Cutting Tools for Machining

Chapter 21

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21.1 Introduction

Improvements in Cutting Tools

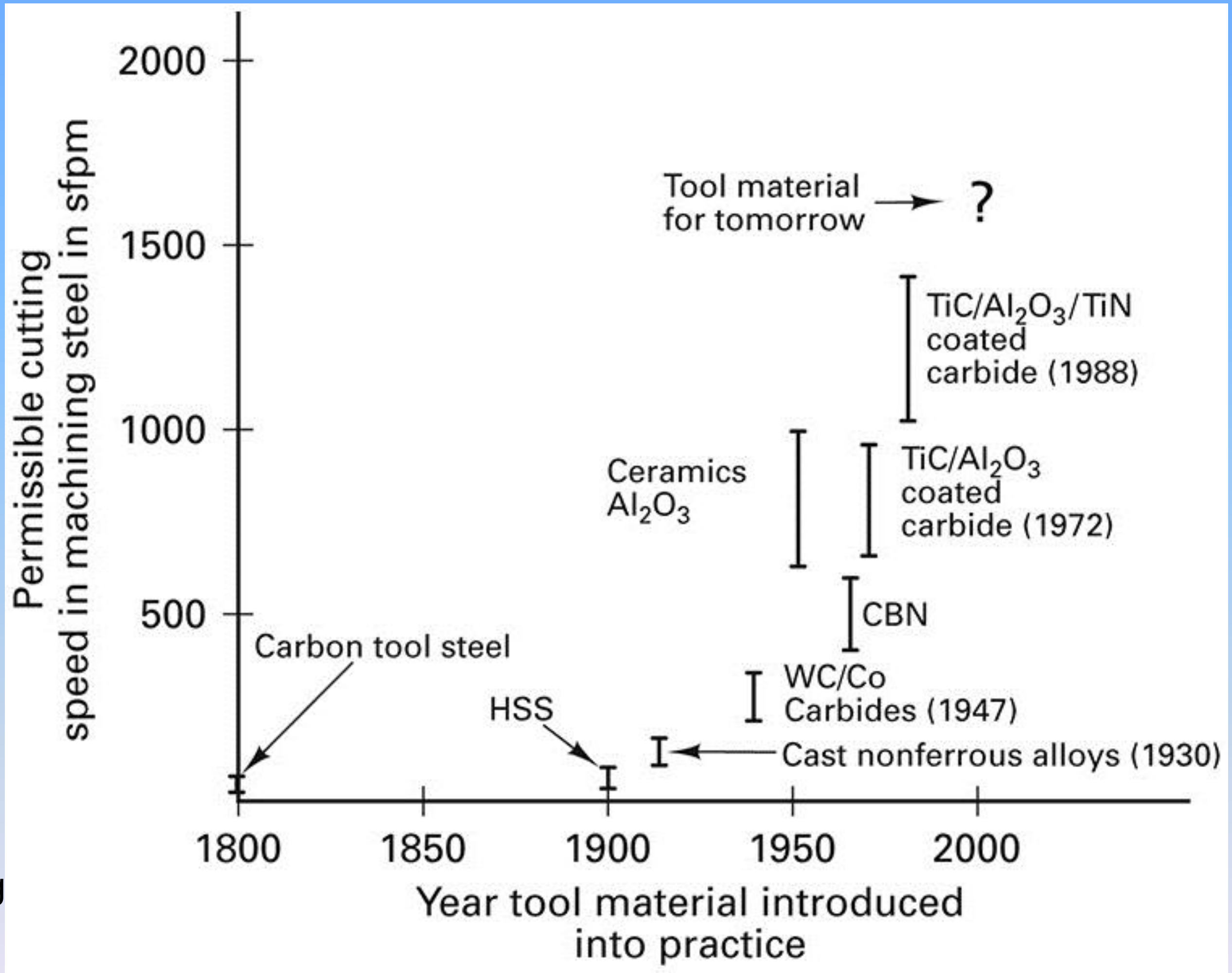
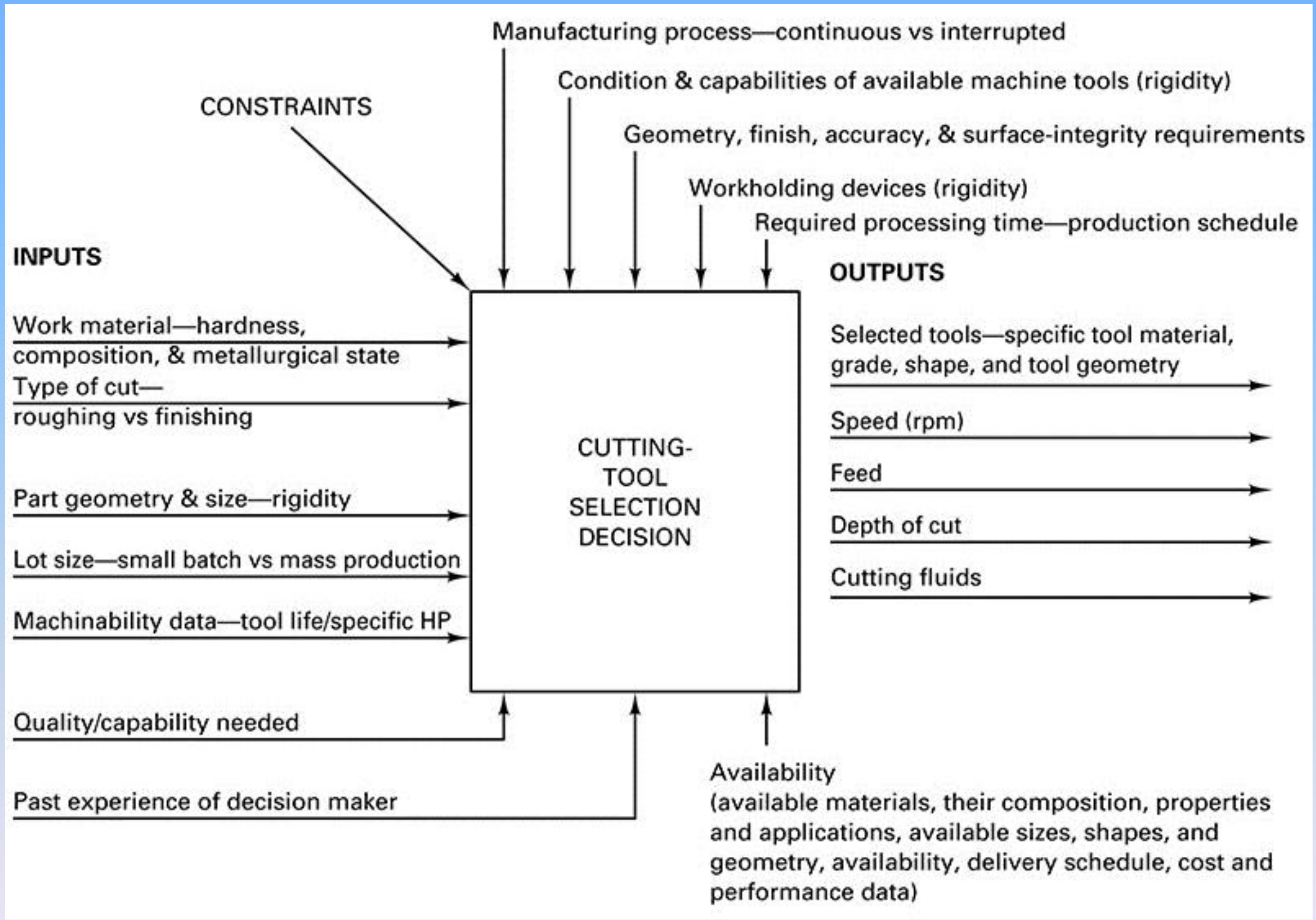


FIGURE 21-1 Improvements in cutting tool materials have led to significant increases in cutting speeds (and productivity) over the years.

Selection of Cutting Tool Materials

FIGURE 21-2 The selection of the cutting-tool material and geometry followed by the selection of cutting conditions for a given application depends upon many variables



