Cutting Tool Design

ITCD – 301-001

Elements of Machining

- Cutting tool
- Tool holding
- Guiding device
- Work piece
- Machine tool

Chip Formation

- Cutting tool harder and wear resistant than the workpiece material
- Interference between the tool and workpiece designated as feed and depth of cut
- Relative motion between the tool and workpiece termed as cutting speed or velocity to overcome the resistance

Cutting process parameters

- The **cutting speed**, V, is the speed with which the cutting tool moves through the work material. This is generally expressed in feet per minute (fpm) or metres per second (ms^{-1}).
- **Feed rate**, f, may be defined as the small relative movement per cycle (per revolution or per stroke) of the cutting tool in a direction usually normal to the cutting speed direction.
- **Depth of cut**, d, is the normal distance between the unmachined surface and the machined surface.

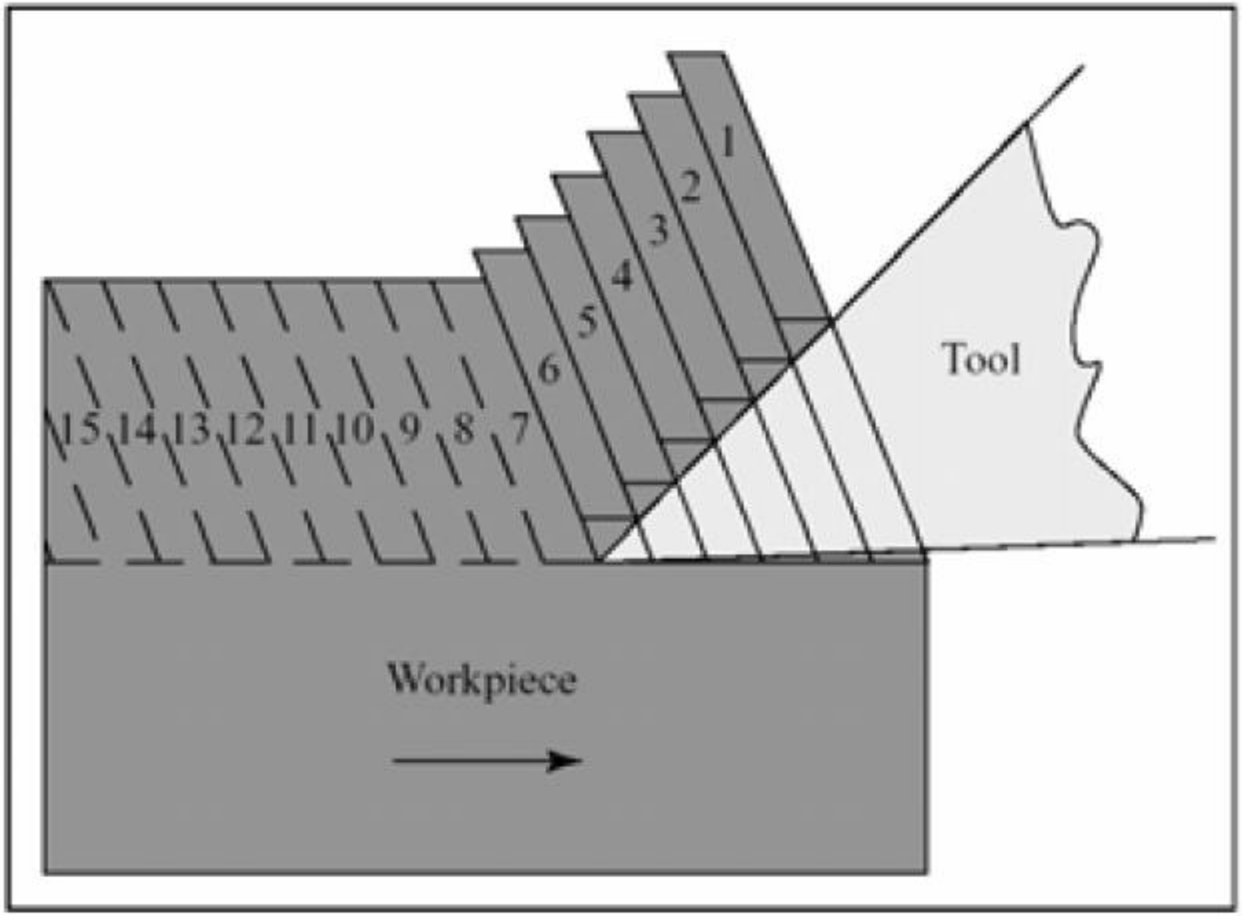


FIGURE 2.4 Chip formation compared to a sliding deck of cards.

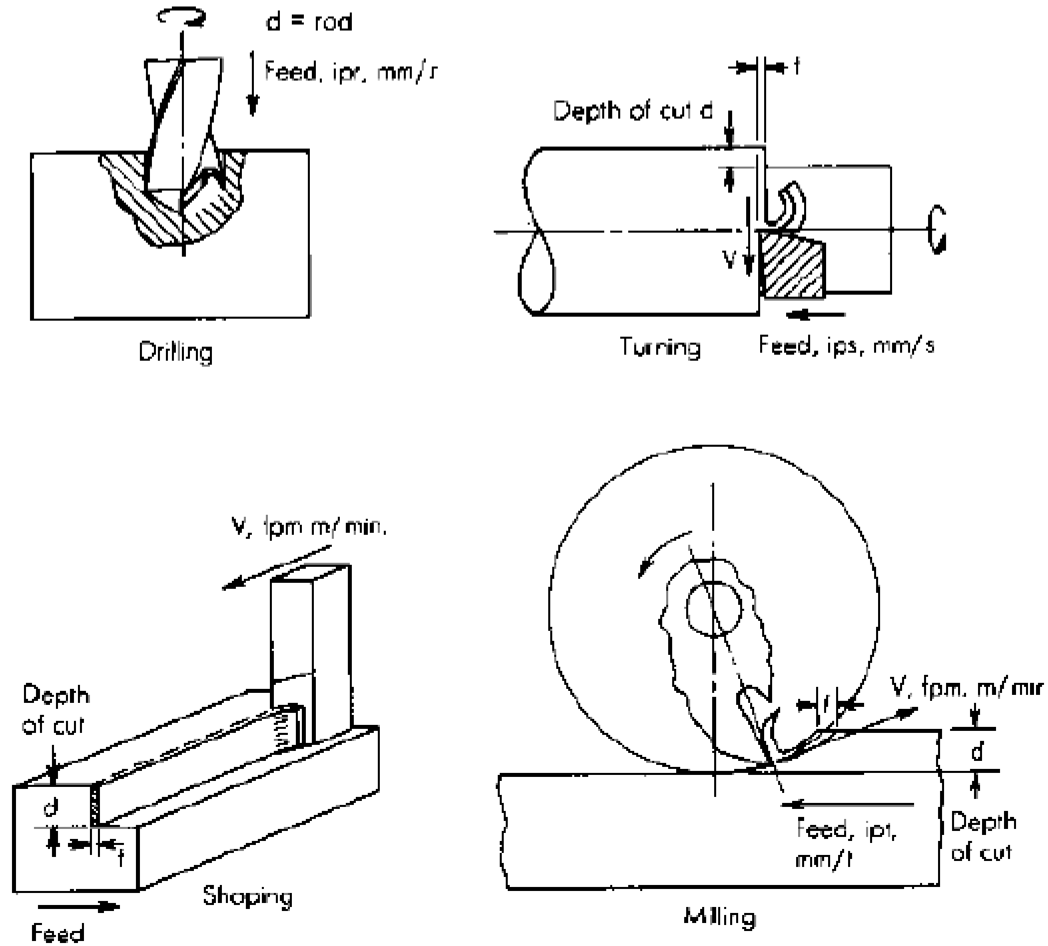


Figure 3-8. Examples of feed depth and velocity relationships for several chip-formation processes.

Type of Chips

- The chip formation in metal cutting could be broadly categorised into three types:
  - Continuous chip,
  - Continuous chip with BUE, and
  - Discontinuous chip

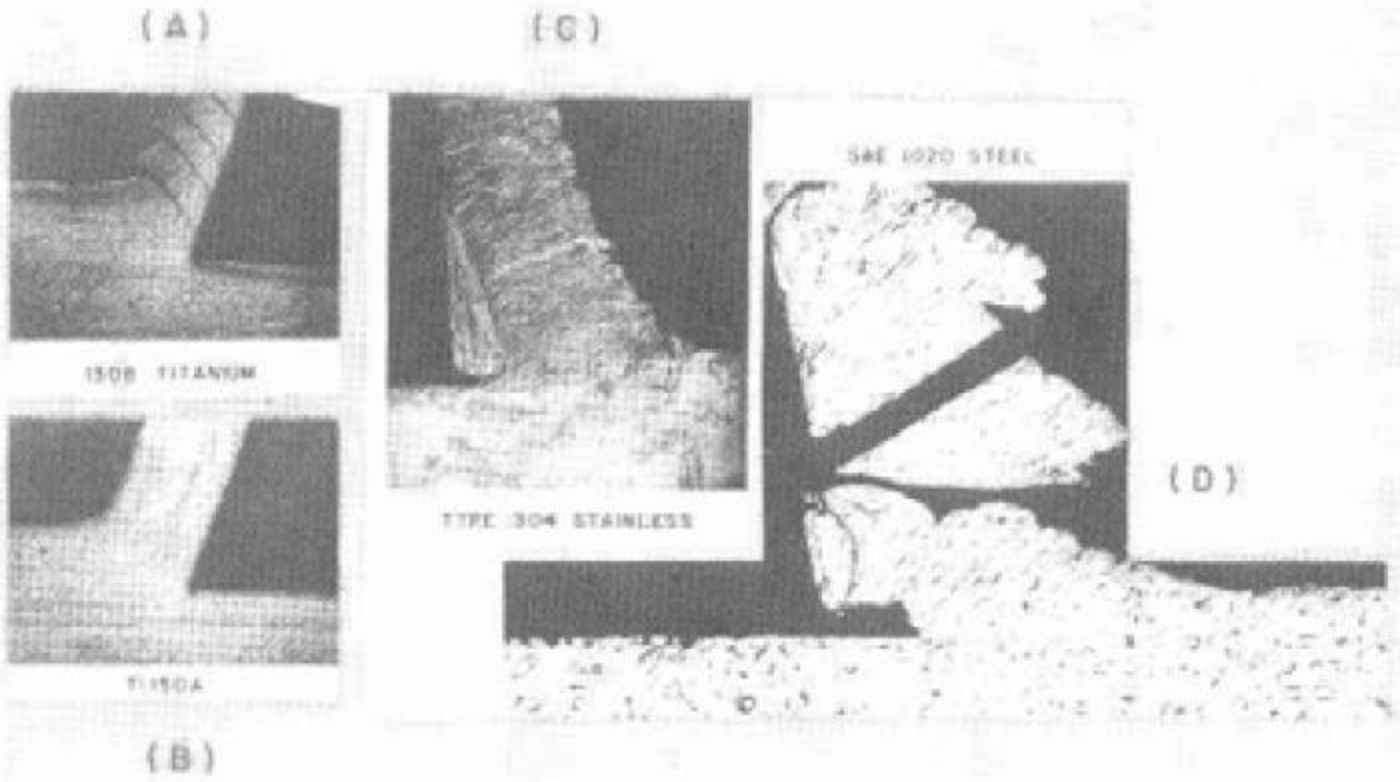


Figure 3-9. Examples of types of chips: (*A*) segmental chip. (*B*) continuous chip without built-up edge. (*C*) continuous chip with built-up edge. Part (*D*) shows the "piling up" or heavy distortion common to soft, ductile materials which have a large capacity for plastic flow.

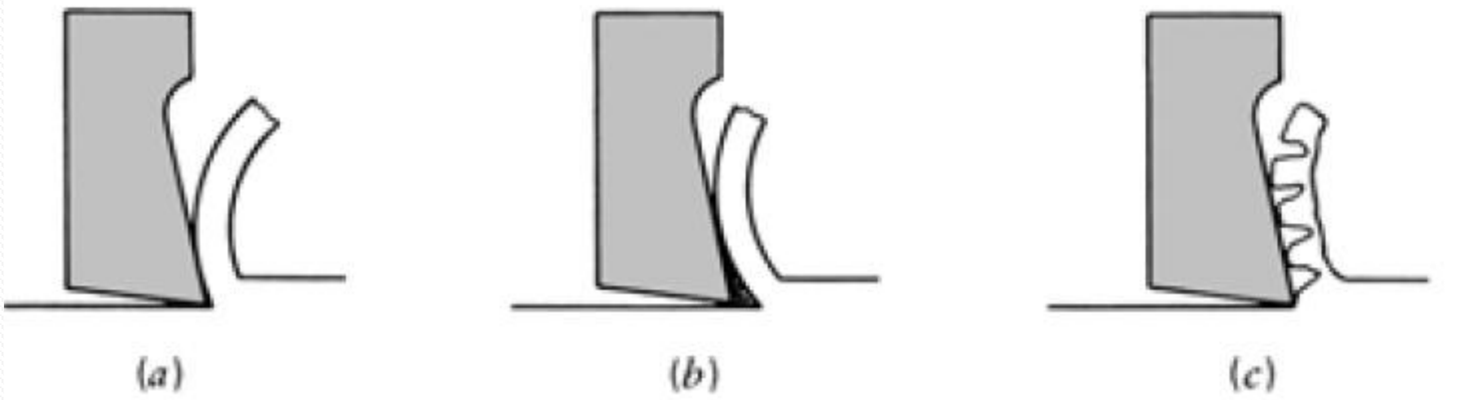
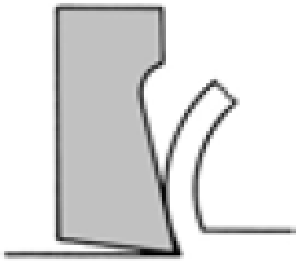


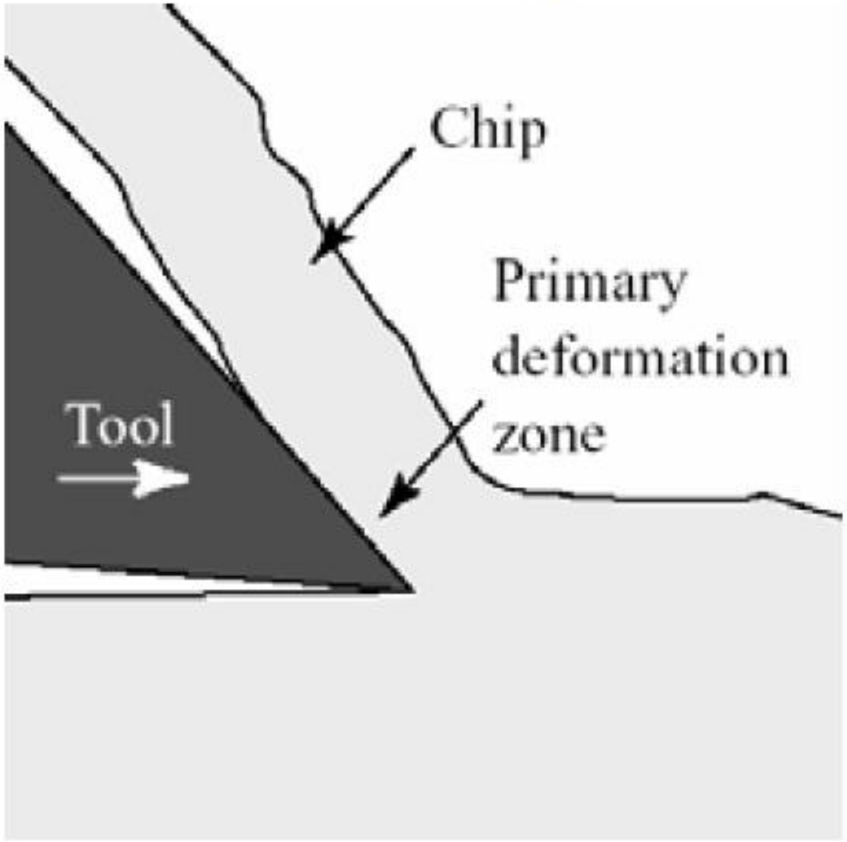
FIGURE F-14 The three types of chip formation: *(a)* continuous; (b) continuous with built-up edge; (c) discontinuous (segmented). (J.E. Neely, *Practical Metallurgy and Materials of Industry*, 2nd ed., Wiley, New York, copyright © 1984.)

Continuous chip



- Continuous chips are normally produced when machining steel or ductile metals at high cutting speeds.
- The continuous chip which is like a ribbon flows along the rake face.
- Continuous chip is possible because of the ductility of metal (steel at high temperature generated due to cutting) flows along the shear plane instead of rupture.

