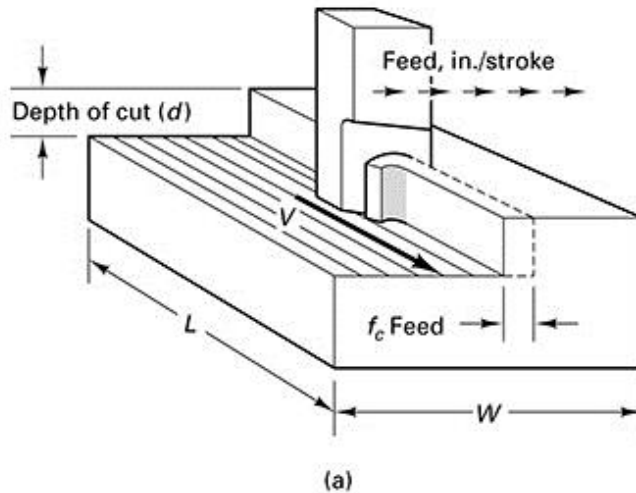
**FIGURE 20-7** Basics of the drilling (hole-making) processes, including equations for cutting time and metal removal rate (MRR).



The  $T_m$  for broaching is  $T_m = L/12V$ . The MRR (per tooth) is  $12tWV$  in.<sup>3</sup>/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

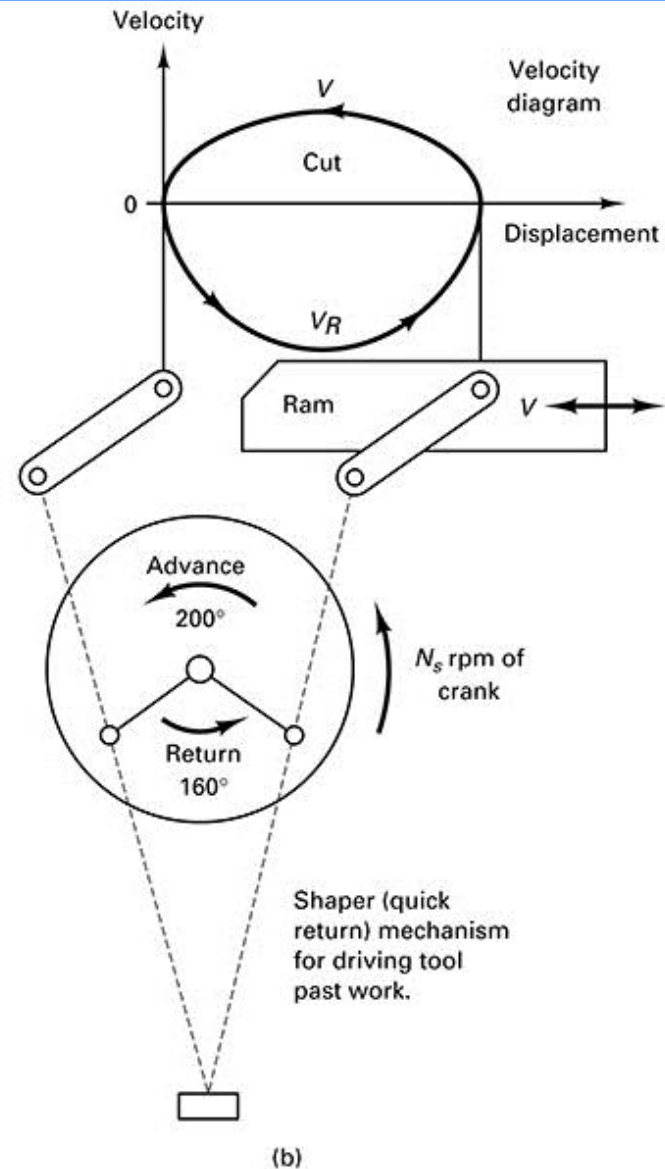
**FIGURE 20-9** (a) Basics of the shaping process, including equations for cutting time ( $T_m$ ) and metal removal rate (MRR). (b) The relationship of the crank rpm  $N_s$  to the cutting velocity  $V$ .

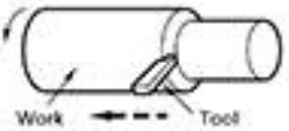
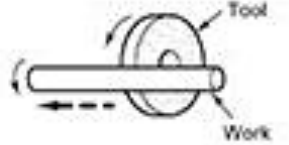
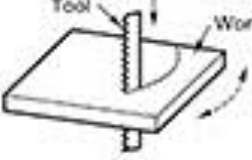
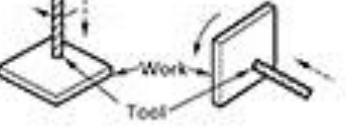
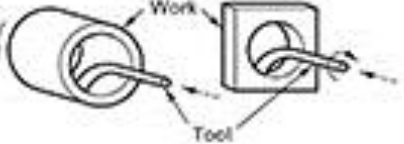


The tool cuts at velocity  $V$  with a return velocity of  $V_R$  dictated by the rpm of the crank,  $N_s$ . The cutting speed  $V = (I + A)N_s/12R_s$  where  $R_s = \text{stroke ratio} = 200^\circ/360^\circ$  and the length of stroke is  $I = L + \text{ALLOW}$ . The tool feed is  $f_c$  inches per stroke.

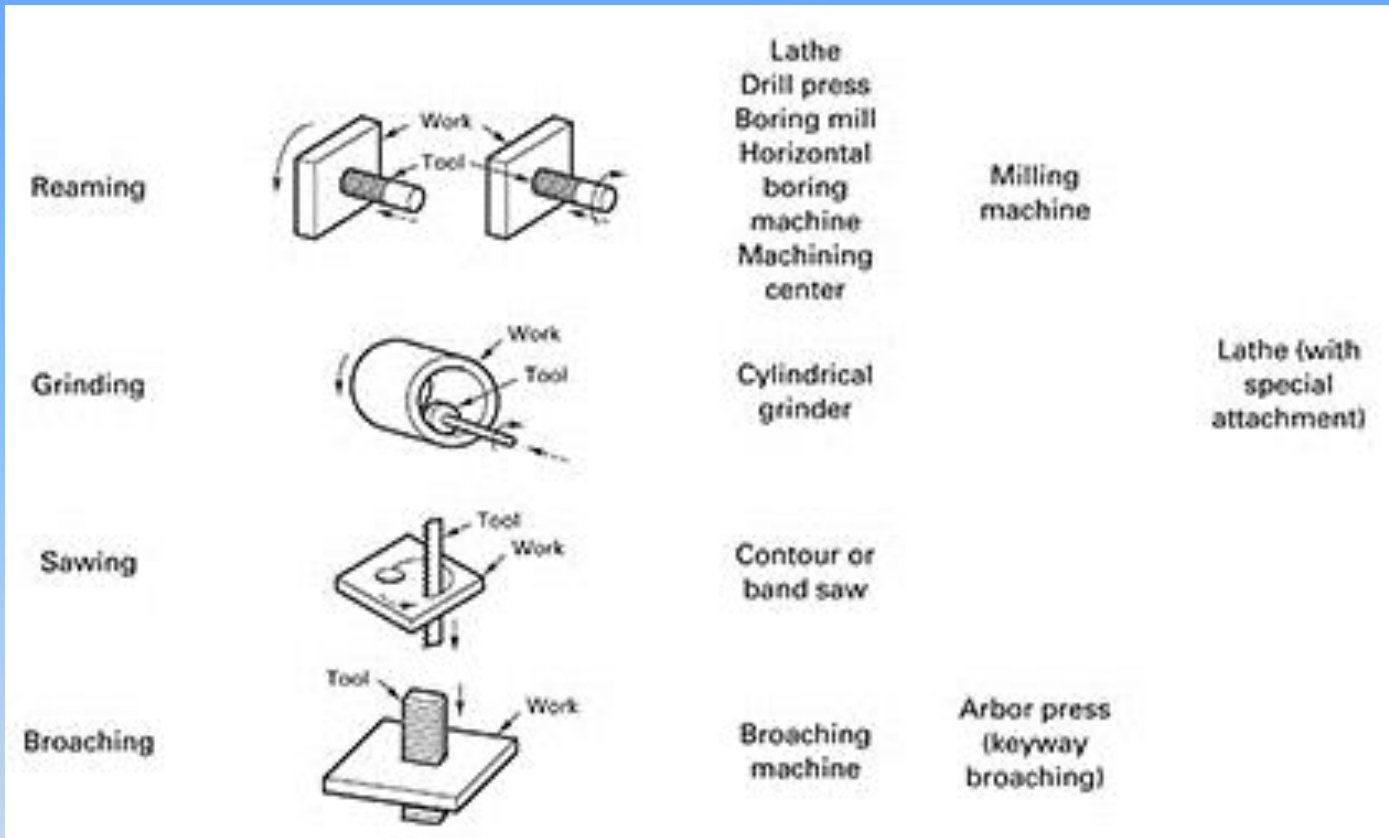
$$T_m = W/N_s f_c$$

$$\text{MRR} = LdN_s f_c \text{ in}^3/\text{min}$$


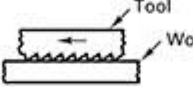
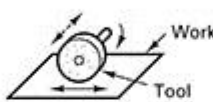
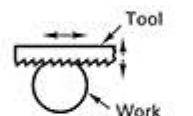
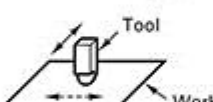
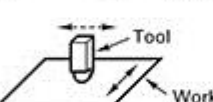
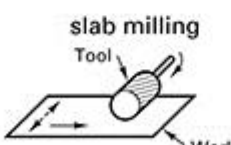
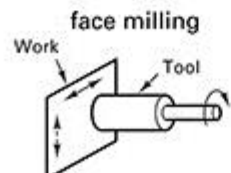


| Operation                     | Block diagram  | Most commonly used machines   | Machines less frequently used        | Machines seldom used                      |
|-------------------------------|--|---|--------------------------------------|---|
| Turning                       |   | Lathe<br>NC lathe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

