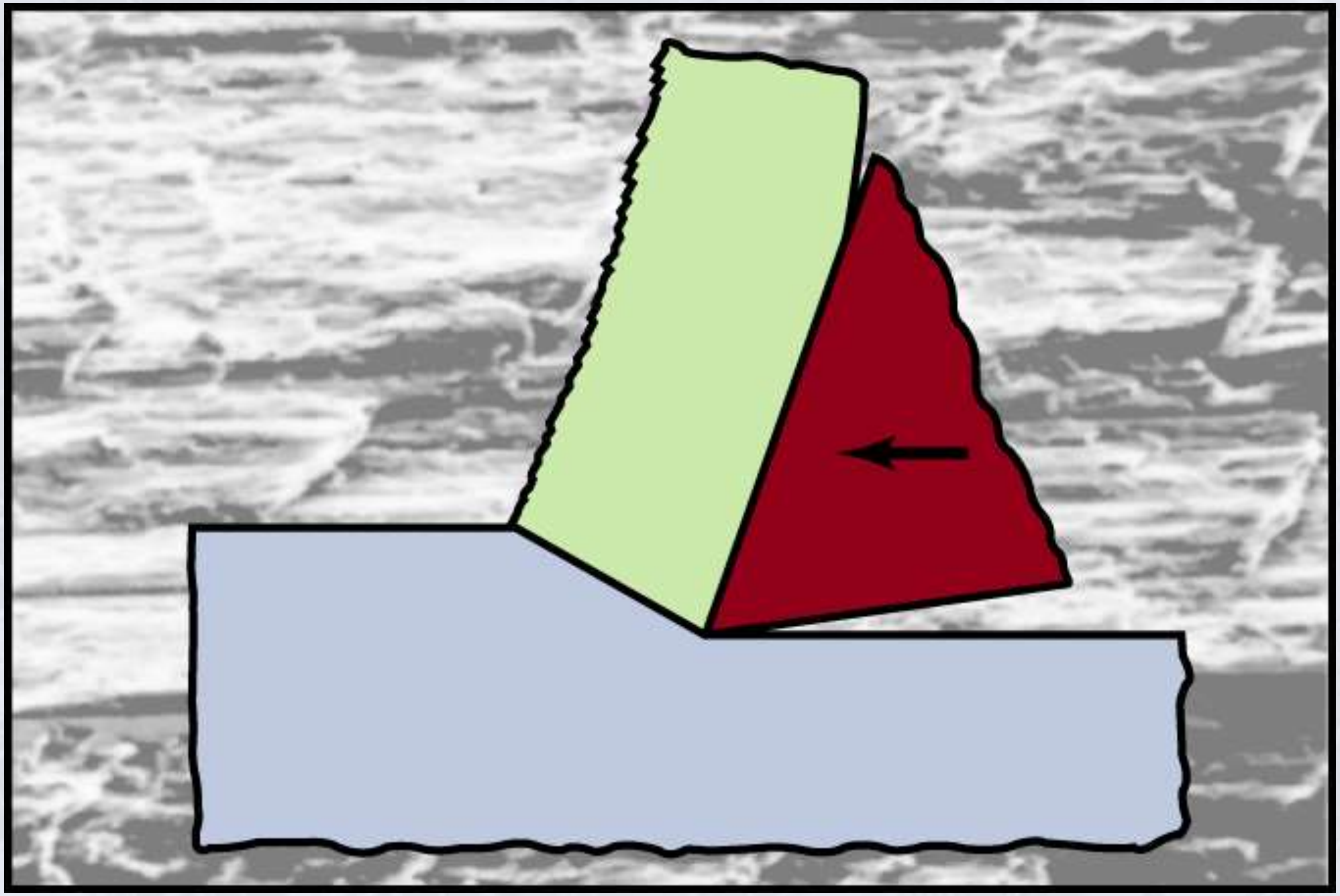
فصل 21

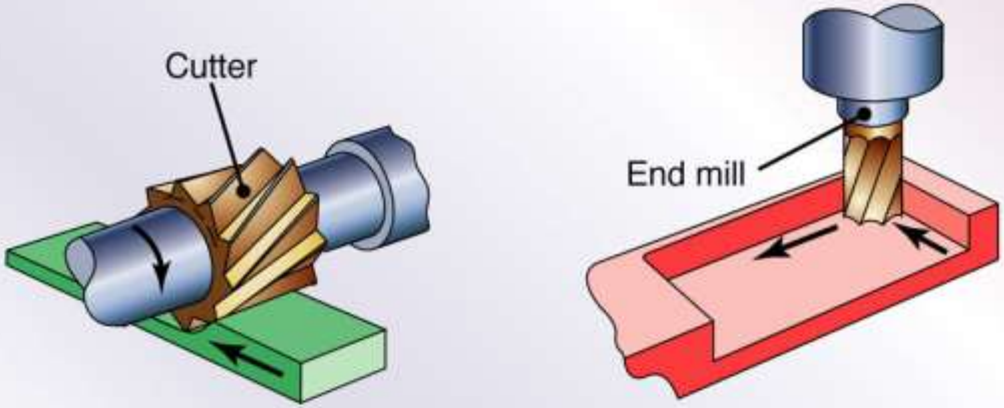
اصول عملیات ماشینکاری



عملیات ماشینکاری عمومی

(a) Straight turning

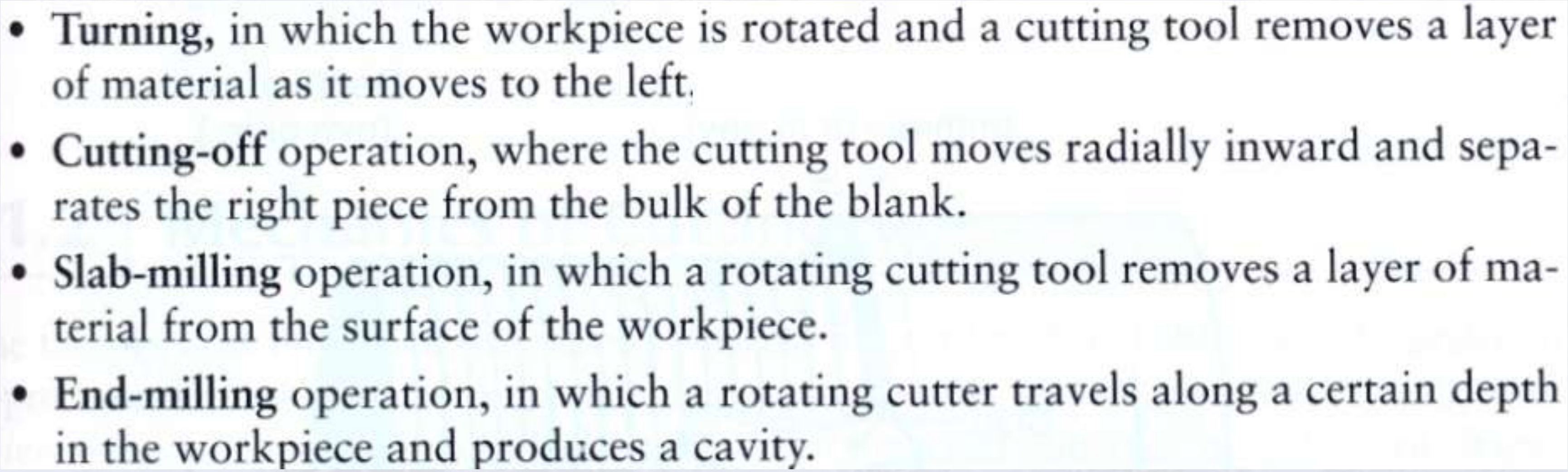
(b) Cutting off



(c) Slab milling

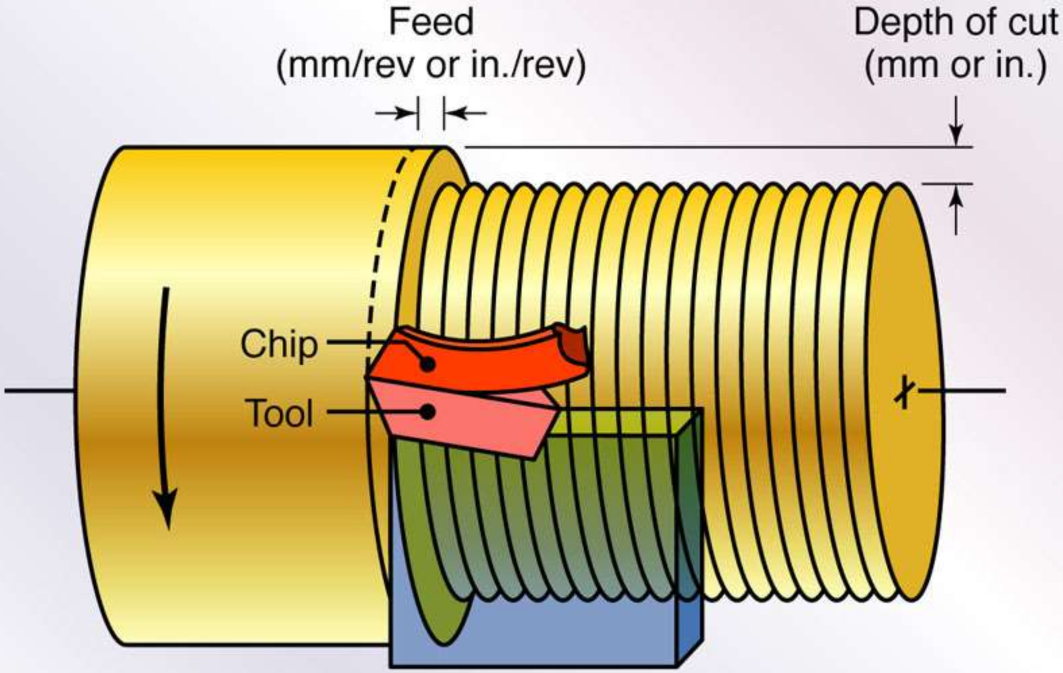
(d) End milling

عملیات ماشینکاری عمومی



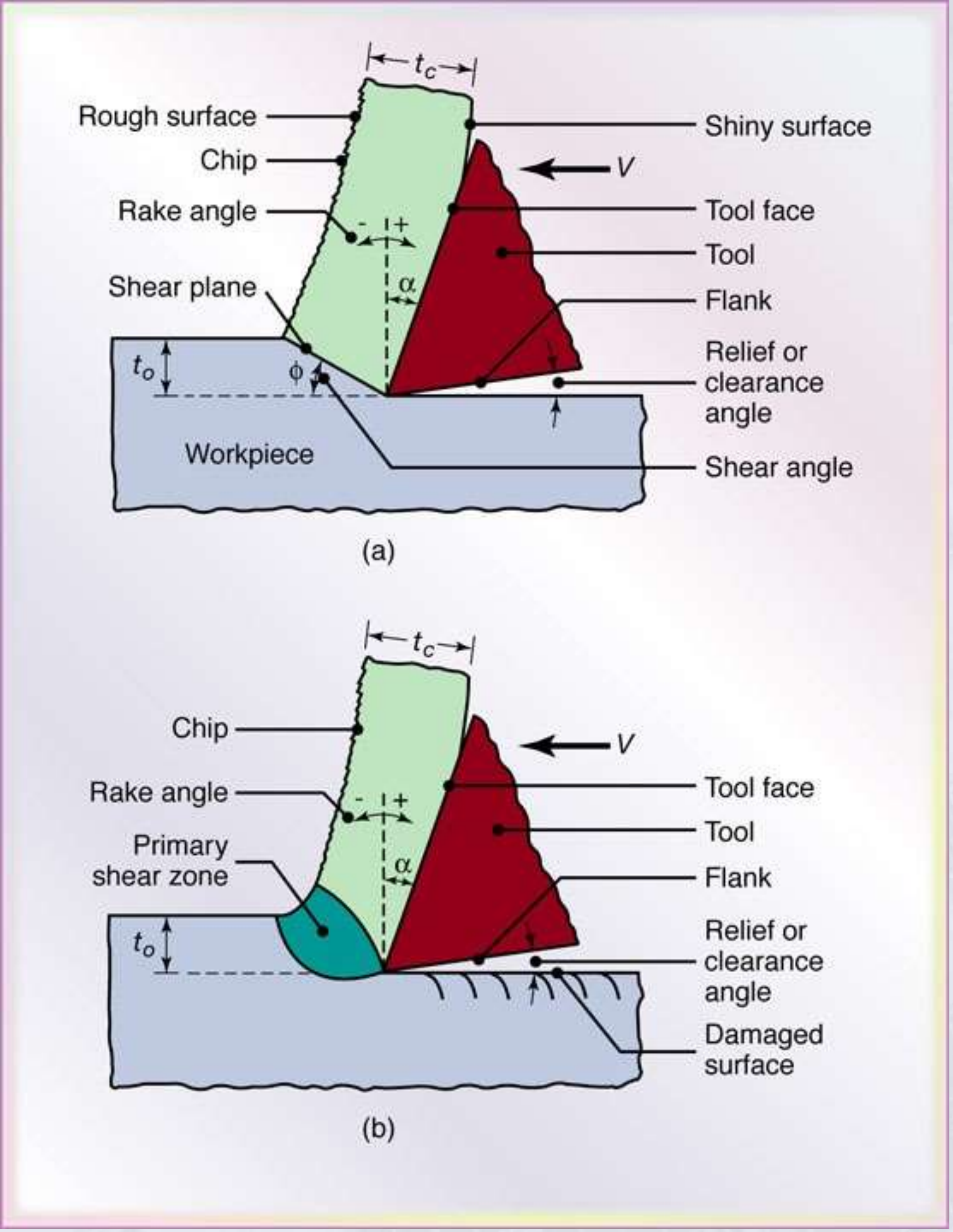
- **Turning,** in which the workpiece is rotated and a cutting tool removes a layer of material as it moves to the left.
- **Cutting-off** operation, where the cutting tool moves radially inward and separates the right piece from the bulk of the blank.
- **Slab-milling** operation, in which a rotating cutting tool removes a layer of material from the surface of the workpiece.
- **End-milling** operation, in which a rotating cutter travels along a certain depth in the workpiece and produces a cavity.

عملیات تراشکاری



تعریف شرایط برشی در عملیات تراشکاری

فرآیند برش دو بعدی
orthogonal cutting



(a) Orthogonal cutting with a well-defined shear plane, also known as the **Merchant Model**.

Note that the tool shape, feed, t_o, and the cutting speed, V, are all independent variables,

(b) Orthogonal cutting without a well-defined shear plane.