Continuous chip



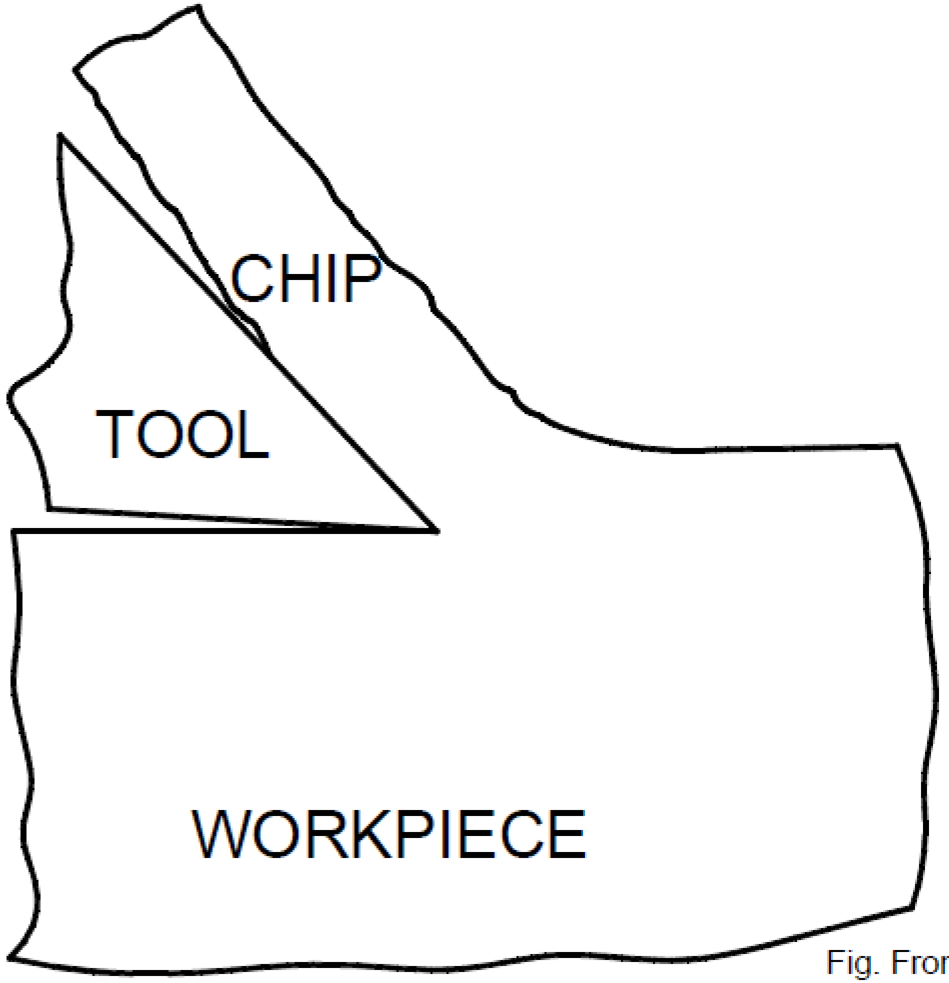
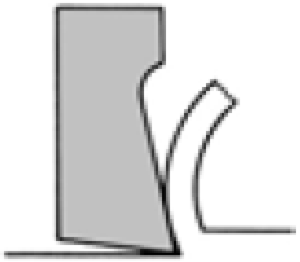


Fig. From P N Rao – Metal Cutting and Machine Tools, Tata McGraw Hill, 2000

Continuous chip



- It can be assumed that each layer of metal flows along the slip plane till it is stopped by work hardening.
- Each of these layers get welded to the previous ones because of the high temperature, thus forming a continuous chip.

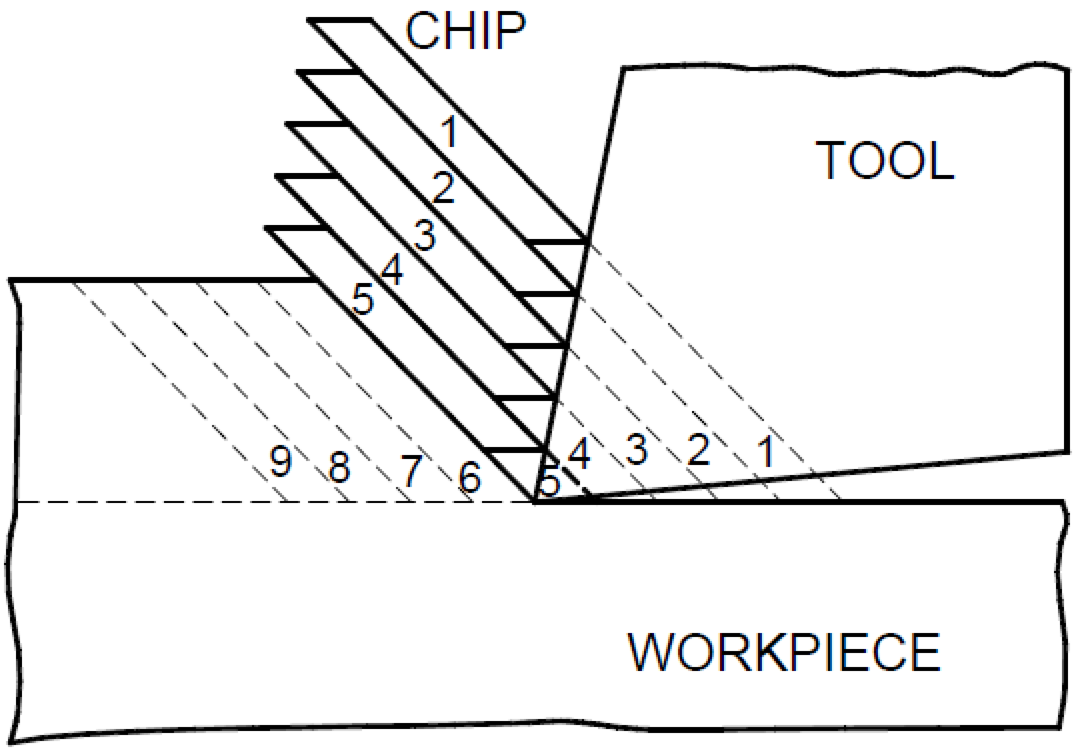
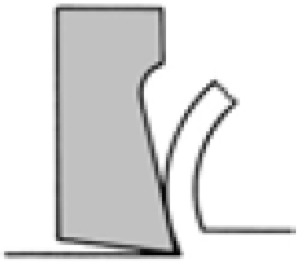


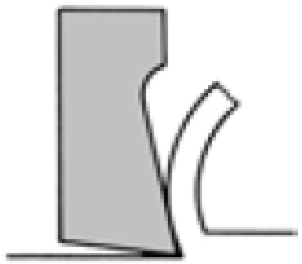
Fig. From P N Rao – Metal Cutting and Machine Tools, Tata McGraw Hill, 2000

Continuous chip



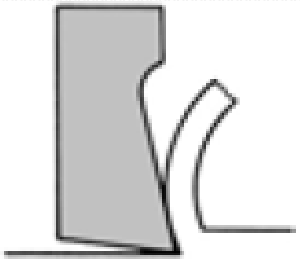
- Some ideal conditions that promote continuous chips in metal cutting are:
  - –sharp cutting edge,
  - –small chip thickness (fine feed),
  - –large rake angle,
  - –high cutting speed,
  - –ductile work materials and
  - –less friction between chip tool interface through efficient lubrication.

Continuous chip



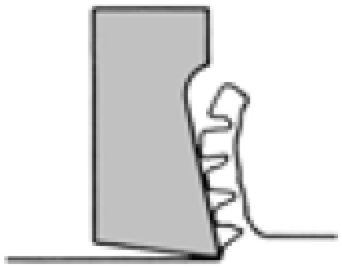
- This is the most desirable form of chip since the surface finish obtained is good and cutting is smooth.
- It also helps in having higher tool life and lower power consumption.
- However, because of the large coils of chips, the chip disposal is a problem.

Continuous chip



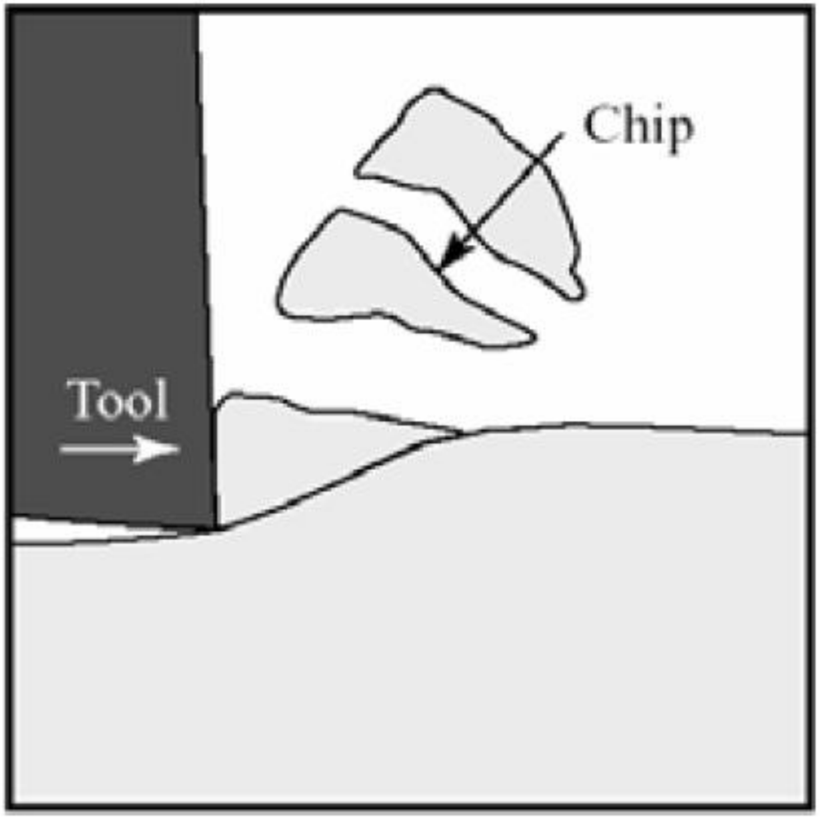
- However, because of the large coils of chips, the chip disposal is a problem.
- To help in this direction various forms of chip breakers have been developed which are in the form of a step or groove in the tool rake face.
- The chip breakers allow the chips to be broken into small pieces so that they can be easily disposed off.

Discontinuous chip

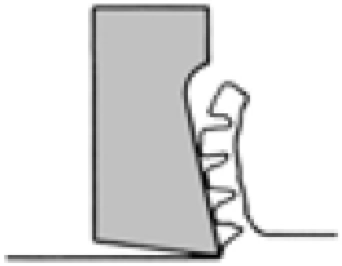


- When brittle materials like cast iron are cut, the deformed material gets fractured very easily and thus the chip produced is in the form of discontinuous segments.
- In this type the deformed material instead of flowing continuously gets ruptured periodically.

Discontinuous chip



Discontinuous chip



- Discontinuous chips are easier from the chip disposal view point.
- However, the cutting force becomes unstable with the variation coinciding with the fracturing cycle.

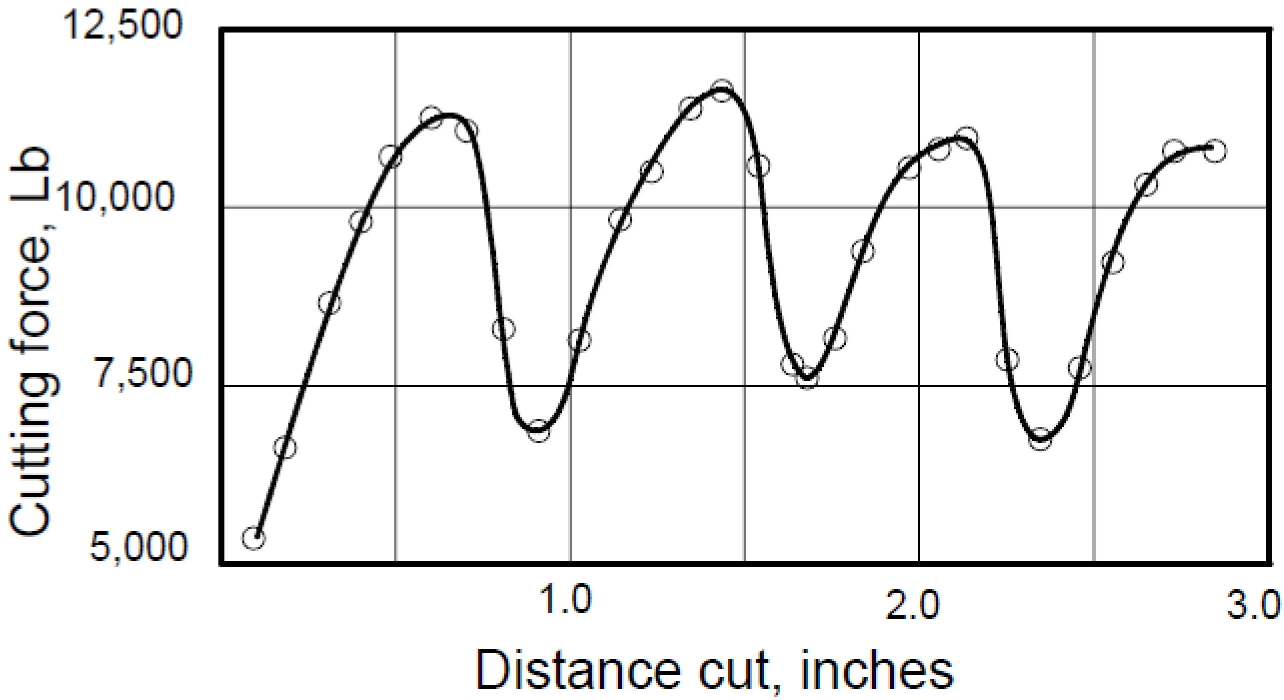
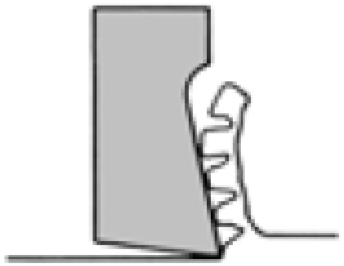


Fig. From P N Rao – Metal Cutting and Machine Tools, Tata McGraw Hill, 2000

Discontinuous chip

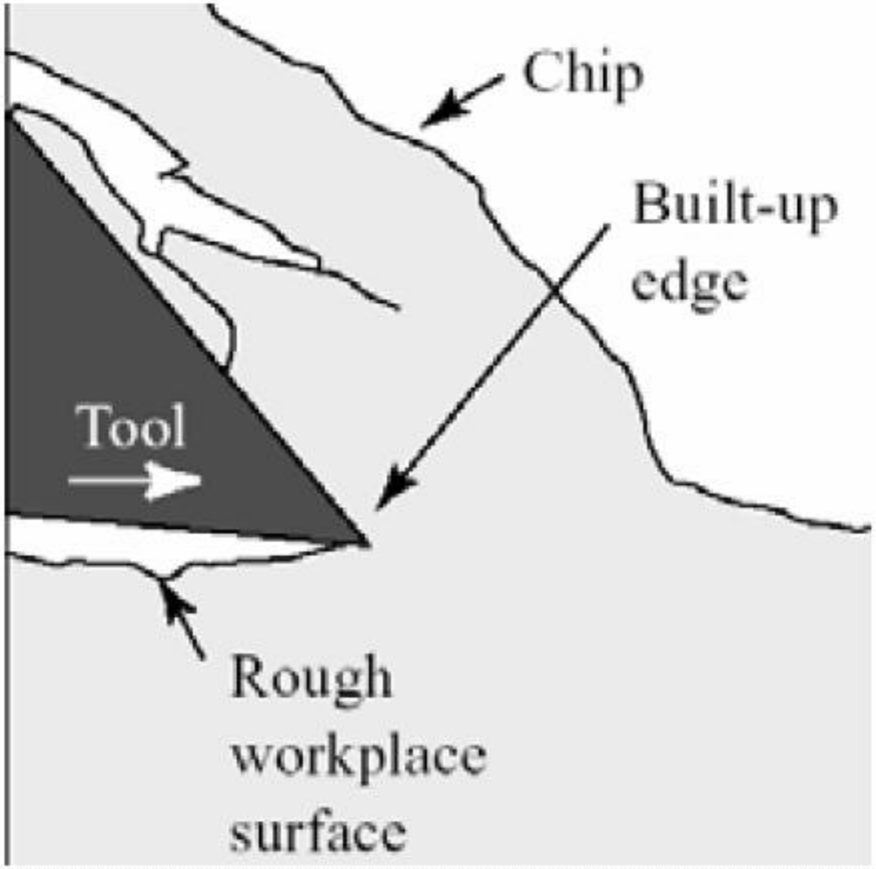


- Also they generally provide better surface finish.
- However, in case of ductile materials they cause poor surface finish and low tool life.
- Higher depths of cut (large chip thickness), low cutting speeds and small rake angles are likely to produce discontinuous chips.