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



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

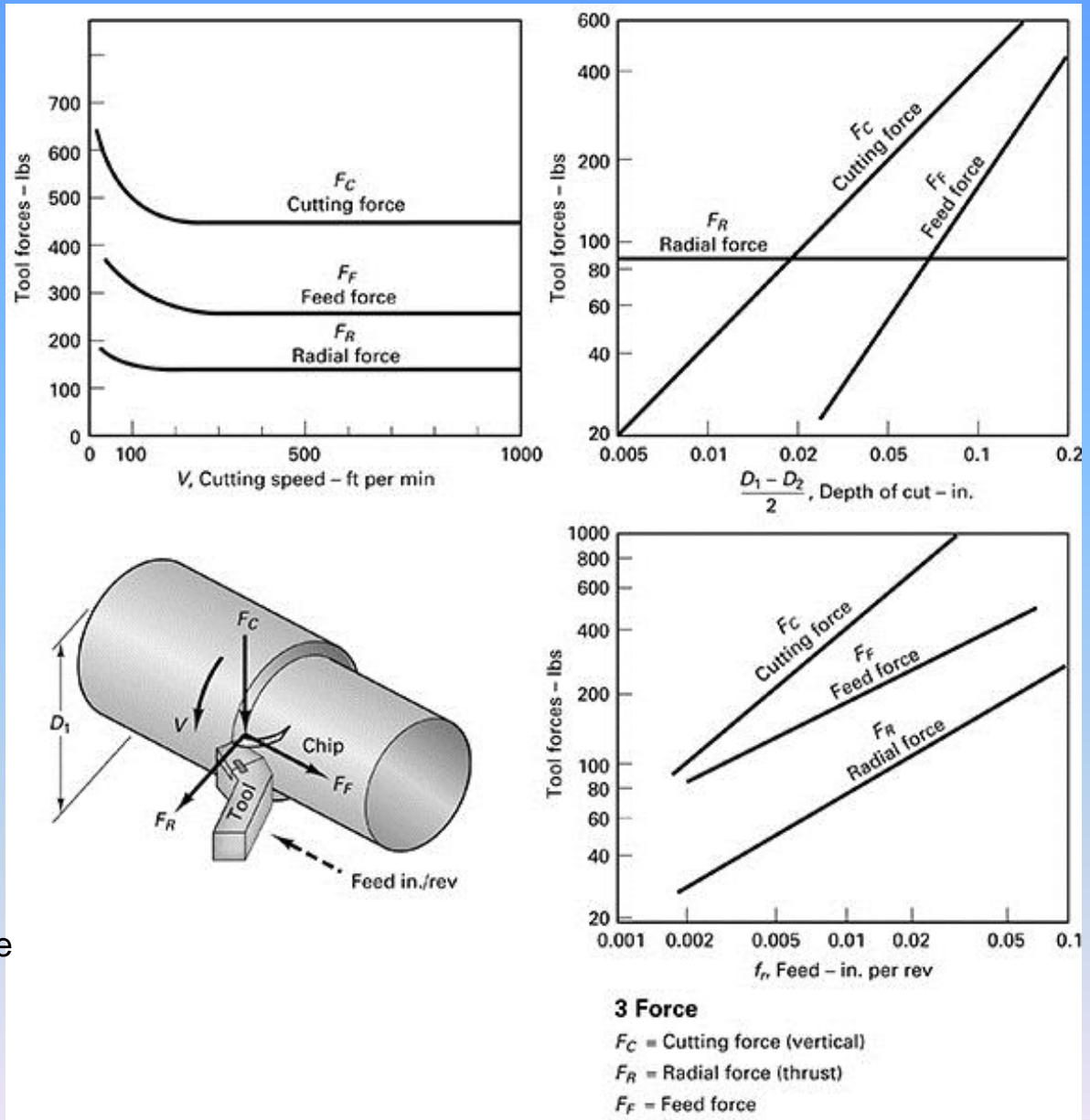
| Operation | Block diagram  | Most commonly used machines         | Machines less frequently used    | Machines seldom used            |
|-----------|--|-------------------------------------|----------------------------------|---------------------------------|
| Facing    |                    | Lathe                               | 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<br>  | Milling machine                     | Lathe with special milling tools |                                 |
|           | face milling<br> | Milling machine<br>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  |   | Typical Production Rate            | Material Choice   | Typical Tolerance   | Typical Surface Roughness |
|-------------------------------------|---|---|---|------------------------------------|---|---|---------------------------|
|                                     |   | Maximum   | Minimum   |                                    |   |   |                           |
| Turning (engine lathes)             | Cylinders, preforms, castings, forgings | 78 in. dia. × 73 in. long                           | $\frac{1}{4}$ 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                           | $\frac{1}{2}$ 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                   | $\frac{1}{4}$ 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 $\frac{1}{2}$ in. dia.             | Collets adapt to less than $\frac{1}{2}$ 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                    | $3\frac{1}{2}$ -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 $\frac{1}{2}$ 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<br>(hp-min. in. <sup>3</sup> )<br>HP <sub>s</sub> | Specific Energy<br>(in.-lb/in. <sup>3</sup> )<br>K, or U | Hardness<br>Brinell<br>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<sub>s</sub>)

$$HP = F_c V / 33000$$

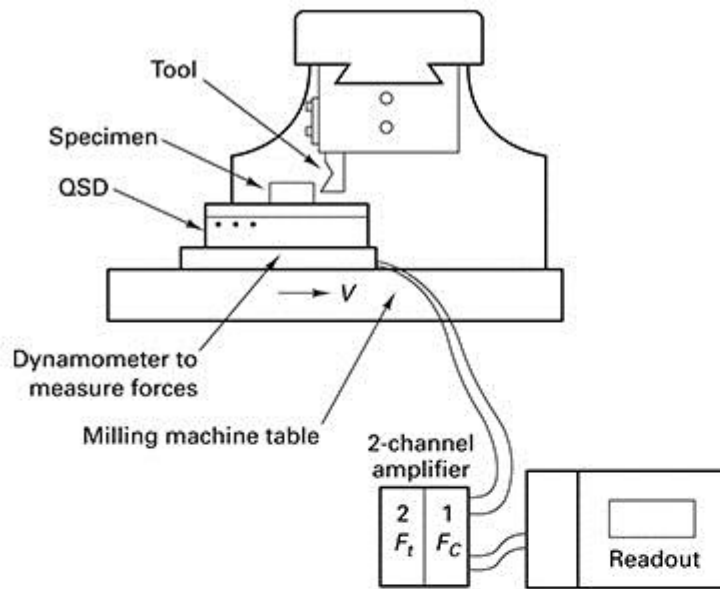
$$HP_s = HP / MRR \text{ Where}$$

$$MRR = 12Vfvc \text{ for tube turning}$$

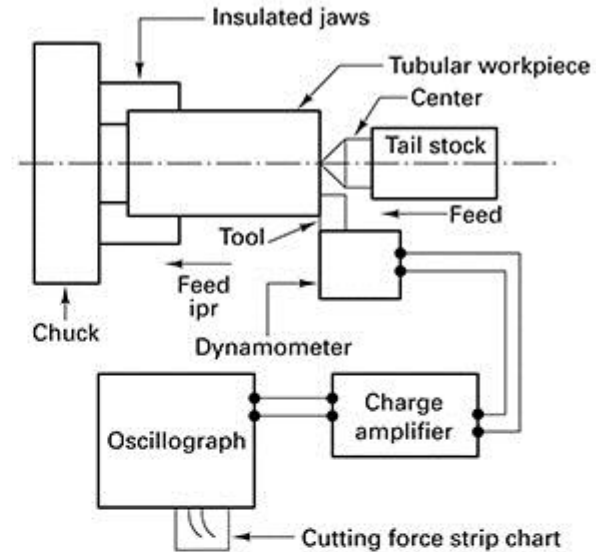
$$HP_s = F_c V / 12Vfvc \times 33000 = F_c / fvc \times 396000$$

Calculation of specific energy (U)

