Expressing each of these cost terms as a function of cutting velocity will permit the summation of all the costs.

$C_1 = T_m \times C_o$ where C_o = operating cost ($/min)
T_m = cutting time (min/piece)

$C_2 = \left(\frac{T_m}{T}\right) C_t$ where T = tool life (min/tool)
C_t = initial cost of tool ($)

$C_3 = t_c \times C_o \left(\frac{T_m}{T}\right)$ where t_c = time to change tool (min)
$\frac{T_m}{T}$ = number of tool changes per piece

C_4 labor, overhead, and machine tool costs consumed while part is being loaded or unloaded, tools are being advanced, machine has broken down, and so on.

Because $T_m = L/Nf_r$ for turning

$$= \pi DL/12Vf_r$$

and $T = (K/V)^{1/n}$, by rewriting equation 21-3, and using "K" for the constant "C", the cost per unit, C, can be expressed in terms of V:

$$C = \frac{L\pi DC_o}{12Vf_r} + \frac{C_t V^{1/n}}{K^{1/n}} + \frac{t_c C_o V^{1/n}}{K^{1/n}} + C_4 \tag{21-8}$$

To find the minimum, take $dc/dV = 0$ and solve for V:

$$V_m = K\left[\frac{n}{1-n} \bullet \frac{C_o}{C_o\, t_t + C_t}\right]^n \tag{21-9}$$

Thus, V_m represents a cutting speed that will minimize the cost per unit, as depicted in Figure 21-26. However, a word of caution here is appropriate. Note that this derivation was totally dependent upon the Taylor tool life equation. Such data may not be available because they are expensive and time consuming to obtain. Even when the tool life data are available, this procedure assumes that the tool fails only by whichever wear mechanism (flank or crater) was described by this equation and by no other failure mechanism. Recall that tool life has a very large coefficient of variation and is probabilistic in nature. This derivation assumes that for a given V, there is one T—and this simply is not the case, as was shown in Figure 21-18. The model also assumes that the workpiece material is homogeneous, the tool geometry is preselected, the depth of cut and feed rate are known and remain unchanged during the entire process, sufficient horsepower is available for the cut at the economic cutting conditions, and the cost of operating time is the same whether the machine is cutting or not cutting.

COST COMPARISONS

Cost comparisons are made between different tools to decide which tool material to use for a given job. Suppose there are four different tools that can be used for turning hot-rolled 8620 steel with triangular inserts. The four tool materials are shown in Table 21-7. Operating costs for the machine tool are $60/hr. The low-force groove insert has only three cutting edges available instead of six. It takes 3 min to change inserts and 0.5 min to unload a finished part and load in a new 6-in.-diameter bar stock. The length of cut is about 24 in. The student should study and analyze this table carefully so that each line is understood. Note that the cutting tool cost per piece is three times higher for the low-force groove tool over the carbide but is really of no consequence, because the major cost per piece comes from two sources: the machining cost per piece and the nonproductive cost per piece.

TABLE 21-7 Cost Comparison of Four Tool Materials, Based on Equal Tool Life of 40 Pieces per Cutting Edge

	Uncoated	TiC-Coated	Al_2O_3-Coated	Al_2O_3 LFG
Cutting speed (surface ft/min)	400	640	1100	1320
Feed (in./rev)	0.020	0.02	0.024	0.028
Cutting edges available per insert	6	6	6	3
Cost of an insert ($/insert)	4.80	5.52	6.72	6.72
Tool life (pieces/cutting edge)	192	108	60	40
Tool-change time per piece (min)	0.075	0.075	0.075	0.075
Nonproductive cost per piece ($/pc)	0.50	0.50	0.50	0.50
Machining time per piece (min/pc)	4.8	2.7	1.50	1.00
Machining cost per piece ($/unit)	4.8	2.7	1.5	1.00
Tool-change cost per piece ($/pc)	0.08	0.08	0.08	0.08
Cutting tool cost per piece ($/pc)	0.02	0.02	0.03	0.06
Total cost per piece ($/pc)	5.40	3.30	2.11	1.64
Production rate (pieces/hr)	11	18	29	38
Improvement in productivity based on pieces/hr (%)	0	64	164	245

Source: Data from T. E. Hale et al., "High Productivity Approaches to Metal Removal," *Materials Technology*, Spring 1980, p. 25.

KEY WORDS

aluminum oxide
back rake angle
BUE (built-up edge)
carbides
cast cobalt alloy
ceramics
cermets
chemical vapor deposition (CVD)
chip groove
coated tools
crater wear
cubic boron nitride (CBN)
cutting fluids
cutting tool materials
depth-of-cut line (DCL)
diamonds
flank wear
hardness
high-speed steel (HSS)
hot hardness
low-force groove (LFG)
machinability
metal cutting
microchipping
physical vapor deposition (PVD)
polycrystalline cubic boron nitride (PCBN)
polycrystalline diamond (PCD)
powder metallurgy (P/M)
sintered carbides
stellite tools
tool life
tool steels
titanium carbide (TiC)
titanium nitride (TiN)

REVIEW QUESTIONS

1. For metal-cutting tools, what is the most important material property (i.e., the most critical characteristic)? Why?
2. What is hot hardness compared to hardness?
3. What is impact strength, and how is it measured?
4. Why is impact strength an important property in cutting tools?
5. Is a cemented carbide tool made by a powder metallurgy method?
6. What are the primary considerations in tool selection?
7. What is the general strategy behind coated tools?
8. What is a cermet?
9. How is a CBN tool manufactured?
10. F. W. Taylor was one of the discoverers of high-speed steel. What else is he well known for?
11. What casting process do you think was used to fabricate cast cobalt alloys?
12. Discuss the constraints in the selection of a cutting tool.
13. What does *cemented* mean in the manufacture of carbides?
14. What advantage do ground carbide inserts have over pressed carbide inserts?
15. What is a chip groove?
16. What is the DCL?
17. Suppose you made four beams out of carbide, HSS, ceramic, and cobalt. The beams are identical in size and shape, differing only in material. Which beam would do each of the following?
    a. Deflect the most, assuming the same load.
    b. Resist penetration the most.
    c. Bend the farthest without breaking.
    d. Support the greatest compressive load.
18. Multiple coats or layers are put on the carbide base for what different purposes?
19. What tool material would you recommend for machining a titanium aircraft part?
20. What makes the process that makes TiC coatings for tools a problem? See equation 21-1.
21. Why does a TiN-coated tool consume less power than an uncoated HSS under exactly the same cutting conditions?
22. For what work material are CBN tools more commonly used, and why?
23. Why is CBN better for machining steel than diamond?
24. What is the typical coefficient of variation for tool life data, and why is this a problem?
25. What is meant by the statement "Tool life is a random variable"?

- AISI A, D, H, M, and air-hardening and tool steel parts.
- Solid carbide tooling.

PVD

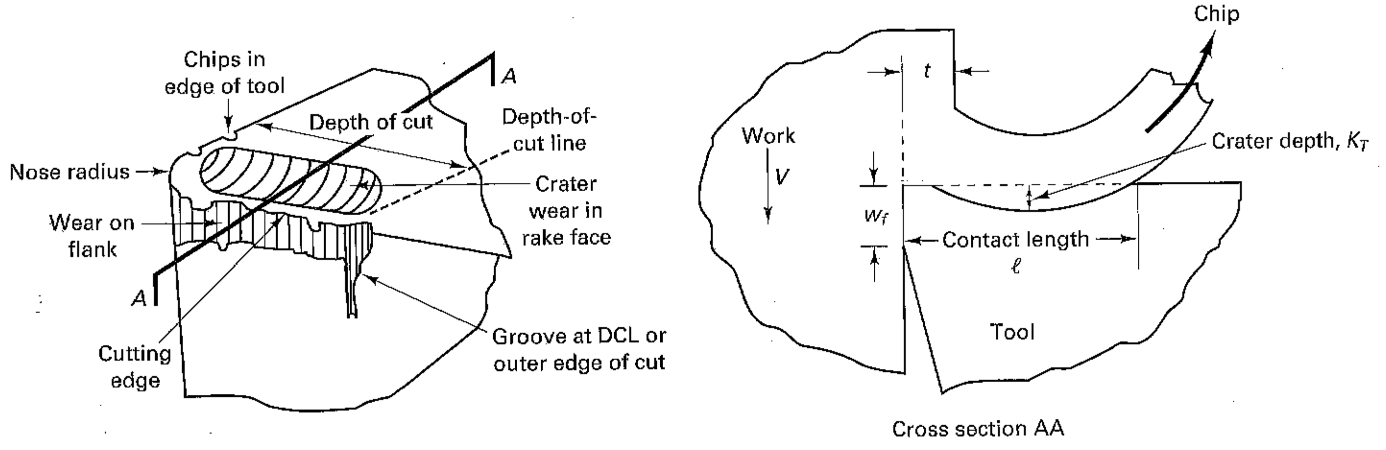
- All HSS, solid carbide, and carbide-tipped cutting tools.
- Fine blanking punches, dies (0.001 in. tolerance or less).
- Non-composition-dependent process; virtually all tooling materials, including mold steels and bronze.