Continuous chip with BUE

- When the friction between tool and chip is high while machining ductile materials, some particles of chip adhere to the tool rake face near the tool tip.
- When such sizeable material piles up on the rake face, it acts as a cutting edge in place of the actual cutting edge.
- This is termed as built up edge (BUE).

Continuous chip with BUE



Continuous chip with BUE

- By virtue of work hardening, BUE is harder than the parent work material.
- As the size of BUE grows larger, it becomes unstable and parts of it gets removed while cutting.
- The removed portions of BUE partly adheres to the chip underside and partly to the machined surface.

Continuous chip with BUE

Fig. From P N Rao – Metal Cutting and Machine Tools, Tata McGraw Hill, 2000

Continuous chip with BUE

- This causes finished surface to be rough.
- However, since the cutting is being carried by the BUE and not the actual tool tip, the life of the cutting tool increases while cutting with BUE.
- That way BUE is not harmful while rough machining.

Continuous chip with BUE

- The conditions that normally induce the formation of BUE are
  - –low cutting speed,
  - –high feed, and
  - –low rake angle.
- One of the prerequisites for the formation of BUE is the work hardenability of the workpiece material.
- Higher the work hardenability, rougher is the machined surface produced.

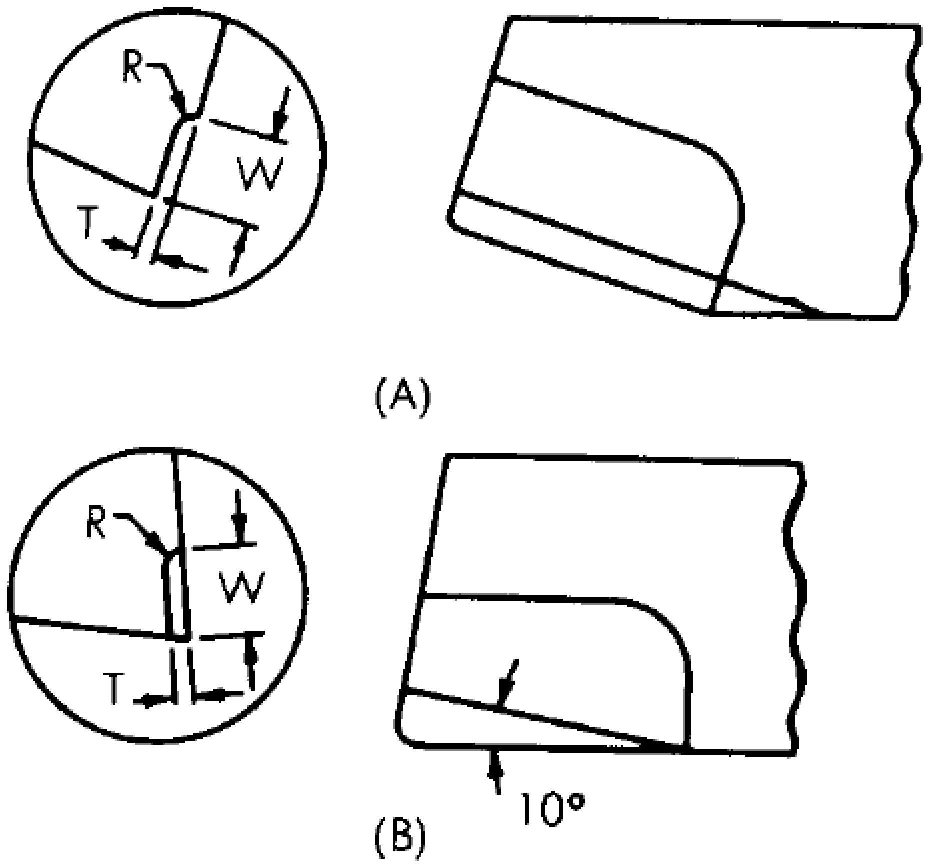


Figure 3-7. Chip grooves ground into tools.

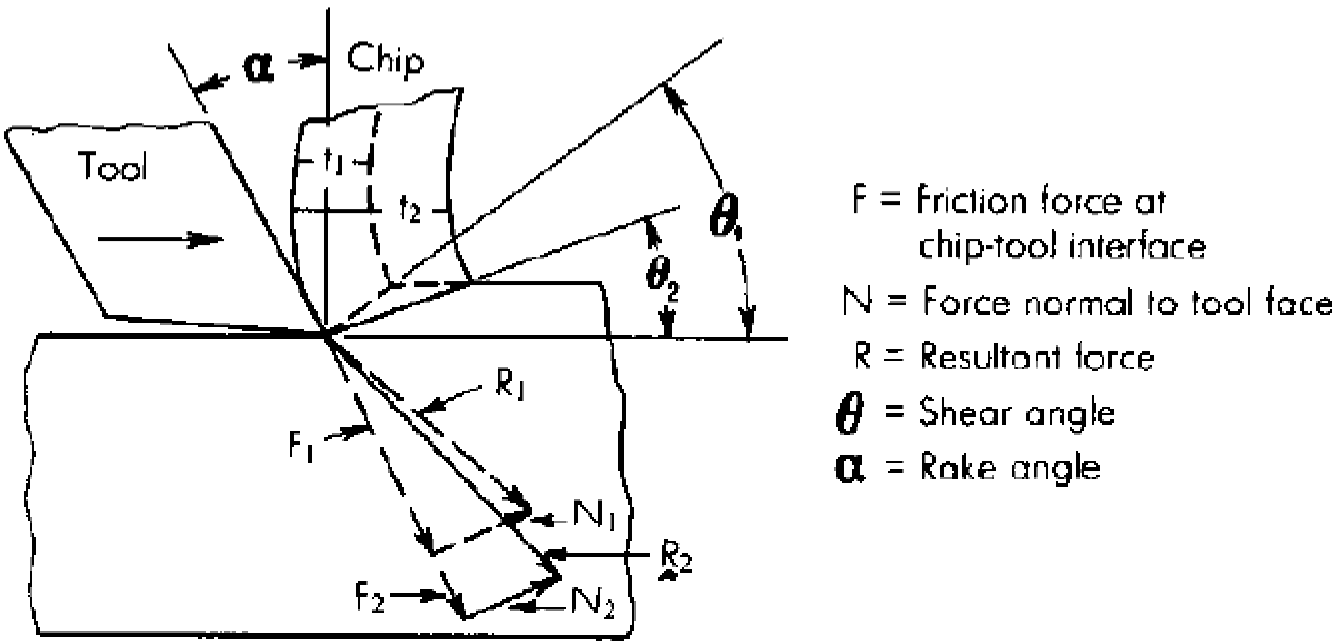
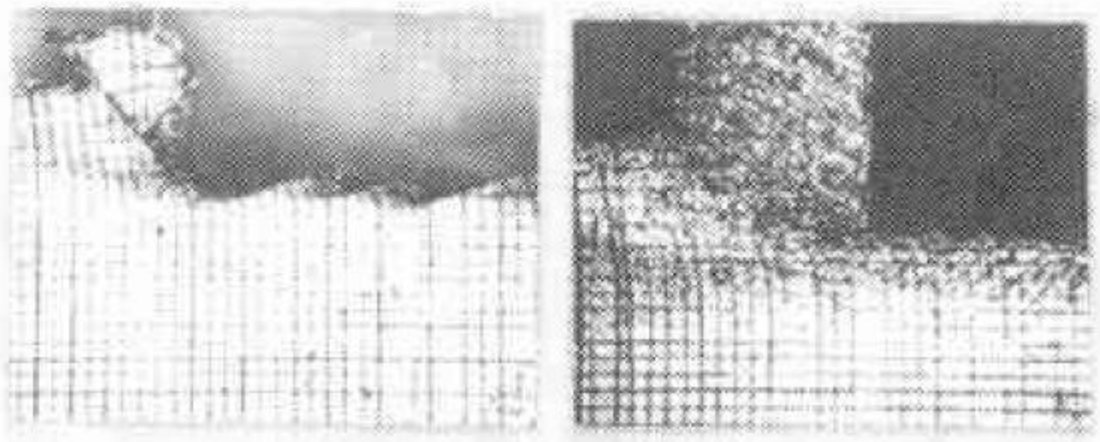


Figure 3-10. Effect of friction force upon shear angle and upon amount of chip distortion. Force polygons show effect of friction force upon magnitude and direction of resultant force.



(A) (B)

Figure 3-11. Grid specimens showing amount of distortion in chip and adjacent area in (*A*) brittle material, and (*B*) ductile material. Grid lines 0.003 in. apart. Line of demarcation between chip and parent material is the shear plane. Wavy surface in (*A*) due to chatter.

Figure 3-12. Underside of a chip that had seized to the face of the cutting tool in the light area along the cutting edge. Part of the built-up edge is shown in the process of passing off with the chip. Part of it was also being forced over the cutting edge of the tool and would eventually be deposited on the work surface.

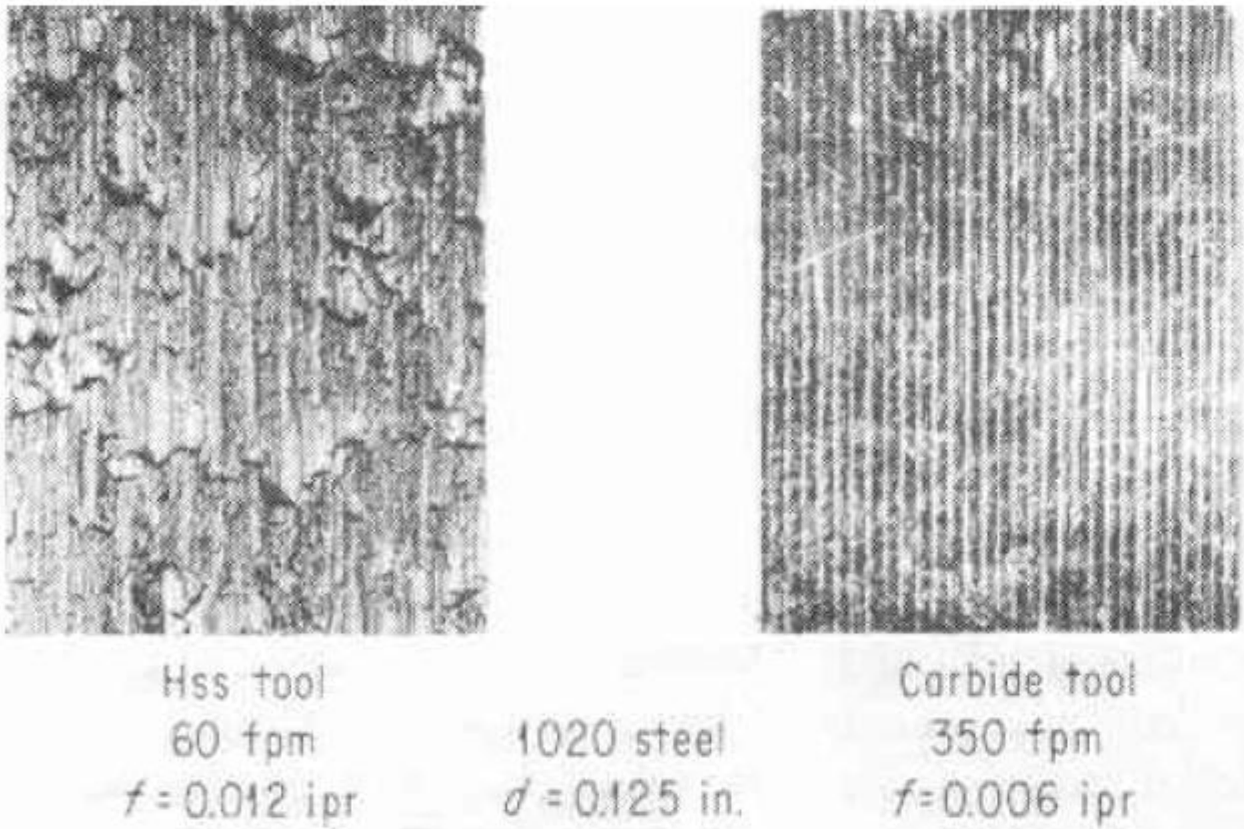


Figure 3-13. Surfaces produced on hot rolled AISI 1020 steel under conditions that resulted in continuous chip formation with built-up edge (left), and without built-up edge (right).

Manipulating Factors

- Cutting speed
- Size of cut
- Effect of tool geometry
- Tool material
- Cutting fluid
- Work piece material

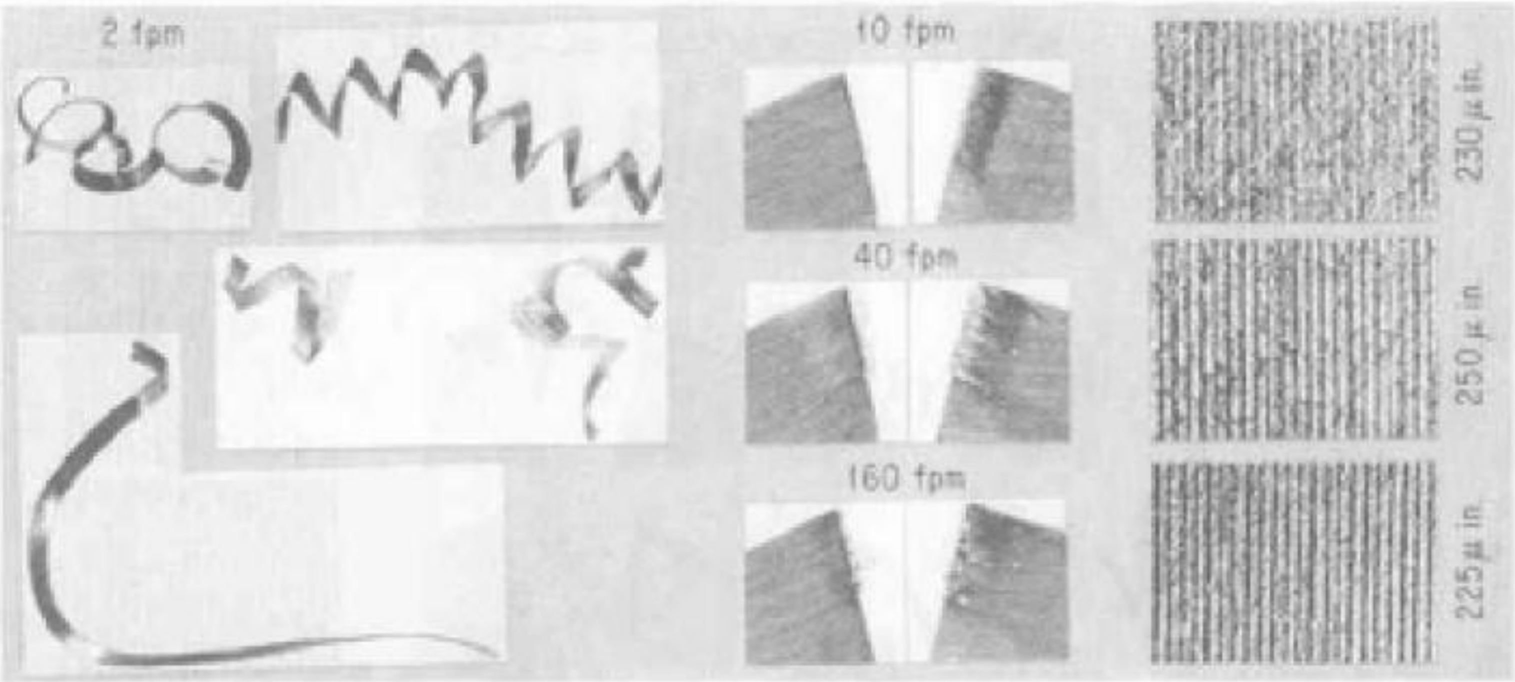
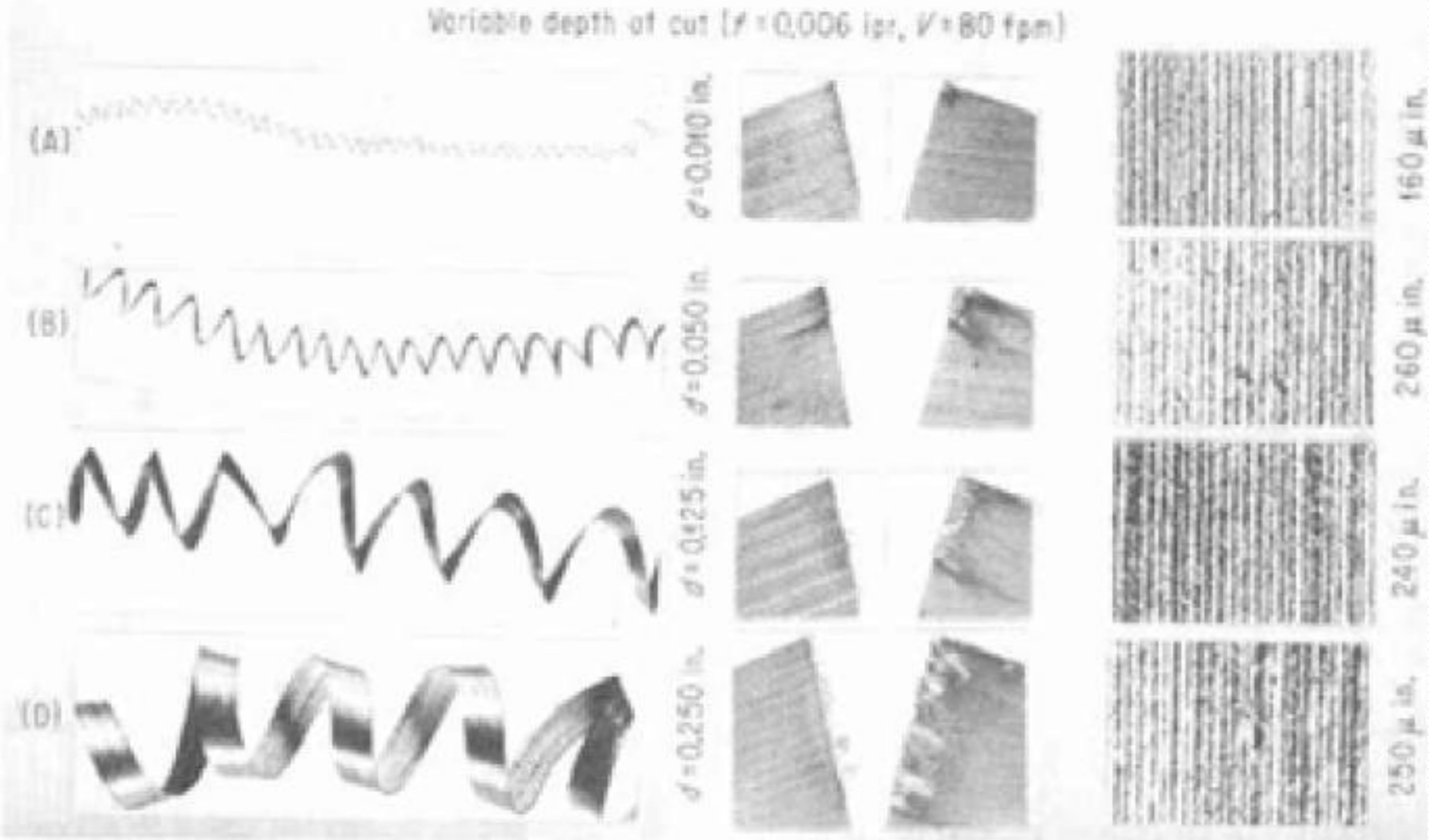