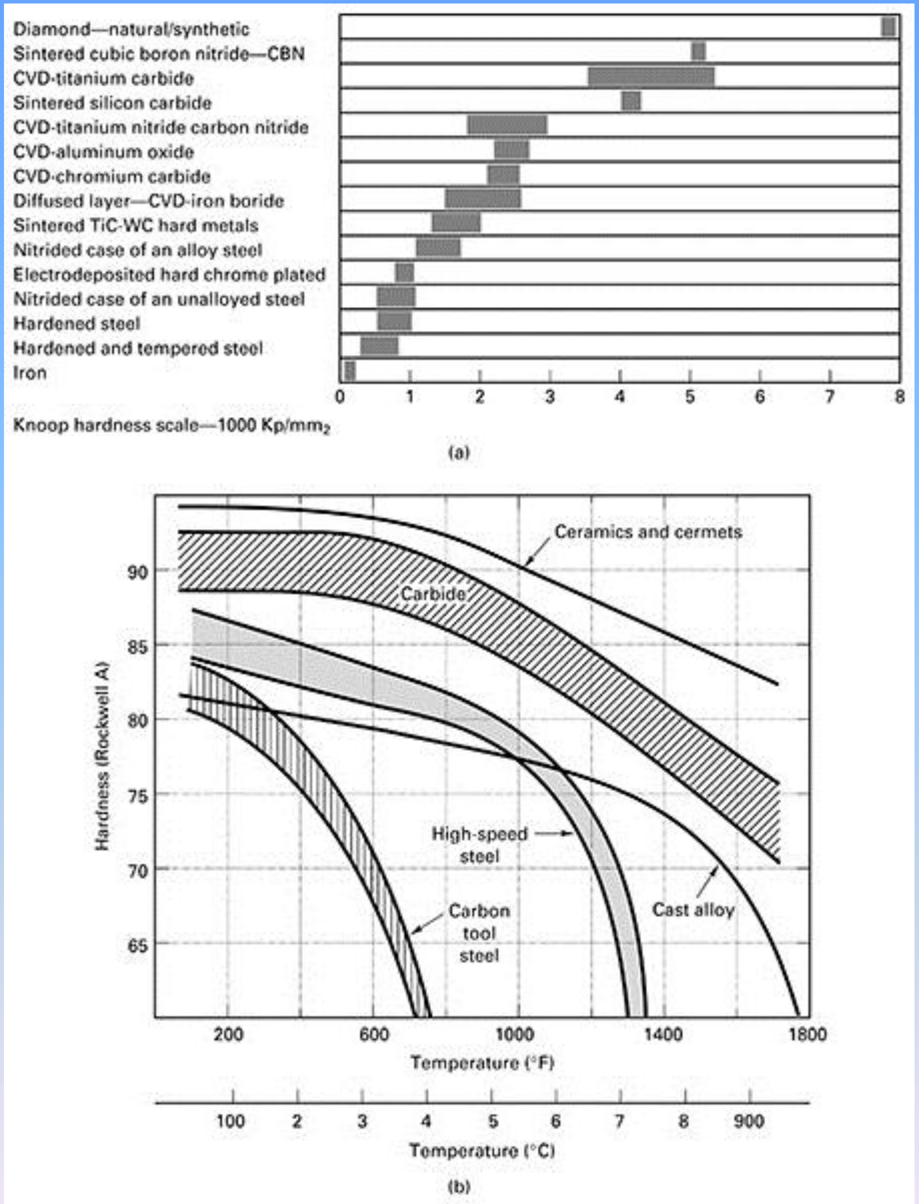
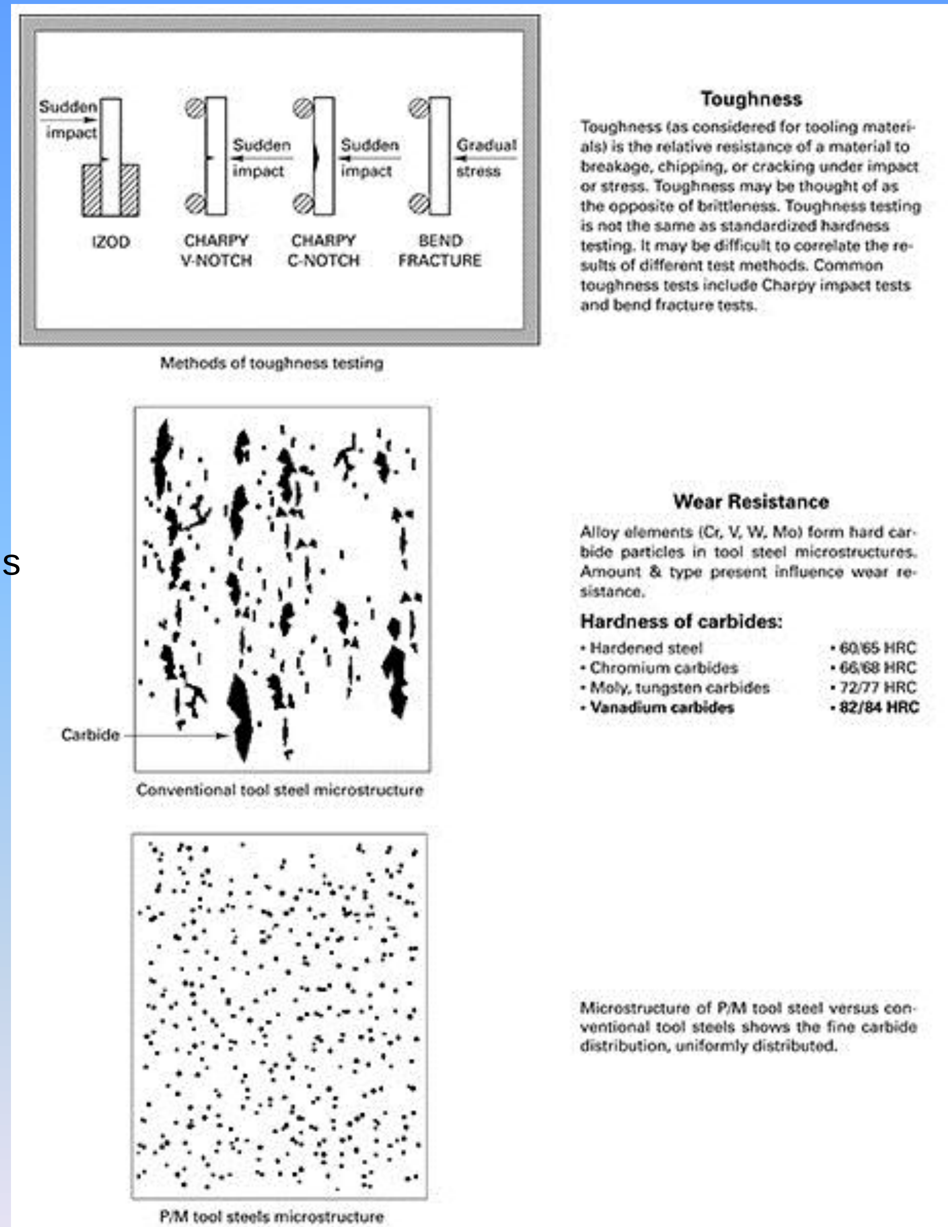


FIGURE 21-3 (a) Hardness of cutting materials and (b) decreasing hardness with increasing temperature, called hot hardness. Some materials display a more rapid drop in hardness above some temperatures. *(From* Metal Cutting Principles, *2nd ed. Courtesy of Ingersoll Cutting Tool Company.)*

FIGURE 21-4 The most important properties of tool steels are:

1. Hardness—resistance to deforming and flattening
2. Toughness—resistance to breakage and chipping
3. Wear resistance—resistance to abrasion and erosion.



Properties of Cutting Tool Materials

FIGURE 21-5 Salient Properties of Cutting Tool Materials[a]

	Carbon and Low-/Medium-Alloy Steels	High-Speed Steels	Sintered Cemented Carbides	Coated HSS	Coated Carbides	Ceramics	Polycrystalline CBN	Diamond
Toughness	▶ Decreasing ▶							
Hot hardness	▶ Increasing ▶							
Impact strength	◀ Decreasing ◀							
Wear resistance	▶ Increasing ▶							
Chipping resistance	◀ Decreasing ◀							
Cutting speed	▶ Increasing ▶							
Depth of cut	Light to medium	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Very light for single-crystal diamond
Finish obtainable	Rough	Rough	Good	Good	Good	Very good	Very good	Excellent
Method of manufacture	Wrought	Wrought cast, HIP sintering	Cold pressing and sintering, PM	PVD[b] after forming	CVD[c]	Cold pressing and sintering or HIP sintering	High-pressure–high-temperature sintering	High-pressure–high-temperature sintering
Fabrication	Machining and grinding	Machining and grinding	Grinding	Machining and grinding, coating	Grinding before coating	Grinding	Grinding and polishing	Grinding and polishing
Thermal shock resistance	▶ Increasing ▶							
Tool material cost	▶ Increasing ▶							

[a] Overlapping characteristics exist in many cases. Exceptions to the rule are very common. In many classes of tool materials, a wide range of compositions and properties are obtainable.
[b] Physical vapor deposition.
[c] Chemical vapor deposition.

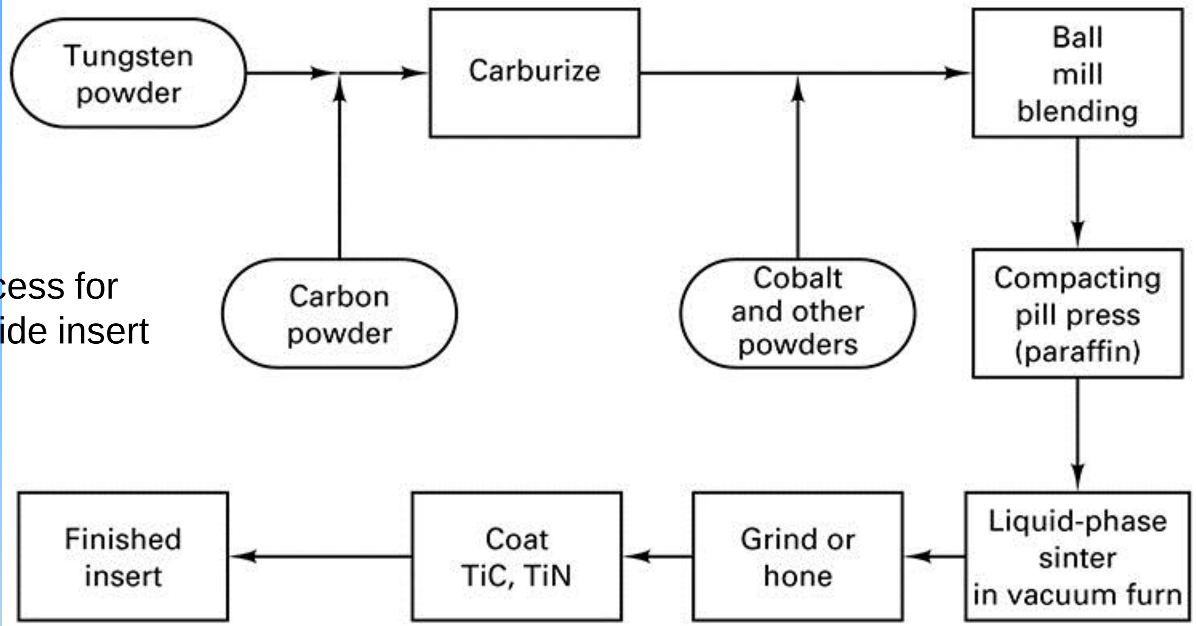
21.2 Cutting-Tools Materials

TABLE 21-1 Surface Treatments for Cutting Tools

Process	Method	Hardness* and Depth	Advantages	Limitations
Black oxide	HSS cutting tools are oxidized in a steam atmosphere at 1000°F	No change in prior steel hardness	Prevents built-up edge formations in machining of steel.	Strictly for HSS tools.
Nitriding case hardening	Steel surface is coated with nitride layer by use of cyanide salt at 900° to 1600°F, or ammonia, gas, or N_2 ions.	To 72 R_c; Case depth: 0.0001 to 0.100 in.	High production rates with bulk handling. High surface hardness. Diffuses into the steel surfaces. Simulates strain hardening.	Can only be applied to steel. Process has embrittling effect because of greater hardness. Post-heat treatment needed for some alloys.
Electrolytic electroplating	The part is the cathode in a chromic acid solution; anode is lead. Hard chrome plating is the most common process for wear resistance.	70-72 R_c; 0.0002 to 0.100 in.	Low friction coefficient, antigalling. Corrosion resistance. High hardness.	Moderate production; pieces must be fixtured. Part must be very clean. Coating does not diffuse into surface, which can affect impact properties.
Vapor deposition chemical vapor deposition (CVD)	Deposition of coating material by chemical reactions in the gaseous phase. Reactive gases replace a protective atmosphere in a vacuum chamber. At temperatures of 1800° to 1200°F, a thin diffusion zone is created between the base metal and the coating.	To 84 R_c; 0.0002 to 0.0004 in.	Large quantities per batch. Short reaction times reduce substrate stresses. Excellent adhesion, recommended for forming tools. Multiple coatings can be applied (TiN, TiC, AL_2O_3). Line-of-sight not a problem.	High temperatures can affect substrate metallurgy, requiring post-heat treatment, which can cause dimensional distortion (except when coating sintered carbides). Necessary to reduce effects of hydrogen chloride on material properties, such as impact strength. Usually not diffused. Tolerances of +0.001 required for HSS tools.
Physical vapor desposition (PVD sputtering)	Plasma is generated in a vacuum chamber by ion bombardment to dislodge particles from a target made of the coating material. Metal is evaporated and is condensed or attracted to substrate surfaces.	To 84 R_c; To 0.0002 in. thick	A useful experimental procedure for developing wear surfaces. Can coat substrates with metals, alloys, compounds, and refractories. Applicable for all tooling.	Not a high-production method. Requires care in cleaning. Usually not diffused.
PVD (electron beam)	A plasma is generated in vacuum by evaporation from a molten pool that is heated by an electron-beam gun.	To 84 R_c; To 0.0002 in. thick	Can coat reasonable quantities per batch cycle. Coating materials are metals, compounds, alloys, and refractories. Substrate metallurgy is preserved. Very good adhesion. Fine particle deposition. Applicable for all tooling.	Parts require fixturing and orientation in line-of-sight process. Ultra-cleanliness required.
PVD/ARC	Titanium is evaporated in a vacuum and reacted with nitrogen Gas. Resulting titanium nitride plasma is ionized and electrically attracted to the substrate surface. A high-energy process with multiple plasma guns.	To 85 R_c; To 0.0002 in. thick	Process at 900°F preserves substrate metallurgy. Excellent coating adhesion. Controllable deposition of grain size and growth. Dimensions, surface finish, and sharp edges are preserved. Can coat all high-speed steels without distortion.	Parts must be fixtured for line-of-sight process. Parts must be very clean. No by-products formed in reaction. Usually only minor diffusion.