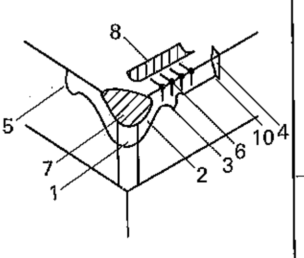
21.5 TOOL FAILURE AND TOOL LIFE

In metal cutting, the failure of the cutting tool can be classified into two broad categories, according to the failure mechanisms that caused the tool to die (or fail):

1. *Physical failures* mainly include gradual tool wear on the flank(s) of the tool below the cutting edge (called **flank wear**) or wear on the rake face of the tool (called **crater wear**) or both.
2. *Chemical failures*, which include wear on the rake face of the tool (crater wear) are rapid, usually unpredictable, and often catastrophic failures resulting from abrupt, premature death of a tool.

Other modes of failure are outlined in Figure 21-17. The selection of failure criteria is also widely varied. Figure 21-17 also shows a sketch of a "worn" tool, showing crater wear and flank wear, along with wear of the tool nose radius and an outer-diameter groove (the DCL groove). Tools also fail by edge chipping and edge fracture.





No.	Failure	Cause	
1-3	Flank wear	Physical	Due to the abrasive effect of hard grains contained in the work material
4-5	Groove		Due to wear at the DCL or outer edge of the cut
6	Chipping		Fine chips caused by high-pressure cutting, chatter, vibration, etc.
7	Partial fracture		Due to the mechanical impact when an excessive force is applied to the cutting edge
8	Crater wear	Chemical	Carbide particles are removed due to degradation of tool performances and chemical reactions at high temperature
9	Deformation		The cutting edge is deformed due to its softening at high temperature
10	Thermal crack		Thermal fatigue in the heating and cooling cycle with interrupted cutting
1	Built-up edge		A portion of the workpiece material adheres to the insert cutting edge

FIGURE 21-17 Tools can fail in many ways. Tool wear during oblique cutting can occur on the flank or the rake face; t = uncut chip thickness; k_t = crater depth; w_f = flank wear land length; DCL = depth-of-cut line.

As the tool wears, its geometry changes. This geometry change will influence the cutting forces, the power being consumed, the surface finish obtained, the dimensional accuracy, and even the dynamic stability of the process. Worn tools are duller, creating greater cutting forces and often resulting in chatter in processes that otherwise are usually relatively free of vibration. The actual wear mechanisms active in this high-temperature environment are abrasion, adhesion, diffusion, or chemical interactions. It appears that in metal cutting, any or all of these mechanisms may be operative at a given time in a given process.

Tool failure by plastic deformation, brittle fracture, fatigue fracture, or edge chipping can be unpredictable. Moreover, it is difficult to predict which mechanism will dominate and result in a tool failure in a particular situation. What can be said is that tools, like people, die (or fail) from a great variety of causes under widely varying conditions. Therefore, **tool life** should be treated as a random variable, or probabilistically, not as a deterministic quantity.

21.6 FLANK WEAR

During machining, the tool is performing in a hostile environment in which high-contact stresses and high temperatures are commonplace; therefore, tool wear is always an unavoidable consequence. At lower speeds and temperatures, the tool most commonly wears on the flank. Suppose that the tool wear experiment were to be repeated 15 times without changing any of the input parameters. The result would look like Figure 21-18, which depicts the variable nature of tool wear and shows why tool wear must be treated as a random variable. In Figure 21-18 the average time is denoted as μ_T and the standard deviation as σ_T, where the wear limit criterion was 0.025 in. At a given time during the test, 35 min, the tool displayed flank wear ranging from 0.013 to 0.021 in, with an average of $\mu_w = 0.00175$ in. with standard deviation σ_w 0.001 in.

In Figure 21-19 four characteristic tool wear curves (average values) are shown for four different cutting speeds, V_1 through V_4; V_1 is the fastest cutting speed and therefore generates the fastest wear rates. Such curves often have three general regions, as shown in the figure. The central region is a steady-state region (or the region of secondary wear). This is the normal operating region for the tool. Such curves are typical for both

w_f values for general life determination (for cemented carbides)

Width of Wear (in.)	Applications
0.008	Finish cutting of nonferrous alloys, fine and light cut, etc.
0.016	Cutting of special steels
0.028	Normal cutting of cast irons, steels, etc.
0.040–0.050	Rough cutting of common cast irons

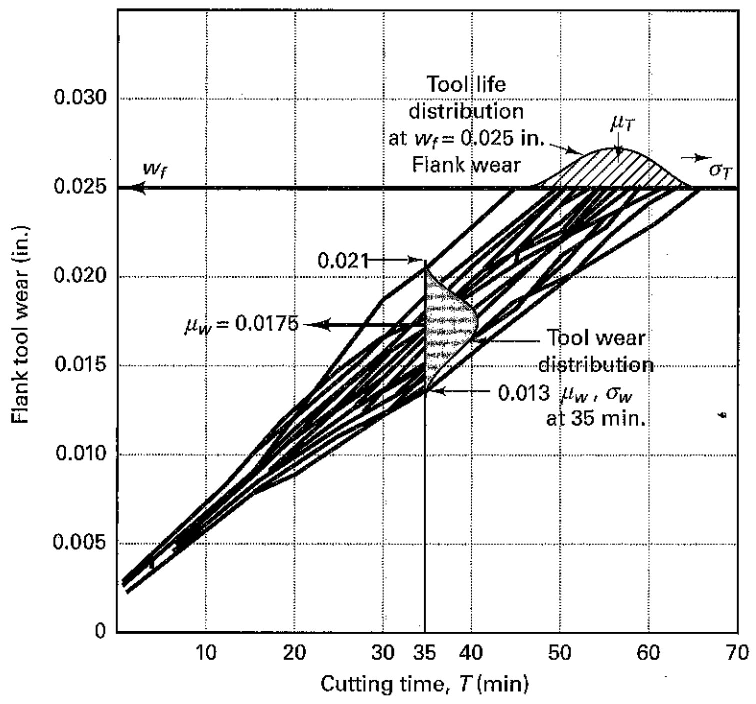


FIGURE 21-18 Tool wear on the flank displays a random nature, as does tool life. w_f = flank wear limit value.

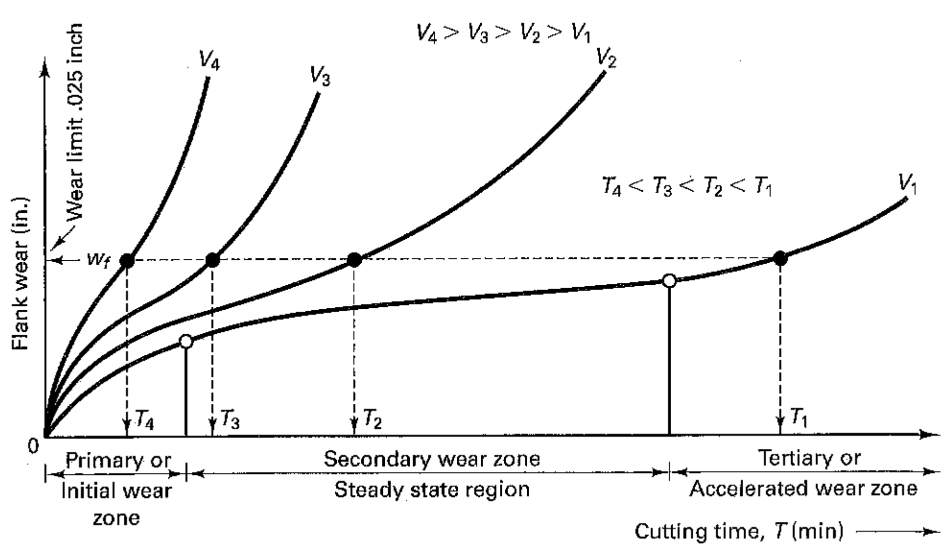


FIGURE 21-19 Typical tool wear curves for flank wear at different velocities. The initial wear is very fast, then it evens out to a more gradual pattern until the limit is reached; after that, the wear substantially increases.

flank wear and crater wear. When the amount of wear reaches the value w_f, the permissible tool wear on the flank, the tool is said to be "worn out." The value w_f is typically set at 0.025 to 0.030 in. for flank wear for high-speed steels and 0.008 to 0.050 for carbides, depending on the application. For crater wear, the depth of the crater, k_b, is used to determine tool failure.