$$U = F_c V / Vfvc = F_c / fvc \text{ for tube turning}$$

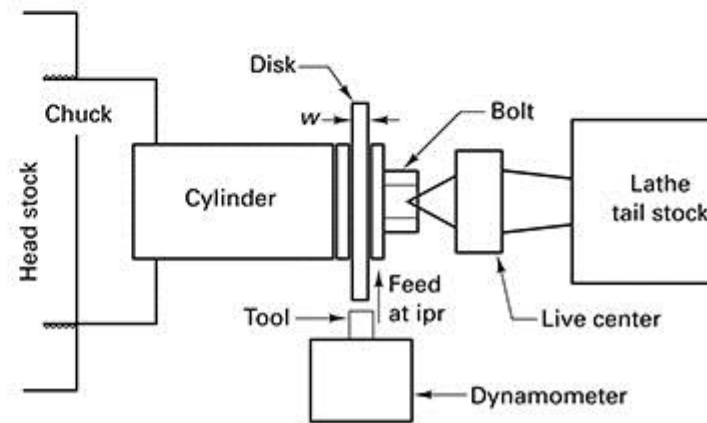


(a) OPM V (Front view) See Figure 21-14



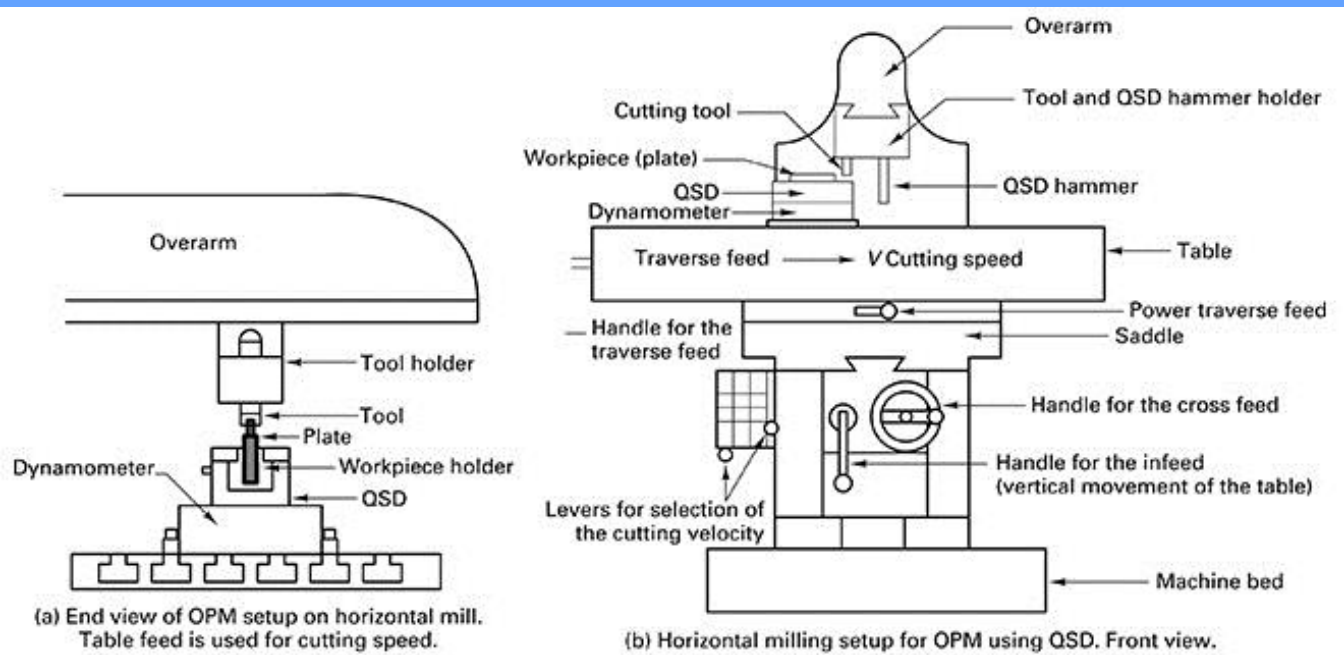
(b) OTT (Top view) See Figure 21-15

**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

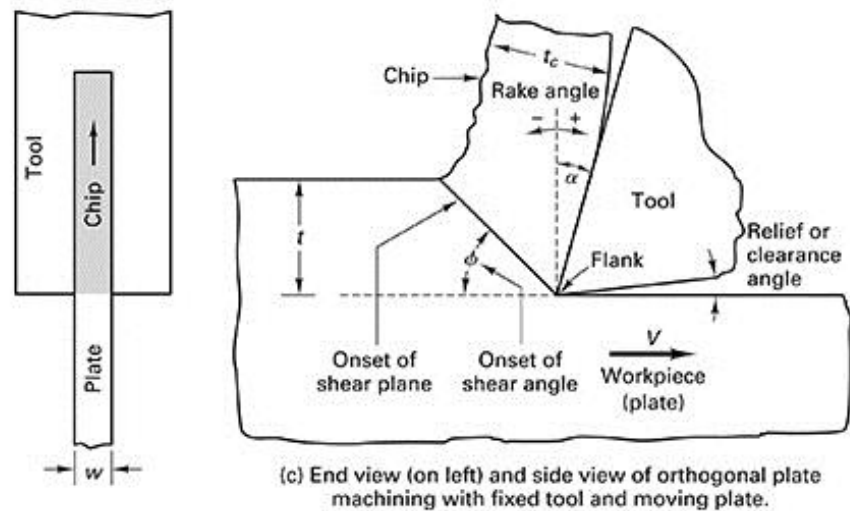


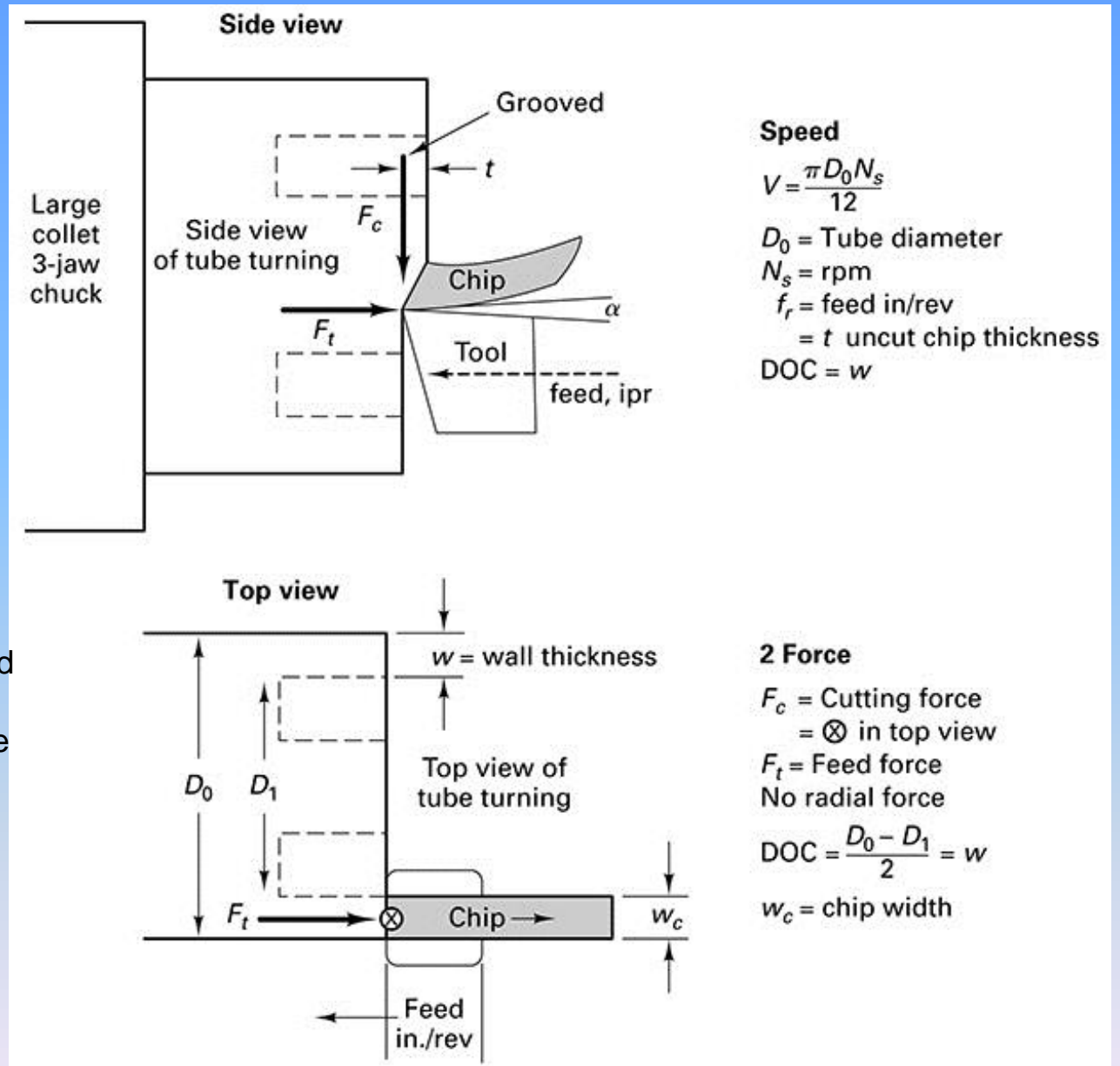
(c) ODM (Top view)

# 20.4 Orthogonal Machining (Two Forces)

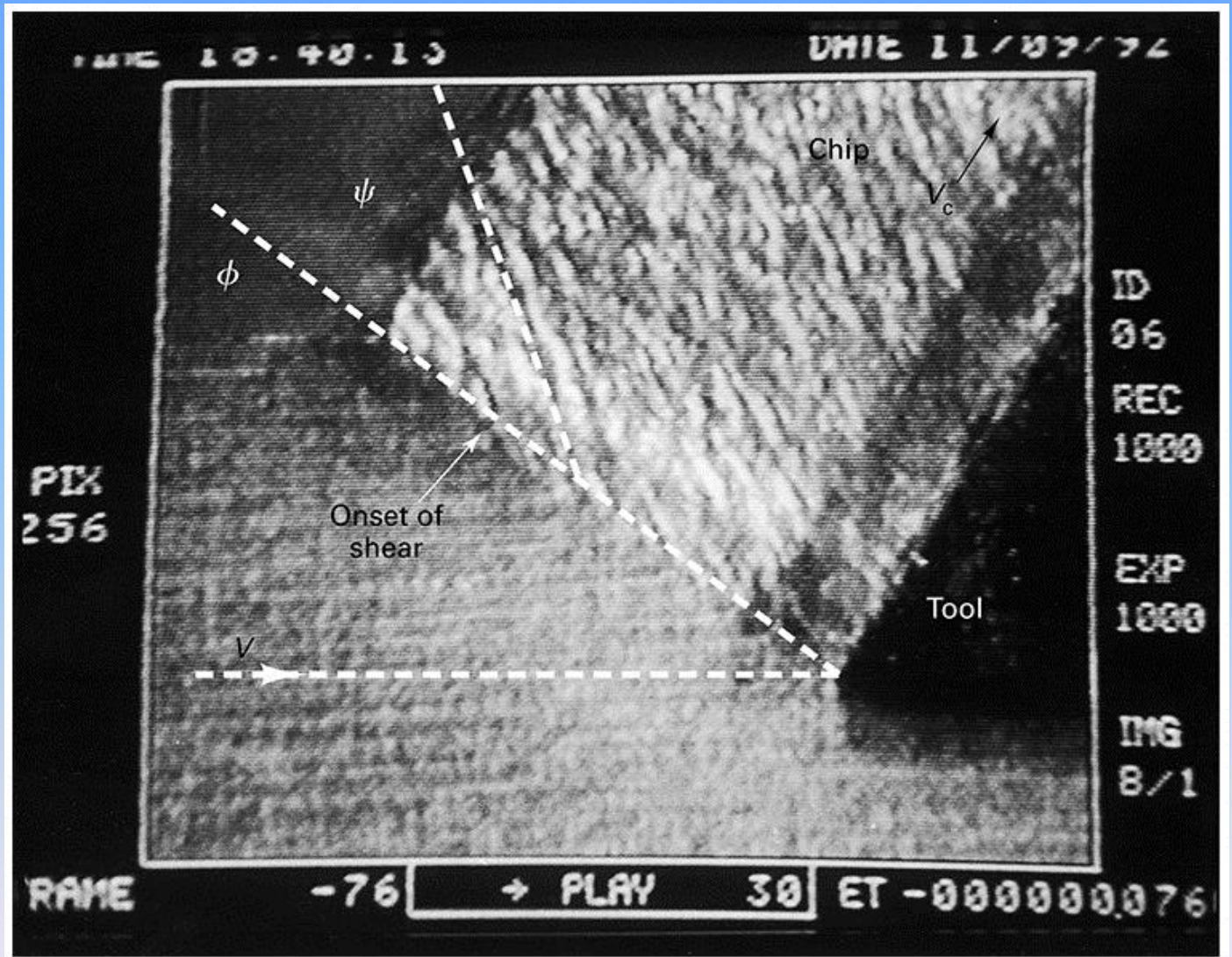


**FIGURE 20-14** Schematics of the orthogonal plate machining setups. (a) End view of table, quick-stop device (QSD), and plate being machined for OPM. (b) Front view of horizontal milling machine. (c) Orthogonal plate machining with fixed tool, moving plate. The feed mechanism of the mill is used to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