Figure 3-14. Examples of chips, tools, and surfaces to show effect of velocity on chip formation, built-up edge, and surface quality. Approximate relative magnifications: chips, 1X; tools, 4X; surface, 10X. Note that velocity has practically no effect upon direction of chip flow as seen by markings on tool face. The relatively small effect of velocity on surface finish is due to the fact that practical permissible velocities with HSS tools are not high enough to completely eliminate built-up edge. Tool material—HSS. Tool shape—8, 21, 6, 6, 6, 15, 0. Work material—SAE 1020. Cutting fluid—dry.


Variable depth of cut (f = 0.006 ipr, V = 80 fpm)
(A)
(B)
(C)
(D)
d = 0.010 in.
d = 0.050 in.
d = 0.125 in.
d = 0.250 in.
160 μ in.
260 μ in.
240 μ in.
250 μ in.

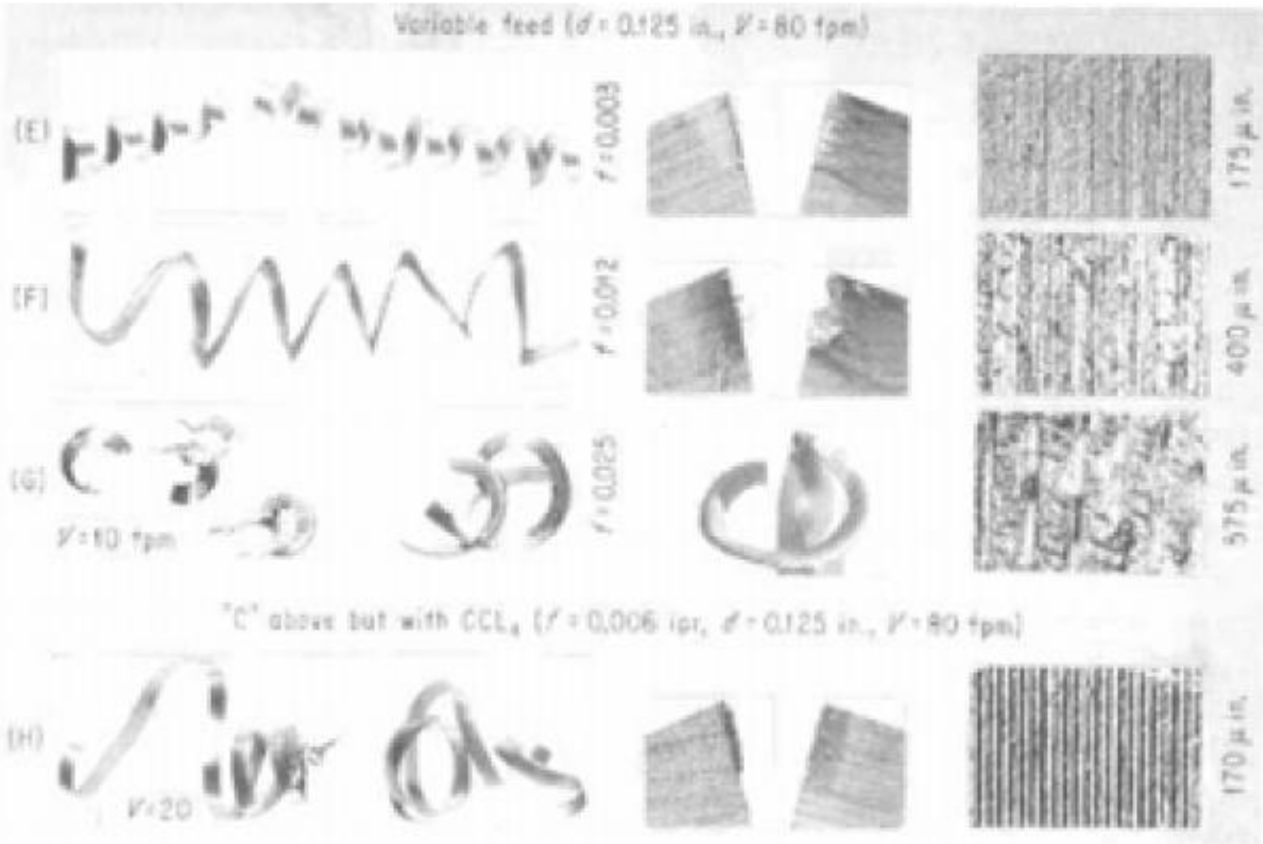
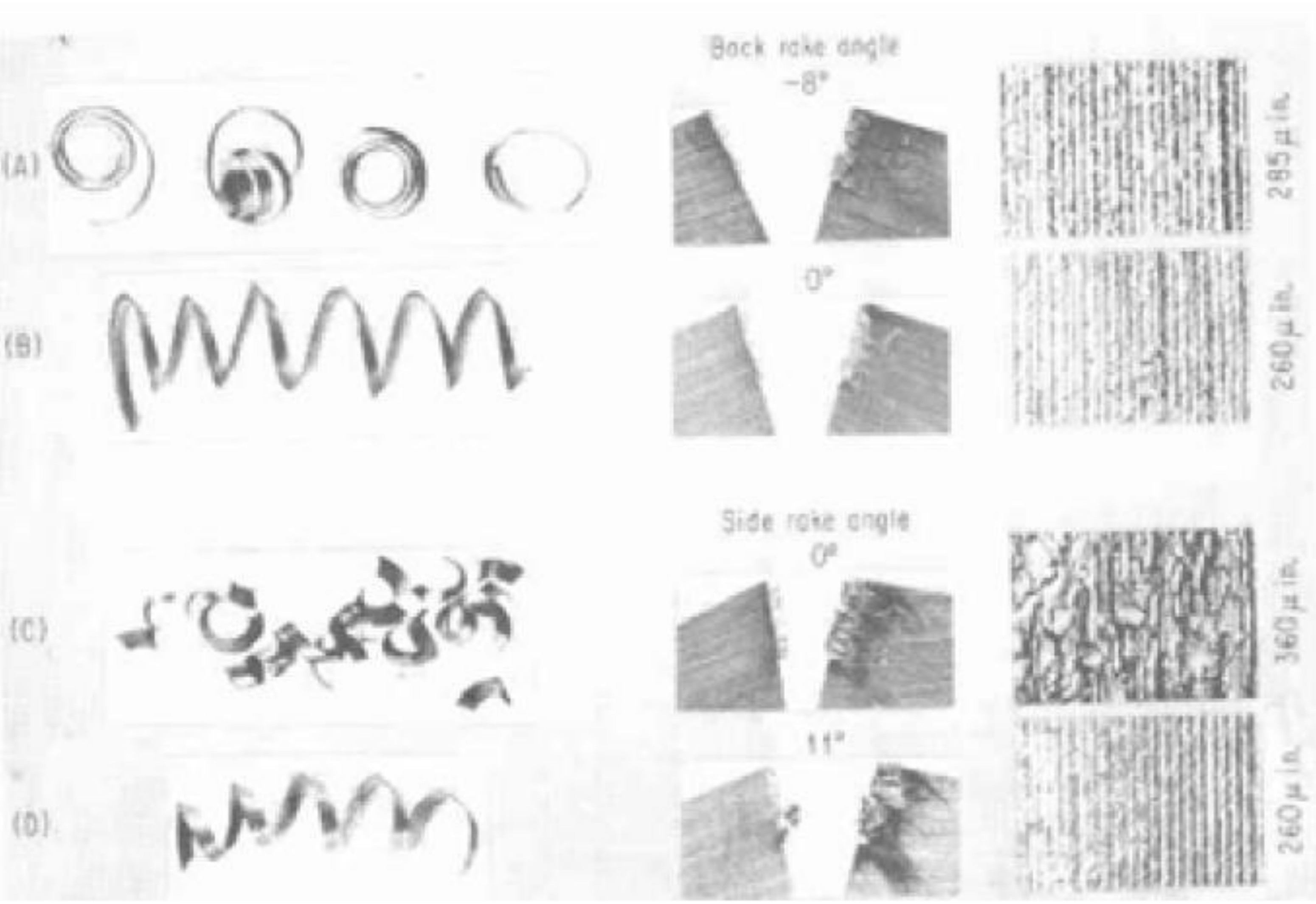


Figure 3-15. Examples showing effect of feed and depth of cut on chip form, built-up edge, and surface quality. Note how direction of chip flow changes with size of cut. Tool material—HSS. Tool shape—8, 21, 6, 6, 6, 15, 0. Work material—SAE 1020. Cutting fluid—dry.


(A)
(B)
(C)
(D)
Back rake angle
−8°
0°
Side rake angle
0°
11°
285 μ in.
260 μ in.
360 μ in.
260 μ in.

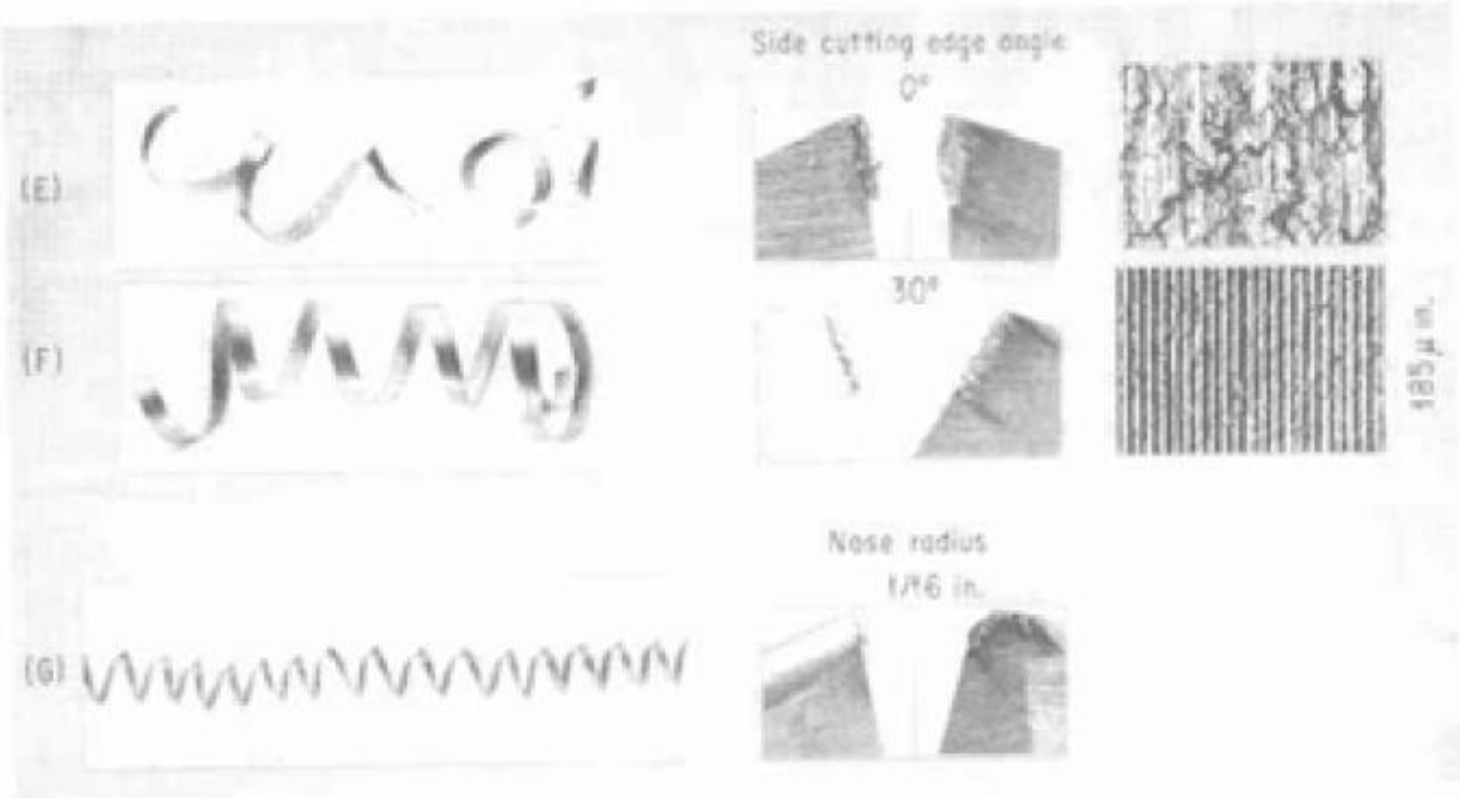
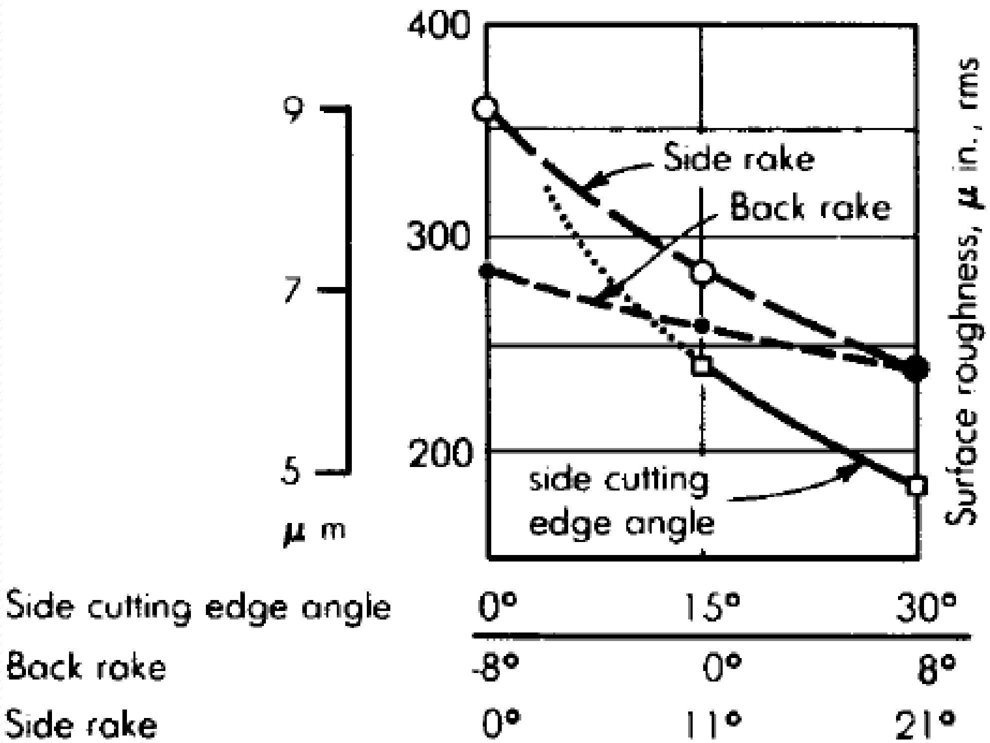


Figure 3-16. Effect of changes in tool geometry upon chip form, built-up edge, and surface quality. Note also the effect upon direction of chip flow. Tool material—HSS. Work material—SAE 1020. Cutting fluid—dry. Basic tool shape—8, 21, 6, 6, 6, 15, 0.