Using the empirical tool wear data shown in Figure 21-19, which used the values of T (time in minutes) associated with V (cutting speed) for a given amount of tool wear, w_f (see the dashed-line construction), Figure 21-20 was developed. When V and T are plotted on log-log scales, a linear relationship appears, described by the equation

$$VT^n = \text{Constant} = C \tag{21-3}$$

This equation is called the Taylor tool life equation because in 1907, F. W Taylor published his now-famous paper, "On the Art of Cutting Metals," in *ASME Transactions*, wherein tool life (T) was related to cutting speed (V) and feed (f). This equation had the form[1]

$$T = \frac{\text{Constant}}{f_x V_y} \tag{21-4}$$

Over the years, the equation took the more widely published form

$$VT^n = C$$

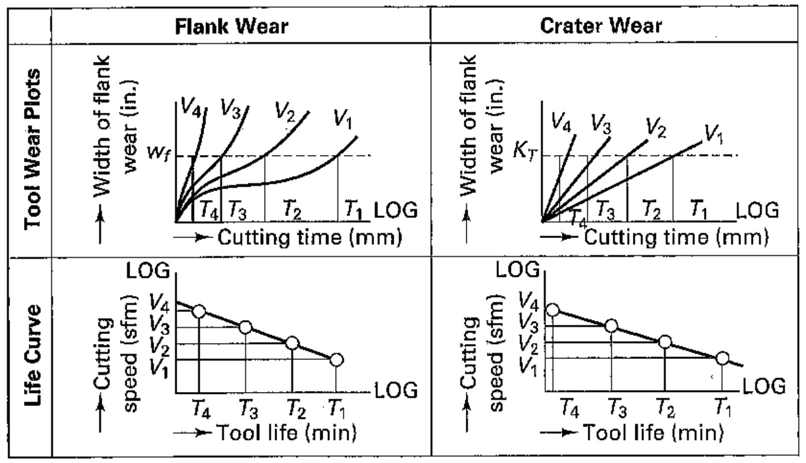


FIGURE 21-20 Construction of the Taylor tool life curve using data from deterministic tool wear plots like those of Figure 21-19. Curves like this can be developed for both flank and crater wear.

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[1] Carl Barth, who was Taylor's mathematical genius, is generally thought to be the author of these formulations along with early versions of slide rules.

TABLE 21-5 Tool Life Information for Various Materials and Conditions

				Size of Cut (in.)			$VT^n = C$	
Source	Tool Material	Geometry	Workpiece Material	Depth	Feed	Cutting Fluid	n	C
1	High-carbon steel	8.14, 6.6, 6.15, 3/64	Yellow brass (.60 Cu,	.050	.0255	Dry	.081	242
			40 Zn, 85 Ni, .006 Pb)	.100	.0127	Dry	.096	299
1	High-carbon steel	8.14, 6.6, 6.15, 3/64	Bronze (.9 Cu, .1.5n)	.050	.0255	Dry	.086	190
				.100	.0127	Dry	.111	232
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Cast iron 160 Bhn	.050	.0255	Dry	.101	172
			Cast iron. Nickel, 164 Bhn	.050	.0255	Dry	.111	186
			Cast iron. Ni-Cr, 207 Bhn	.050	.0255	Dry	.088	102
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE B1113 C.D.	.050	.0127	Dry	.080	260
			Stell, SAE B1112 C.D.	.050	.0127	Dry	.105	225
			Stell, SAE B1120 C.D.	.050	.0127	Dry	.100	270
			Stell, SAE B1120 + Pb C.D.	.050	.0127	Dry	.060	290
			Stell, SAE B1035 C.D.	.050	.0127	Dry	.110	130
			Stell, SAE B1035 + Pb C.D.	.050	.0127	Dry	.110	147
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 1045 CD.	.100	.0127	Dry	.110	192
		8.14, 6.6, 6.13, 3/64	Stell, SAE 2340 185 Bhn	.100	.0125	Dry	.147	143
		8.14, 6.6, 6.15, 3/64	Stell, SAE 2345 198 Bhn	.050	.0255	Dry	.105	126
		8.14, 6.6, 6.15, 3/64	Stell, SAE 3140 190 Bhn	.100	.0125	Dry	.160	178
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 4350 363 Bhn	.0125	.0127	Dry	.080	181
			Stell, SAE 4350 363 Bhn	.0125	.0255	Dry	.125	146
			Stell, SAE 4350 363 Bhn	.0250	.0255	Dry	.125	95
			Stell, SAE 4350 353 Bhn	.100	.0127	Dry	.110	78
			Stell, SAE 4350 363 Bhn	.100	.0255	Dry	.110	46
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 4140 230 Bhn	.050	.0127	Dry	.180	190
			Stell, SAE 4140 271 Bhn	.050	.0127	Dry	.180	159
			Stell, SAE 6140 240 Bhn	.050	.0127	Dry	.150	197
1	HSS-18-4-1	8.22, 6.6, 6.15, 3/64	Monel metal 215 Bhn	.100	.0127	Dry	.084	170
				.150	.0255	Dry	.074	127
				.100	.0127	Em	.080	185
				.100	.0127	SMO	.105	189
1	Stellite 2400	0.0, 6.6, 6.0, 3/32	Steel. SAE 3240 annealed	.187	.031	Dry	.190	215
				.125	.031	Dry	.190	240
				.062	.031	Dry	.190	270
				.031	.031	Dry	.190	310
1	Stellite No. 3	0.0, 6.6, 6.0, 3/32	Cast iron 200 Bhn	.062	0.31	Dry	.150	205
1	Carbide (T 64)	6.12, 5.5, 10.45	Steel. SAE 1040 annealed	.062	.025	Dry	.156	800
			Steel. SAE 1060 annealed	.125	.025	Dry	.167	660
			Steel. SAE 1060 annealed	.187	.025	Dry	.167	615
			Steel. SAE 1060 annealed	.250	.025	Dry	.167	560
			Steel. SAE 1060 annealed	.062	.021	Dry	.167	880
			Steel. SAE 1060 annealed	.062	.042	Dry	.164	510
			Steel. SAE 1060 annealed	.062	.062	Dry	.162	400
			Steel. SAE 2340 annealed	.062	.025	Dry	.162	630
2	Ceramic	not available	AISI 4150	.160	.016	Dry	.400	2000
			AISI 4150	.160	.016	Dry	.200	620

Sources: 1 - *Fundamentals of Tool Design*, ASTME. A. R. Koneeny, W. J. Potthoff; 2 - *Theory of Metal Cutting*, P. N. Black

where n is an exponent that depends mostly on tool material but is affected by work material, cutting conditions, and environment and C is a constant that depends on all the input parameters, including feed. Table 21-5 provides some data on Taylor tool life constants.

Figure 21-21 shows typical tool life curves for one tool material and three work materials. Notice that all three plots have about the same slope, n. Typical values for n

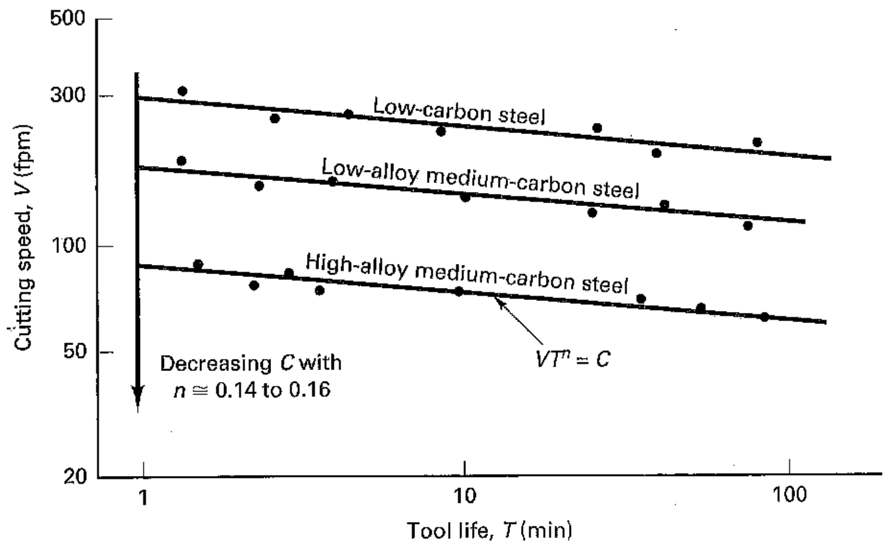


FIGURE 21-21 Log-log tool life plots for three steel work materials cut with HSS tool material.

are 0.14 to 0.16 for HSS, 0.21 to 0.25 for uncoated carbides, 0.30 for TiC inserts, 0.33 for poly-diamonds, 0.35 for TiN inserts, and 0.40 for ceramic-coated inserts.