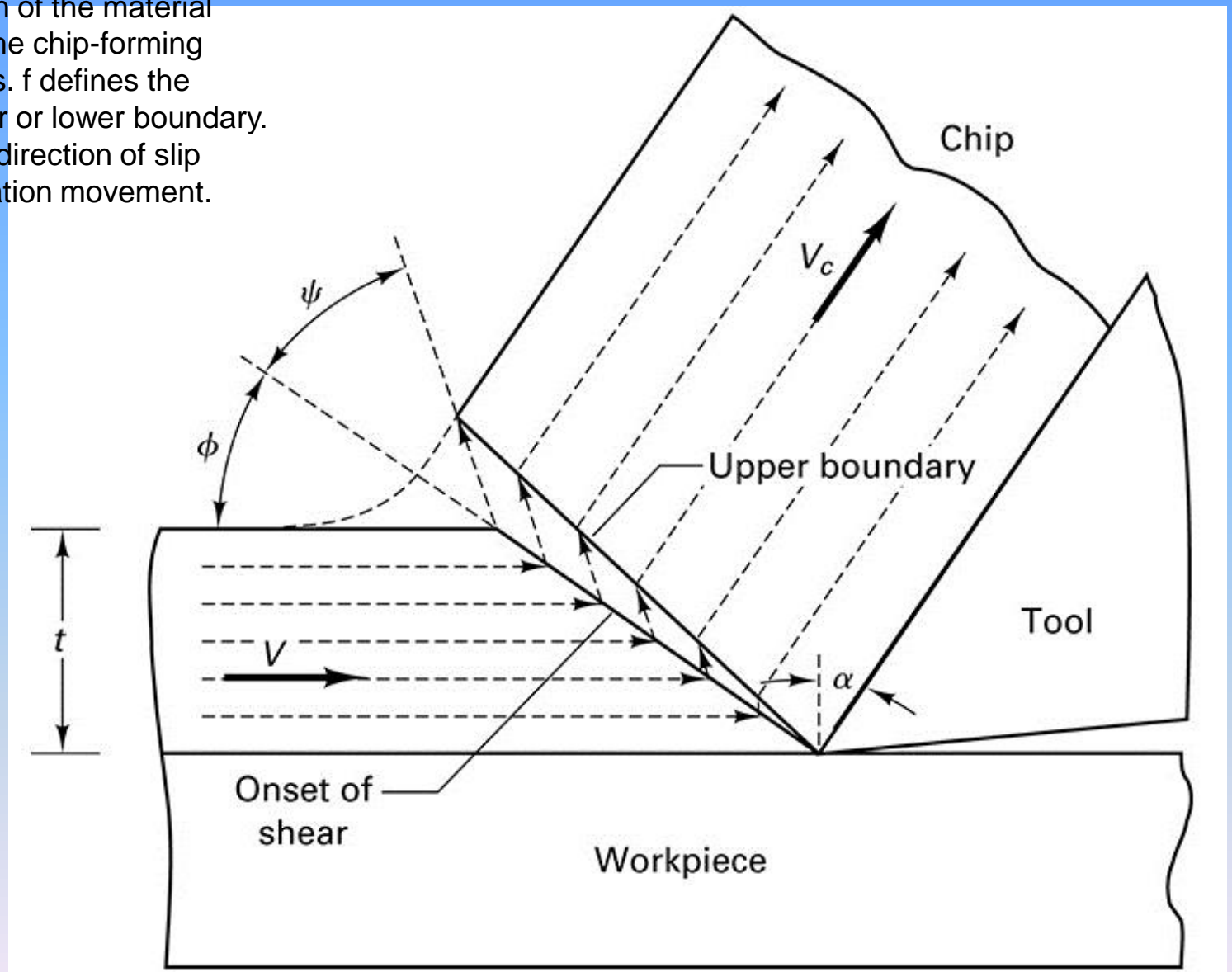


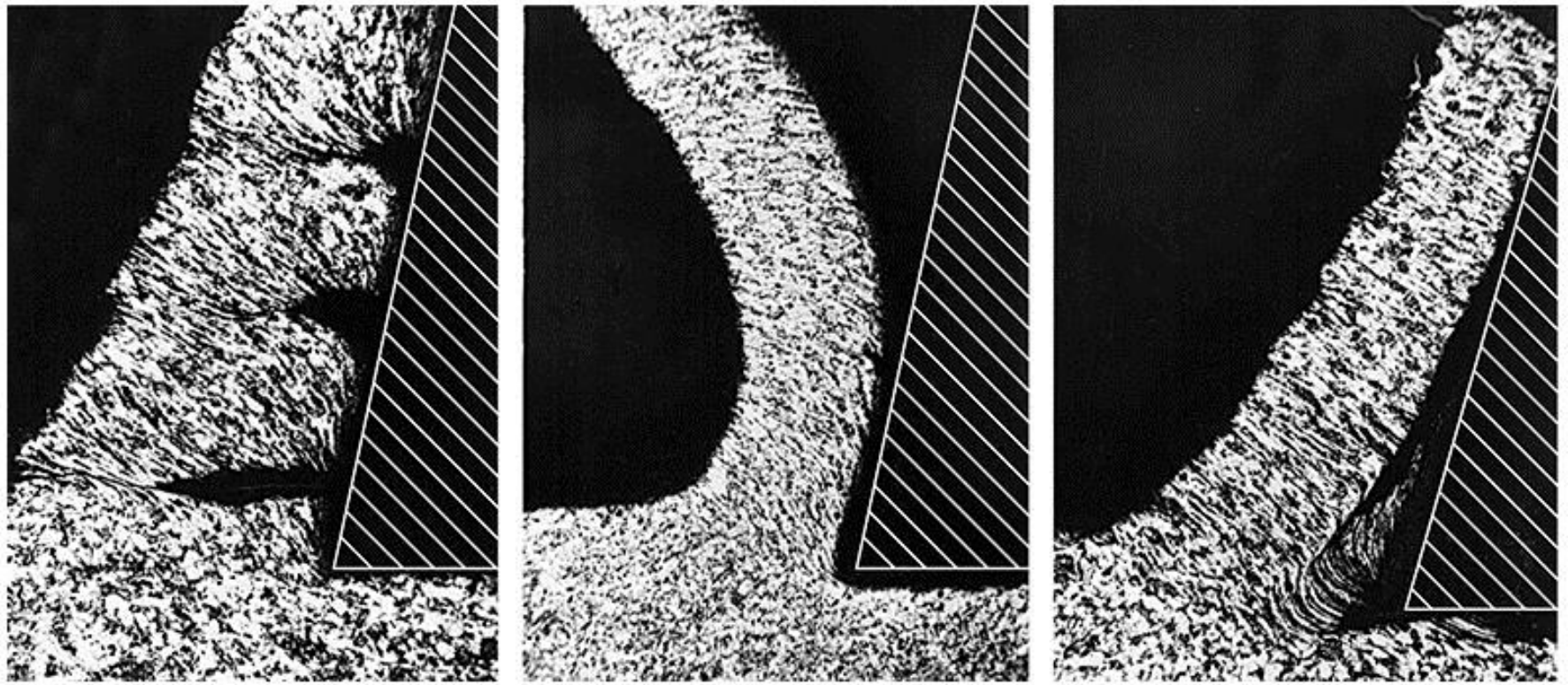
**FIGURE 20-15** Orthogonal tube turning (OTT) produces a two-force cutting operation at speeds equivalent to those used in most oblique machining operations. The slight difference in cutting speed between the inside and outside edge of the chip can be neglected.



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

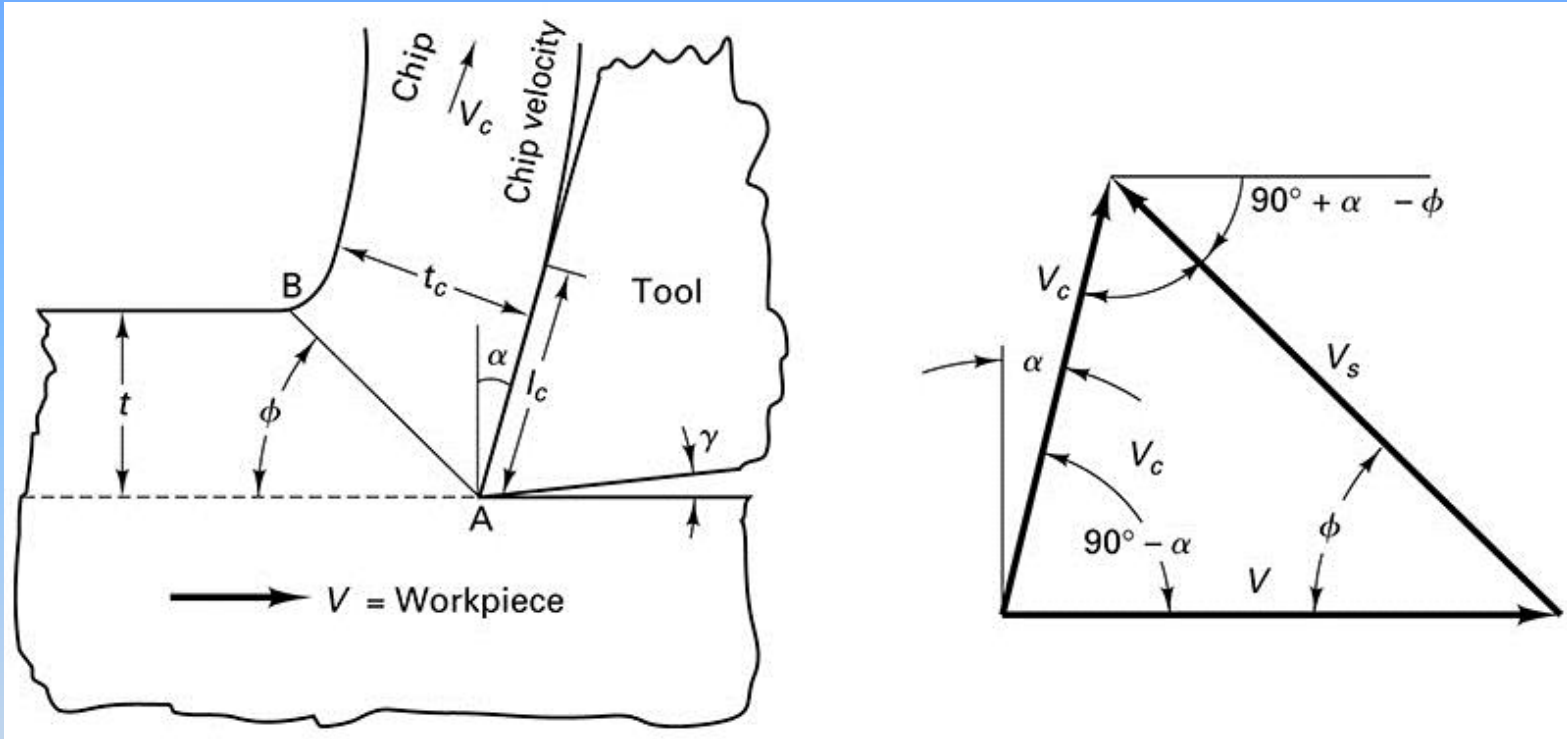
**FIGURE 20-17** Schematic representation of the material flow, that is, the chip-forming shear process.  $f$  defines the onset of shear or lower boundary.  $c$  defines the direction of slip due to dislocation movement.