Effect of tool geometry

f = 0.006 ipr (0.15 mm/r)

d = 0.125″ (3.18 mm)

V = 80 fpm (24.38 m/min.)

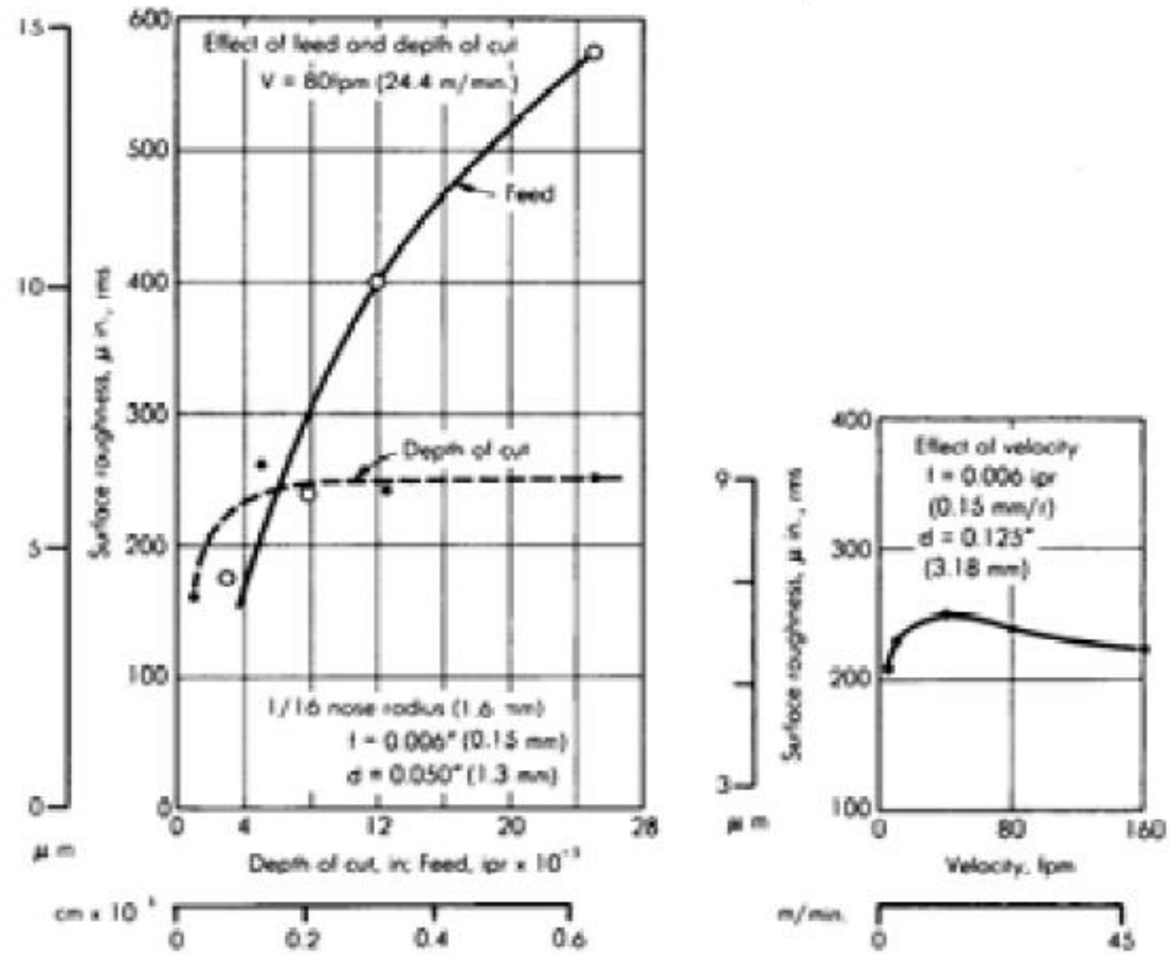


Figure 3-17. Summary of surface roughness results given in *Figures 3-14* through *3-16*. Standard tool geometry—8,21,6,6,6,15,0. HSS tools. Work material—AISI 1020 hot rolled steel.

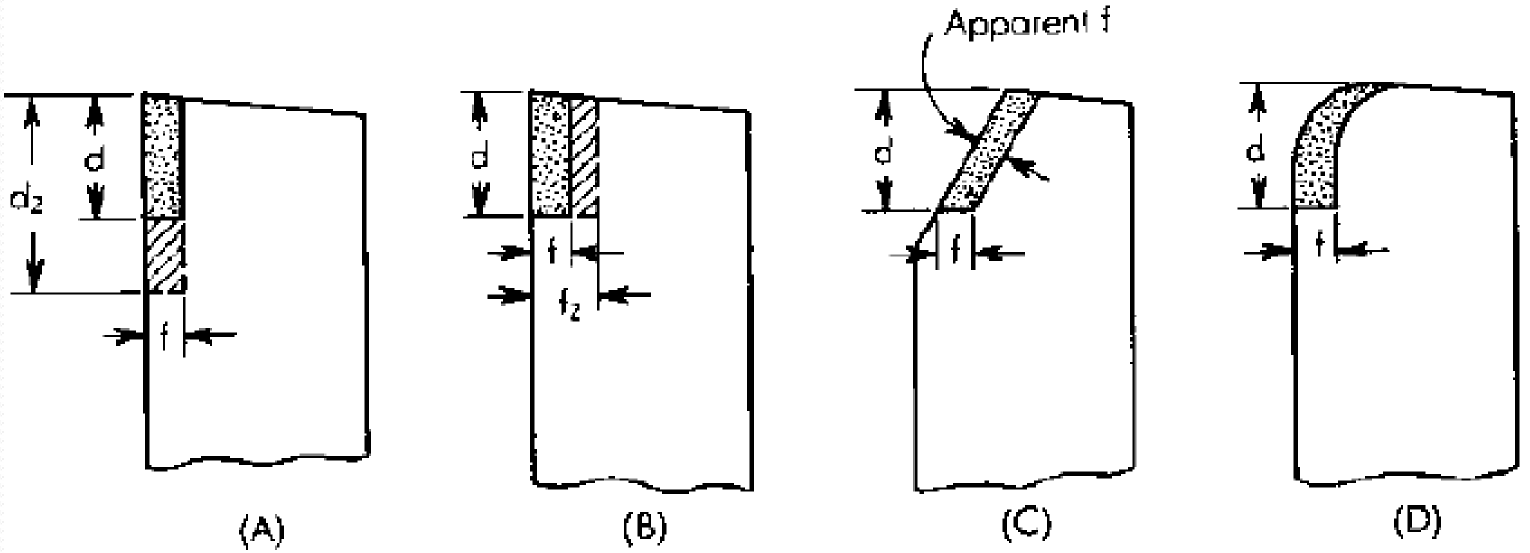


Figure 3-18. Effect of size of cut and changes in tool geometry upon chip thickness: (*A*) change in depth, (*B*) change in feed, (*C*) effect of side cutting edge angle, and (*D*) effect of nose radius. Crosshatched portions represent increase in contact area.

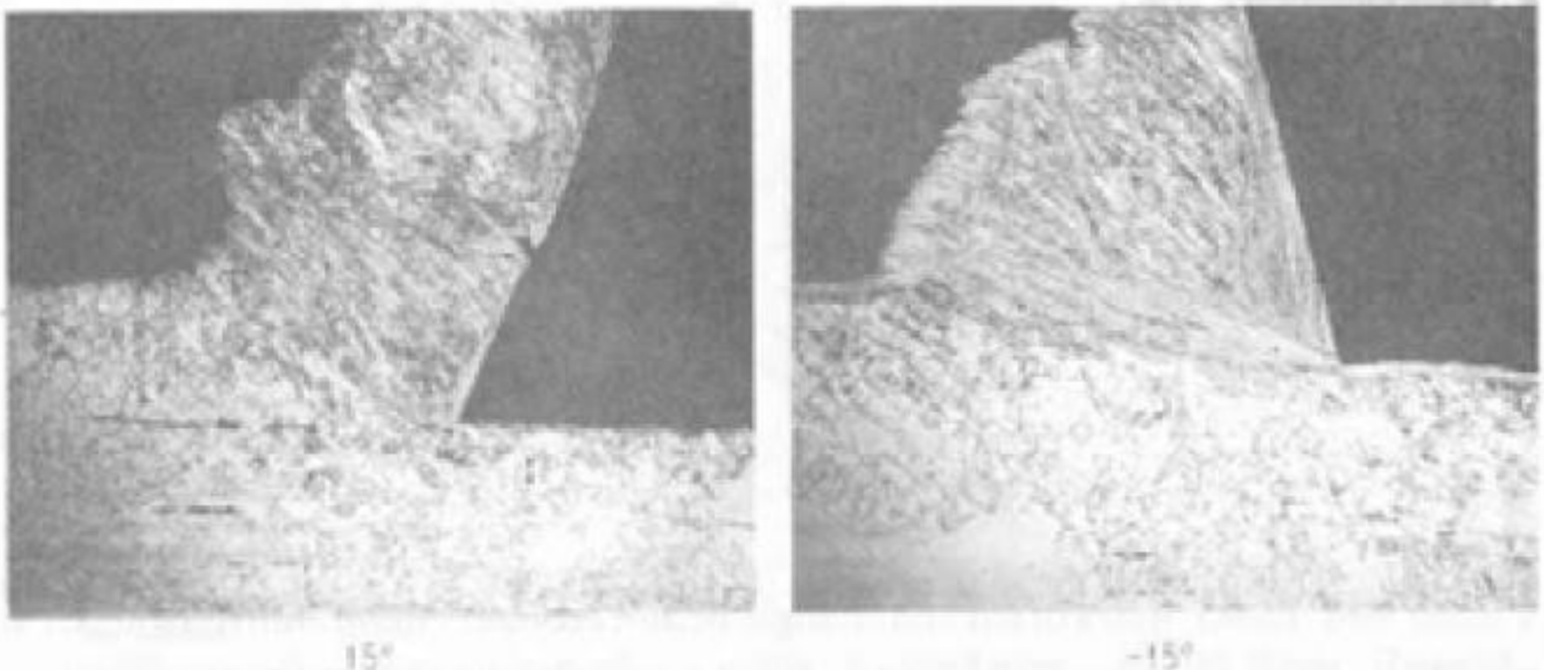
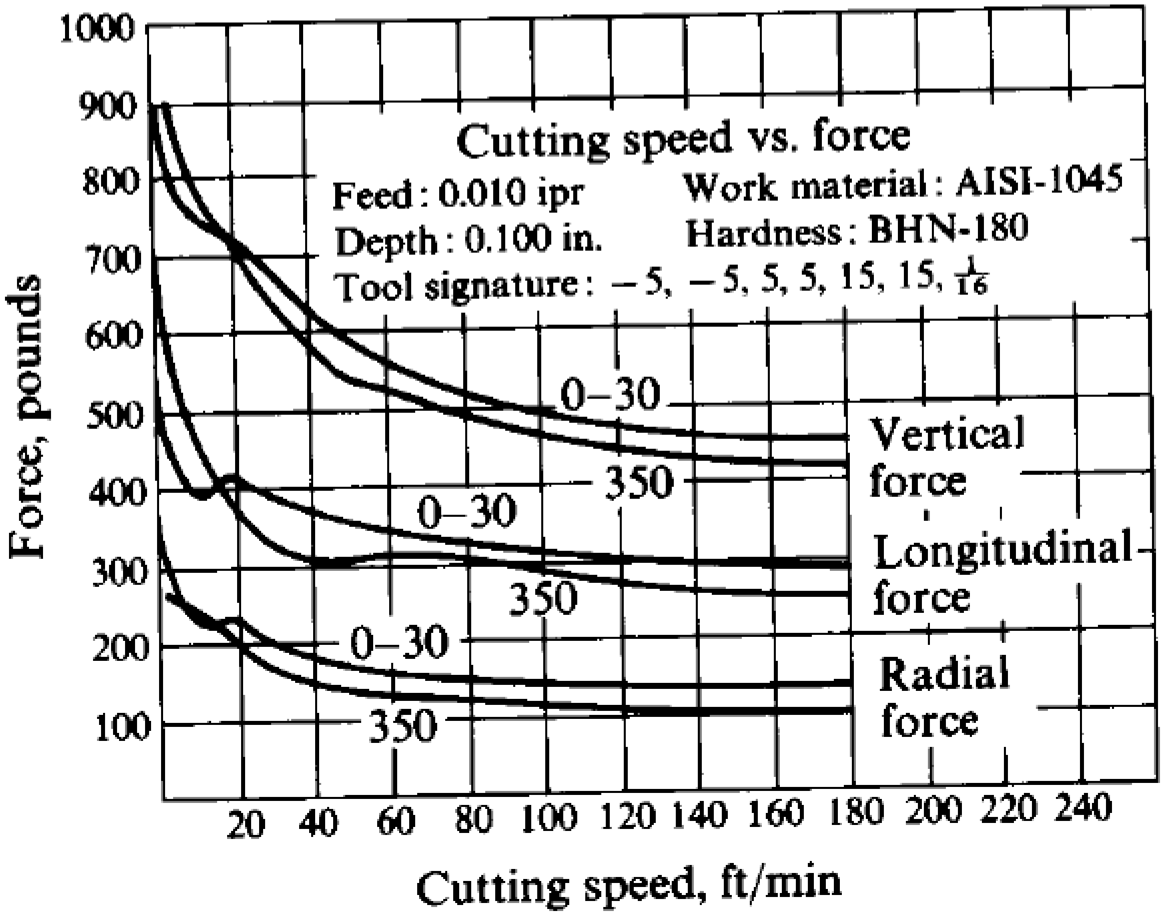


Figure 3-19. Photomicrographs showing effect of rake angle upon shear angle, chip distortion, built-up edge, and work hardening of machined surface. Shaper tools set for some depth of cut. Apparent difference in depth due to higher separating force and greater tool deflection with negative rake tool. Work material—304 stainless steel.

Cutting Forces

- Cutting force
- Radial force
- Axial force

Cutting speed vs. force.