عوامل موثر در فرآیند ماشینکاری

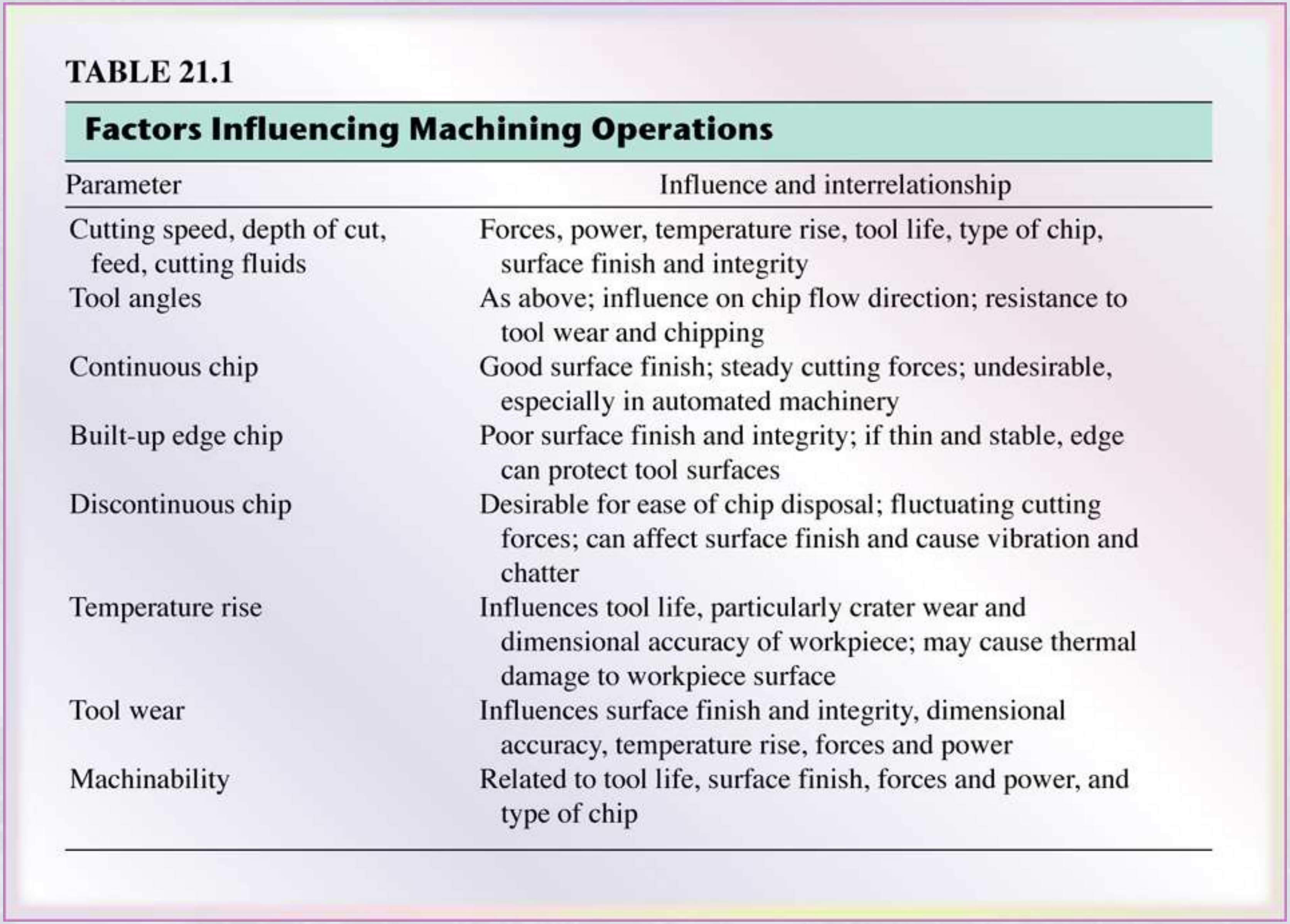


TABLE 21.1

Factors Influencing Machining Operations

Parameter	Influence and interrelationship
Cutting speed, depth of cut, feed, cutting fluids	Forces, power, temperature rise, tool life, type of chip, surface finish and integrity
Tool angles	As above; influence on chip flow direction; resistance to tool wear and chipping
Continuous chip	Good surface finish; steady cutting forces; undesirable, especially in automated machinery
Built-up edge chip	Poor surface finish and integrity; if thin and stable, edge can protect tool surfaces
Discontinuous chip	Desirable for ease of chip disposal; fluctuating cutting forces; can affect surface finish and cause vibration and chatter
Temperature rise	Influences tool life, particularly crater wear and dimensional accuracy of workpiece; may cause thermal damage to workpiece surface
Tool wear	Influences surface finish and integrity, dimensional accuracy, temperature rise, forces and power
Machinability	Related to tool life, surface finish, forces and power, and type of chip