**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.)

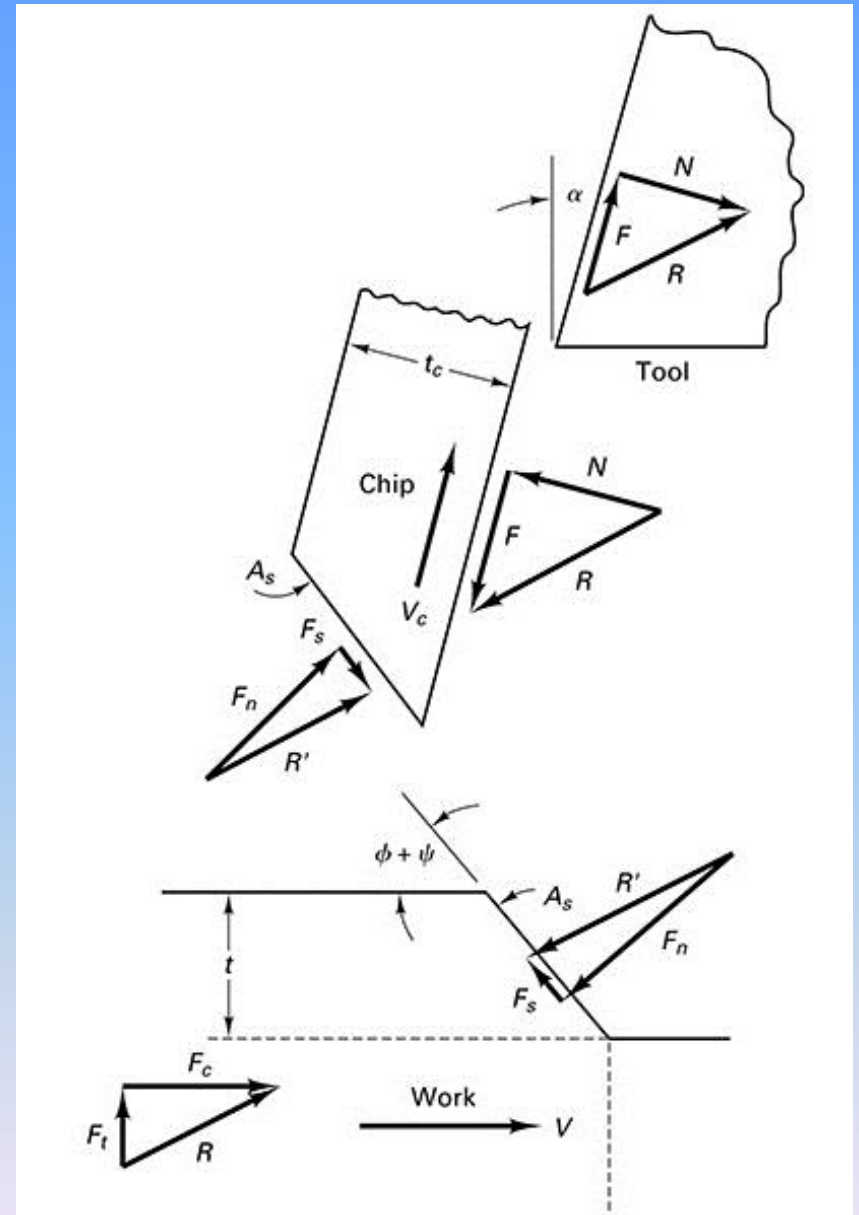
# 20.5 Merchant's Model

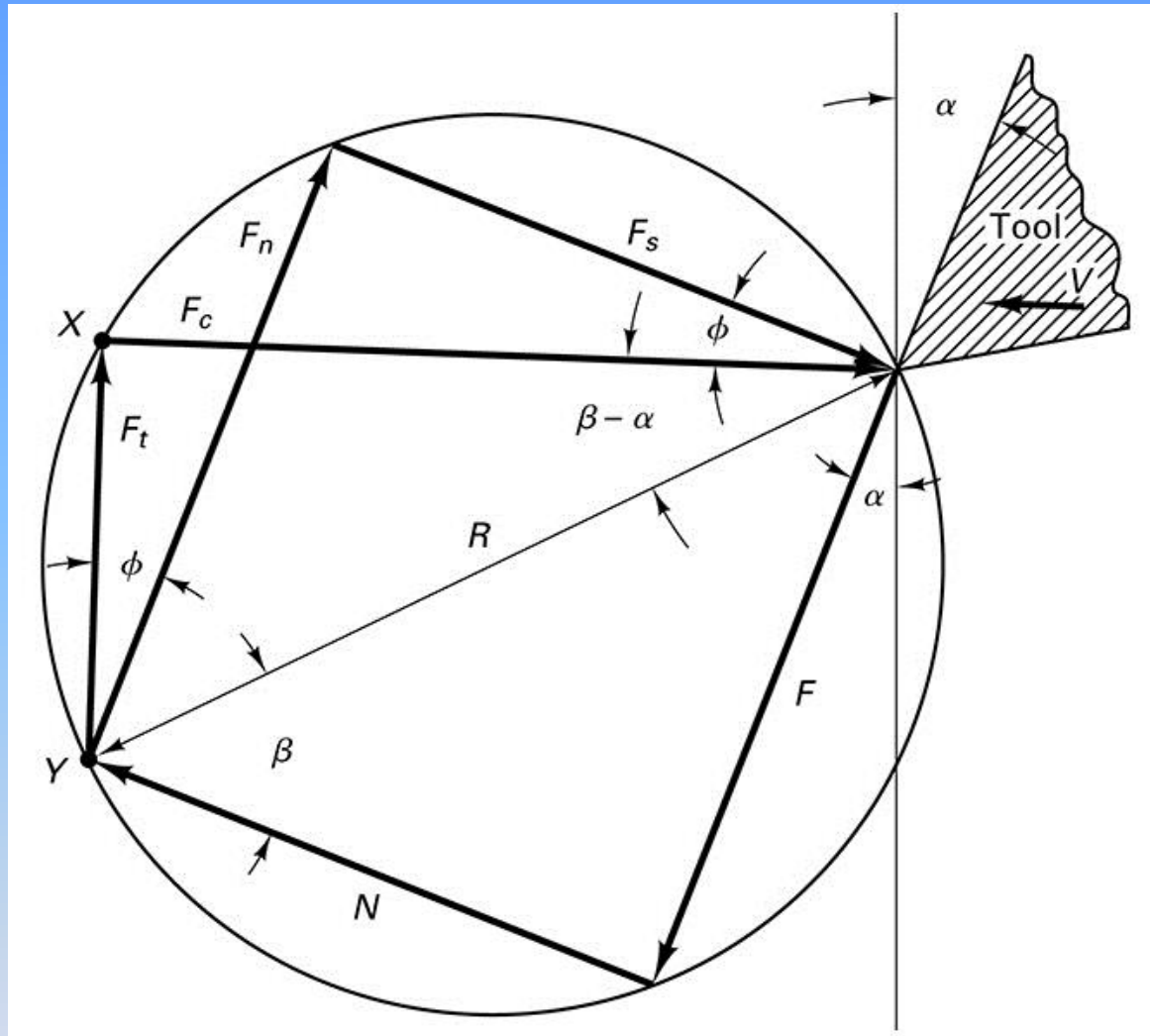


**FIGURE 20-19** Velocity diagram associated with Merchant's orthogonal machining model.

# 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  $R'$ .

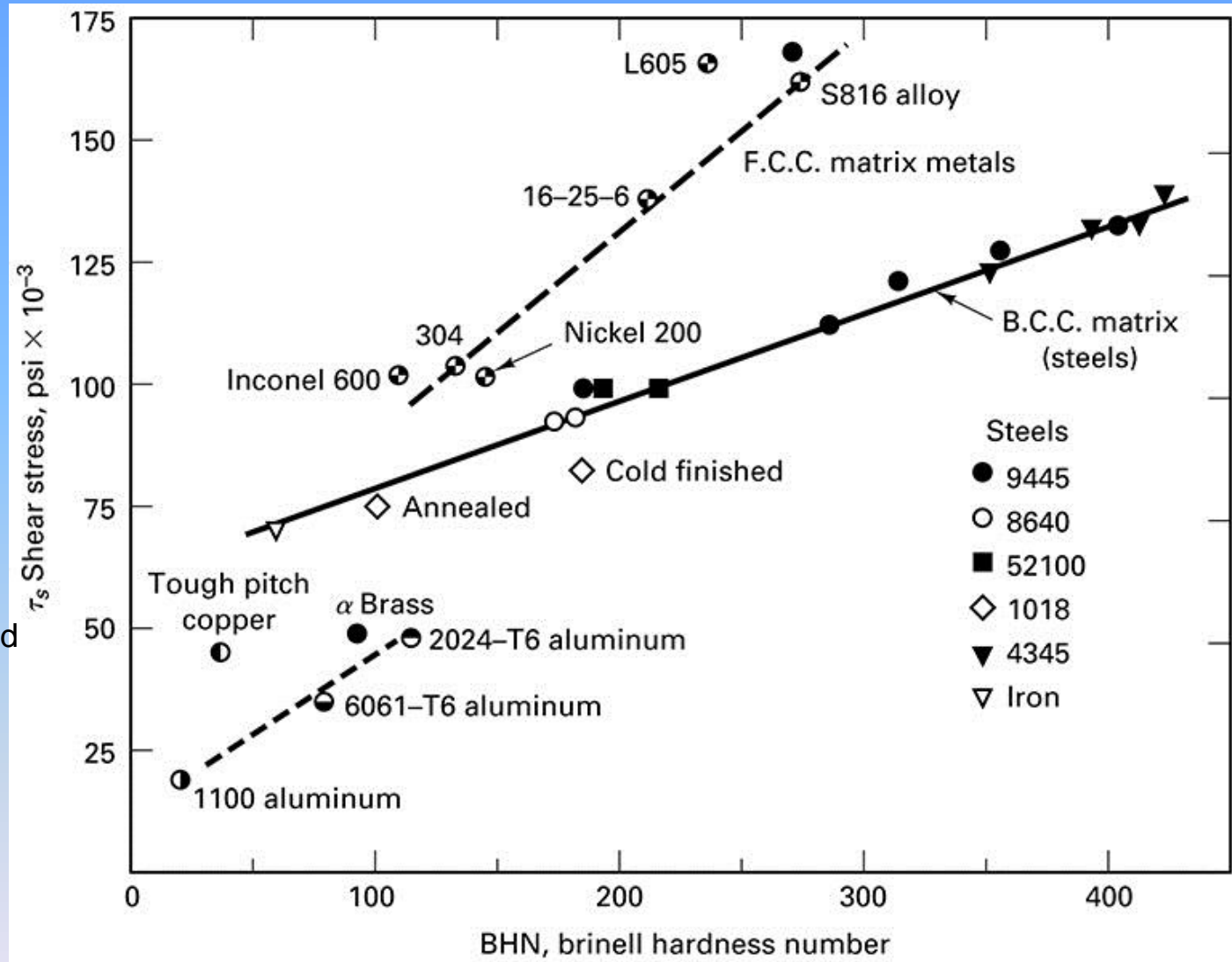




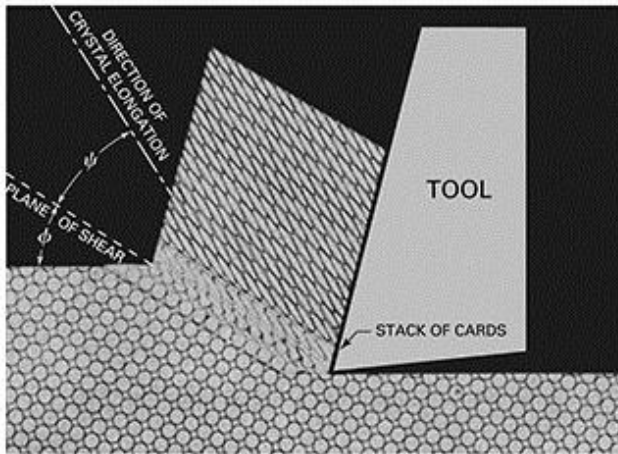
**FIGURE 20-21** Merchant's circular force diagram used to derive equations for  $F_s$ ,  $F_r$ ,  $F_t$ , and  $N$  as functions of  $F_c$ ,  $F_r$ ,  $f$ ,  $a$ , and  $b$ .

# 20.7 Shear Strain and Shear Front Angle

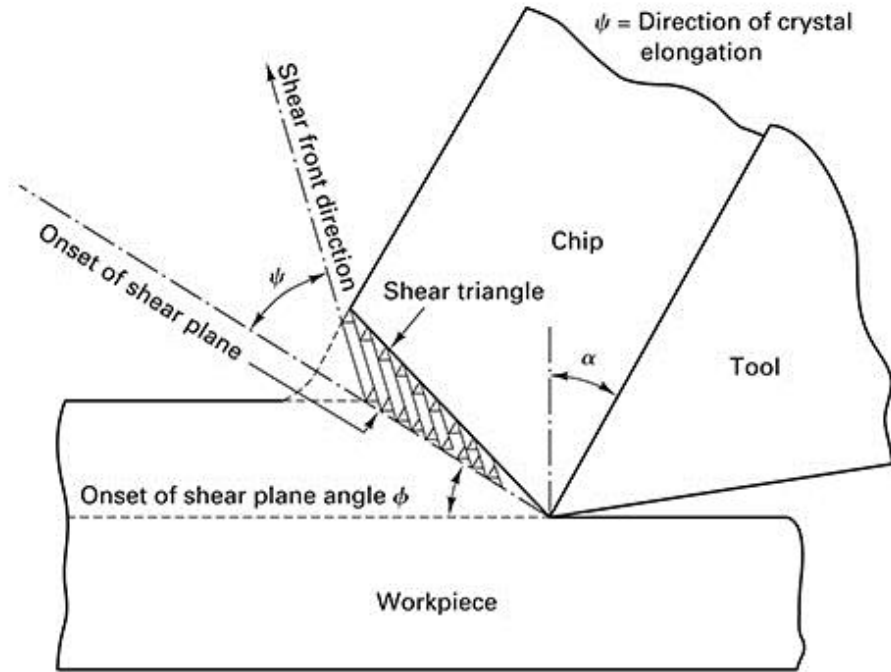
**FIGURE 20-22** Shear stress  $\tau_s$  variation with the Brinell hardness number for a group of steels and aerospace alloys. Data of some selected fcc metals are also included. (Adapted with permission from S. Ramalingham and K. J. Trigger, *Advances in Machine Tool Design and Research*, 1971, Pergamon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