*Rockwell hardness values above 68 are estimates.

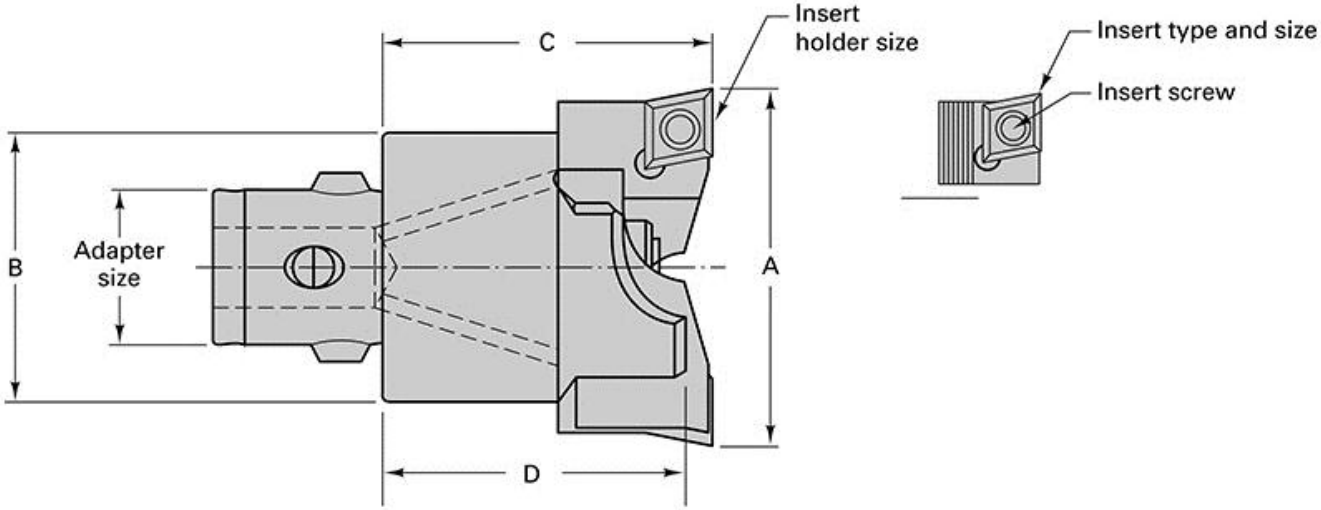
Cemented Carbide Inserts



Tungsten is carburized in a high-temperature furnace, mixed with cobalt and blended in large ball mills. After ball milling, the powder is screened and dried. Paraffin is added to hold the mixture together for compacting. Carbide inserts are compacted using a pill press. The compacted powder is sintered in a high-temperature vacuum furnace.The solid cobalt dissolves some tungsten carbide, then melts and fills the space between adjacent tungsten carbide grains. As the mixture is cooled, most of the dissolved tungsten carbide precipitates onto the surface of existing grains. After cooling, inserts are finish ground and honed or used in the pressed condition.

FIGURE 21-6 P/M process for making cemented carbide insert tools.

Boring Head



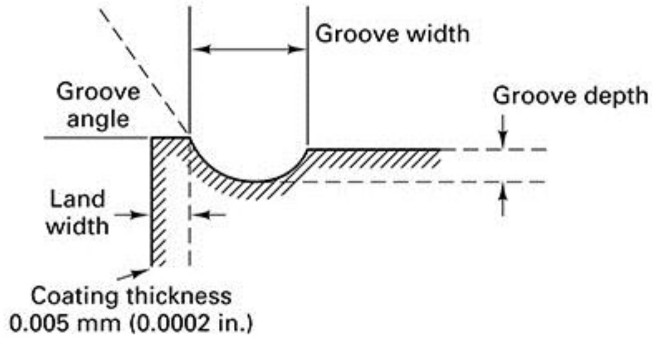
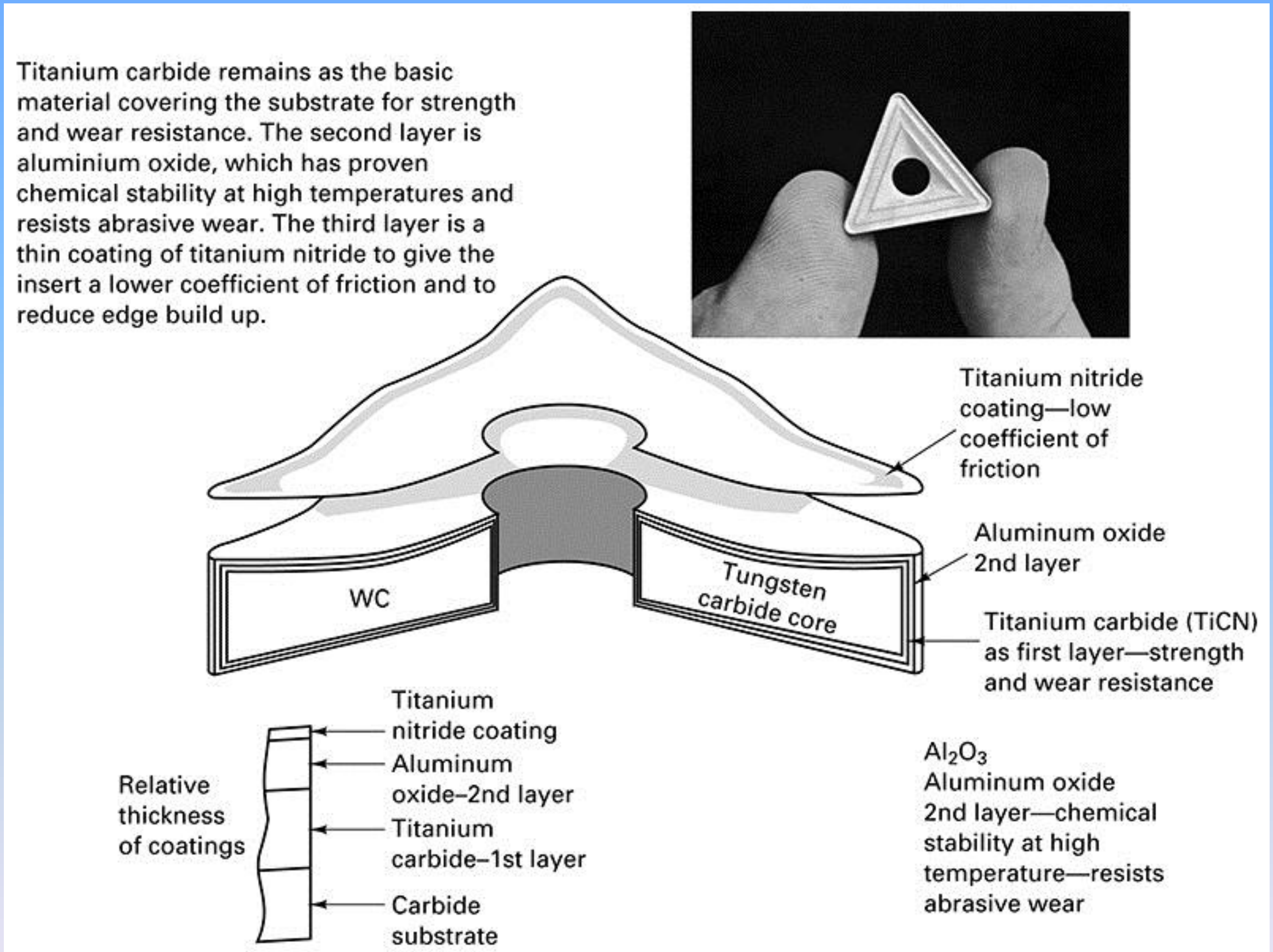


FIGURE 21-7 Boring head with carbide insert cutting tools. These inserts have a chip groove that can cause the chips to curl tightly and break into small, easily disposed lengths.

Triple Coated Carbide Tools

FIGURE 21-8 Triple-coated carbide tools provide resistance to wear and plastic deformation in machining of steel, abrasive wear in cast iron, and built-up edge formation.



Triple Coated Carbide Tools

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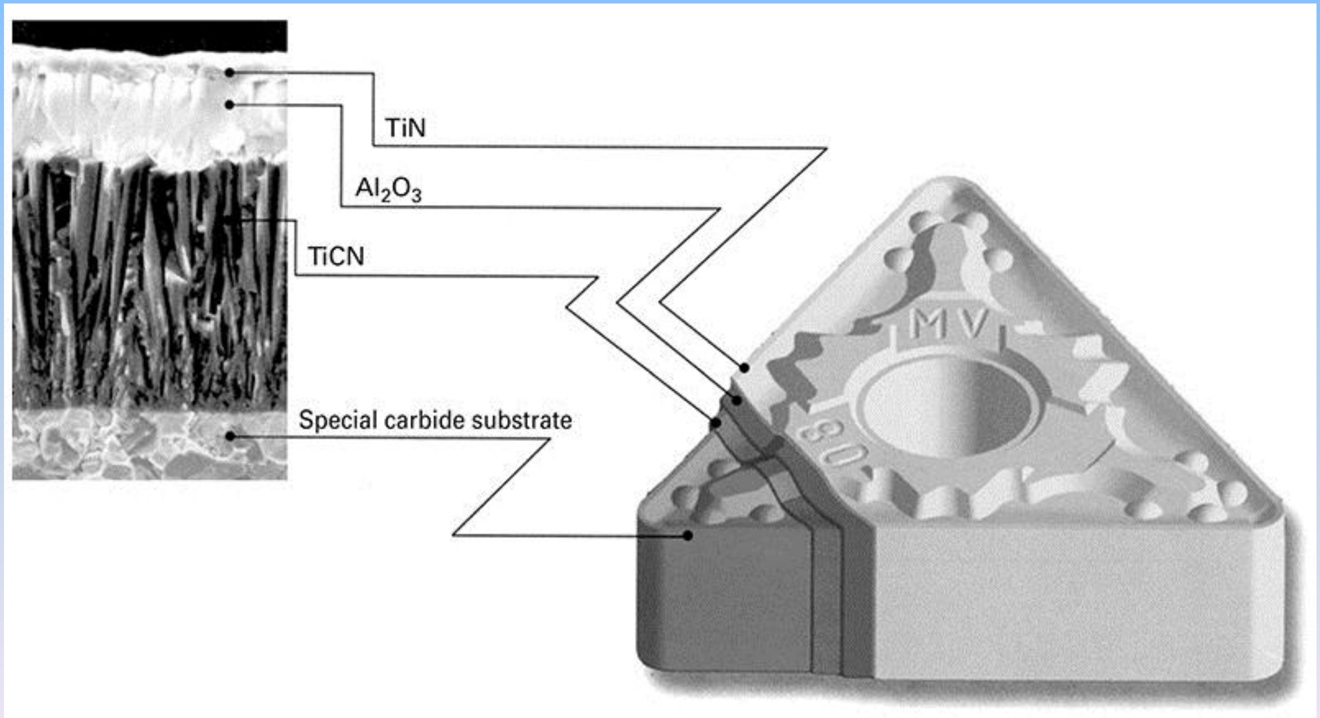
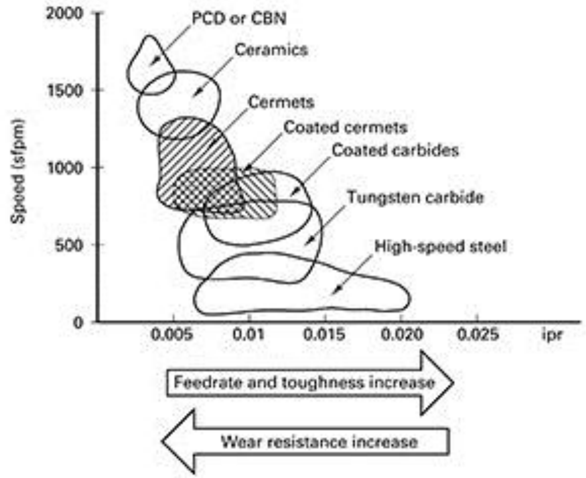