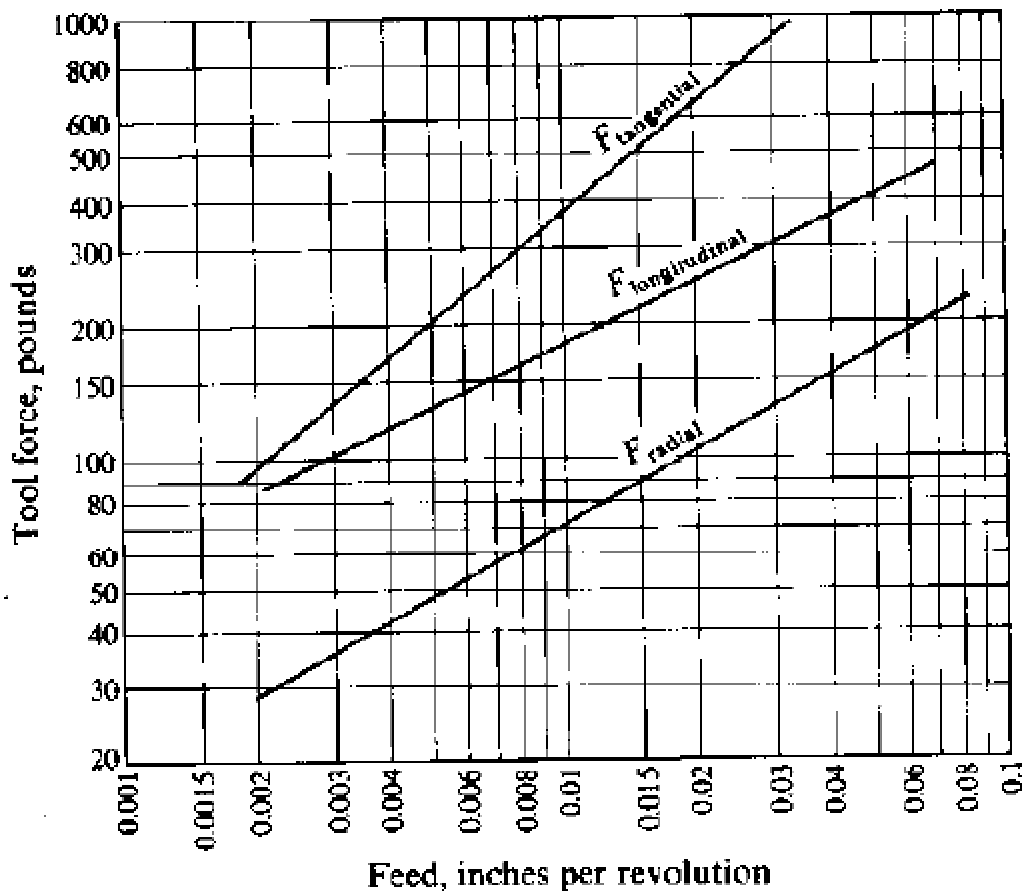


FIGURE 4-20
Effect of feed on the components of the tool force when turning 0.21 carbon steel with a high-speed-steel tool. (Tool designation, 8, 14, 6, 6, 6, 0, $\frac{5}{64}$. Depth of cut, $\frac{1}{8}$ in.; cutting speed, 80 fpm.) (*Metallurgical*

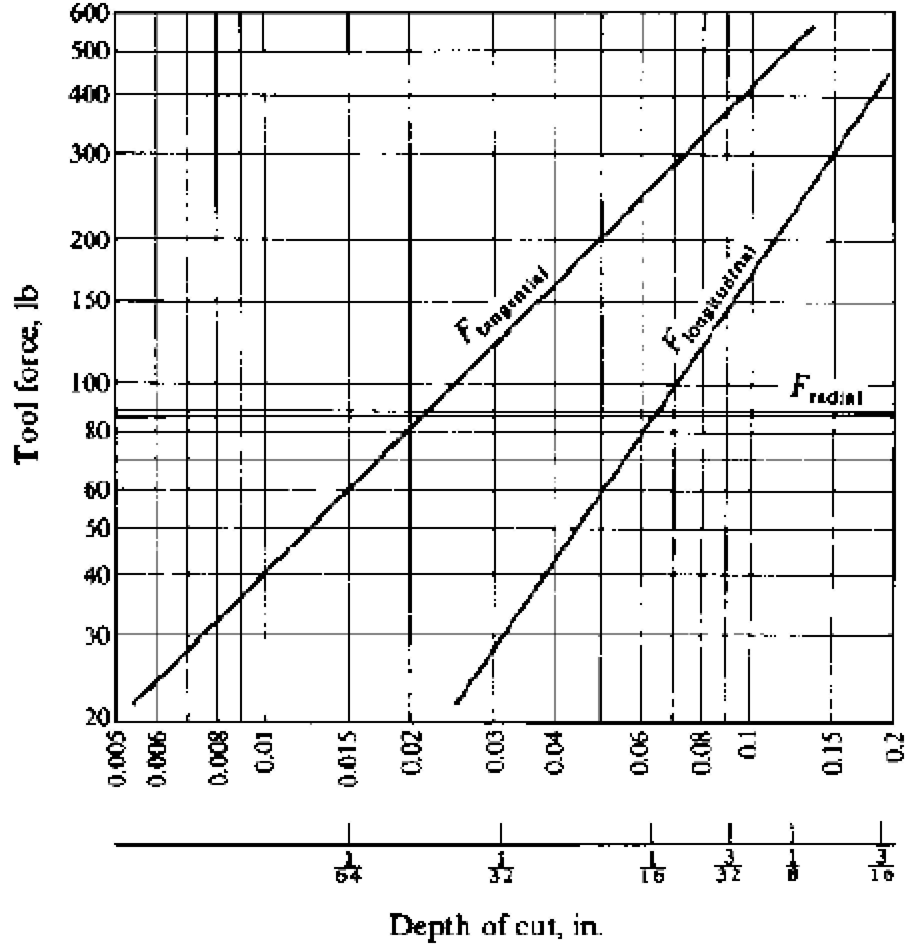
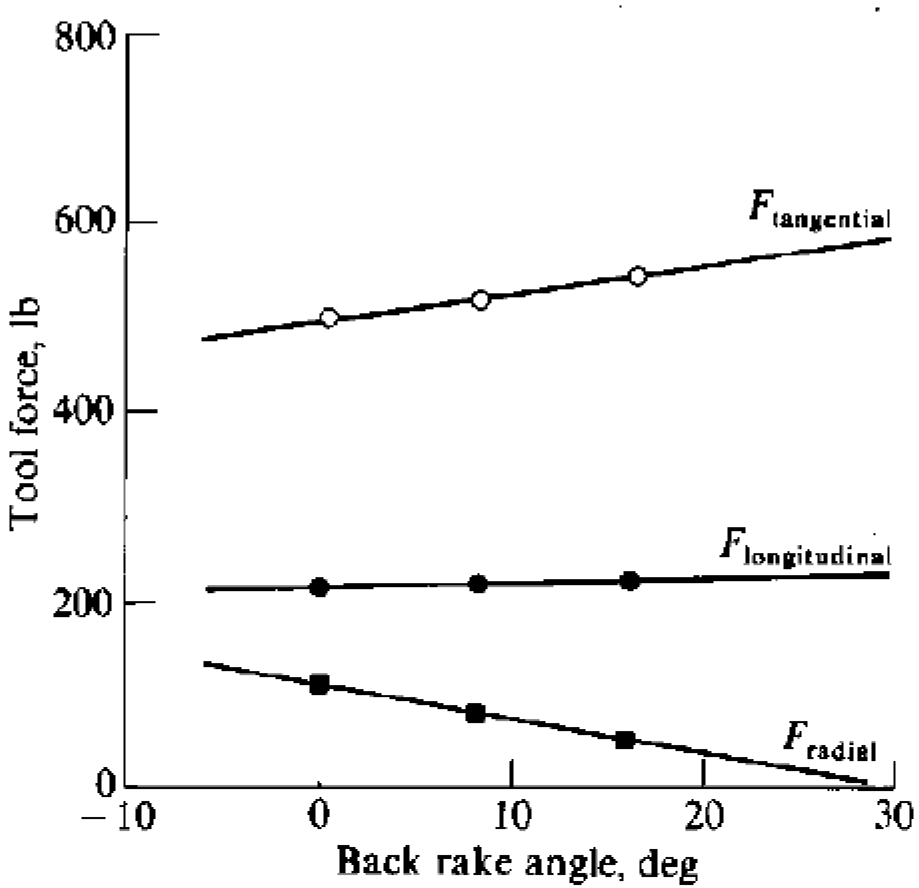
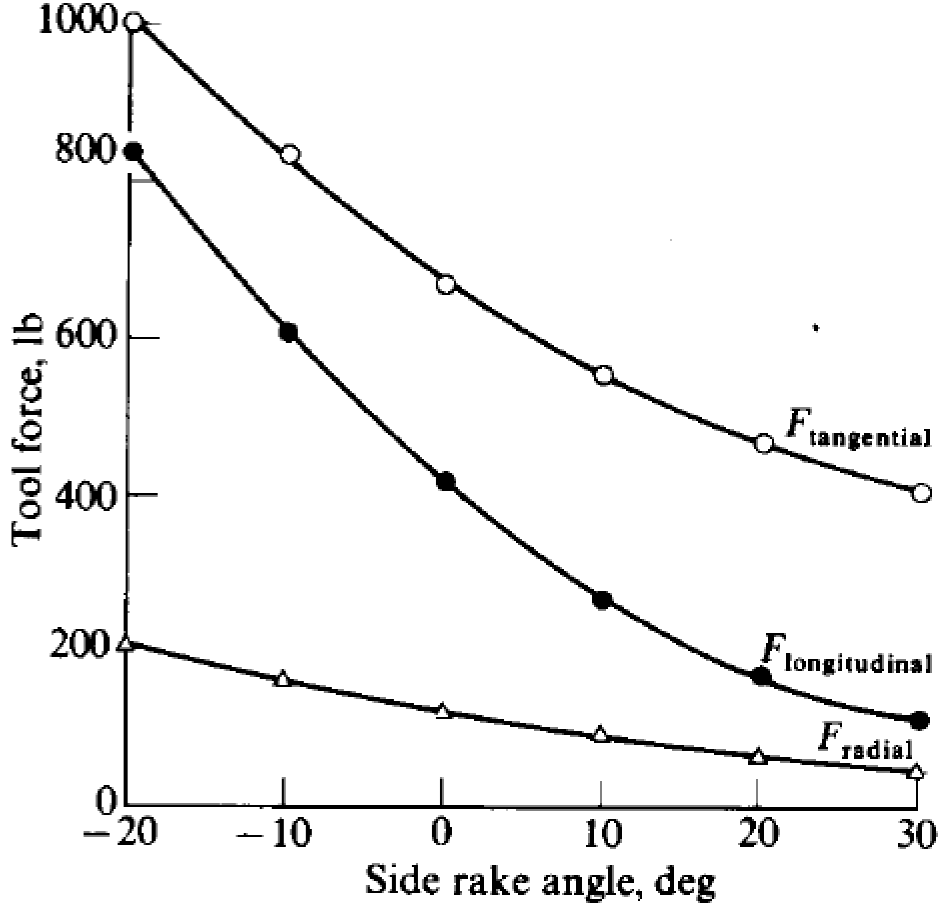


FIGURE 4-21
Effect of depth of cut on tool-force components. (Test conditions same as Fig. 4-20 except that a constant feed of $\frac{1}{64}$ in. was used.) (*Metal-*


800
600
400
200
0
Tool force, lb
$F_{tangential}$
$F_{longitudinal}$
F_{radial}
−10
0
10
20
30
Back rake angle, deg
(a)



1000
800
600
400
200
0
Tool force, lb
$F_{tangential}$
$F_{longitudinal}$
F_{radial}
– 20
– 10
0
10
20
30
Side rake angle, deg
200 fpm

(b)

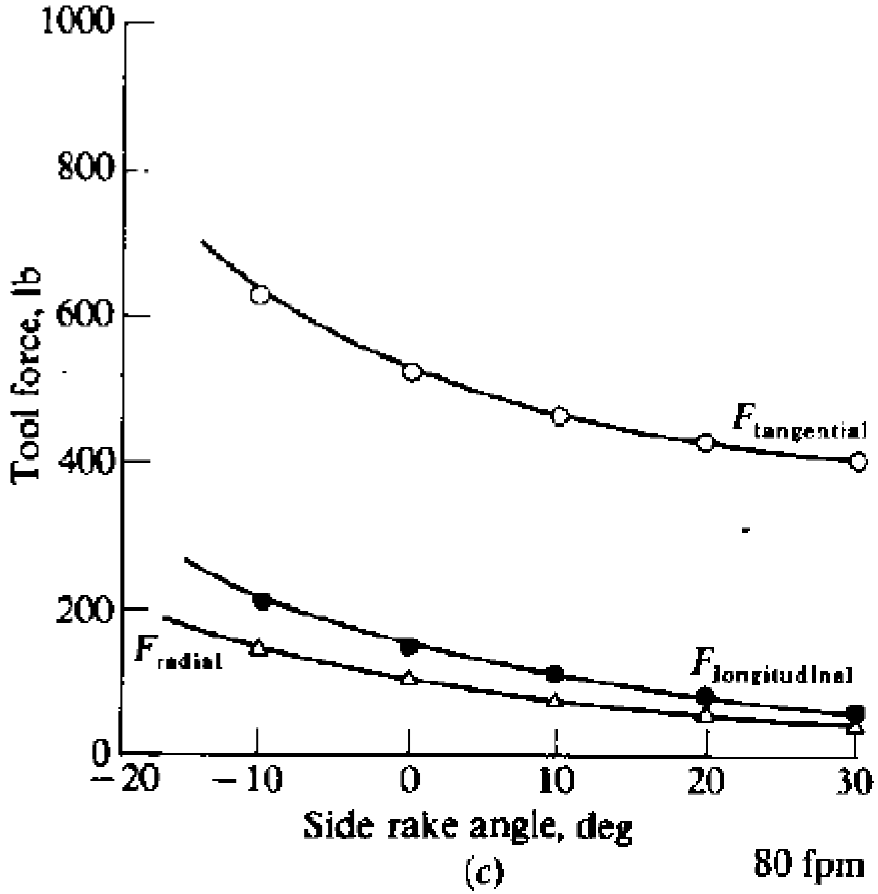
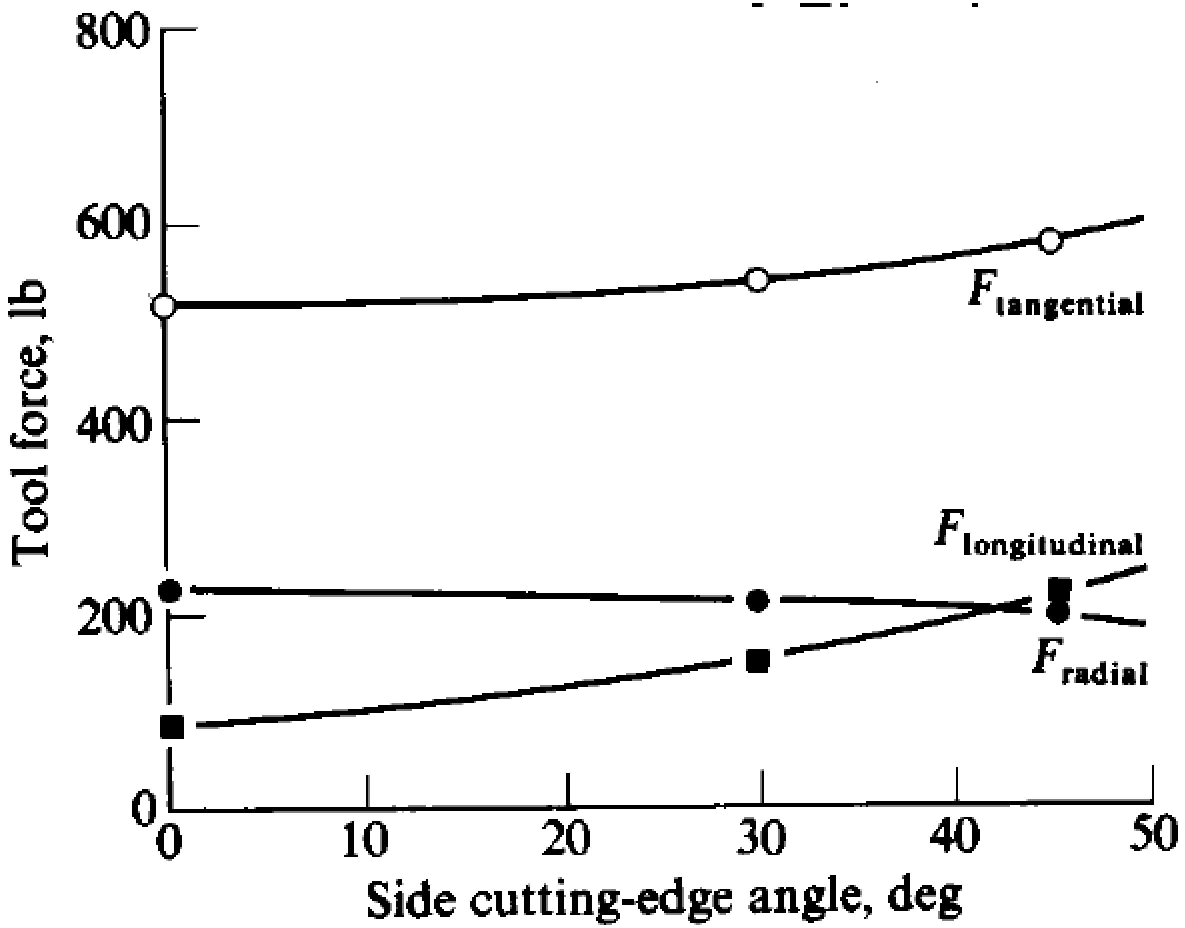
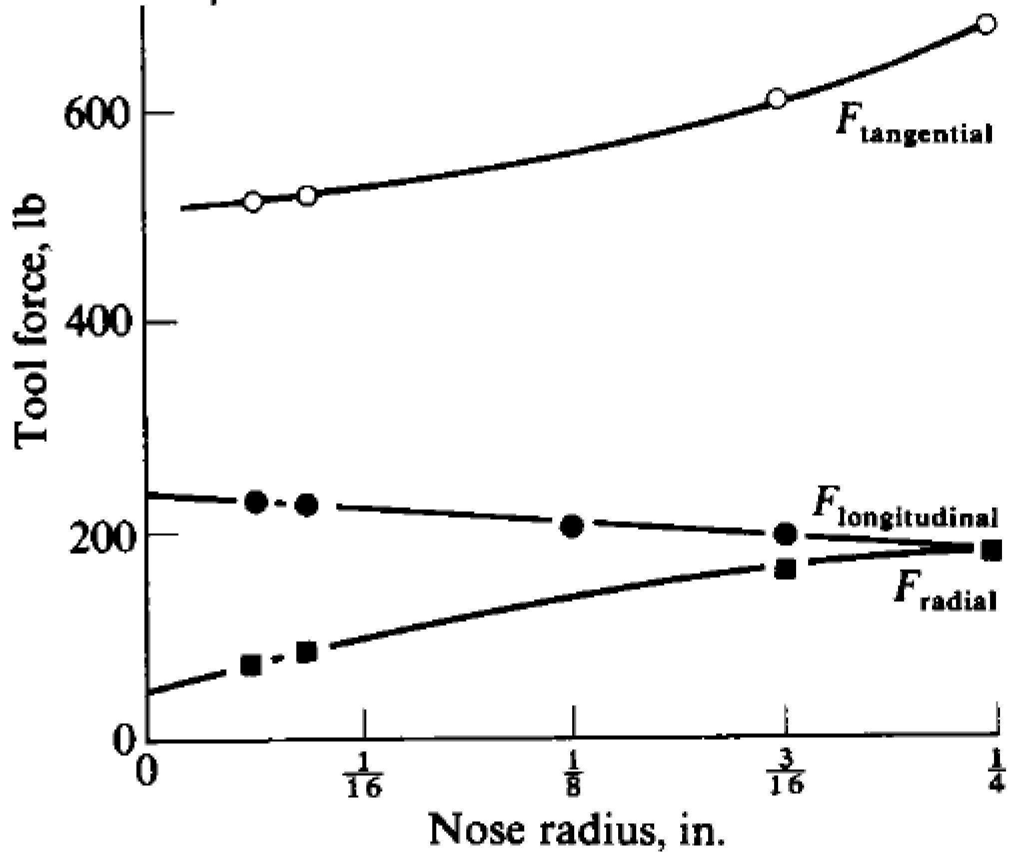