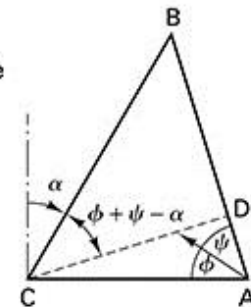


Merchant's bubble model of chip formation

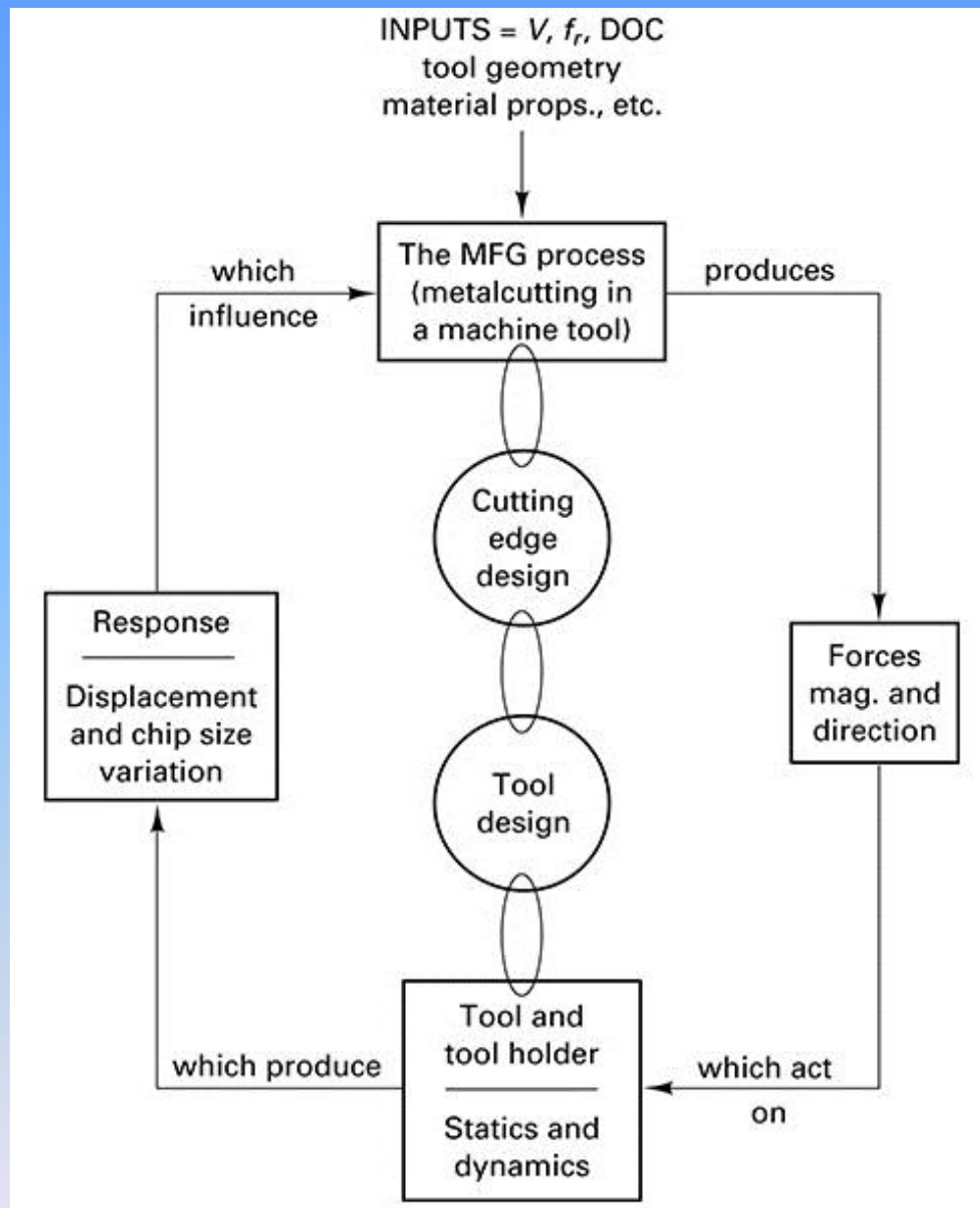


Black-Huang stack-of-cards model

The shaded shear triangle on the right is used to develop the basic equation for shear strain,  $\gamma$ .

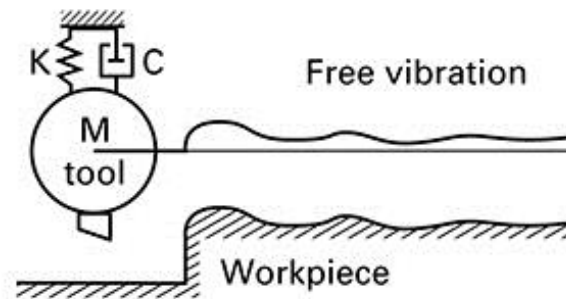


# 20.8 Mechanics of Machining (Dynamics)

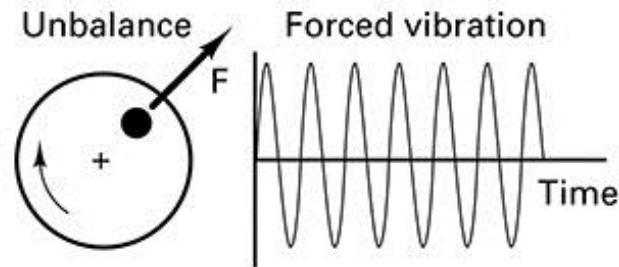


**FIGURE 20-24** Machining dynamics is a closed-loop interactive process that creates a force-displacement response.

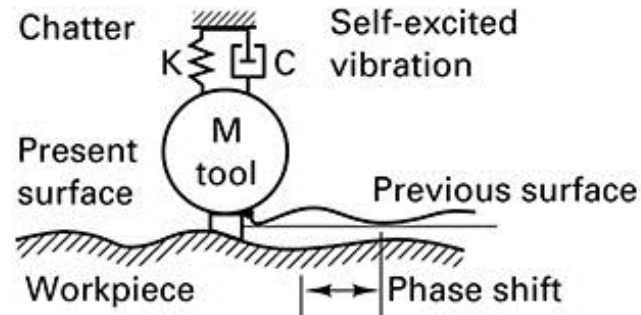
- **Free Vibration** The response to an initial condition or sudden change. The amplitude of the vibration decreases with time and occurs at the natural frequency of the system often produced by interrupted machining. Often appears as lines or shadows following a surface discontinuity.



- **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.

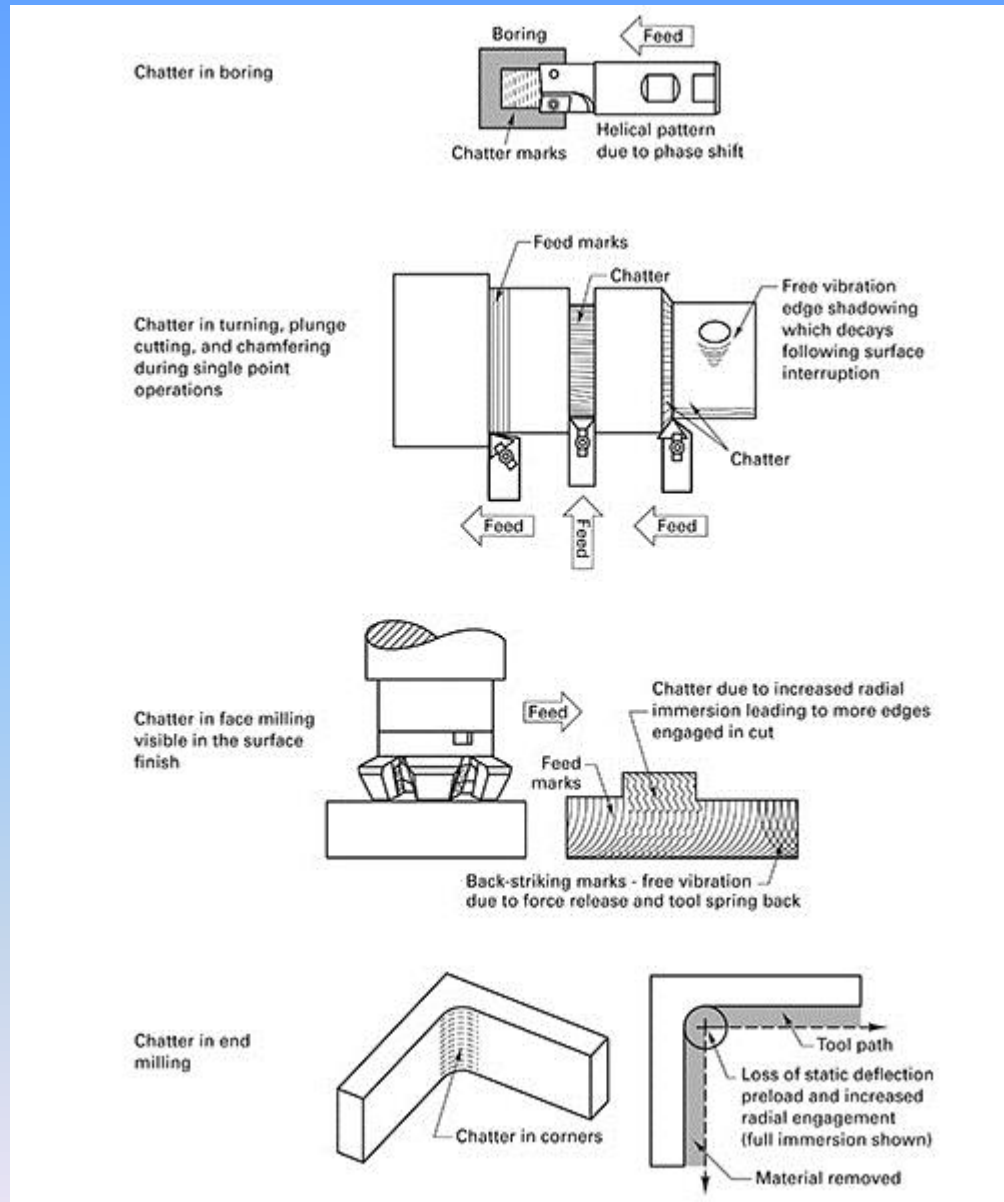


- **Self-Excited Vibration** The periodic response of the system to a constant input. The vibration may grow in amplitude (unstable) and occurs near the natural frequency of the system regardless of the input. Chatter due to the regeneration of surface waviness is the most common metal cutting example.