Cutting Tool Material Properties

TABLE 21-2 Properties of Cutting-Tool Materials Compared for Carbides, Ceramics, HSS, and Cast Cobalt[a]

	Hardness Rockwell A or C	Transverse Rupture (bend) Strength ($\times 10^3$ psi)	Compressive Strength ($\times 10^3$ psi)	Modulus of Elasticity (e)($\times 10^6$ psi)
Carbide C1–C4	90–95 R_A	250–320	750–860	89–93
Carbide C5–C8	91–93 R_A	100–250	710–840	66–81
High-speed steel	86 R_A	600	600–650	30
Ceramic (oxide)	92–94 R_A	100–125	400–650	50–60
Cast cobalt	46–62 R_C	80–120	220–335	40

[a]Exact properties depend upon materials, grain size, bonder content, volume.



Tool Material Group	General Applications	Versus Cermet
PCD (polycrystal diamond)	High-speed machining of aluminum alloys, nonferrous metals, and nonmetals.	Cermets can machine same materials, but at lower speeds and significantly less cost per corner.
CBN (cubic boron nitride)	Hard workpieces and high-speed machining on cast irons.	Cermets cannot machine the harder workpieces that CBN can. Cermets cannot machine cast iron at the speeds CBN can. The cost per corner of cermets is significantly less.
Ceramics (cold press)	High-speed turning and grooving of steels and cast iron.	Cermets are more versatile and less expensive than cold press ceramics but cannot run at the higher speeds.
Ceramics (hot press)	Turning and grooving of hard workpieces; high-speed finish machining of steels and irons.	Cermets cannot machine the harder workpieces or run at the same speeds on steels and irons but are more versatile and less expensive.
Ceramics (silicon nitride)	Rough and semirough machining of cast irons in turning and milling applications at high speeds and under unfavorable conditions.	Cermets cannot machine cast iron at the high speeds of silicon nitride ceramics, but in moderate-speed applications cermets may be more cost effective.
Coated carbide	General-purpose machining of steels, stainless steels, cast iron, etc.	Cermets can run at higher cutting speeds and provide better tool life at less cost for semiroughing to finishing applications.
Carbides	Tough material for lower-speed applications on various materials.	Cermets can run at higher speeds, provide better surface finishes and longer tool life for semiroughing to finishing applications.

FIGURE 21-9
Comparison of cermets with various cutting-tool materials.

Polycrystalline Diamond Tools

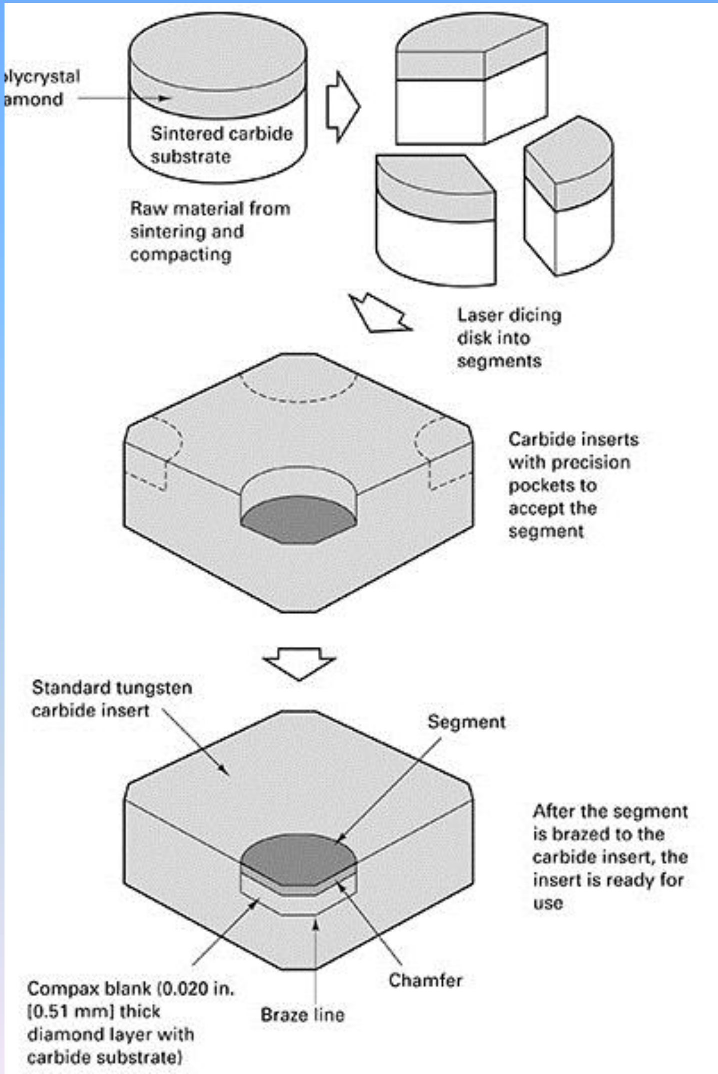


FIGURE 21-10 Polycrystalline diamond tools are carbides with diamond inserts. They are restricted to simple geometries.

Cost Comparison

TABLE 21-3 Cost Comparison for Machining Liner Bores in 1500 Engine Blocks[a]

	Ceramic TNG-433	PCBN BTNG-433
Cost per insert	\$14.90	\$208.00
Edges per insert	6	3
Cost per edge	\$2.48	\$69.33
Time per index (6 tools)	0.25 hr	0.25 hr
Cost per index at \$45 per hour	\$11.25	\$11.25
Indexes per 1500 blocks	43	3
Indexing cost (indexes × \$11.25)	\$483.75	\$33.75
Insert cost for 6 spindles	\$638.34	\$1248.00
Labor and tool cost	\$1122.09	\$1281.00
Cost per bore	\$.125	\$.142
Total number of tool changes	43	3
	× 0.25 hr	× 0.25 hr
Downtime for 1500 blocks	10.75 hr	0.75 hr

[a]To see the economy of using PCBN cutting tools, it is important to consider all factors of the operation, especially downtime for tool changing.

Application Comparison

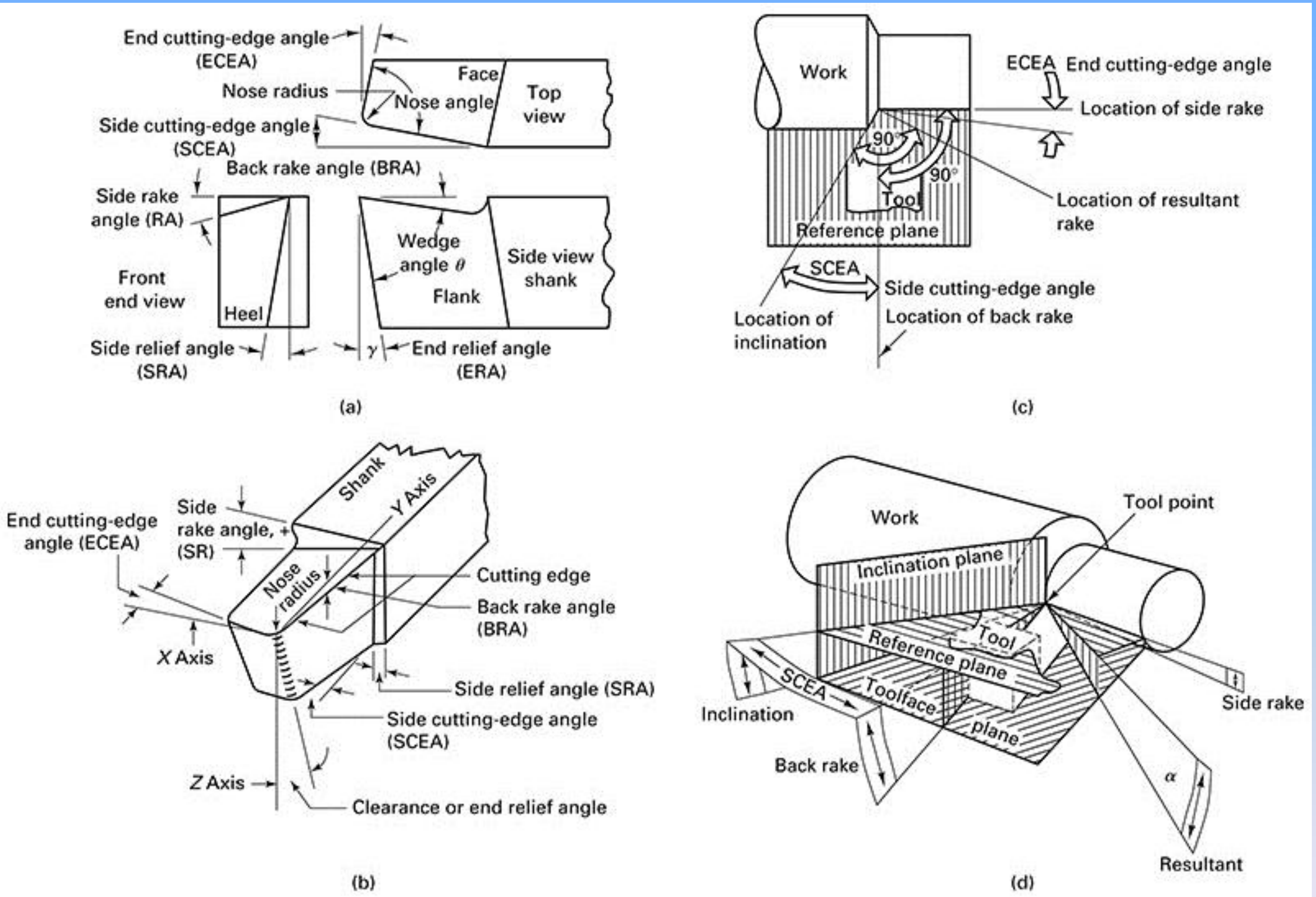
TABLE 21-4 Application of Cutting Tool Materials to Workpiece Materials