FIGURE 4-22
The influence of rake angles on cutting forces.

Effect of side cutting-edge angle on cutting forces. (*Metallurgical Pro-*



Effect of nose radius on cutting forces. Note that radial force increases from 50 lb with 0° nose radius to 175 lb with a $\frac{1}{4}$-in. radius



Power requirements in Turning

$$HP = \frac{C\,V\ \ f^{n3}\ d^{n4}}{33{,}000}$$

Table 3.1 (p 47)

Dry Cutting; Depth, 1/8 in. (3.2 mm); Feed, 1/64 ipr (0.4 mm/r)			
Material cut	Tool shape	Brinell hardness no.	HP_c/in.^{3} per min. (kW/cm^3 per sec.)
Plain carbon steel		126	0.59-0.66 (1.6-1.8)
		179	0.70-0.79 (1.9-2.2)
		262	0.85-0.95 (2.3-2.6)
Free-cutting steel		118	0.36-0.39 (1.0-1.1)
		179	0.44-0.48 (1.2-1.3)
	8, 14, 6, 6, 6, 0, 1/16	229	0.50-0.54 (1.4-1.5)
Alloy steel		131	0.46-0.57 (1.3-1.6)
		179	0.55-0.68 (1.5-1.9)
		269	0.67-0.83 (1.8-2.3)
		429	1.10-1.90 (3.0-5.2)
Cast iron		140	0.22-0.32 (0.6-0.9)
		179	0.45-0.68 (1.2-1.9)
		256	0.85-1.30 (2.3-3.5)
Leaded brass		33	0.18-0.27 (0.5-0.7)
		76	0.22-0.31 (0.6-0.8)
		131	0.25-0.35 (0.7-1.0)

Tool Wear

- Crater wear
- Flank wear

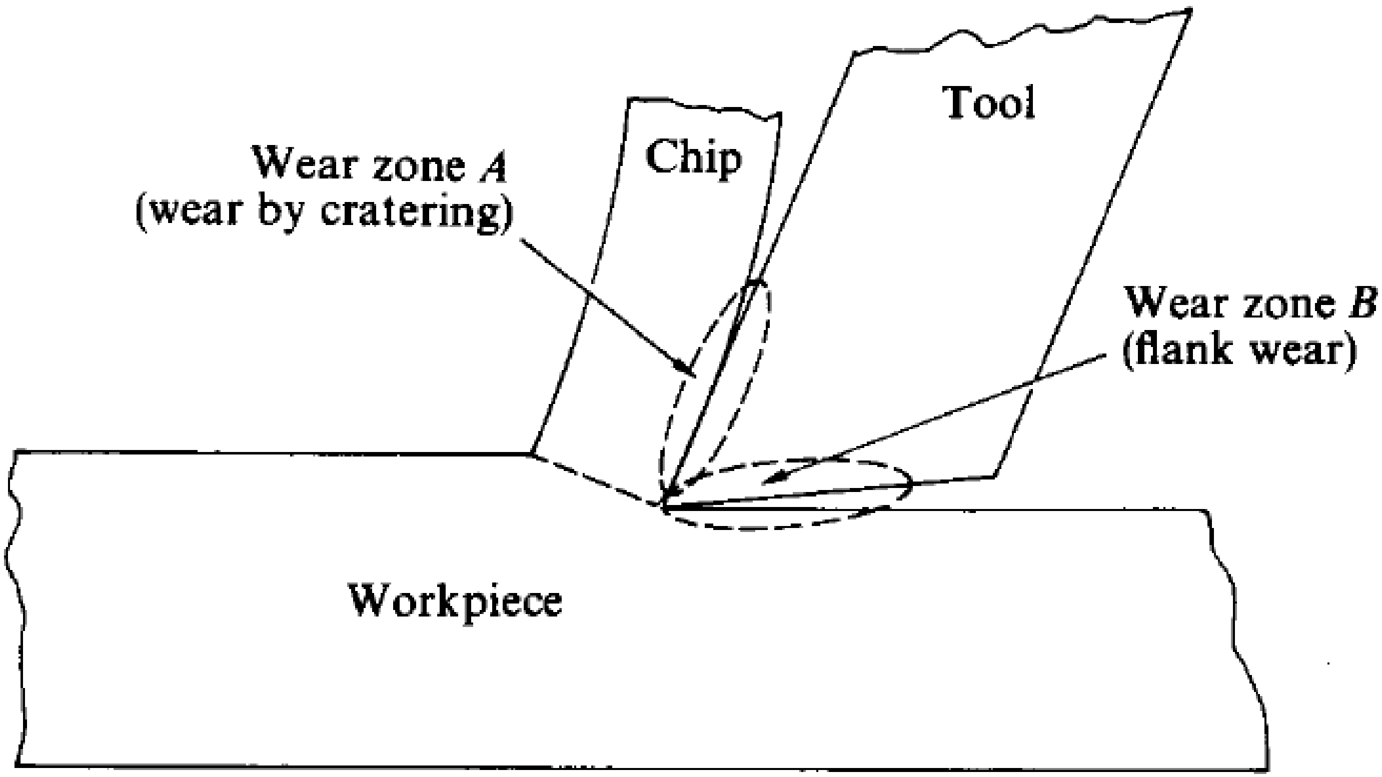
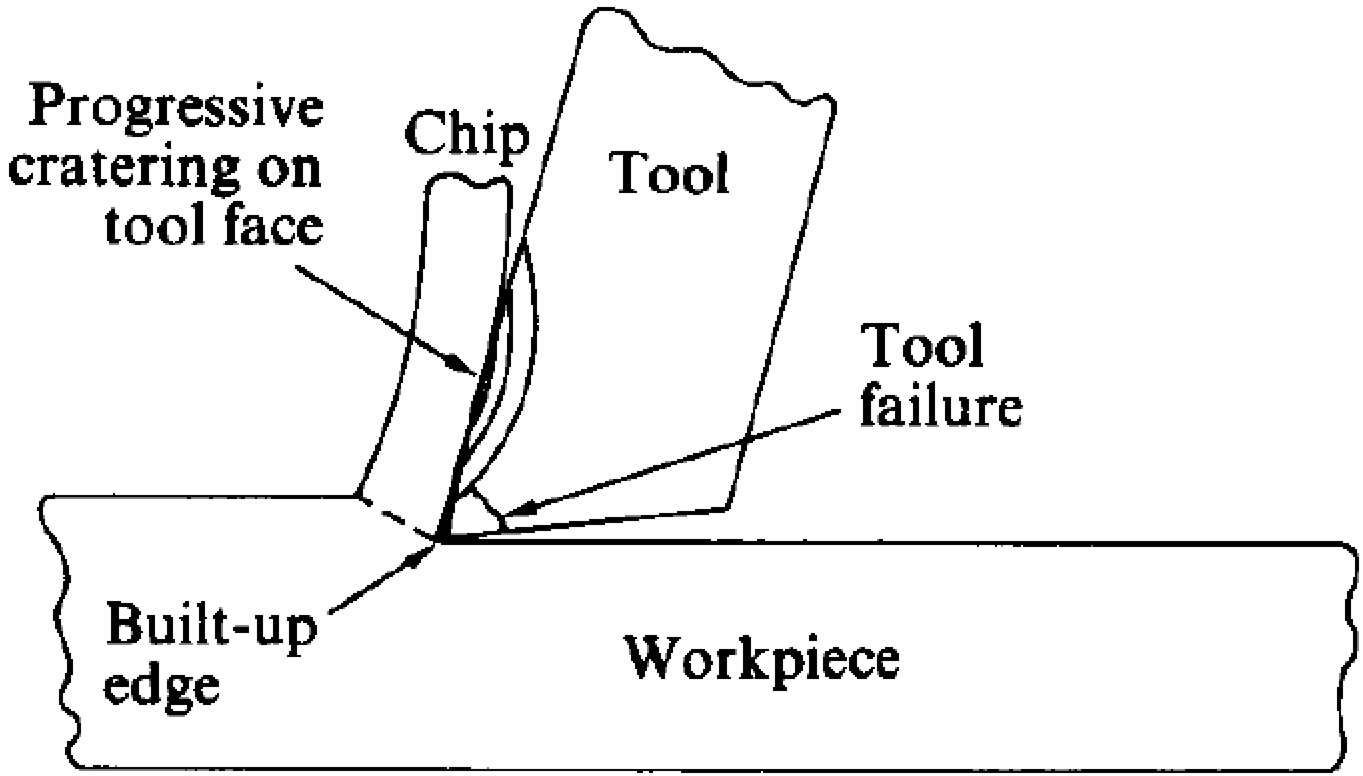


FIGURE 4-29
Areas of tool wear.

Tool wear by cratering.



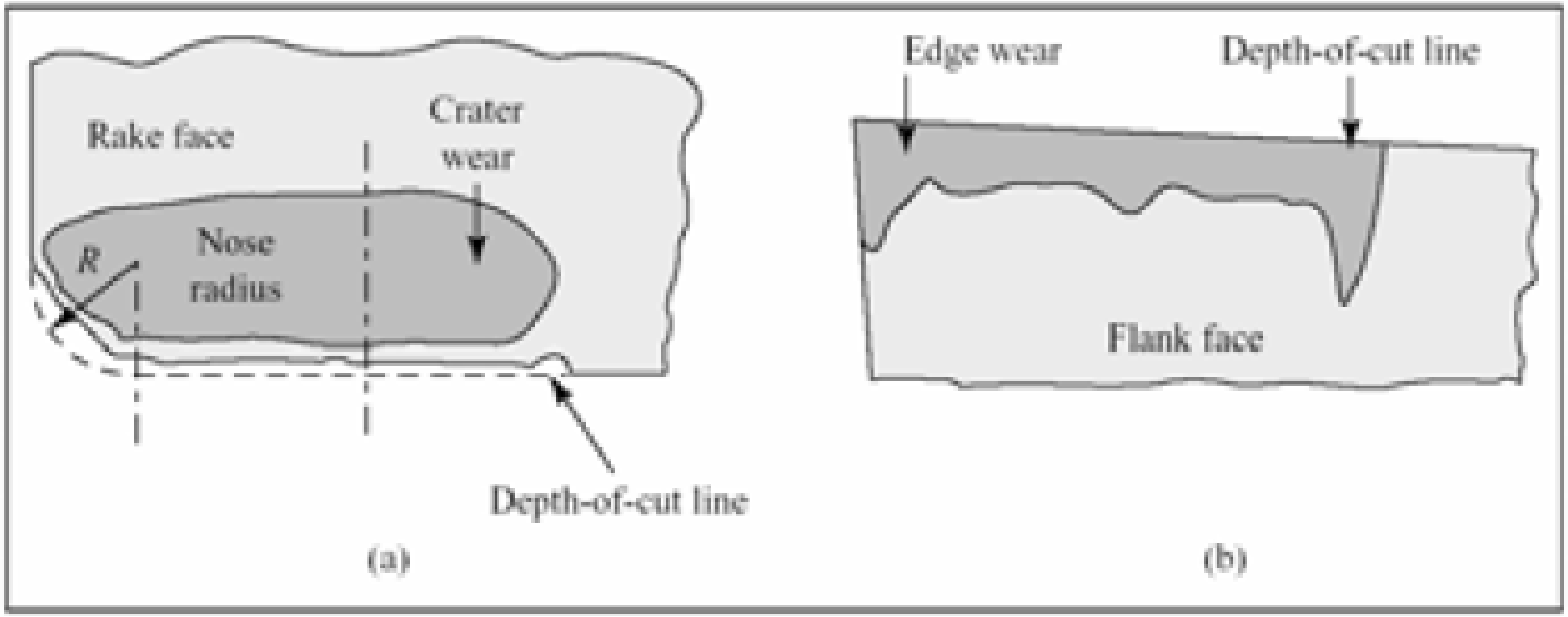
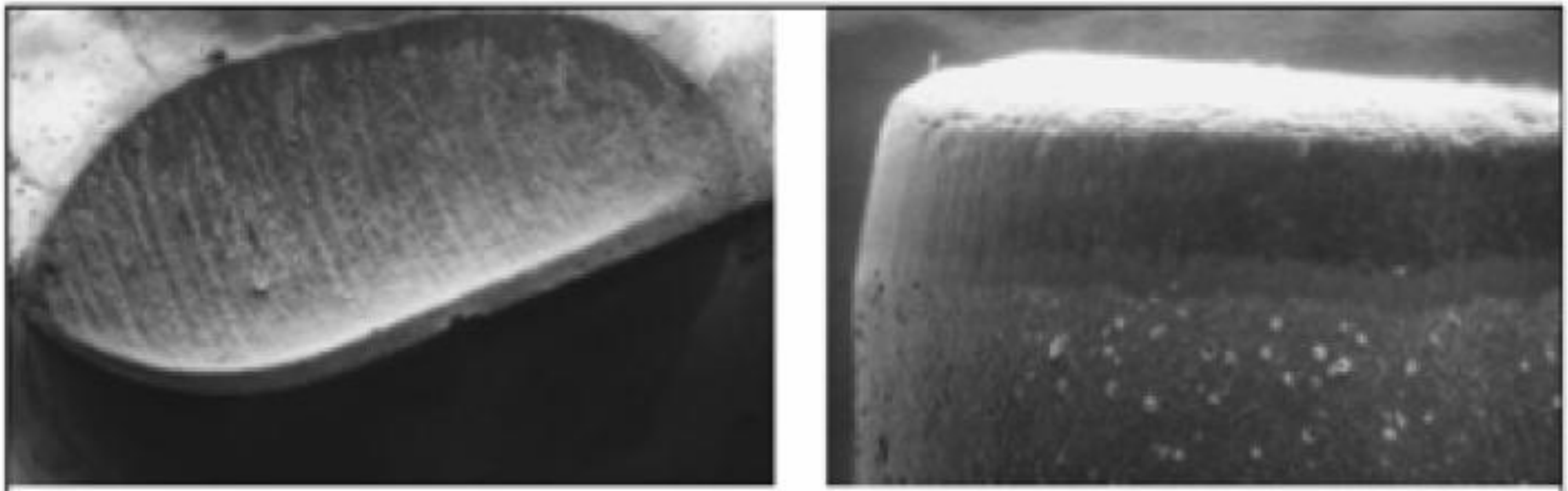


FIGURE 2.9 Carbide insert wear patterns: (a) crater wear, (b) edge wear.