عوامل موثر در فرآیند ماشینکاری

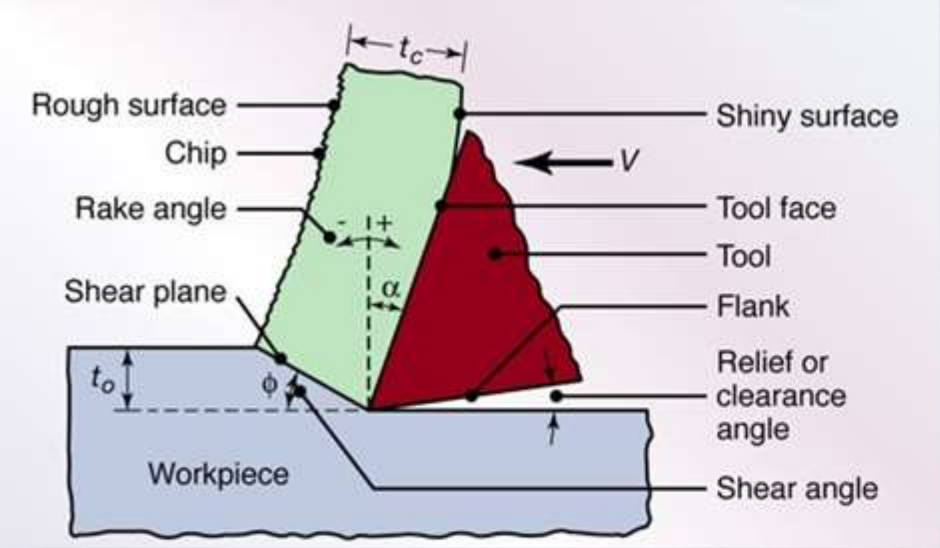
major *independent variables*

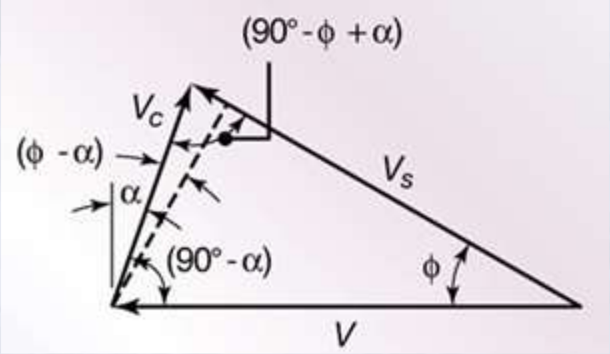
- (a) tool material and coatings;
- (b) tool shape, surface finish, and sharpness;
- (c) work-piece material and condition;
- (d) cutting speed, feed, and depth of cut;
- (e) cutting fluids;
- (f) characteristics of the machine tool; and
- (g) work-holding and fixturing.

***Dependent variables those that are influenced by* independent variables**

- (a) type of chip produced,
- (b) force and energy dissipated during cuning,
- (c) temperature rise in the workpiece, the tool,and the chip,
- (d) tool wear and failure, and
- (e) surface finish and surface integrity of the workpiece.

مکانیک برش





Cutting ratio, $r = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)}$

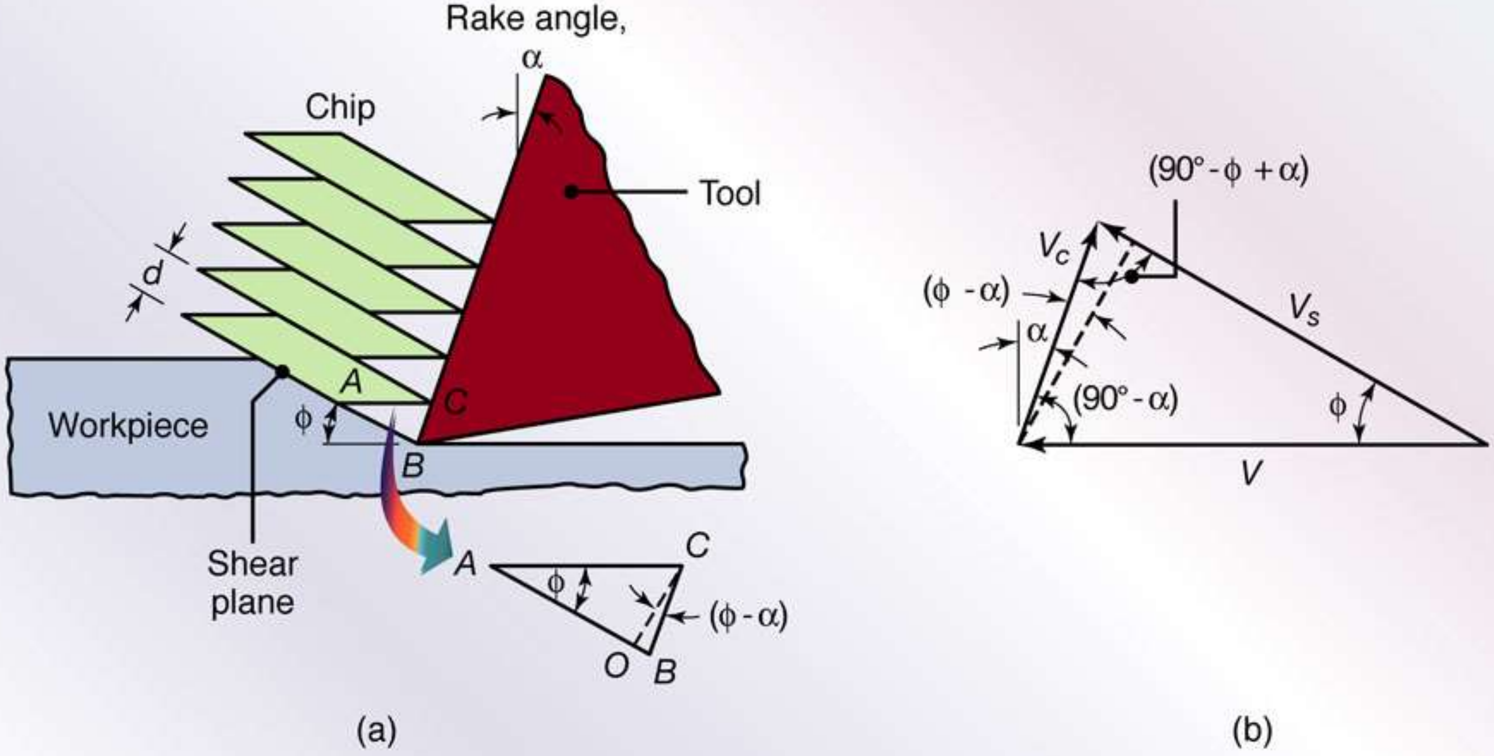
Shear angle preditions:

$$\phi = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$$

$$\phi = 45° + \alpha - \beta$$

Velocities, $V_c = \frac{V\sin\phi}{\cos(\phi-\alpha)}$

شکل گیری براده توسط عمل برش



(a) Schematic illustration of the basic mechanism of chip formation by shearing.