	Applicable Tool Material			
Workpiece Material	Carbide-Coated Carbide	Ceramic, Cermet	Cubic Boron Nitride	Diamond Compacts
Cast irons, carbon steels	X	uninterrupted finishing cuts X		
Alloy steels, alloy cast iron	X	X	X	
Aluminum, brass	X	X		X
High-silicon aluminum	X			X
Nickel-based	X	X	X	
Titanium	X			
Plastic composites	X		X	

21.3 Tool Geometry

Tool Geometry Terminology

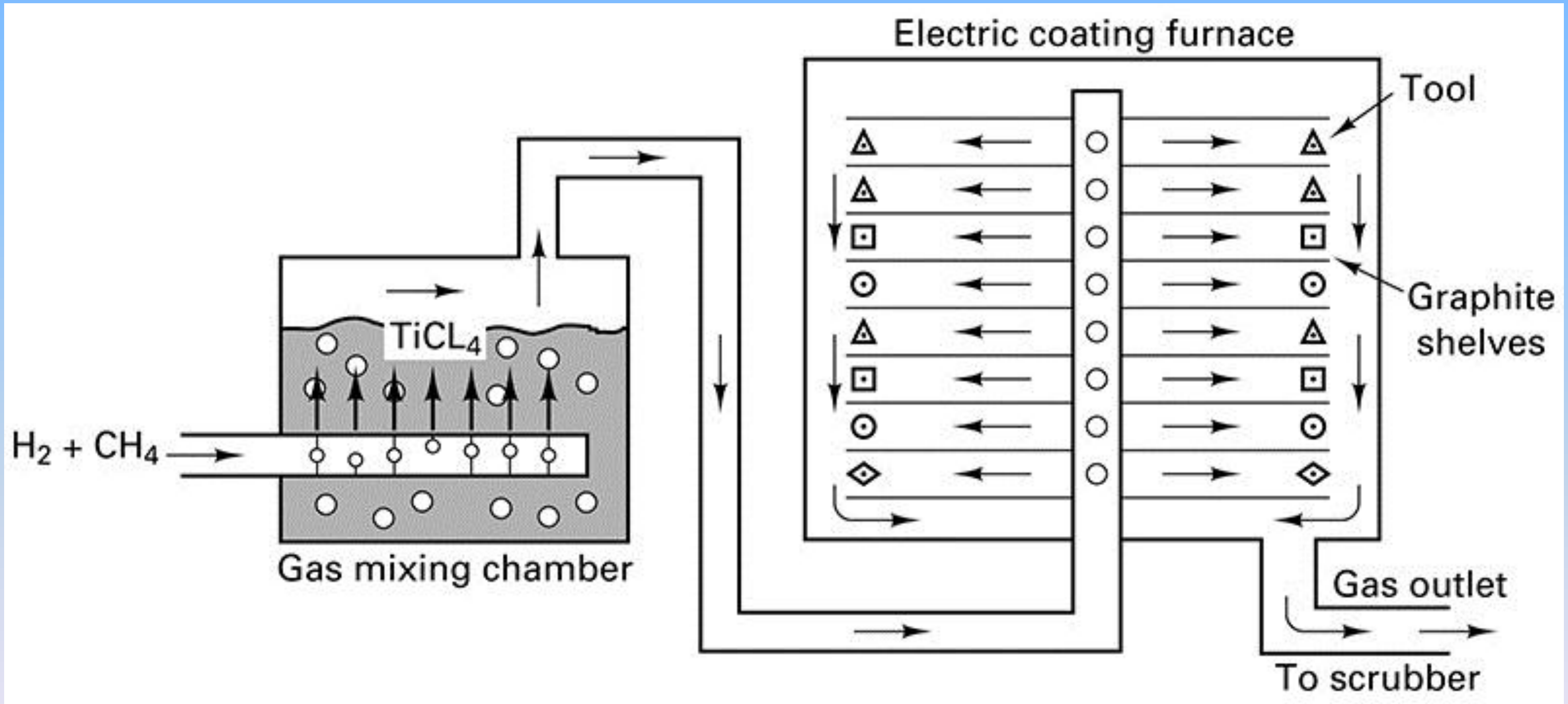
FIGURE 21-11 Standard terminology to describe the geometry of single-point tools: (a) three dimensional views of tool, (b) oblique view of tool from cutting edge, (c) top view of turning with single-point tool, (d) oblique view from shank end of single-point turning tool.



21.4 Tools Coating Processes

CVD Process

FIGURE 21-12 Chemical vapor deposition is used to apply layers (TiC, TiN, etc.) to carbide cutting tools.



PVC Arc Process

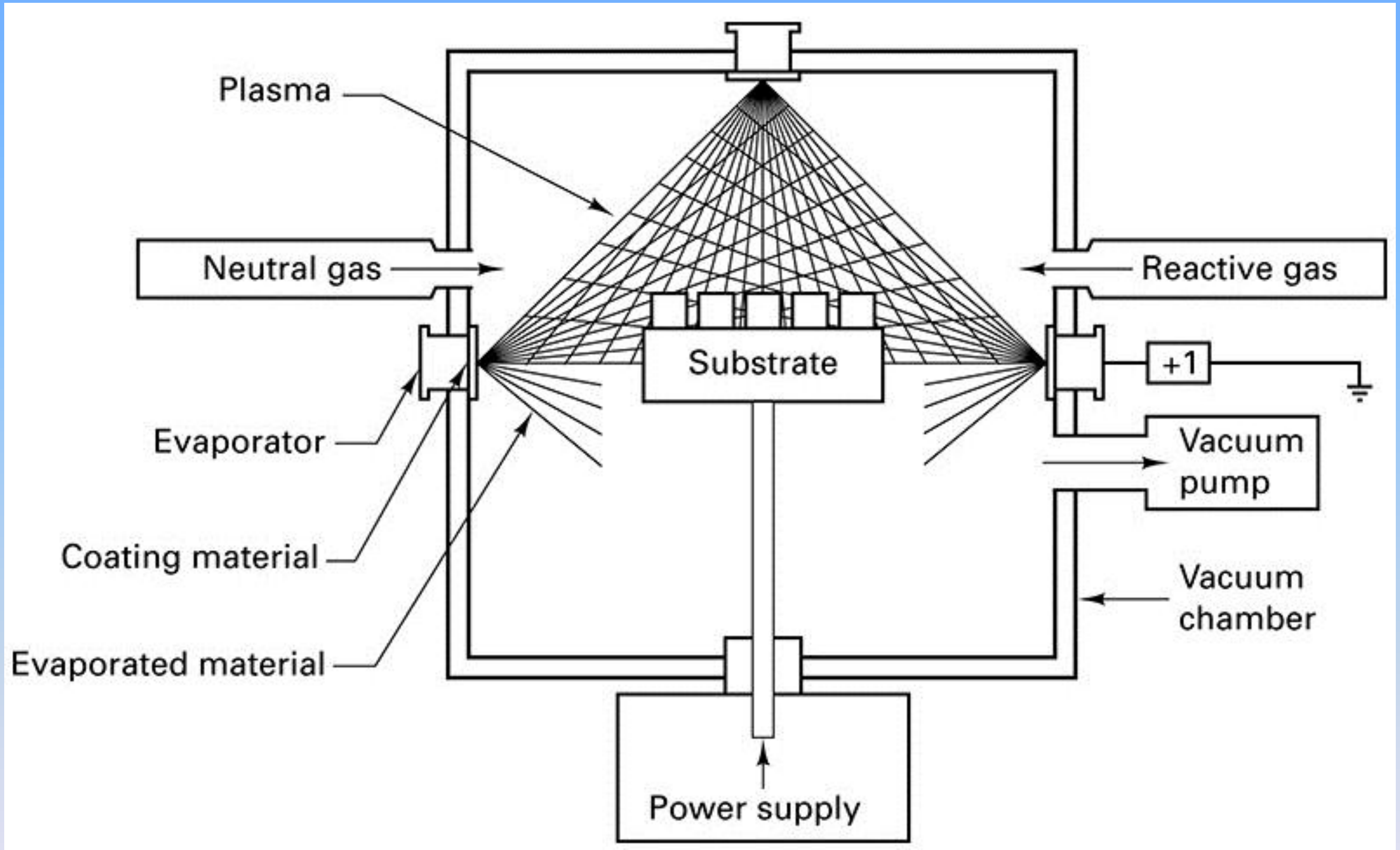


FIGURE 21-13 Schematic of PVC arc evaporation process

Comparison of PVD Processes

Comparison of PVD Process Characteristics

Process	Processing Temperature, °C	Throwing Power	Coating Materials	Coating Applications and Special Features
Vacuum evaporation	RT—700, usually <200	Line-of-sight	Chiefly metal, especially Al (a few simple alloys/ a few simple compounds)	Electronic, optical, decorative, simple masking.
Ion implantation	200–400, best <250 for N	Line-of-sight	Usually N (B, C)	Wear resistance for tools, dies, etc. Effect much deeper than original implantation depth. Precise area treatment, excellent process control.
Ion plating, ARE	RT—0.7 T_m of coating. Best at elevated temperatures.	Moderate to good	Ion plating: Al, other metals (few alloys) ARE: TiN and other compounds	Electronic, optical, decorative. Corrosion and wear resistance. Dry lubricants. Thicker engineering coatings.
Sputtering	RT—0.7 T_m of metal coatings. Best >200 for nonmetals.	Line-of-sight	Metals, alloys, glasses, oxides. TiN, and other compounds	Electronic, optical, wear resistance. Architectural (decorative). Generally thin coatings. Excellent process control.
CVD	300–2000, usually 600–1200	Very good	Metals, especially refractory TiN and other compounds; pyrolytic BN	Thin, wear-resistant films on metal and carbide dies, tools, etc. Free-standing bodies or refractory metals and pyrolytic C or BN.