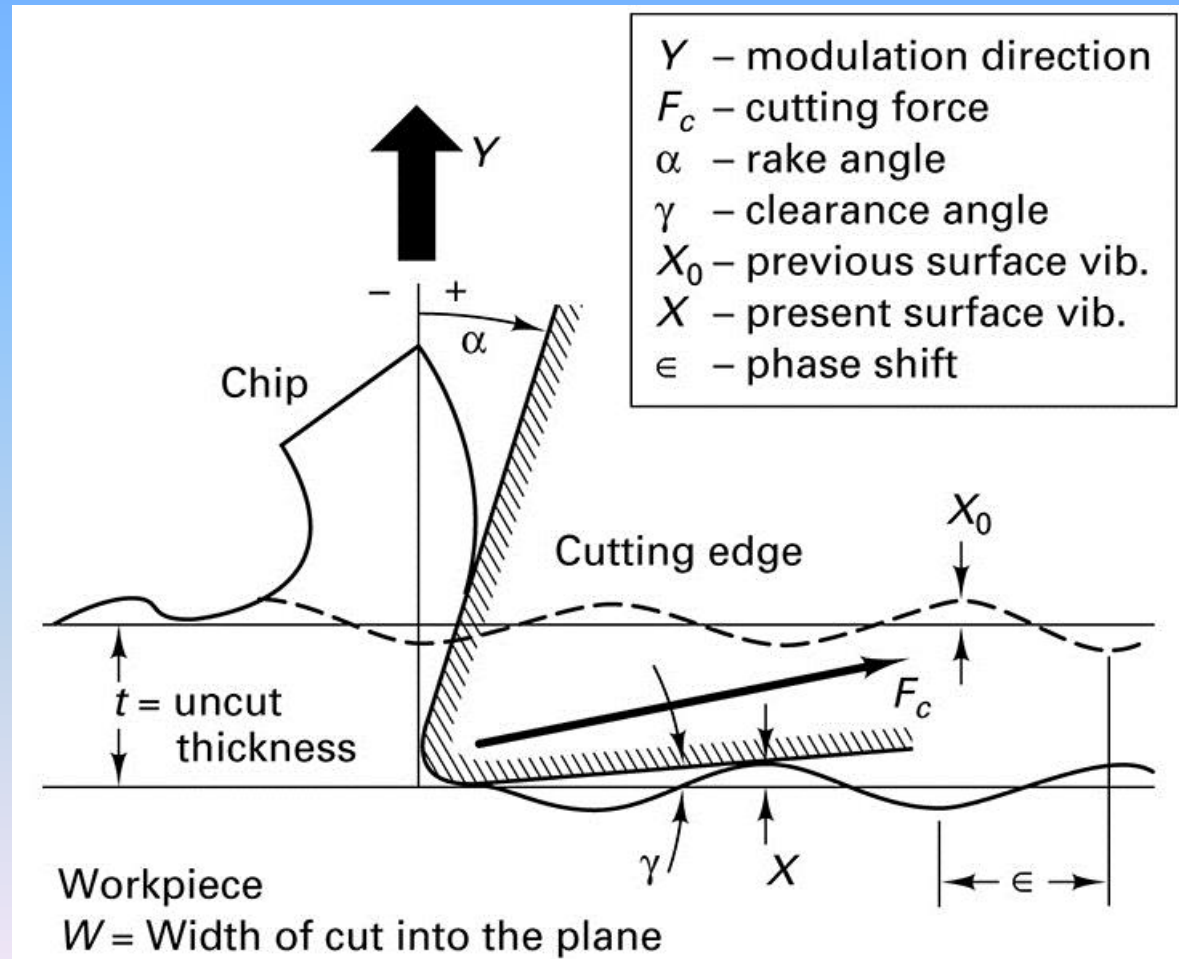


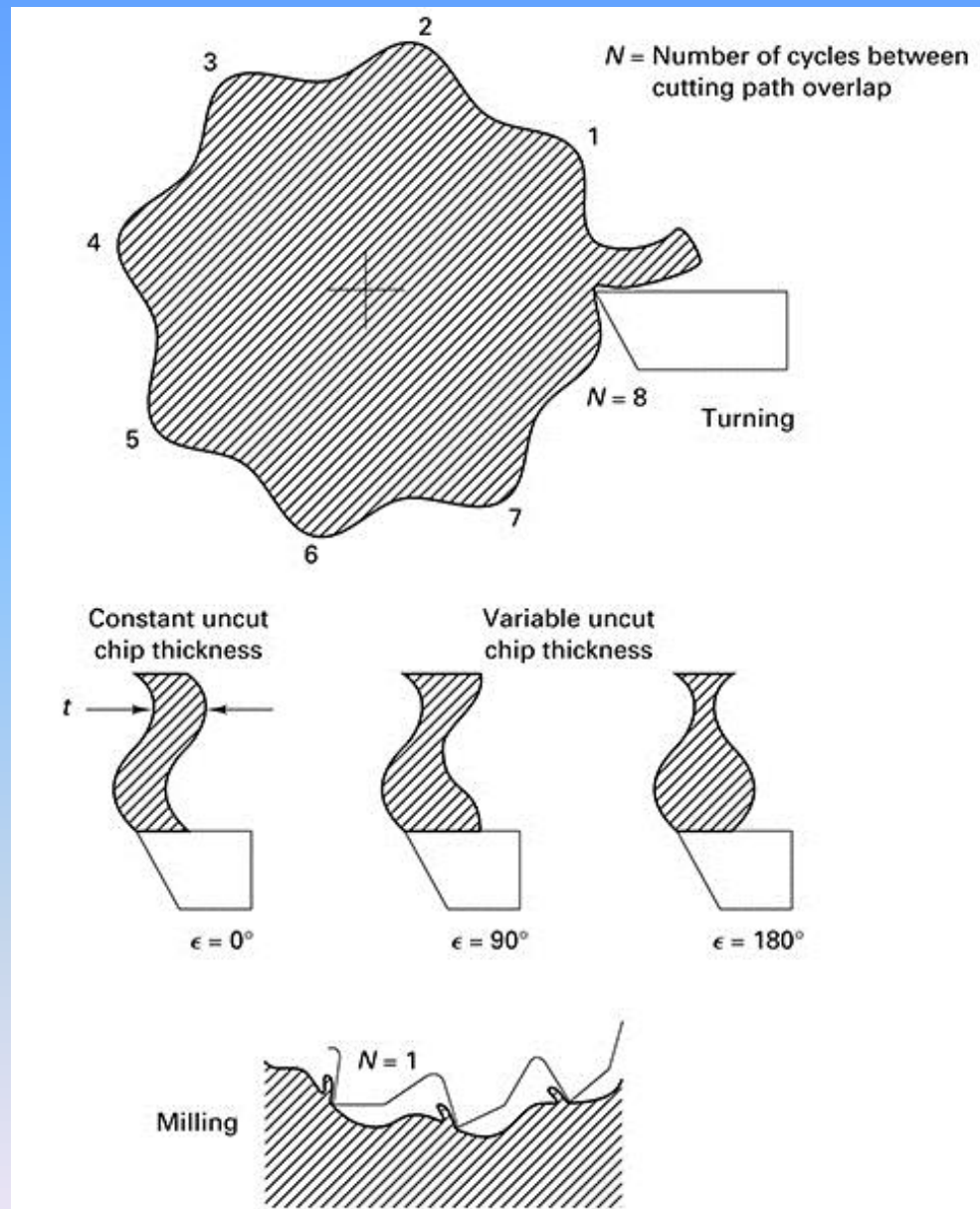
**FIGURE 20-25**  
There are three types of vibration in machining.

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

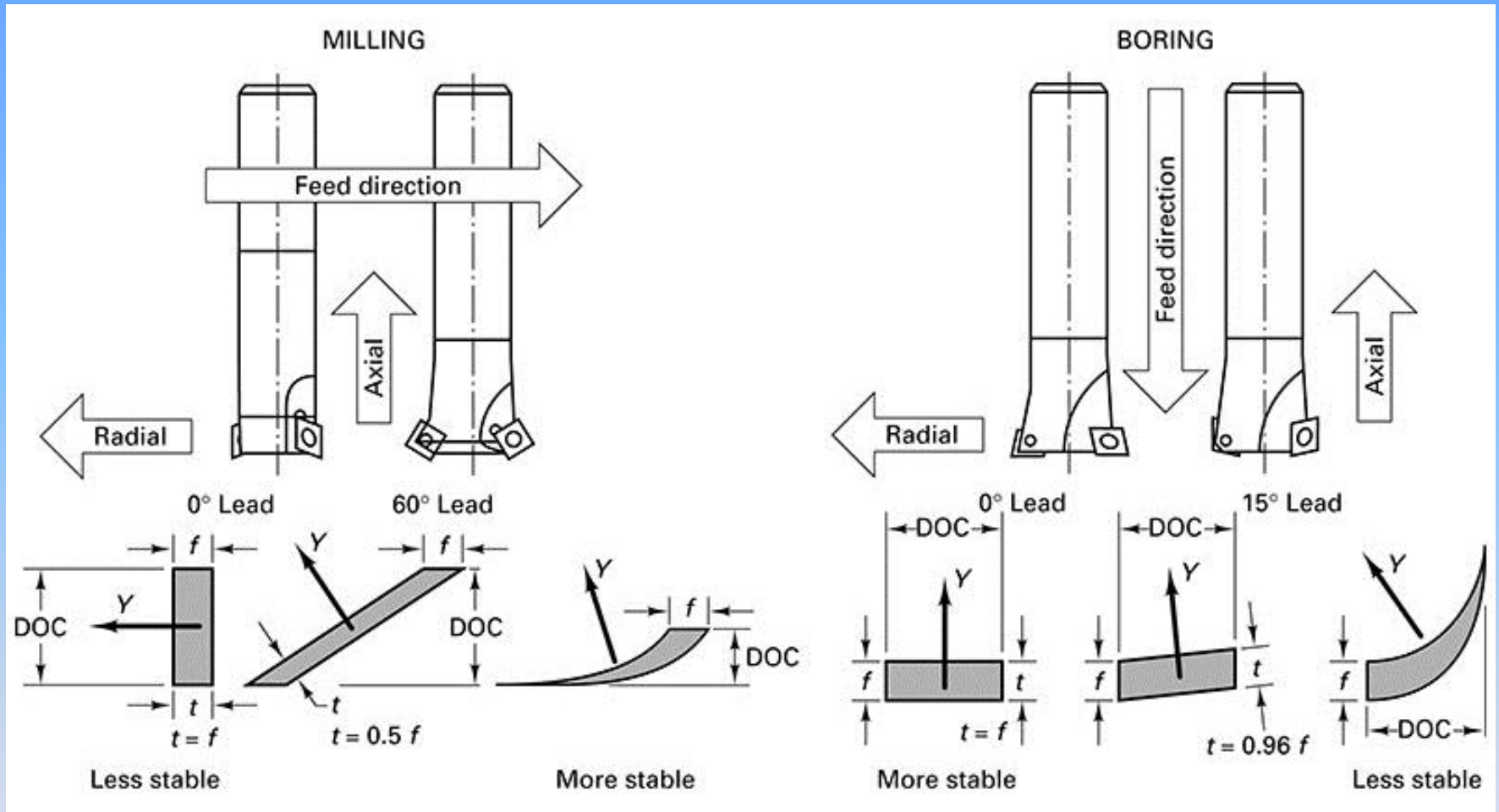


**FIGURE 20-27** When the overlapping cuts get out of phase with each other, a variable chip thickness is produced, resulting in a change in  $F_c$  on the tool or workpiece.