It takes a great deal of experimental effort to obtain the constants for the Taylor equation because each combination of tool and work material will have different constants. Note that for a tool life of 1 min, $C = V$, or the cutting speed that yields about 1 min of tool life for this tool.

A great deal of research has gone into developing more sophisticated versions of the Taylor equation, wherein constants for other input parameters (typically feed, depth of cut, and work material hardness) are experimentally determined. For example,

$$VT^nF^md^p = K' \tag{21-5}$$

where n, m, and p are exponents and K' is a constant. Equations of this form are also deterministic and determined empirically.

The problem has been approached probabilistically in the following way. Because T depends on speed, feed, materials, and so on, one writes

$$T = \frac{K^{1/n}}{V^{1/n}} = \frac{K}{V^m} \tag{21-6}$$

where K is now a random variable that represents the effects of all unmeasured factors and is an input variable.

The sources of tool life variability include factors such as:

1. Variation in work material hardness (from part to part and within a part).
2. Variability in cutting tool materials, geometry, and preparation.
3. Vibrations in machine tool, including rigidity of work and tool-holding devices.
4. Changing surface characteristics of workpieces.

The examination of the data from a large number of tool life studies in which a variety of steels were machined shows that regardless of the tool material or process, tool life distributions are usually log normal and typically have a large standard deviation. As shown in Figure 21-22, tool life distributions have a large coefficient of variation, which means that tool life is not very predictable.

Other criteria can be used to define tool death in addition to wear limits:

- When surface finish deteriorates unacceptably.
- When workpiece dimension is out of tolerance.

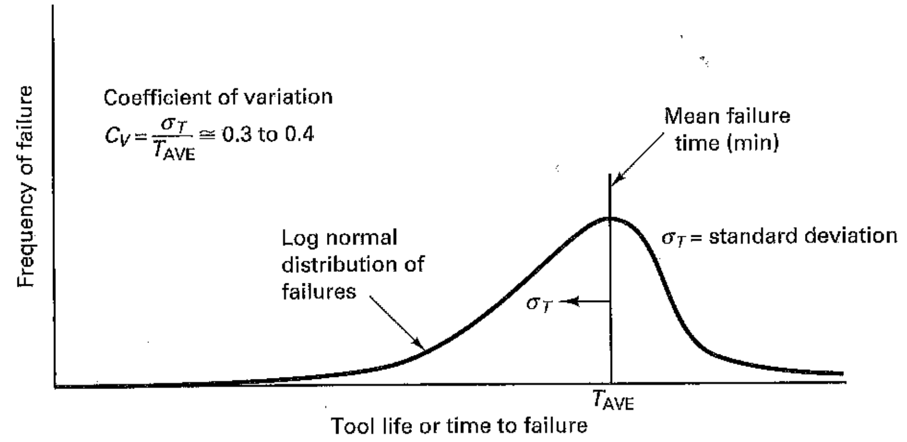


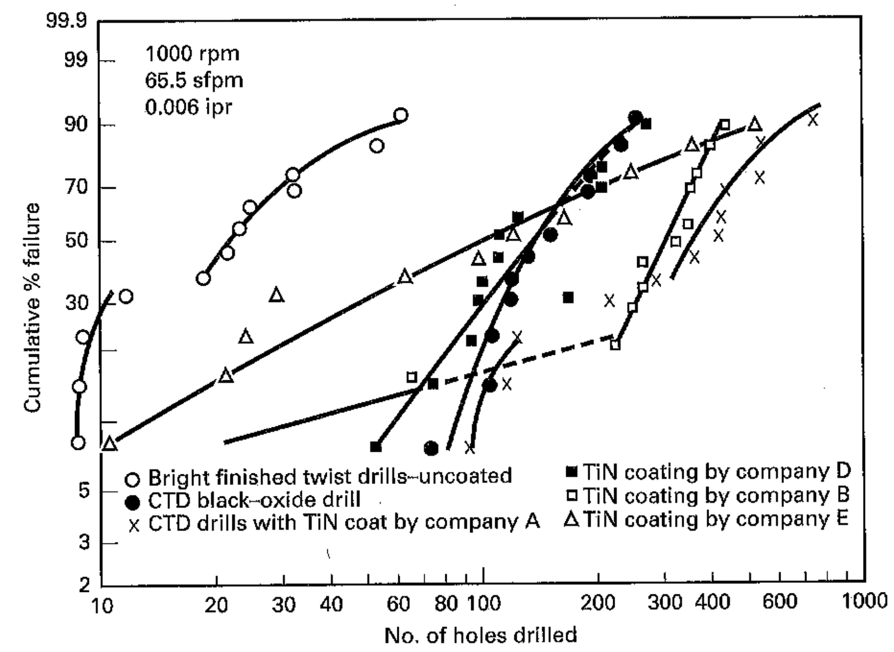
FIGURE 21-22 Tool life viewed as a random variable has a log normal distribution with a large coefficient of variation.

- When power consumption or cutting forces increase to a limit.
- Sparking or chip discoloration and disfigurement.
- Cutting time or component quantity.

In automated processes, it is very beneficial to be able to monitor the tool wear online so that the tool can be replaced prior to failure, wherein defective products may also result. The feed force has been shown to be a good, indirect measure of tool wear. That is, as the tool wears and dulls, the feed force increases more than the cutting force increases.

Once criteria for failure have been established, tool life is that time elapsed between start and finish of the cut, in minutes. Other ways to express tool life, other than time, include:

1. Volume of metal removed between regrinds or replacement of tool.
2. Number of pieces machined per tool.
3. Number of holes drilled with a given tool (see Figure 21-23).



Drill performance based on the number of holes drilled with 1/4-in.-diameter drills in T–1 structural steel.

FIGURE 21-23 Tool life test data for various coated drills. TiN-coated HSS drills outperform uncoated drills. Life based on the number of holes drilled before drill failure.

Drilling tool failure is discussed more in Chapter 23 and is very complex because of the varied and complex geometry of the tools and as shown here in Figure 21-23, the tool material.

MACHINABILITY

Machinability is a much-maligned term that has many different meanings but generally refers to the ease with which a metal can be machined to an acceptable surface finish. The principal definitions of the term are entirely different—the first based on material properties, the second based on tool life, and the third based on cutting speed.

1. Machinability is defined by the ease or difficulty with which the metal can be machined. In this light, specific energy, specific horsepower, and shear stress are used as measures, and, in general, the larger the shear stress or specific power values, the more difficult the material is to machine, requiring greater forces and lower speeds. In this definition, the material is the key.
2. Machinability is defined by the relative cutting speed for a given tool life while cutting some material, compared to a standard material cut with the same tool material. As shown in Figure 21-24, tool life curves are used to develop machinability ratings. For example, in steels, the material chosen for the standard material was B1112 steel, which has a tool life of 60 min at a cutting speed of 100 sfpm. Material X has a 70% rating, which implies that steel X has a cutting speed of 70% of B1112 for equal tool life. Note that this definition assumes that the tool fails when machining material X by whatever mechanism dominated the tool failure when machining the B1112. There is no guarantee that this will be the case. ISO standard 3685 has machinability index numbers based on 30 min of tool life with flank wear of 0.33 mm.
3. Cutting speed is measured by the maximum speed at which a tool can provide satisfactory performance for a specified time under specified conditions. (See ASTM standard E 618-81, "Evaluating Machining Performance of Ferrous Metals Using an Automatic Screw Bar Machine.")
4. Other definitions of machinability are based on the ease of removal of the chips (chip disposal), the quality of the surface finish of the part itself, the dimensional stability of the process, or the cost to remove a given volume of metal.

Further definitions are being developed based on the probabilistic nature of the tool failure, in which machinability is defined by a tool reliability index. Using such indexes, various tool replacement strategies can be examined and optimum cutting rates obtained. These approaches account for the tool life variability by developing coefficients of variation for common combinations of cutting tools and work materials.

The results to date are very promising. One thing is clear, however, from this sort of research: although many manufacturers of tools have worked at developing materials that have greater tool life at higher speeds, few have worked to develop tools that have less variability in tool life at all speeds. The reduction in variability is fundamental to achieving smaller coefficients of variation, which typically are of the order of 0.3 to 0.4. This means that a tool with a 100-min average tool life has a standard deviation of 30 to 40 min, so there is a good probability that the tool will fail early. In automated equipment, where early, unpredicted tool failures are extremely costly, reduction of the tool life variability will pay great benefits in improved productivity and reduced costs.