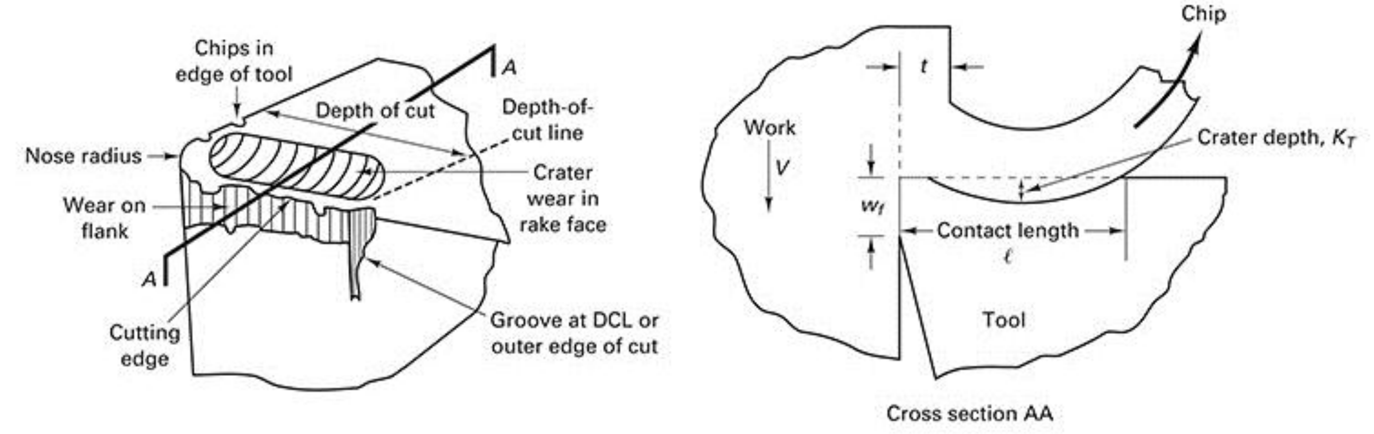
RT= room temperature; ARE = activated reactive evaporation; T_m = absolute melting temperature. (a) Compounds: oxides, nitrides, carbides, silicides, and borides of Al, B, Cr, Hf, Mo, Nb, Ni, Re, Si, Ta, Ti, V, W, Zr.

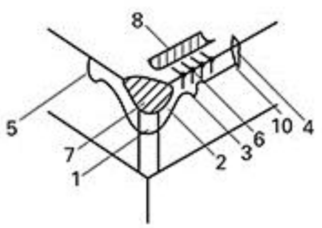
Source: Advanced Materials and Processes, December 2001.

FIGURE 21-14 Comparison of PVD methods for depositing thin films on microelectronic devices as well as cutting tools.

21.5 Tool Failure and Tool Life

Tool Failure





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 21-15 Tools can fail in many ways. Tool wear during oblique cutting can occur on the flank or the rake face; *t* = uncut chip thickness; *kt* = crater depth; *wf* = flank wear land length; DCL = depth-of-cut line.

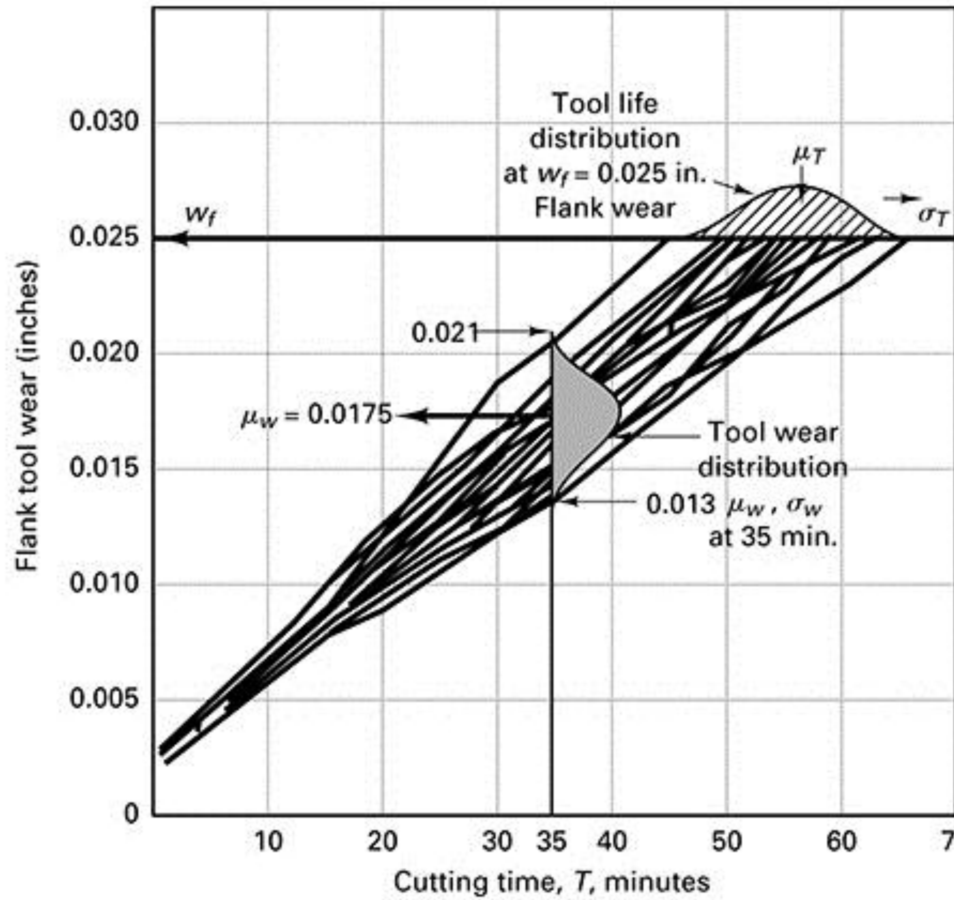
21.6 Flank Wear

Tools Wear

FIGURE 21-16 Tool wear on the flank displays a random nature, as does tool life. *Wf* = flank wear limit value.

w_f values for general life determination (for cemented carbides)

Width of Wear in.	Applications
0.008	Finish cutting of nonferrous alloys, fine & 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



Typical Tool Wear Curves

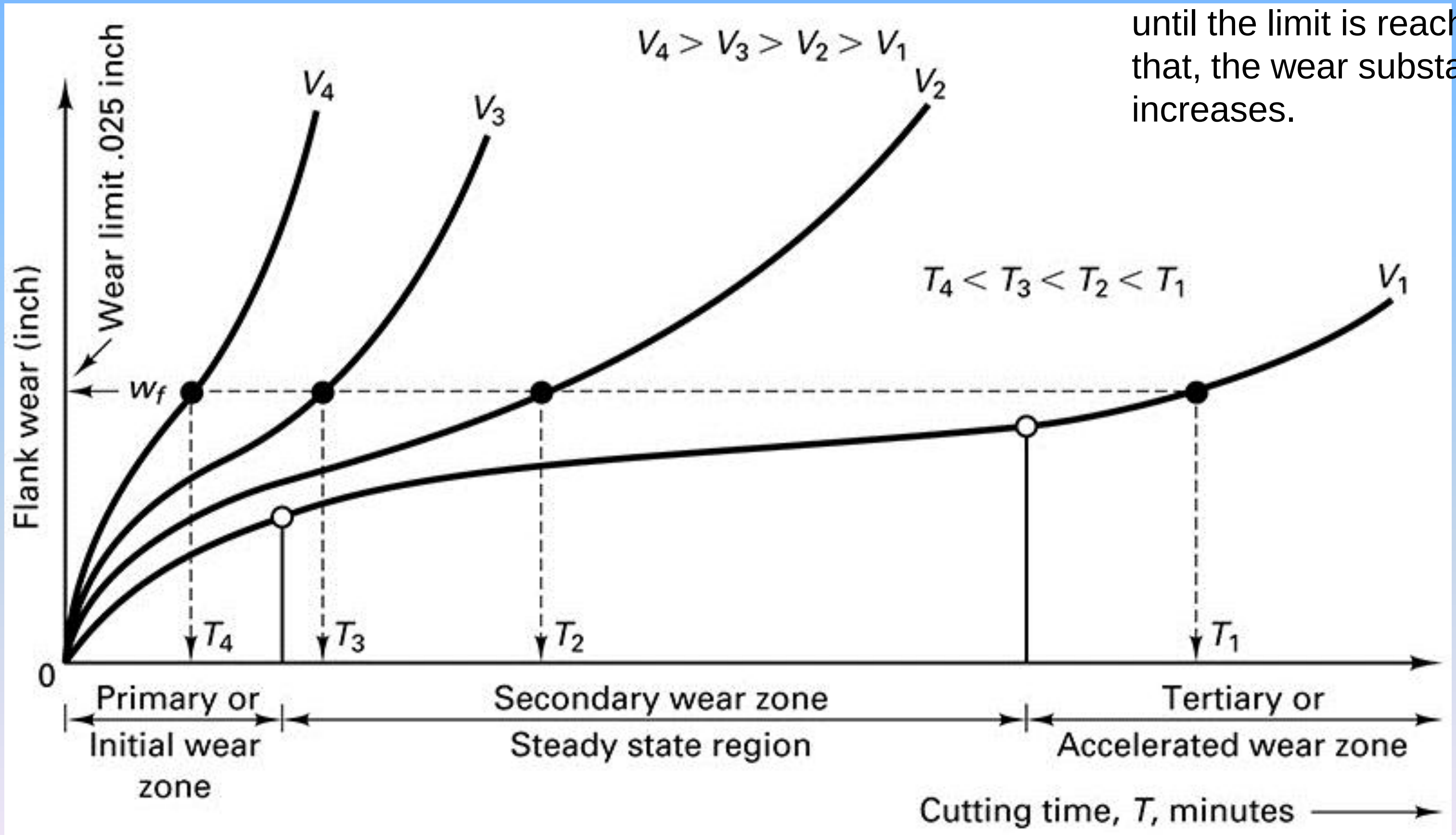


FIGURE 21-17 Typical tool wear curves for flank wear at different velocities. The initial wear is very fast, then it evens out to a more gradual pattern until the limit is reached; after that, the wear substantially increases.