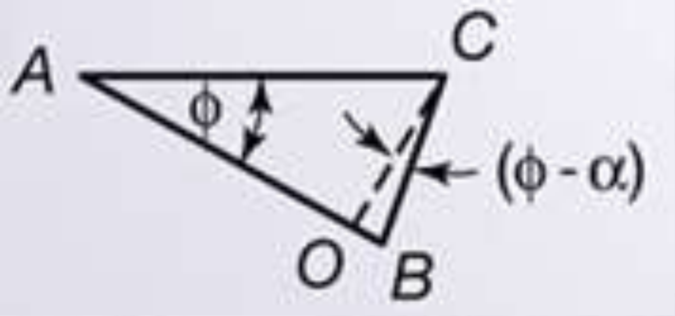
(b) Velocity diagram showing angular relationships among the three speeds in the cutting zone.

کرنش برشی

Shear strain

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC}$$

$$\gamma = \cot\phi + \tan(\phi - \alpha)$$



large shear strains are associated with low shear angles or with low or negative rake angles.

Shear strains of 5 or higher have been observed in actual cutting operations.

Compared to forming and shaping processes, the work-piece material undergoes greater deformation during cutting.

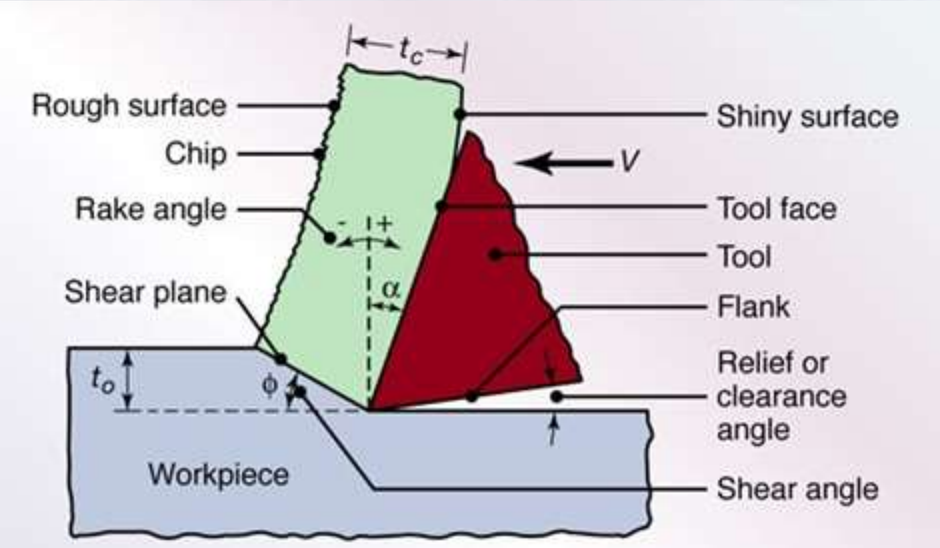
سرعتها در ناحیه برش

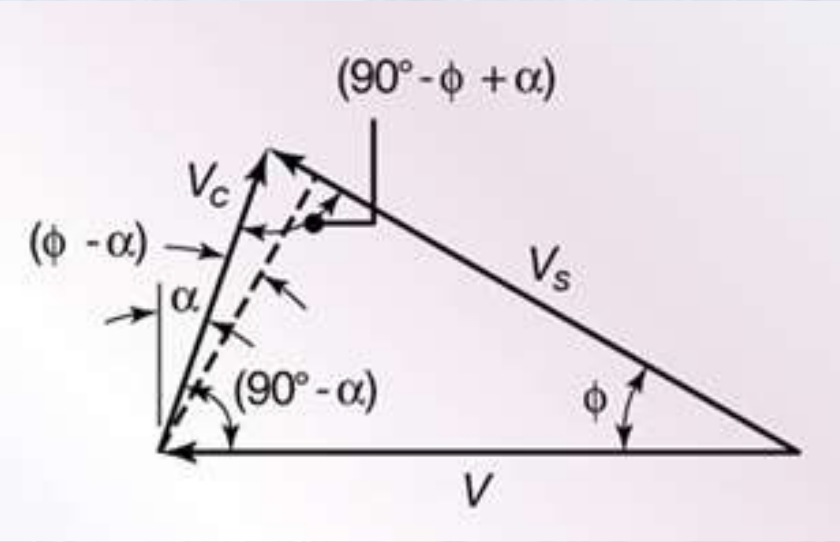
V, cutting speed,

V_s is the velocity at which shearing takes place in the shear plane

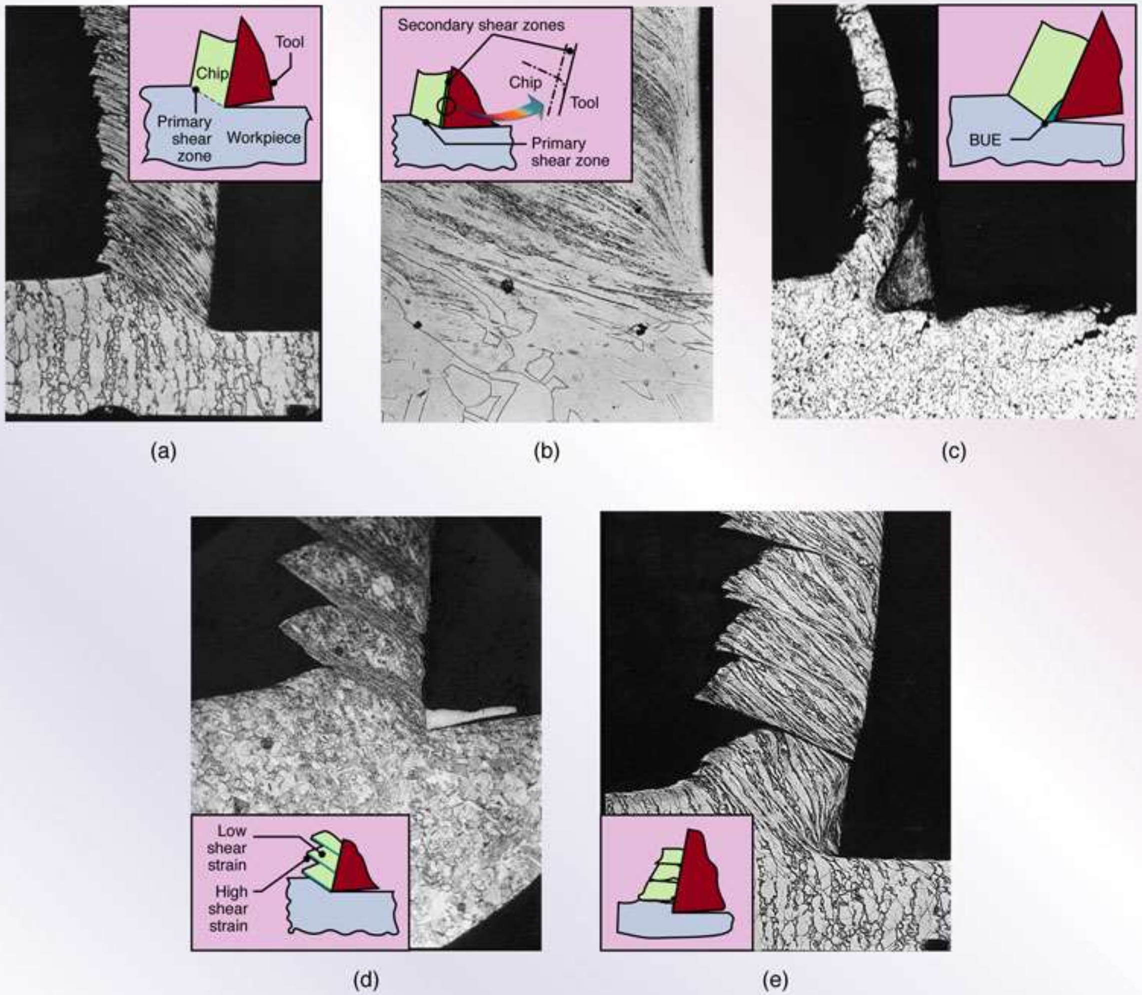
$$\text{Velocities, } V_c = \frac{V\sin\phi}{\cos(\phi-\alpha)}$$

V_c, the velocity of the chip





انواع براده تولید شده در برش دوبعدی



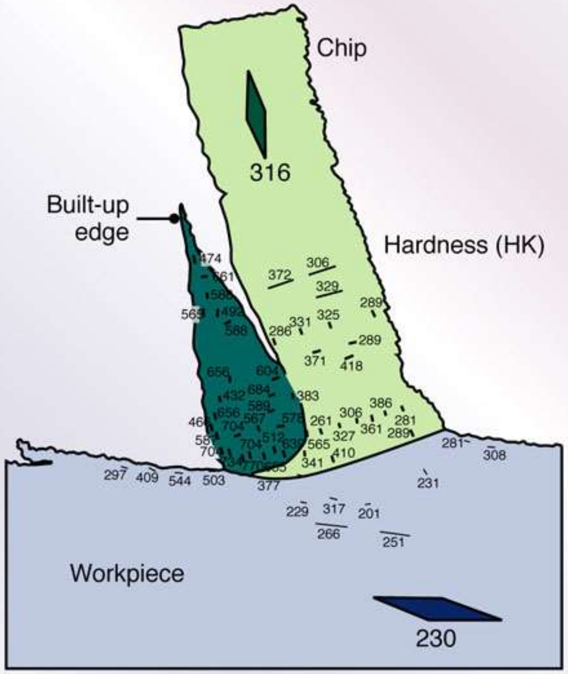
(a) continuous chip with narrow, straight, and primary shear zone;

(b) continuous chip with secondary shear zone at the cip-tool interface;