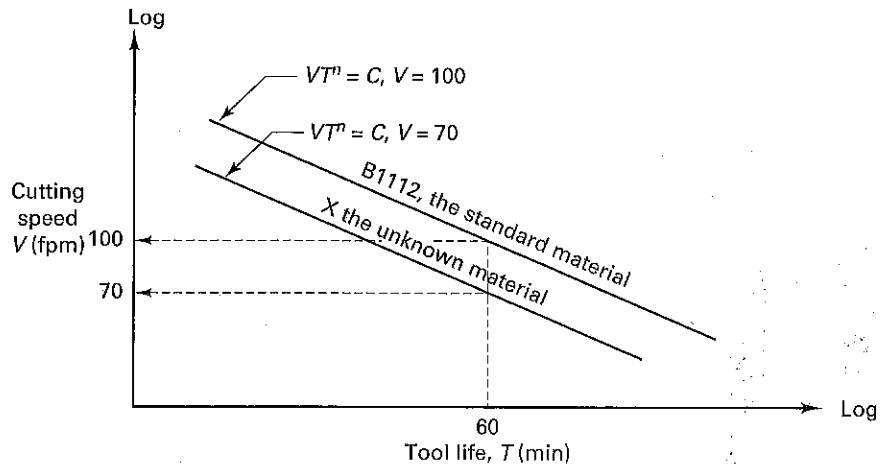


FIGURE 21-24 Machinability ratings defined by deterministic tool life curves.

RECONDITIONING CUTTING TOOLS

In the reconditioning of tools by sharpening and recoating, care must be taken in grinding the tool's surfaces. The following guidelines should be observed:

1. Resharpen to original tool geometry specifications. Restoring the original tool geometry will help the tool achieve consistent results on subsequent uses. Computer numerical control (CNC) grinding machines for tool resharpening have made it easier to restore a tool's original geometry.
2. Grind cutting edges and surfaces to a fine finish. Rough finishes left by poor and abusive regrinding hinder the performance of resharpened tools. For coated tools, tops of ridges left by rough grinding will break away in early tool use, leaving uncoated and unprotected surfaces that will cause premature tool failure.
3. Remove all burrs on resharpened cutting edges. If a tool with a burr is coated, premature failure can occur because the burr will break away in the first cut, leaving an uncoated surface exposed to wear.
4. Avoid resharpening practices that overheat and burn or melt (called *glazing over*) the tool surfaces, because this will cause problems in coating adhesion. Polishing or wire brushing of tools causes similar problems.

The cost of each recoating is about one-fifth the cost of purchasing a new tool. By recoating, the tooling cost per workpiece can be cut by between 20 and 30%, depending on the number of parts being machined.

21.7 CUTTING FLUIDS

From the day that Frederick W. Taylor demonstrated that a heavy stream of water flowing directly on the cutting process allowed the cutting speeds to be doubled or tripled, **cutting fluids** have flourished in use and variety and have been employed in virtually every machining process. The cutting fluid acts primarily as a coolant and secondly as a lubricant, reducing the friction effects at the tool/chip interface and the work flank regions. The cutting fluids also carry away the chips and provide friction (and force) reductions in regions where the bodies of the tools rub against the workpiece. Thus, in processes such as drilling, sawing, tapping, and reaming, portions of the tool apart from the cutting edges come in contact with the work, and these (sliding friction) contacts greatly increase the power needed to perform the process, unless properly lubricated.

The reduction in temperature greatly aids in retaining the hardness of the tool, thereby extending the tool life or permitting increased cutting speed with equal tool life. In addition, the removal of heat from the cutting zone reduces thermal distortion of the work and permits better dimensional control. Coolant effectiveness is closely related to the thermal capacity and conductivity of the fluid used. Water is very effective in this respect but presents a rust hazard to both the work and tools and also is ineffective as a lubricant. Oils offer less effective coolant capacity but do not cause rust and have some lubricant value. In practice, straight cutting oils or emulsion combinations of oil and water or wax and water are frequently used. Various chemicals can also be added to serve as wetting agents or detergents, rust inhibitors, or polarizing agents to promote formation of a protective oil film on the work. The extent to which the flow of a cutting fluid washes the very hot chips away from the cutting area is an important factor in heat removal. Thus, the application of a coolant should be copious and of some velocity.

TABLE 21-6 Cutting Fluid Contaminants

Category	Contaminants	Effects
Solids	Metallic fines, chips Grease and sludge Debris and trash	Scratch product's surface Plug coolant lines Produce wear on tools and machines
Tramp fluids	Hydraulic oils (coolant) Water (oils)	Decrease cooling efficiency Cause smoking Clog paper filters Grow bacteria faster
Biologicals (coolants)	Bacteria Fungi Mold	Acidity coolant **Break down** emulsions Cause rancidity, dermatitis Require toxic biocides

The possibility of a cutting fluid providing lubrication between the chip and the tool face is an attractive one. An effective lubricant can modify the process, perhaps producing a cooler chip, discouraging the formation of a built-up edge on the tool, and promoting improved surface finish. However, the extreme pressure at the tool/chip interface and the rapid movement of the chip away from the cutting edge make it virtually impossible to maintain a conventional hydrodynamic lubricating film at the tool/chip interface. Consequently, any lubrication action is associated primarily with the formation of solid chemical compounds of low shear strength on the freshly cut chip face, thereby reducing tool/chip shear forces or friction. For example, carbon tetrachloride is very effective in reducing friction in machining several different metals and yet would hardly be classified as a good lubricant in the usual sense. Chemically active compounds, such as chlorinated or sulfurized oils, can be added to cutting fluids to achieve such a lubrication effect. Extreme-pressure lubricants are especially valuable in severe operations, such as internal threading (tapping), where the extensive tool-work contact results in high friction with limited access for a fluid. In addition to functional effectiveness as coolant and lubricant, cutting fluids should be stable in use and storage, noncorrosive to work and machines, and nontoxic to operating personnel. The cutting fluid should also be restorable by using a closed recycling system that will purify the used coolant and cutting oils. Cutting fluids become contaminated in three ways (Table 21-6). All these contaminants can be eliminated by filtering, hydrocycloning, pasteurizing, and centrifuging. Coolant restoration eliminates 99% of the cost of disposal and 80% or more of new fluid purchases. See Figure 21-25 for a schematic of a coolant recycling system.

■ 21.8 ECONOMICS OF MACHINING

The cutting speed has such a great influence on the tool life compared to the feed or the depth of cut that it greatly influences the overall economics of the machining process. For a given combination of work material and tool material, a 50% increase in speed results in a 90% decrease in tool life, while a 50% increase in feed results in a 60% decrease in tool life. A 50% increase in depth of cut produces only a 15% decrease in tool life. Therefore, in limited-horsepower situations, depth of cut and then feed should be maximized, while speed is held constant and horsepower consumed is maintained within limits. As cutting speed is increased, the machining time decreases, but the tools wear out faster and must be changed more often. In terms of costs, the situation is as shown in Figure 21-26, which shows the effect of cutting speed on the cost per piece.

The total cost per operation is comprised of four individual costs: machining costs, tool costs, tool-changing costs, and handling costs. The machining cost is observed to decrease with increasing cutting speed because the cutting time decreases. Cutting time is proportional to the machining costs. Both the tool costs and the tool-changing costs increase with increases in cutting speeds. The handling costs are independent of cutting speed. Adding up each of the individual costs results in a total unit cost curve that is observed to go through a minimum point. For a turning operation, the total cost per piece C equals

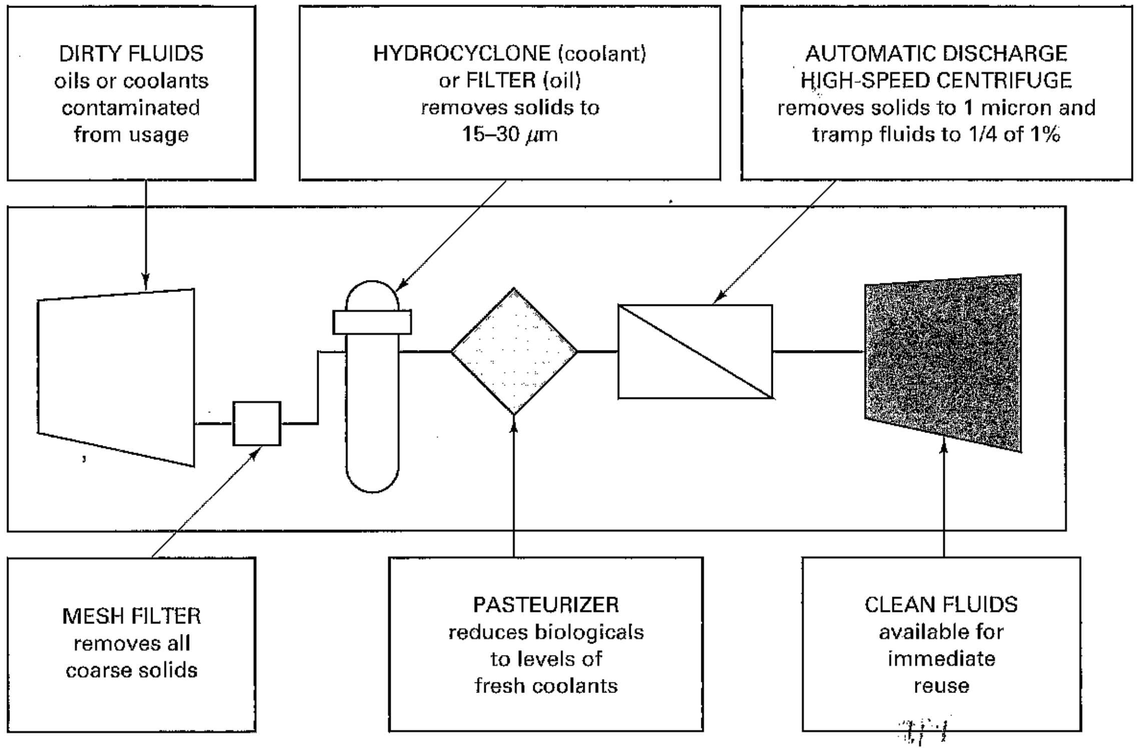


FIGURE 21-25 A well-designed recycling system for coolants will return more than 99% of the fluid for reuse.