Taylor Tool Life Curves

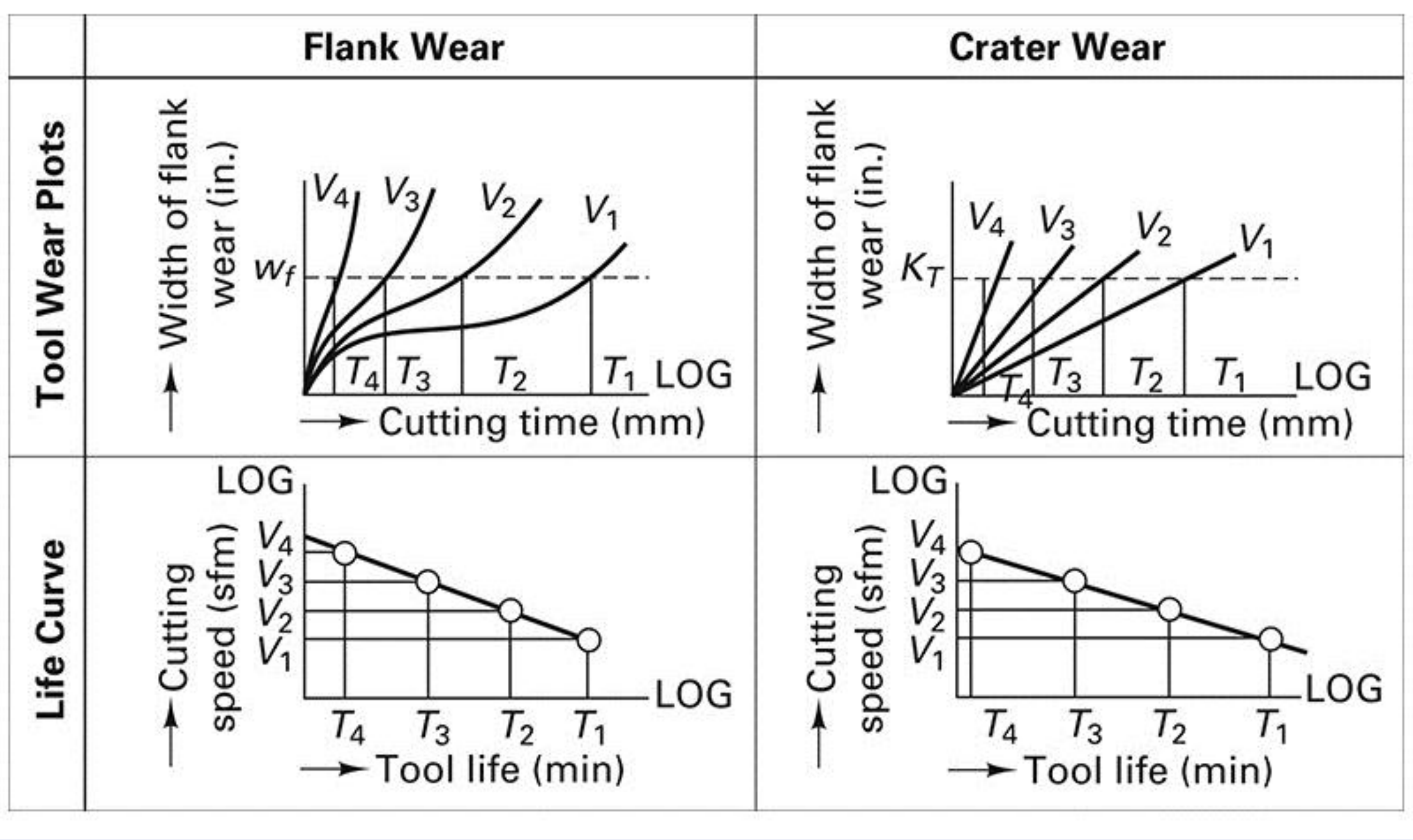


FIGURE 21-18 Construction of the Taylor tool life curve using data from deterministic tool wear plots like those of Figure 21-17. Curves like this can be developed for both flank and crater wear.

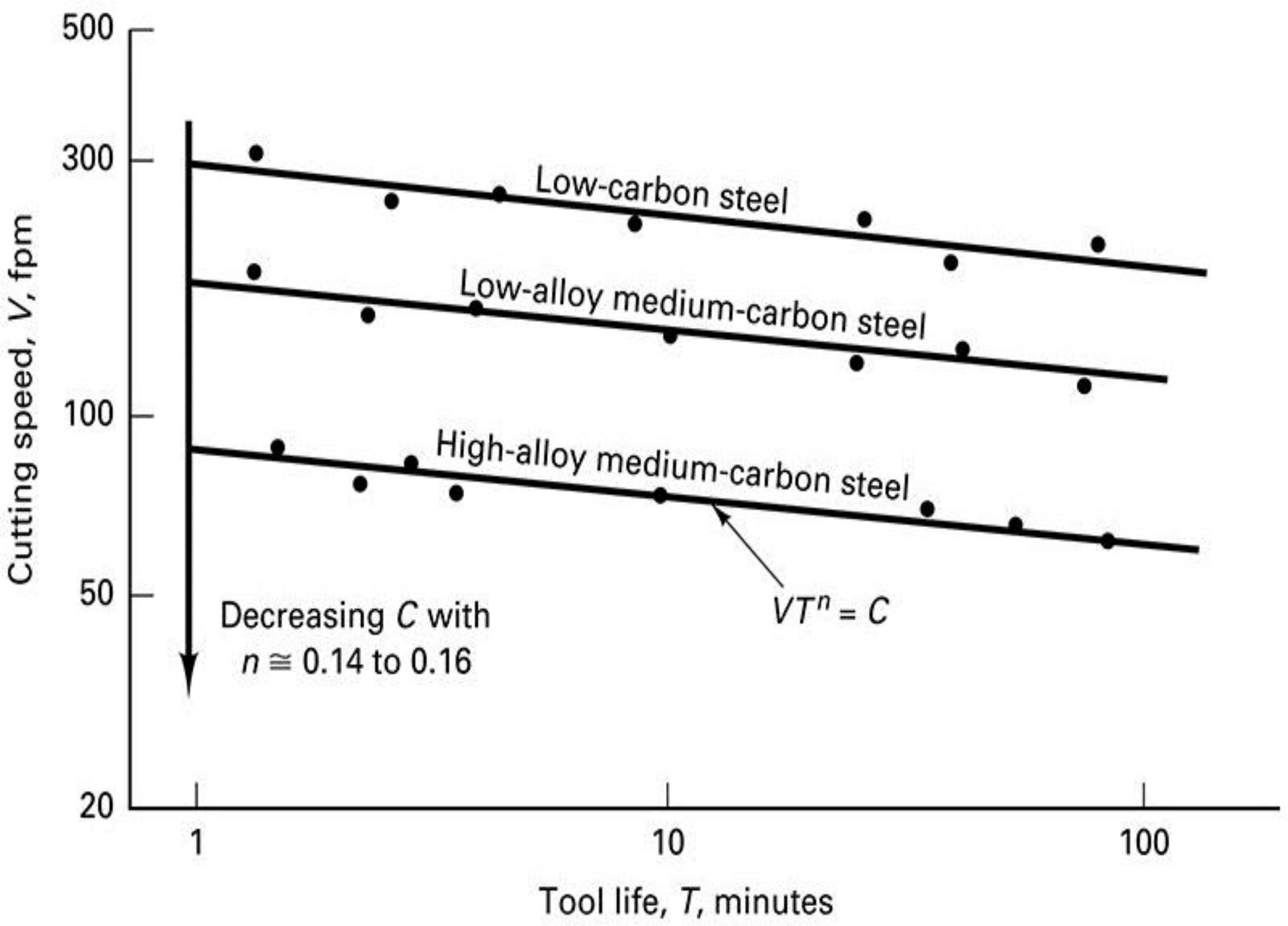
TABLE 21-5 Tool Life Information for Various Materials and Conditions

Source	Tool Material	Geometry	Workpiece Material	Size of Cut (in.) Depth	Feed	Cutting Fluid	$VT^n = C$ 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 C.D.	.100	.0127	Dry	.110	192
		8.14, 6.6, 6.13, 3/66	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 363 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	.080	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

Tool Life Plots

FIGURE 21-19 Log-log tool life plots for three steel work materials cut with HSS tool material.



Tools Life

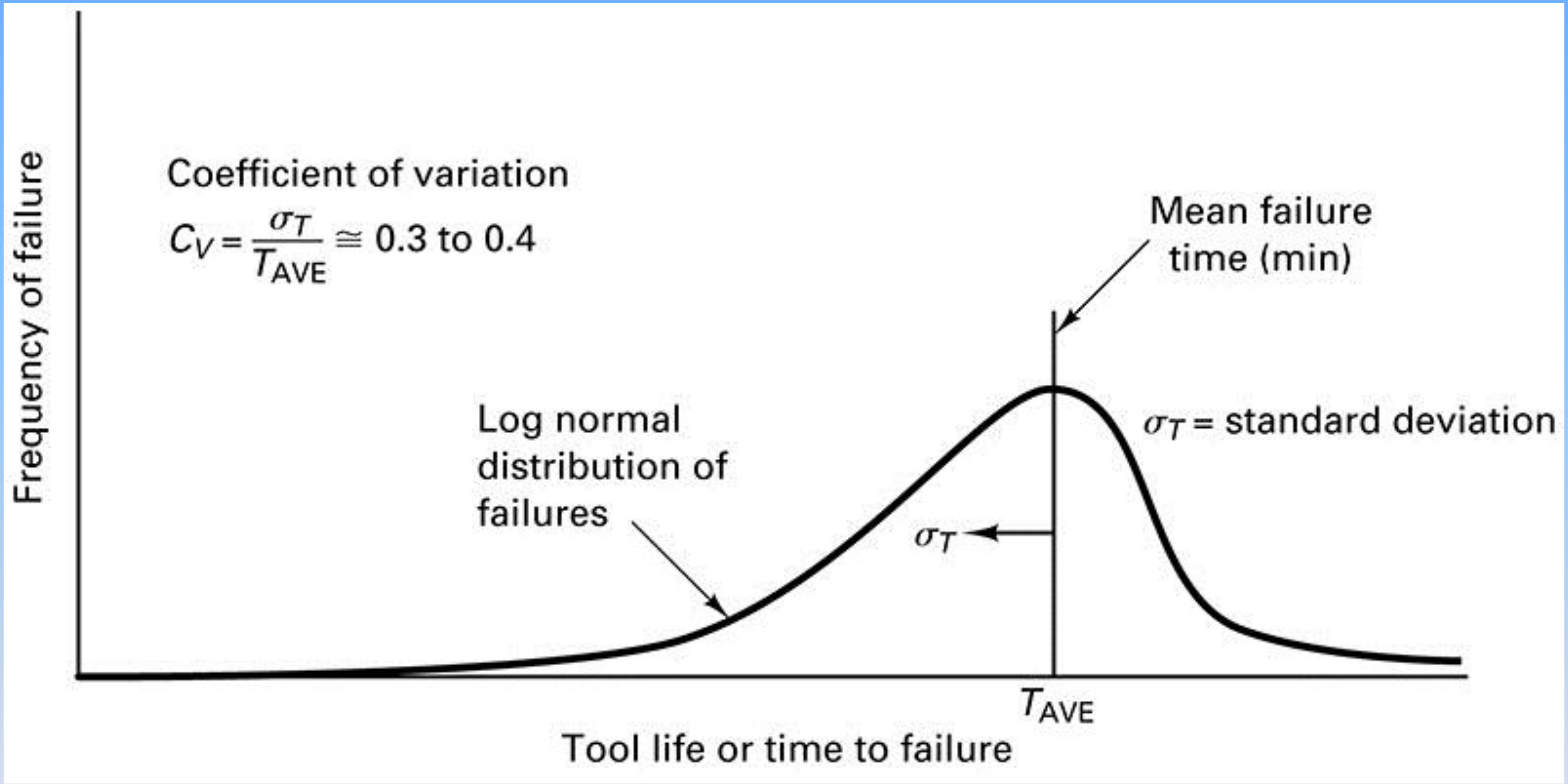
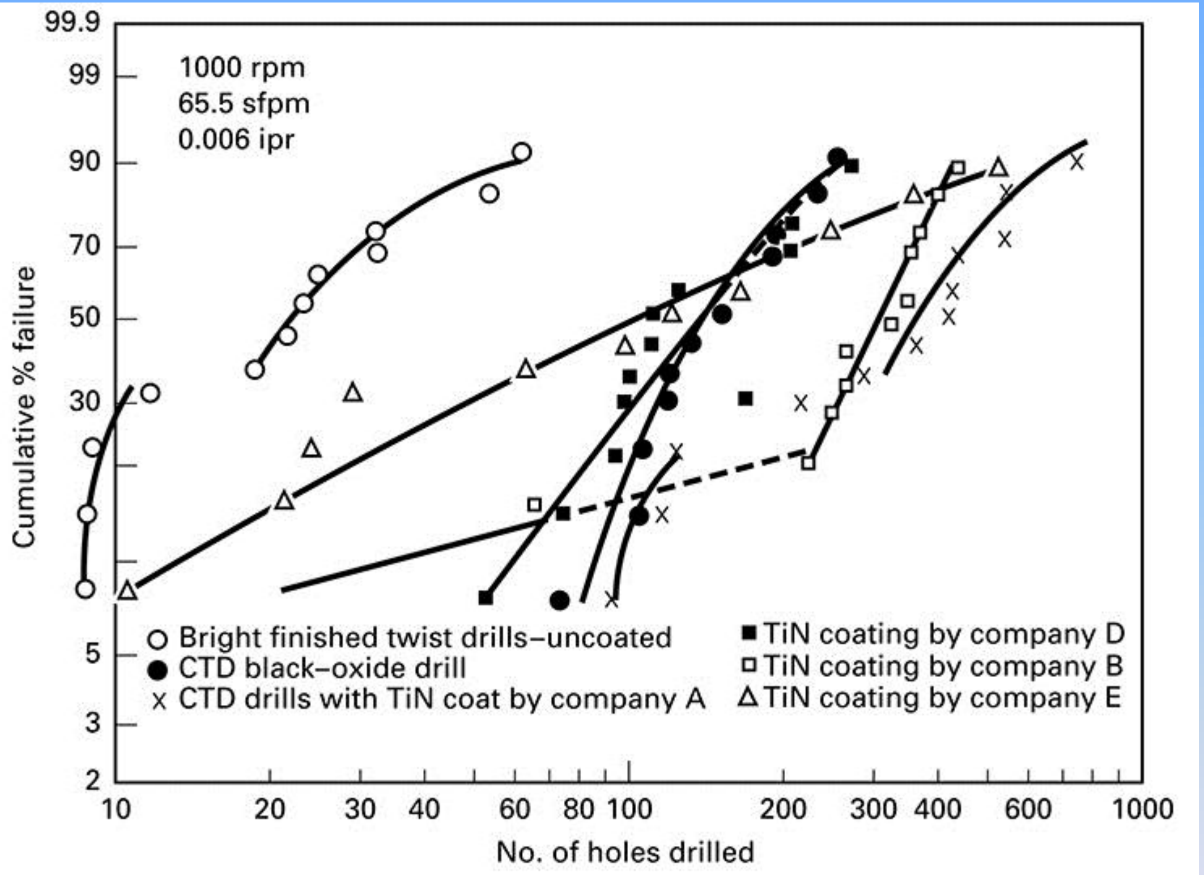