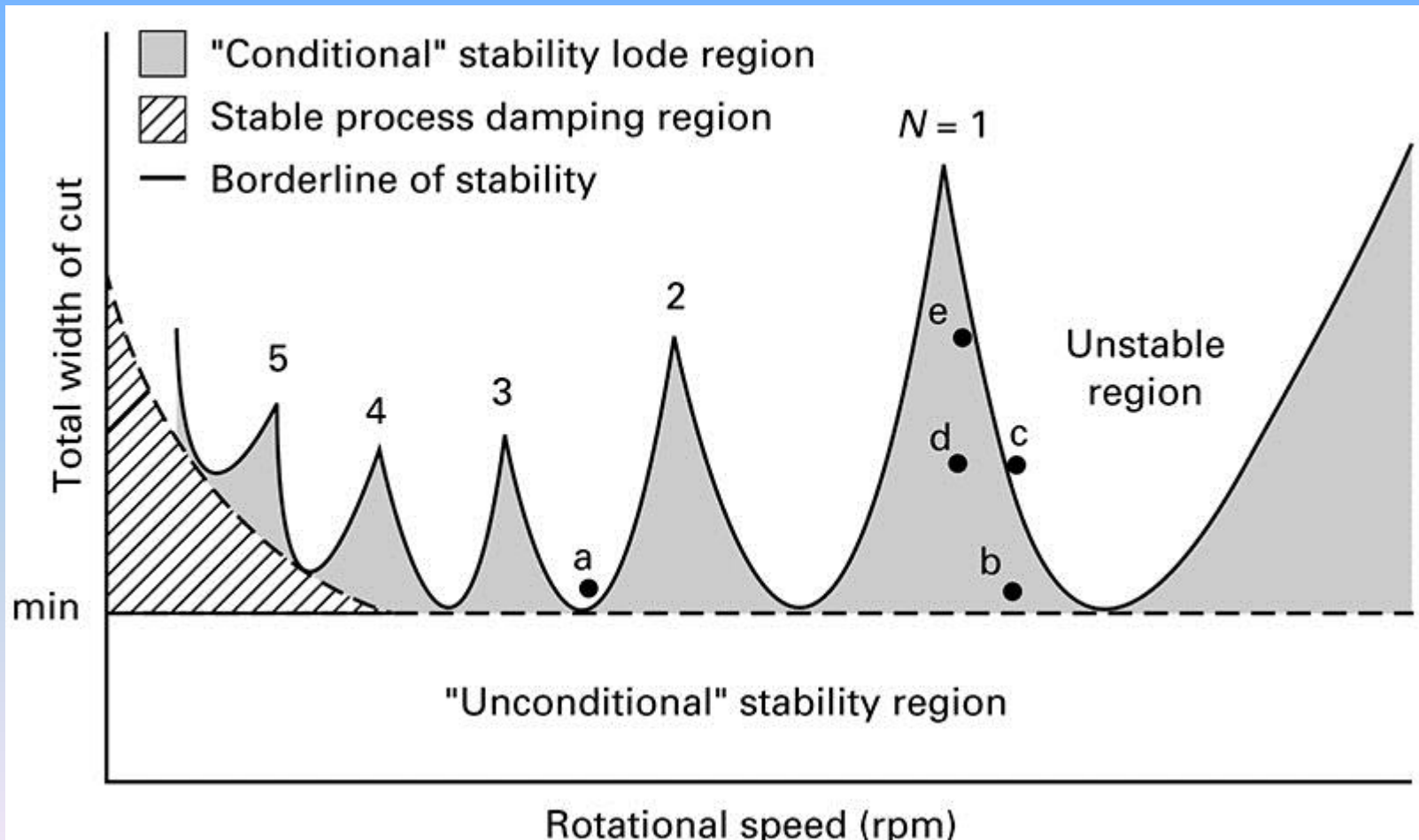


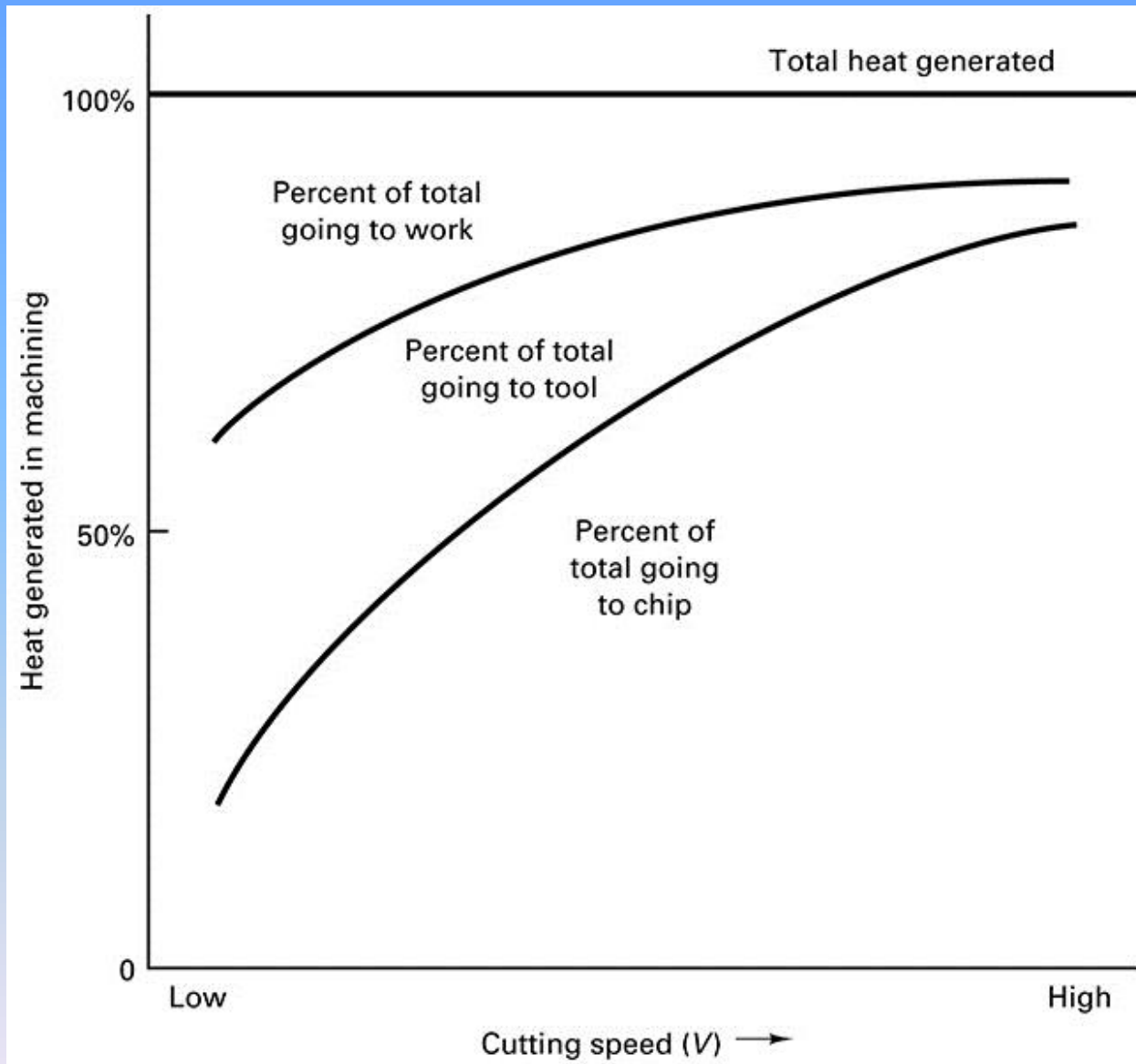
**FIGURE 20-28** Regenerative chatter in turning and milling produced by variable uncut chip thickness.



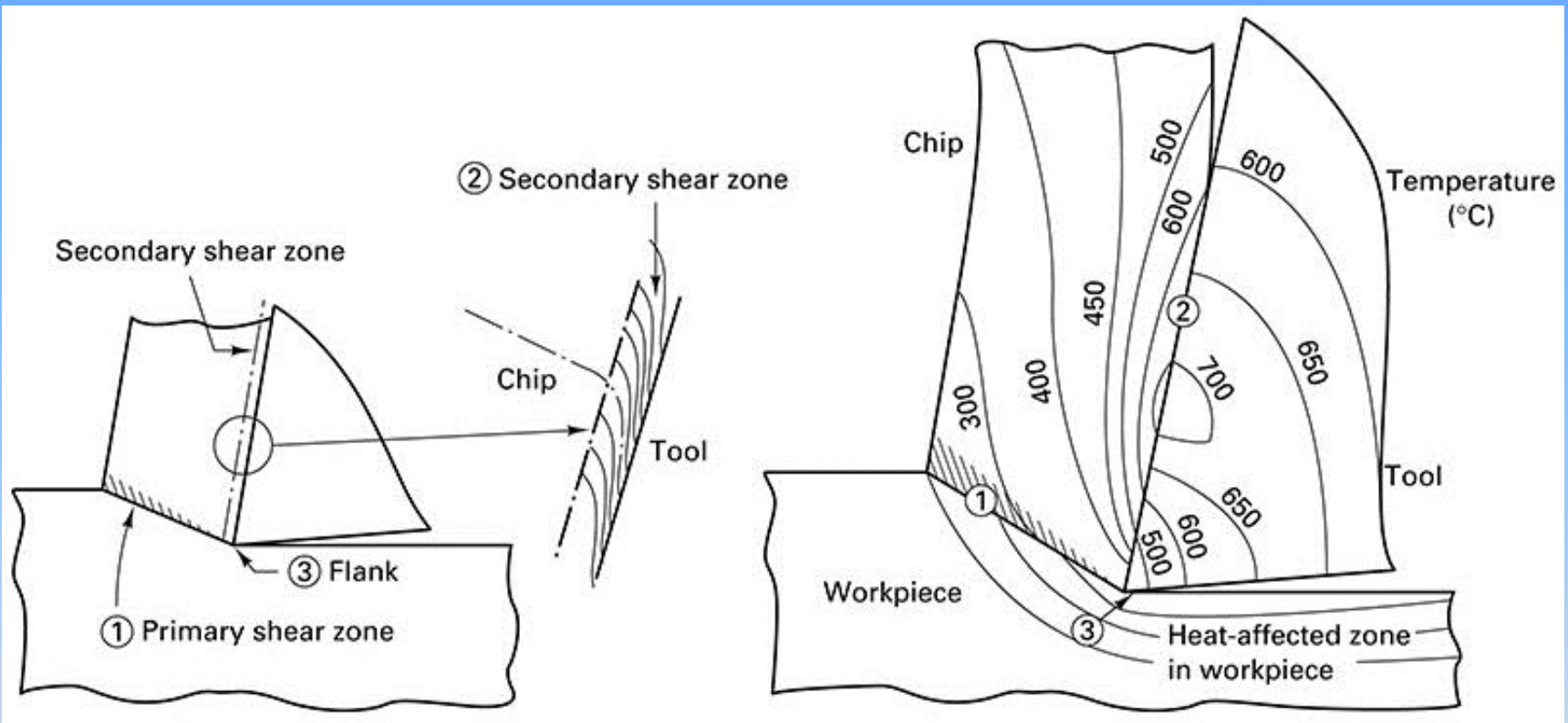
**FIGURE 20-29** Milling and boring operations can be made more stable by correct selection of insert geometry.

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

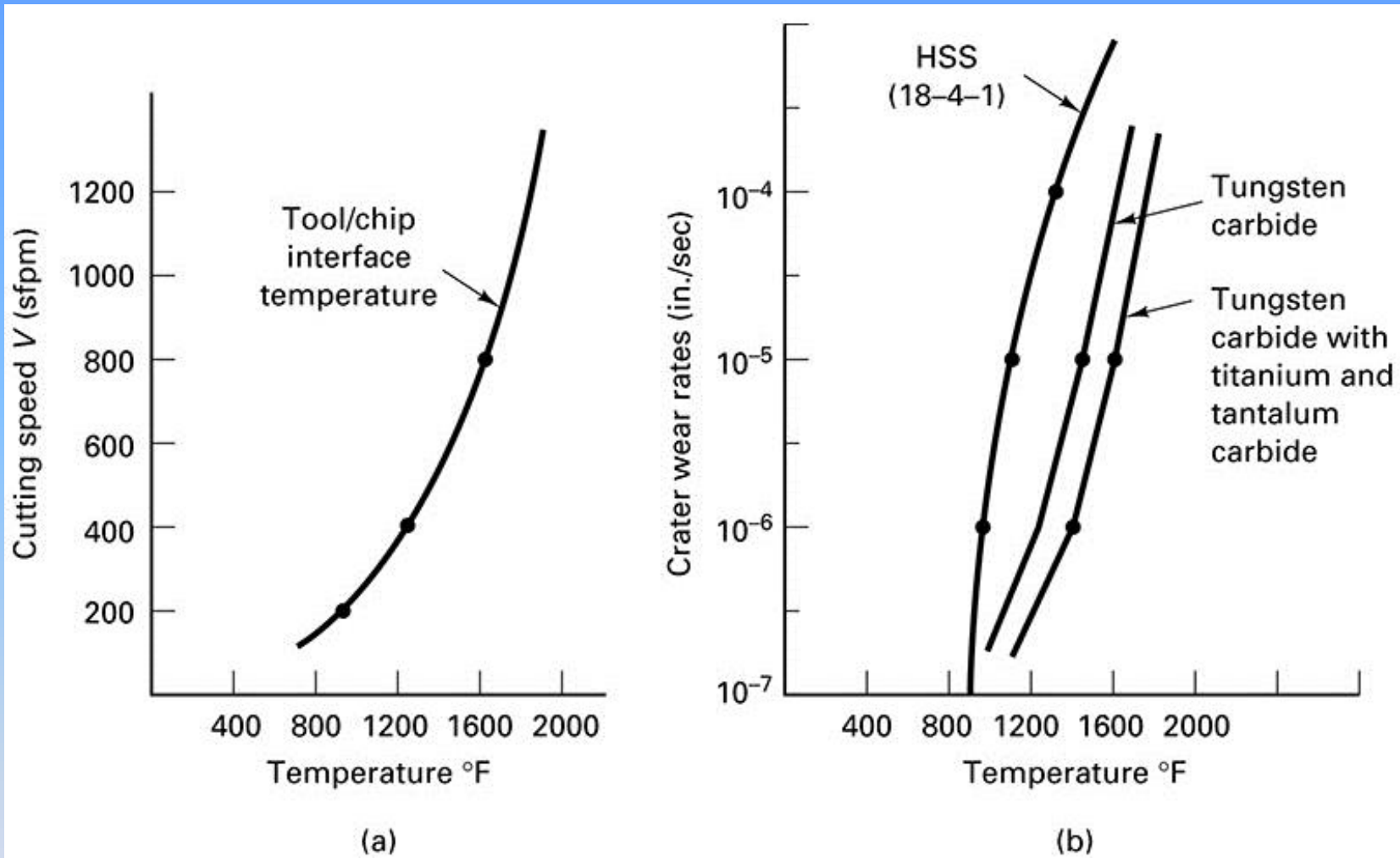




**FIGURE 20-31** Distribution of heat generated in machining to the chip, tool, and workpiece. Heat going to the environment is not shown. Figure based on the work of A. O. Schmidt.



**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