(a) (b)

FIGURE 2.10 Carbide insert wear patterns: (a) crater wear, (b) edge wear. (Courtesy Kennametal Inc.)

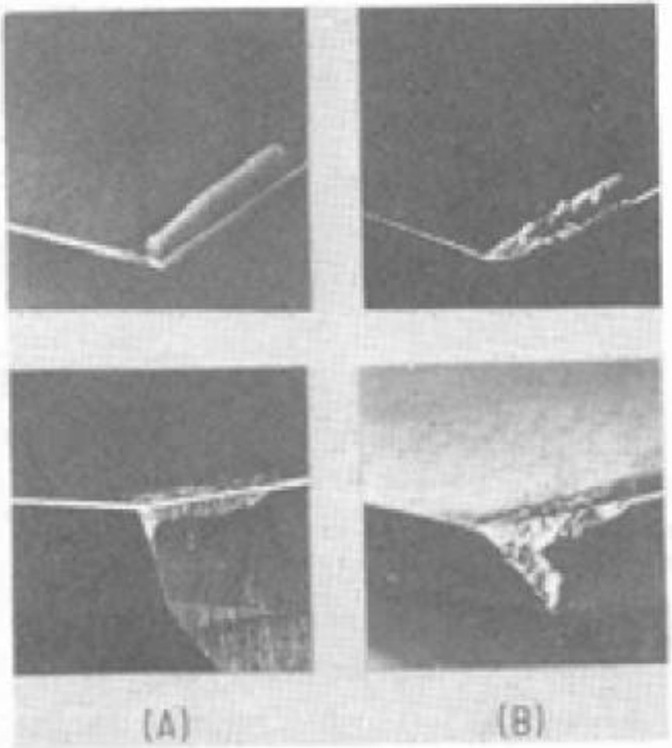


Figure 3-20. Representative wear patterns on face, flank, and nose of cutting tool, typical of chip-removal process on ductile materials. Crater on face of tool in (*A*) started well back of cutting edge. In (*B*) crater wear had progressed to point where weak cutting edge broke down under cutting forces.

Mechanism of tool wear

- Abrasive action of hard particles of work material
- Plastic deformation of the cutting edge
- Chemical decomposition of the cutting tool contact surfaces
- Diffusion between work and tool surfaces
- Welding of asperities between work and tool

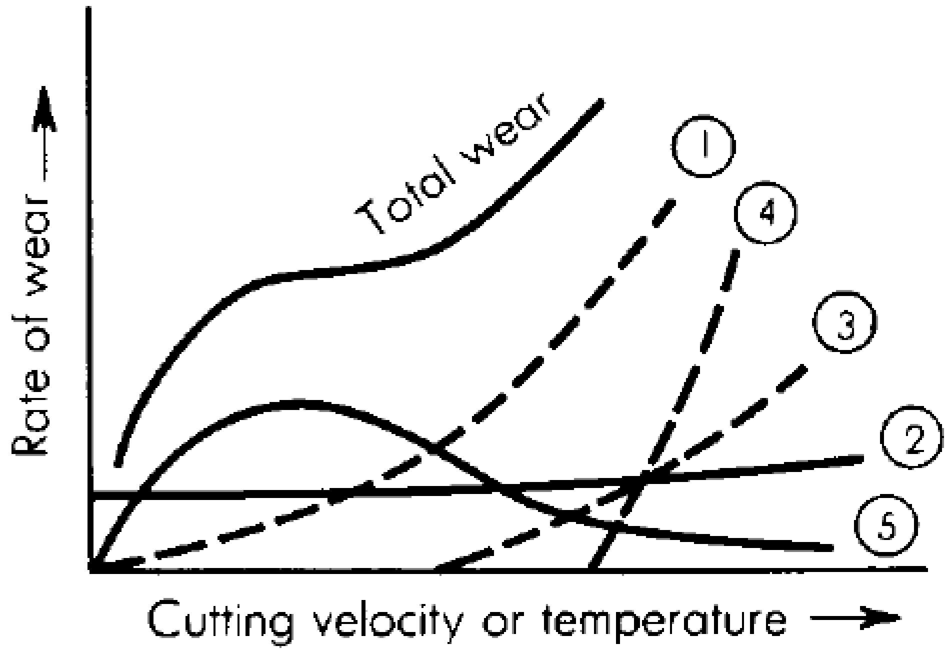


Figure 3-21. Relative effects of various causes of tool wear: (1) abrasive wear, (2) plastic deformation of cutting edge, (3) chemical decomposition, (4) diffusion, (5) welding of asperities.

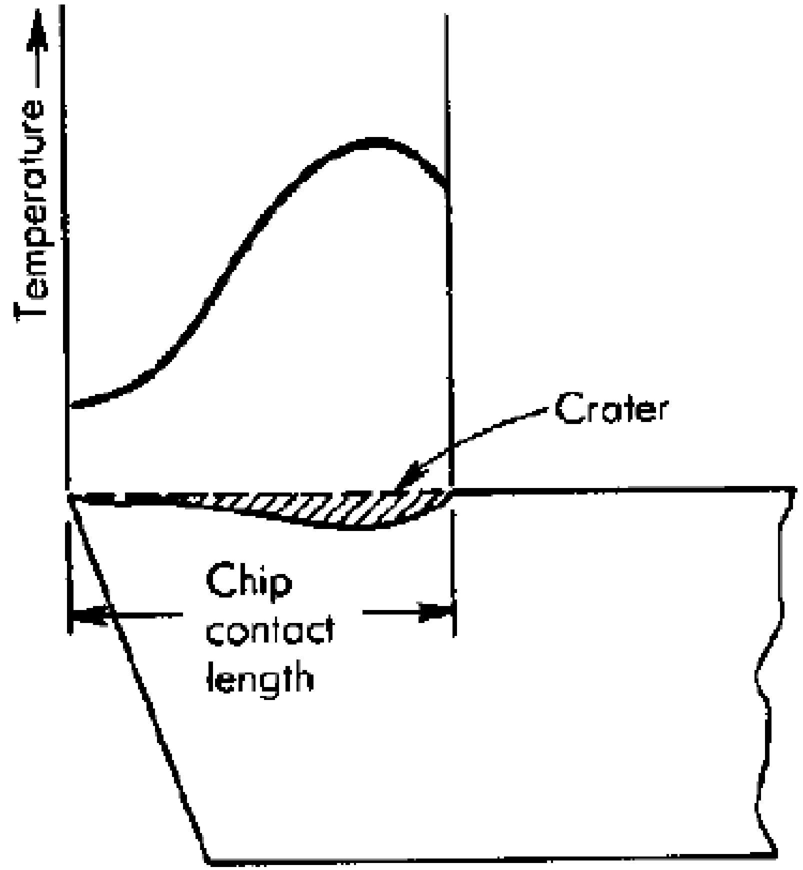


Figure 3-22. **Temperature distribution along tool-chip contact length.**[6]

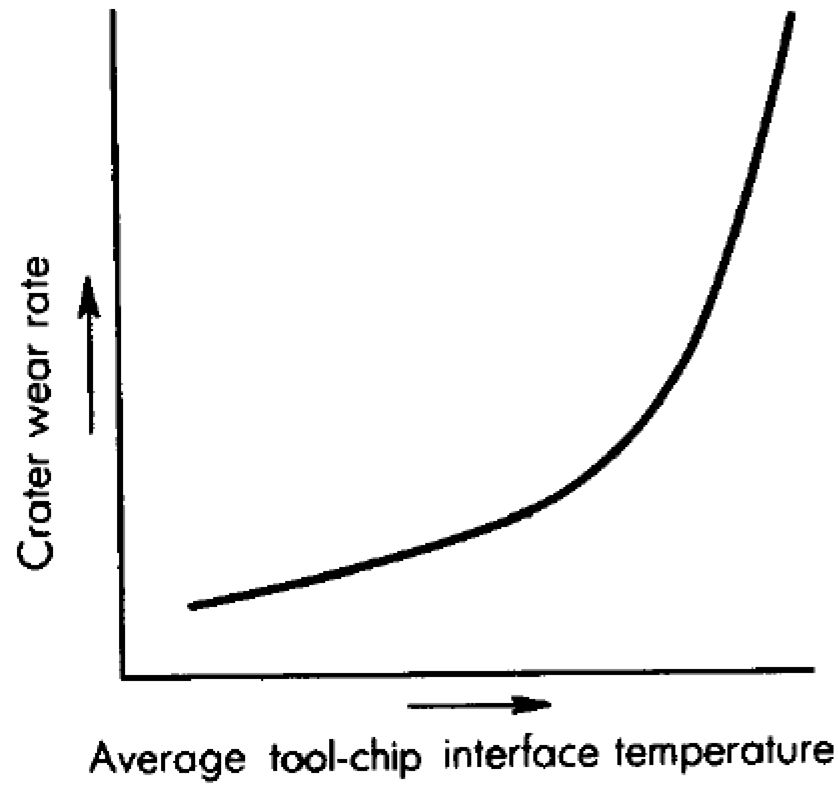


Figure 3-23. Relationship between rate of crater wear and average tool-chip interface temperature.[6]

Tool Life

- Criteria for tool life
  - Change of quality of the machined surface
  - Change in the magnitude of the cutting force
  - Change in the cutting temperature
  - Costs

Tool Life Equation

$$V \, T^n = C$$

- V = cutting speed, fpm
- T = tool life, minutes
- C = a constant
- n is a constant
  - HSS = 0.10 to 0.15
  - Carbides = 0.20 to 0.25
  - Ceramics = 0.6 to 1.0

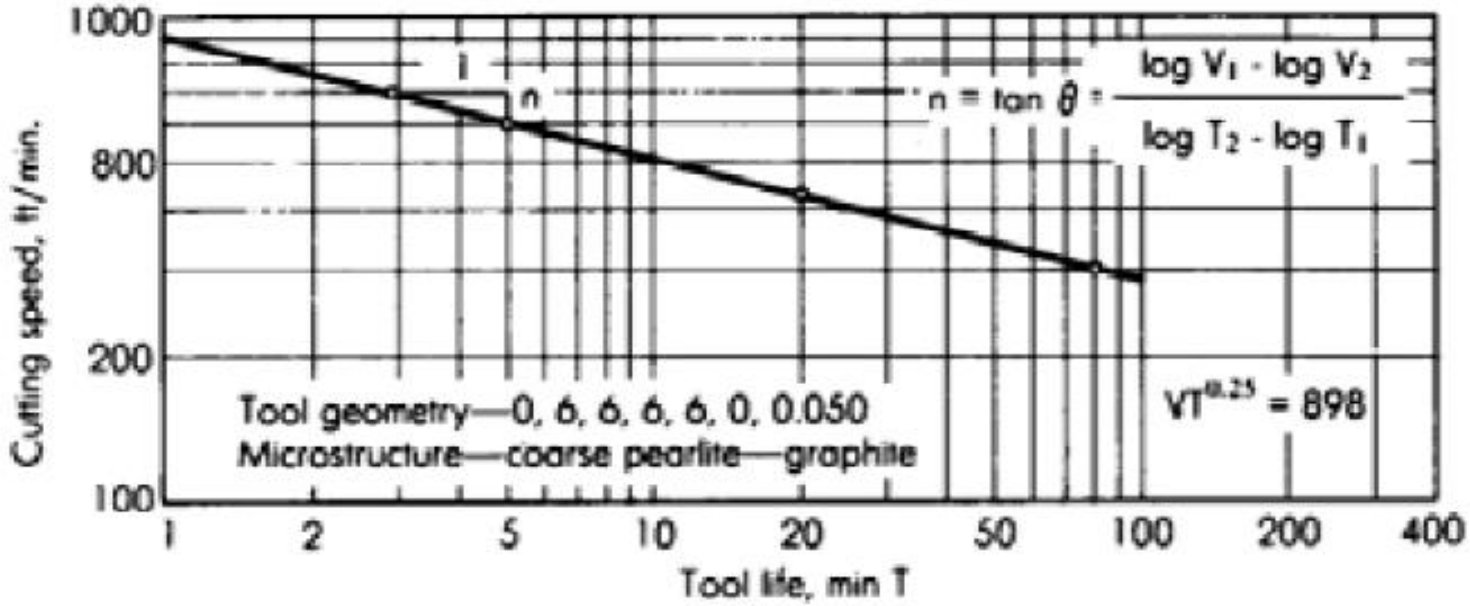


Figure 3-32. Tool life vs. cutting speed. Tool material—Kennametal carbide. Tool geometry—0, 6, 6, 6, 6, 0, 0.050. Work material—gray cast iron, 195 Bhn.

Tool Life Equation

$$V\ T^{n}\ f^{n1}\ d^{n2} = K$$

- V = cutting speed, feet per minute
- T = tool life, minutes
- d = depth of cut, in
- f = feed rate, inches per revolution
- K = a constant
- n1 = exponent for feed (0.5 to 0.8)
- n2 = exponent for depth of cut (0.2 to 0.4)

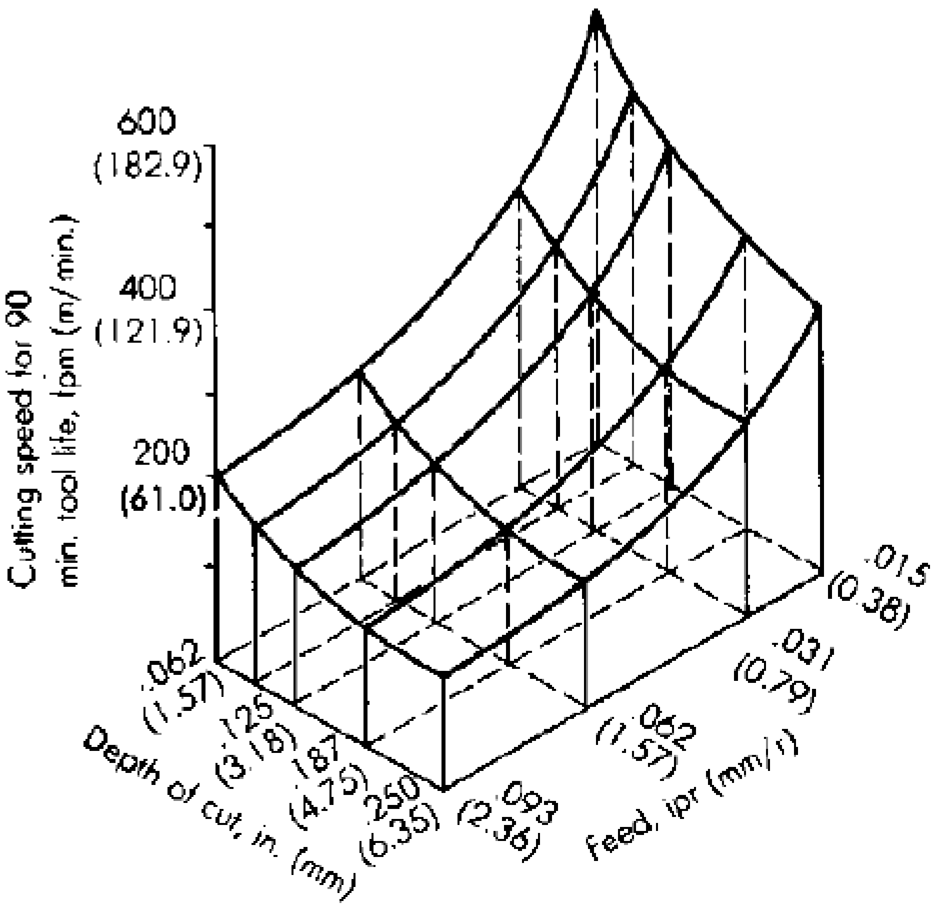


Figure 3-34. Effect of feed and depth of cut on cutting speed for 90-min tool life.[1] Workpiece material—gray cast iron. Tool material—HSS.

The following equation was obtained when machining AISI 2340 steel with HSS tool. A 100 minute tool life was obtained using V = 75 fpm, f = 0.0125 ipr, d = 0.10 in.Calculate the effect upon the tool life for a 20% increase in the cutting speed, feed and depth of cut, taking each separately. Calculate the effect of a 20% increase in each of the above parameters taken together.

$$V\ T^{0.13}\ f^{0.77}\ d^{0.37} = 2.035$$

Other tool life equations

$$K = V\ T^{n}\ f^{n1}\ d^{n2}\ Bhn^{1.25}$$

References

- Fundamentals of tool design, fifth edition, Society of Manufacturing Engineers
- Donaldson, and Lecain, Tool Design, McGraw Hill

Questions?