$$C = C_1 + C_2 + C_3 + C_4$$
$$= \text{Machining cost} + \text{Tooling cost} + \text{Tool-changing cost} + \text{Handling cost per piece} \quad (21\text{-}7)$$

Note: This "C" is not the same "C" used in the Taylor Tool life equation. In this analysis, that "C" will be called "K."

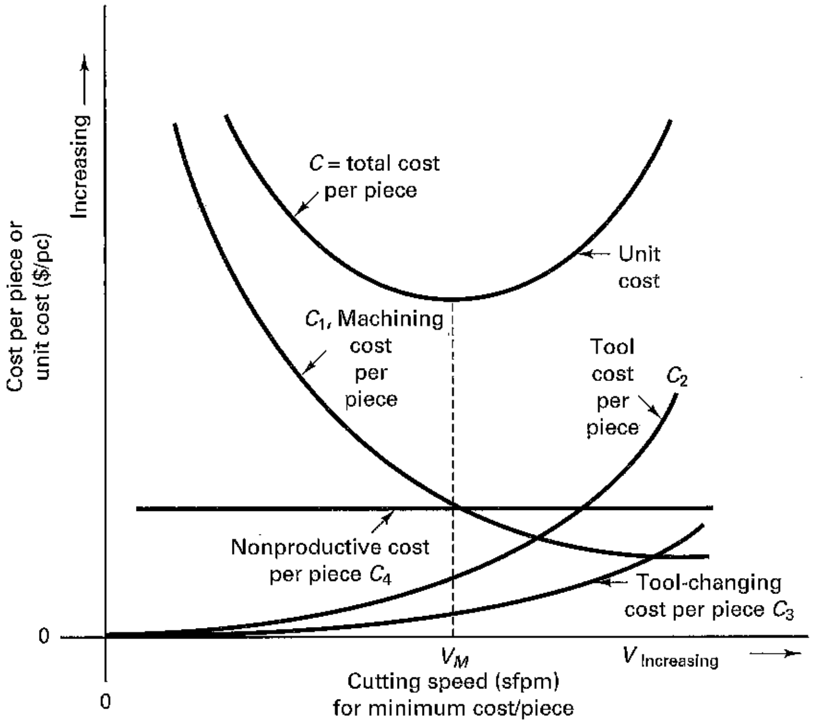


FIGURE 21-26 Cost per unit for a machining process versus cutting speed. Note that the "C" in this figure and related equations is not the same "C" used in the Taylor tool life (equation 21-3).

Expressing each of these cost terms as a function of cutting velocity will permit the summation of all the costs.

$C_1 = T_m \times C_o$ where C_o = operating cost ($/min)
T_m = cutting time (min/piece)

$C_2 = \left(\frac{T_m}{T}\right) C_t$ where T = tool life (min/tool)
C_t = initial cost of tool ($)

$C_3 = t_c \times C_o \left(\frac{T_m}{T}\right)$ where t_c = time to change tool (min)
$\frac{T_m}{T}$ = number of tool changes per piece

C_4 labor, overhead, and machine tool costs consumed while part is being loaded or unloaded, tools are being advanced, machine has broken down, and so on.

Because $T_m = L/Nf_r$ for turning

$= \pi DL/12Vf_r$

and $T = (K/V)^{1/n}$, by rewriting equation 21-3, and using "K" for the constant "C", the cost per unit, C, can be expressed in terms of V:

$$C = \frac{L\pi DC_o}{12Vf_r} + \frac{C_t V^{1/n}}{K^{1/n}} + \frac{t_c C_o V^{1/n}}{K^{1/n}} + C_4 \qquad (21\text{-}8)$$

To find the minimum, take $dc/dV = 0$ and solve for V:

$$V_m = K\left[\frac{n}{1-n} \bullet \frac{C_o}{C_o\, t_t + C_t}\right]^n \qquad (21\text{-}9)$$

Thus, V_m represents a cutting speed that will minimize the cost per unit, as depicted in Figure 21-26. However, a word of caution here is appropriate. Note that this derivation was totally dependent upon the Taylor tool life equation. Such data may not be available because they are expensive and time consuming to obtain. Even when the tool life data are available, this procedure assumes that the tool fails only by whichever wear mechanism (flank or crater) was described by this equation and by no other failure mechanism. Recall that tool life has a very large coefficient of variation and is probabilistic in nature. This derivation assumes that for a given V, there is one T—and this simply is not the case, as was shown in Figure 21-18. The model also assumes that the workpiece material is homogeneous, the tool geometry is preselected, the depth of cut and feed rate are known and remain unchanged during the entire process, sufficient horsepower is available for the cut at the economic cutting conditions, and the cost of operating time is the same whether the machine is cutting or not cutting.

COST COMPARISONS

Cost comparisons are made between different tools to decide which tool material to use for a given job. Suppose there are four different tools that can be used for turning hot-rolled 8620 steel with triangular inserts. The four tool materials are shown in Table 21-7. Operating costs for the machine tool are $60/hr. The low-force groove insert has only three cutting edges available instead of six. It takes 3 min to change inserts and 0.5 min to unload a finished part and load in a new 6-in.-diameter bar stock. The length of cut is about 24 in. The student should study and analyze this table carefully so that each line is understood. Note that the cutting tool cost per piece is three times higher for the low-force groove tool over the carbide but is really of no consequence, because the major cost per piece comes from two sources: the machining cost per piece and the nonproductive cost per piece.

TABLE 21-7 Cost Comparison of Four Tool Materials, Based on Equal Tool Life of 40 Pieces per Cutting Edge

	Uncoated	TiC-Coated	Al_2O_3-Coated	Al_2O_3 LFG
Cutting speed (surface ft/min)	400	640	1100	1320
Feed (in./rev)	0.020	0.02	0.024	0.028
Cutting edges available per insert	6	6	6	3
Cost of an insert ($/insert)	4.80	5.52	6.72	6.72
Tool life (pieces/cutting edge)	192	108	60	40
Tool-change time per piece (min)	0.075	0.075	0.075	0.075
Nonproductive cost per piece ($/pc)	0.50	0.50	0.50	0.50
Machining time per piece (min/pc)	4.8	2.7	1.50	1.00
Machining cost per piece ($/unit)	4.8	2.7	1.5	1.00
Tool-change cost per piece ($/pc)	0.08	0.08	0.08	0.08
Cutting tool cost per piece ($/pc)	0.02	0.02	0.03	0.06
Total cost per piece ($/pc)	5.40	3.30	2.11	1.64
Production rate (pieces/hr)	11	18	29	38
Improvement in productivity based on pieces/hr (%)	0	64	164	245

Source: Data from T. E. Hale et al., "High Productivity Approaches to Metal Removal," *Materials Technology*, Spring 1980, p. 25.

