Work hardness prior to machining is an important factor because it controls the onset of shear. Onset is delayed by increased hardness, so \( \phi \) increases, as does \( \tau \). Highly ductile materials not only permit extensive plastic deformation of the chip during cutting, which increases heat generation and temperature, but also result in longer, “continuous” chips that remain in contact longer with the tool face, thus causing more frictional heat. Chips of this type are severely deformed and have a characteristic curl. On the other hand, materials that are already heavily work hardened or brittle, such as gray cast iron, lack the ductility necessary for appreciable plastic deformation. Consequently, the compressed material ahead of the tool fails in brittle fracture, sometimes along the shear front, producing small fragments. Such chips are termed discontinuous or segmented.

A variation of the continuous chip, often encountered in machining ductile materials, is associated with a built-up edge (BUE) formation on the cutting tool. The local high temperature and extreme pressure in the cutting zone cause the work material to adhere or pressure weld to the cutting edge of the tool forming the built-up edge, rather like a dead metal zone in the extrusion process. Although this material protects the cutting edge from wear, it modifies the geometry of the tool. BUEs are not stable and will break off periodically, adhering to the chip or passing under the tool and remaining on the machined surface. Built-up edge formation can be eliminated or minimized by reducing the depth of cut, altering the cutting speed, using positive rake tools, applying a coolant, or changing cutting-tool materials.

### Key Words

- back rake angle
- boring
- broaching
- built-up edge
- chatter
- chip ratio
- chip velocity
- cutting force
- cutting stiffness
- cutting tool
- depth of cut
- drilling
- dynamics
- feed
- flow stress
- friction force
- grinding (abrasive machining)
- machine tool
- metalcutting
- milling
- oblique machining
- onset of shear
- orthogonal machining
- regenerative chatter
- sawing
- self-excited vibration
- shaping
- shear angles
- shear force
- shear strain
- shear velocity
- specific horsepower
- speed
- stability lobe diagram
- turning
- vibration
- workholding device
- workpiece

### Review Questions

1. Why has the metalcutting process resisted theoretical solution for so many years?
2. What variables must be considered in understanding a machining process?
3. Which of the seven basic chip formation processes are single point, and which are multiple point? See Figure 20-2.
4. How is feed related to speed in the machining operations called turning?
5. Before you select speed and feed for a machining operation, what have you had to decide? (Hint: See Figure 20-4.)
6. Milling has two feeds. What are they, and which one is an input parameter to the machine tool?
7. What is the fundamental mechanism of chip formation?
8. What are the implications of Figure 20-17, given that this videograph was made at a very low cutting speed?
9. What is the difference between oblique machining and orthogonal machining?
10. Note that the units for the approximate equation for MRR for turning are not correct. When is the approximate equation not very good (yields a large error in MRR values)?
11. For orthogonal machining, the cutting edge radius is assumed to be small compared to the uncut chip thickness. Why?
12. How do the magnitude of the strain and strain rate values of metal cutting compare to those of tensile testing?
13. Why is titanium such a difficult metal to machine? (Note its high value of HP).
14. Explain why you get segmented or discontinuous chips when you machine cast iron.
15. Why is metal cutting shear stress such an important determination?
16. Which of the three cutting forces in oblique cutting consumes most of the power?
17. How is the energy in a machining process typically consumed?
18. Where does the energy consumed in metalcutting ultimately go?
19. State two ways of estimating the primary cutting force \( F_c \).
20. How is cutting speed related to tool wear?
21. What is the relationship between hardness and temperature in metal cutting tool materials?
22. Why does the cutting force \( F_c \) increase with increased feed or DOC?
23. Why doesn't the cutting force $F_c$ increase with increased speed $V$?
24. How do the selection of the machining parameters (speed, feed, DOC) influence chatter?
25. You had a machining operation (boring) running perfectly and you changed work materials. All of a sudden, you are getting lots of chatter. Why?
26. Explain Figure 20-31. Why is the percentage of total heat generated during machining changing as speed increases?

## Problems

1. For a turning operation, you have selected an HSS tool and turning a hot rolled free machining steel, BHN = 300. Your depth of cut will be 0.150 in. The diameter of the workpiece is 1.00 inches.
   a. What speed and feed would you select for this job?
   b. Using a speed of 105 sfpm and a feed of 0.015, calculate the spindle rpm for this operation.
   c. Calculate the metal removal rate.
   d. Calculate the cutting time for the operation with a length of cut of 4 in. and 0.10-in. allowance.
2. For a slab milling operation using a 5-in.-diameter, 11-tooth cutter (see Figure 20-6), the feed per tooth is 0.005 in/tooth with a cutting speed of 100 sfpm (HSS steel). Calculate the rpm of the cutter and the feed rate ($f_p$) of the table, then calculate the metal removal rate, MRR, where the width of the block being machined is 2 in. and the depth of cut is 0.25 in. Calculate the time to machine ($T_{ma}$) a 6-in.-long block of metal with this setup. Suppose you switched to a coated-carbide tool, so you increase the cutting speed to 400 sfpm. Now recalculate the machining time ($T_{ma}$) with all the other parameters the same.
3. The power required to machine metal is related to the cutting force ($F_c$) and the cutting speed. For Problem 1, estimate cutting force $F_c$ for this turning operation. (Hint: You have to estimate a value of HPs for this material.)
4. In order to drill a hole in the material described in Problem 1 using an HSS drill, you have to select a cutting speed and a feed rate. Using a speed of 105 sfpm for the HSS drill, calculate the rpm for a 3⁄4-in.-diameter drill and the MRR if the feed rate is 0.008 inches per revolution.
5. Explain how the constant 33,000 in equation 20-8 is obtained.
6. Explain how the constant 396,000 in equation 20-10 is obtained.
7. Suppose you have the following data obtained from a metal-cutting experiment (orthogonal machining). Compute the shear angle, the shear stress, the specific energy, the shear strain, and the coefficient of friction at the tool–chip interface.

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<th>$r_t$</th>
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<th>HP</th>
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