FIGURE 21-20 Tool life viewed as a random variable has a log normal distribution with a large coefficient of variation.

Tool Life Data

FIGURE 21-21 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.

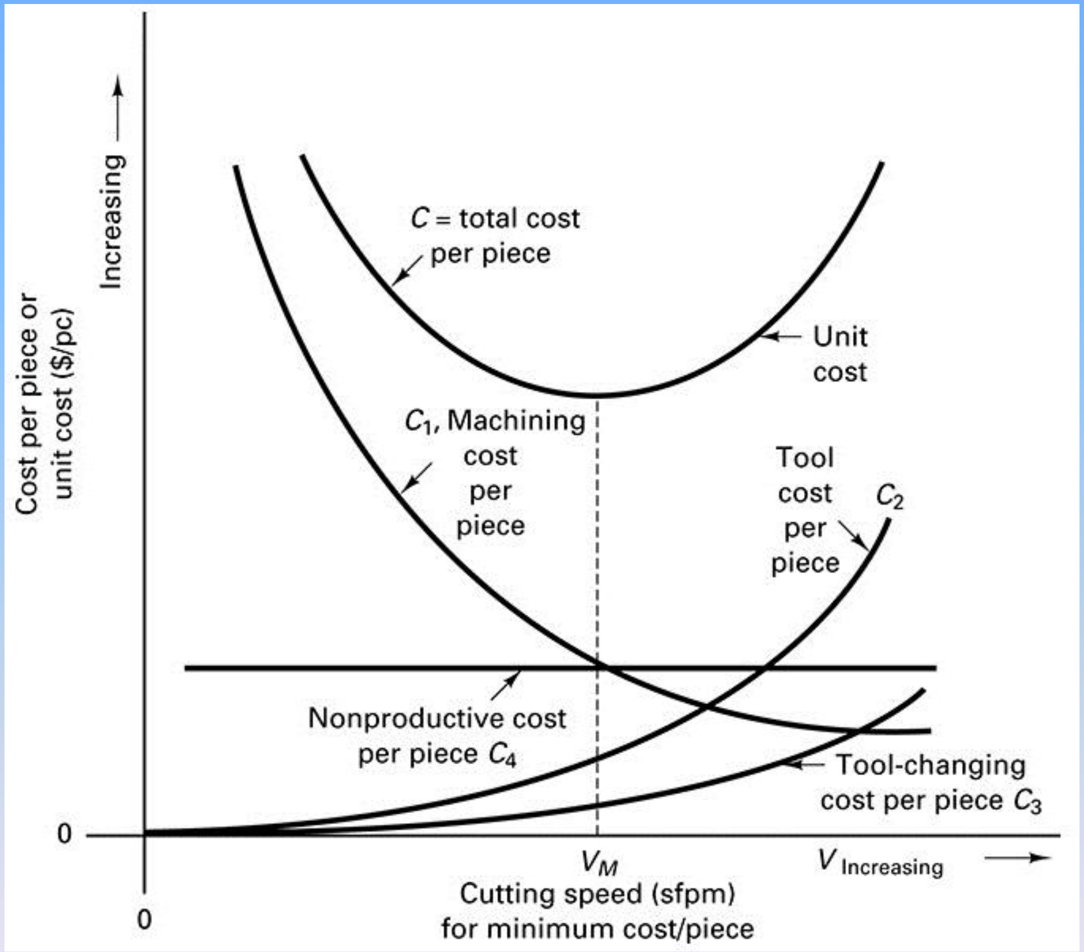


Drill performance based on the number of holes drilled with 1/4-in.-diameter drills in T–1 structural steel.

21.7 Economics of Machining

Cost per Unit

FIGURE 21-22 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).



Cost Comparison

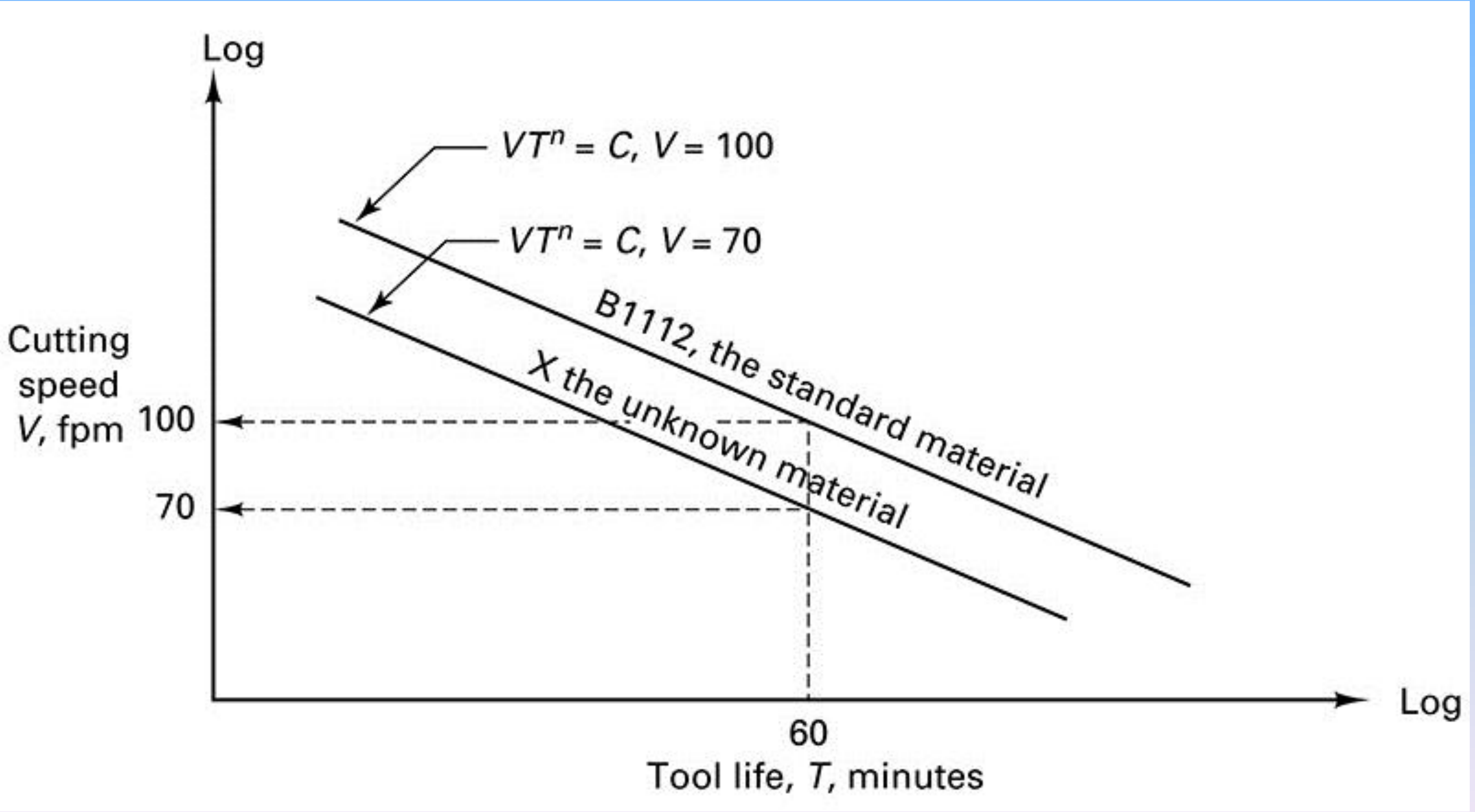
TABLE 21-6 Cost Comparison of Four Tool Materials, Based on Equal Tool Life of 40 Pieces per Cutting Edge

	Uncoated	TiC-Coated	$A1_2O_3$-Coated	$A1_2O_3$LFG
Cutting speed (surface ft/min)	400	640	1100	1320
Feed (in./rev)	0.020	0.022	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.

Machinability Rating

FIGURE 21-23 Machinability ratings defined by deterministic tool life curves.



21.8 Cutting Fluids

Cutting Fluid Contaminants

TABLE 21-7 Cutting Fluid Contaminants

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

Fluid Recycling System

FIGURE 21-24 A well-designed recycling system for coolants will return more than 99% of the fluid for reuse.