KEY WORDS

aluminum oxide
back rake angle
BUE (built-up edge)
carbides
cast cobalt alloy
ceramics
cermets
chemical vapor deposition (CVD)
chip groove
coated tools
crater wear
cubic boron nitride (CBN)
cutting fluids
cutting tool materials
depth-of-cut line (DCL)
diamonds
flank wear
hardness
high-speed steel (HSS)
hot hardness
low-force groove (LFG)
machinability
metal cutting
microchipping
physical vapor deposition (PVD)
polycrystalline cubic boron nitride (PCBN)
polycrystalline diamond (PCD)
powder metallurgy (P/M)
sintered carbides
stellite tools
tool life
tool steels
titanium carbide (TiC)
titanium nitride (TiN)

REVIEW QUESTIONS

1. For metal-cutting tools, what is the most important material property (i.e., the most critical characteristic)? Why?
2. What is hot hardness compared to hardness?
3. What is impact strength, and how is it measured?
4. Why is impact strength an important property in cutting tools?
5. Is a cemented carbide tool made by a powder metallurgy method?
6. What are the primary considerations in tool selection?
7. What is the general strategy behind coated tools?
8. What is a cermet?
9. How is a CBN tool manufactured?
10. F. W. Taylor was one of the discoverers of high-speed steel. What else is he well known for?
11. What casting process do you think was used to fabricate cast cobalt alloys?
12. Discuss the constraints in the selection of a cutting tool.
13. What does *cemented* mean in the manufacture of carbides?
14. What advantage do ground carbide inserts have over pressed carbide inserts?
15. What is a chip groove?
16. What is the DCL?
17. Suppose you made four beams out of carbide, HSS, ceramic, and cobalt. The beams are identical in size and shape, differing only in material. Which beam would do each of the following?
    a. Deflect the most, assuming the same load.
    b. Resist penetration the most.
    c. Bend the farthest without breaking.
    d. Support the greatest compressive load.
18. Multiple coats or layers are put on the carbide base for what different purposes?
19. What tool material would you recommend for machining a titanium aircraft part?
20. What makes the process that makes TiC coatings for tools a problem? See equation 21-1.
21. Why does a TiN-coated tool consume less power than an uncoated HSS under exactly the same cutting conditions?
22. For what work material are CBN tools more commonly used, and why?
23. Why is CBN better for machining steel than diamond?
24. What is the typical coefficient of variation for tool life data, and why is this a problem?
25. What is meant by the statement "Tool life is a random variable"?

26. The typical value of a coefficient of variation in metal-cutting tool life distributions is 0.3. How could it be reduced?
27. Machinability is defined in many ways. Explain how a rating is obtained.
28. What are the chief functions of cutting fluids?
29. How are CVD tools manufactured?
30. Why is the PVD process used to coat HSS tools?
31. Why is there no universal cutting tool material?
32. What is an 18-4-1 HSS composed of?
33. Over the years, tool materials have been developed that have allowed significant increases in MRR. Nevertheless, HSS is still widely used. Under what conditions might HSS be the material of choice?
34. Why is the rigidity of the machine tool an important consideration in the selection of the cutting tool material?
35. Explain how it can be that the tool wears when it may be four times as hard as the work material.
36. What is a honed edge on a cutting tool and why is it done?

PROBLEMS

1. Figure 21-A gives data for cutting speed and tool life. Determine the constants for the Taylor tool life equation for these data. What do you think the tool material might have been?

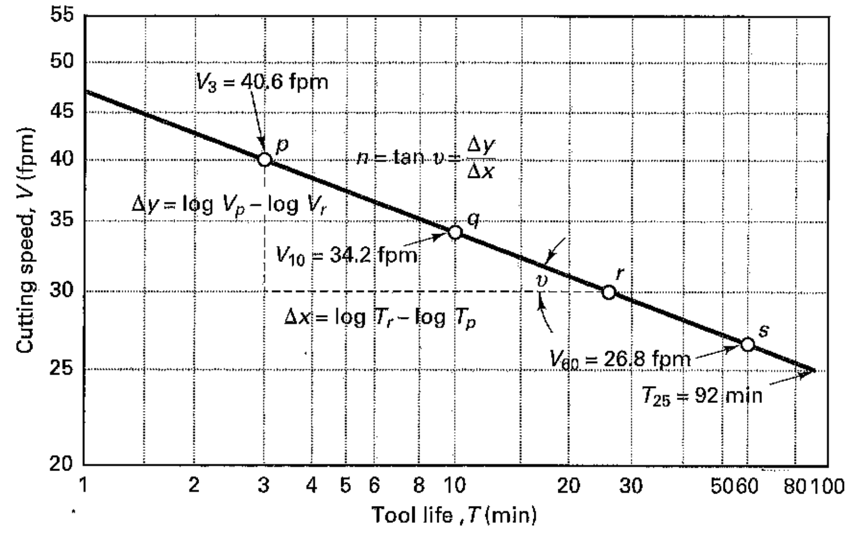
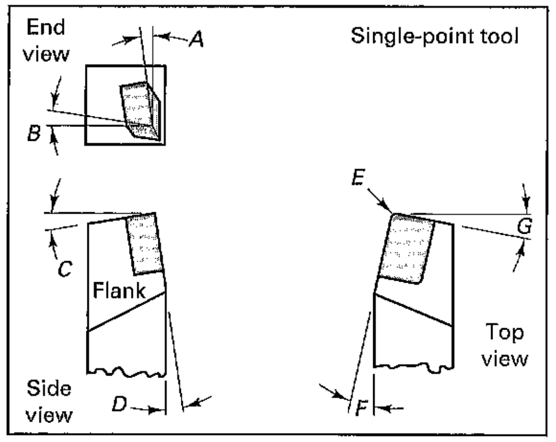


FIGURE 21-A

2. Suppose you have a turning operation using a tool with a zero back rake and 5-degree end relief. The insert flank has a wear land on it of 0.020 in. How much has the diameter of the workpiece grown (increased) due to this flank wear, assuming the tool has not been reset to compensate for the flank wear?

3. In Figure 21-B, a single-point tool is shown. Identify points *A* through *G* using tool nomenclature.



A = ____________
B = ____________
C = ____________
D = ____________
E = ____________
F = ____________
G = ____________

FIGURE 21-B

4. The following data have been obtained for machining an Si-Al alloy:

Workpiece Material	Tool Material	Cutting Speed (m/min) for Tool Life (m/min) of 20 min	30 min	60 min
Sand casting	Diamond polycrystal	731	642	514
Permanent-mold casting	Diamond polycrystal	591	517	411
PMC with flood cooling	Diamond polycrystal	608	554	472
Sand casting	WC-K-20	175	161	139

Compute the *C* and *n* values for the Taylor tool life equation. How do these *n* values compare to the typical values?

5. In Figure 21-C, the insert at the top is set with a 0-degree side cutting-edge angle. The insert at the bottom is set so that the edge contact length is increased from a 0.250-in. depth of cut to 0.289 in. The feed was 0.010 ipr.
   a. Determine the side cutting-edge angle for the offset tool.
   b. What is the uncut chip thickness in the offset position?
   c. What effect will this have on the forces and the process?

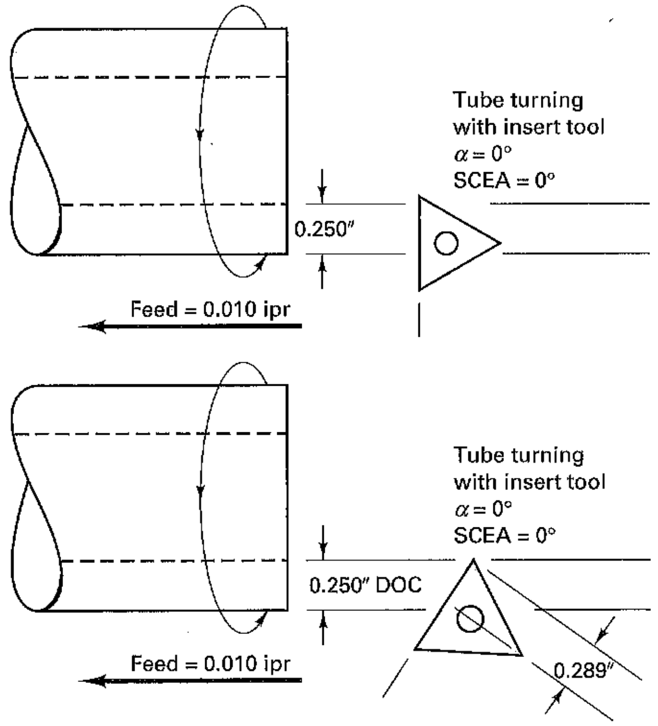


FIGURE 21-C

6. Tool cost is often used as the major criterion for justifying tool selection. Either silicon nitride or PCBN insert tips can be used to machine (bore) a cylinder block on a transfer line at a rate of 312,000 part/yr (material: gray cast iron). The operation requires 12 inserts (2 per tool), as six bores are machined simultaneously. The machine was run at 2600 sfpm with a feed of 0.014 in. at 0.005-in. DOC for finishing. Here are some additional data:

	SiN	PCBN
Tips in use per part	12	12
Tool life (parts per tool)	200	4700
Cost per tip	$1.25	$28.50

   a. Which tool material would you recommend?
   b. On what basis?

7. A 2-in.-diameter bar of steel was turned at 284 rpm, and tool failure occurred in 10 min. The speed was changed to 132 rpm, and the tool failed in 30 min of cutting. Assume that a straight-line relationship exists. What cutting speed should be used to obtain a 60-min tool life of V_{60}?
8. Table 21-7 shows a cost comparison for four tool materials. Show how the data in this table were generated.
9. Problem 6 provided data stating the cutting speed for this job was 2600 sfpm. Use equation 21-9 to verify that speed.
10. The outside diameter of a roll for a steel (AISI 1015) rolling mill is to be turned. In the final pass, Starting diameter = 26.25 in.

and Length = 48.0 in. The cutting conditions will be Feed = 0.0100 in./rev and Depth of cut = 0.125 in. A cemented carbide cutting tool is to be used, and the parameters of the Taylor tool life equation for this setup are $n = 0.25$ and $C = 1300$. It is desirable to operate at a cutting speed such that the tool will not need to be changed during the cut. Determine the cutting speed that will make the tool life equal to the time required to complete this turning operation. (Problem suggested by Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, 2nd ed., John Wiley & Sons, 2002.)

11. Using data from Problems 8 and 10, estimate the necessary horsepower for the machine tool to make this cut.
12. Figure 21-B shows a sketch of a single-point tool and its associated tool signature. Put the signature from the tool in Figure 21-B in the same order as shown in Figure 21-D. Which tool would produce the larger F_c, given that both are cutting at the same V, f_r, and DOC in the same material?

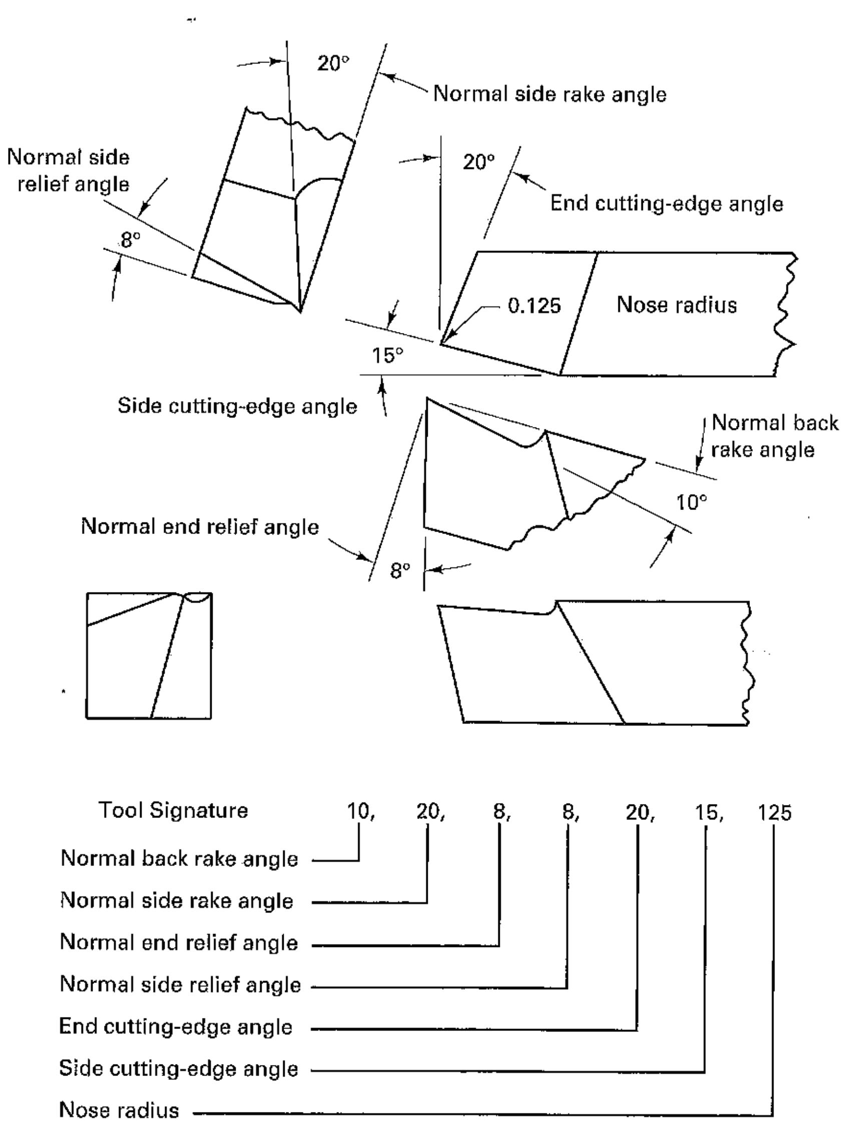


FIGURE 21-D

13. What are the various ways a cutting tool can fail and what can be done to remedy this? See Figures 21-17 and 21-E.

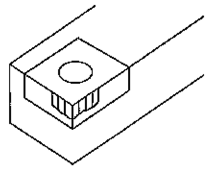
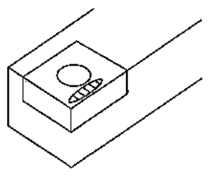
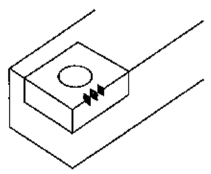
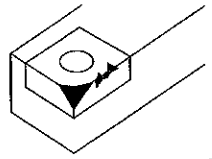
	Failure		Basic Remedy
Edge Failure	Excessive flank wear 	Tool material Cutting conditions	• Use a more wear-resistant grade carbide → {coated, cermet} • Decrease speed
	Excessive crater wear 	Tool material Tool design Cutting conditions	• Use a more wear-resistant grade carbide → {coated, cermet} • Enlarge the rake angle • Select the correct chip breaker • Decrease speed • Reduce the depth of cut and feed
	Cutting-edge chipping 	Tool material Tool design Cutting conditions	• Use tougher grades If carbide, (AC2000 → AC3000) • If built-up edge occurs, change to a less susceptible grade (cermet) • Reinforce the cutting edge (honing) • Reduce the rake angle • Increase speed (if caused by edge build-up)
	Partial fracture of cutting edges 	Tool material Tool design Cutting conditions	• Use tougher grades if carbide, (AC2000 → AC3000) • Use holder with a large approach angle • Use larger shank-size holder • Reduce the depth of cut and feed
	Built-up edge	Tool material Cutting conditions	• Change to a grade that is adhesion resistant • Increase the cutting speed and feed • Use cutting fluids
	Plastic deformation	Tool material Cutting conditions	• Change to highly thermal-resistant grades • Reduce the cutting speed and feed

FIGURE 21-E

Chapter 21 CASE STUDY

Comparing Tool Materials Based on Tool Life

The Zachary Milling Company is trying to decide on what kind of inserts to use in their milling cutters. These milling cutters often provide a marked productivity improvement compared to conventional HDD drills, particularly when they are combined with coated insert tools. The company is trying to determine which type of insert to use in the drill for machining some hot-rolled 8620 steel shafts using triangular inserts. The operating cost of the machine tool is \$60/hr. It takes about 3 min to change the inserts and about 30 s to unload a finished part and load a new part in the machine. The company is currently using uncoated inserts at the following operating conditions: 400 sfpm and 0.020 ipr. These speeds and feeds resulted in each cutting edge producing about 40 pieces before the tool's cutting edge became dull. The tool was then indexed. Because it was a triangular tool, each tool had six cutting edges available before it had to be replaced. At these speeds and feeds, the milling time was 4.8 min and the production rate was 11 part/hr, while the machining cost per piece was \$4.80 (\$1.00/min × 4.8 min/pc). The manufacturing engineer on the job, Brian Graney, has found three new tool materials being used in face mills. They are listed in Table CS-24 along with the data for the uncoated tool. The new materials are TiC-coated carbide, Al_2O_3 coated carbide, and a ceramic-coated insert with a single-side, low-force groove geometry. The expected cutting conditions, speeds, and feeds are given in the table along with Brian's estimates of the production rates in pieces per hour for each of these new tool materials. The low-force groove geometry tools can only be used three times—they cannot be flipped over—so only three cutting edges are available per insert before it has to be replaced. Brian has argued that even though the ceramic-coated inserts cost more, they result in a lower cost per piece, considering all the costs. Determine the machining cost per piece, the tool-changing cost per piece, and the tool cost per piece that make up the total cost per piece, and verify Brian's belief that these coated tools will provide some cost savings.

TABLE CS-21 Cost Comparison of Four Tool Materials, Based on Equal Tool Life

	Uncoated	TiC-Coated	Al_2O_3-coated	Al_2O_3 LFG
Cutting speed (surface ft/min)	400	640	1100	1320
Feed (in/rev)	0.020	0.02	0.024	0.028
Cutting edges available per insert	6	6	6	3
Cost of an insert (\$/insert)	4.80	5.52	6.72	6.72
Tool life (pieces/cutting edge)	192	108	60	40
Tool change time per piece (min)	0.075	0.075	0.075	0.075
Nonproductive cost per piece (\$/pc)	0.50	0.50	0.50	0.50