(c) built-up edge;

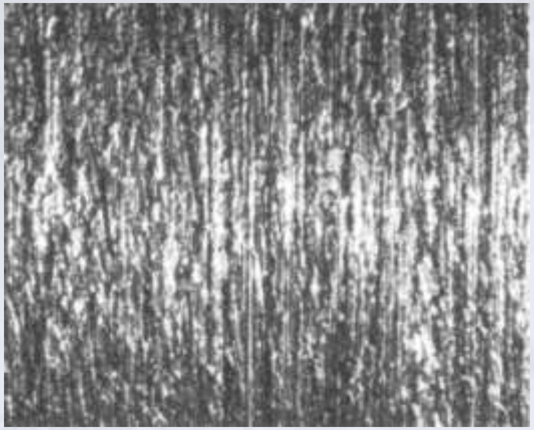
(d) segmented or non-homogeneous chip; and (e) discontinuous chip.

براده با لبه انباشته



(a)

(b)



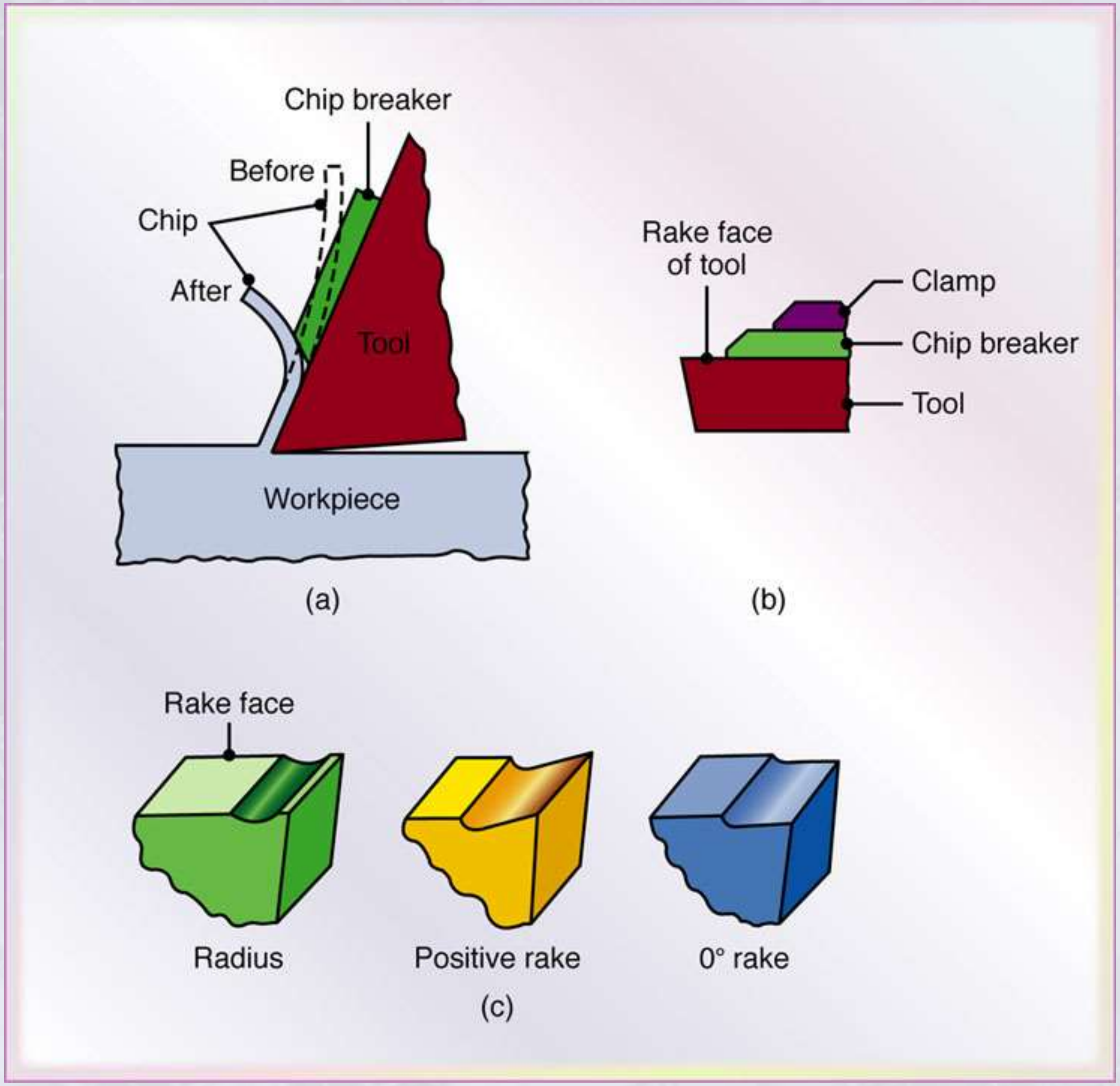
(c)

(a) Hardness distribution with a built-up edge in the cutting zone (material, 3115 steel). Note that some regions in the built-up edge are as much as three times harder than the bulk metal of the work-piece.

(b) Surface finish produced in turning 5130 steel with a built-up edge.

(c) Surface finish on 1018 steel in face milling. Magnifications: 15x.

براده شکن

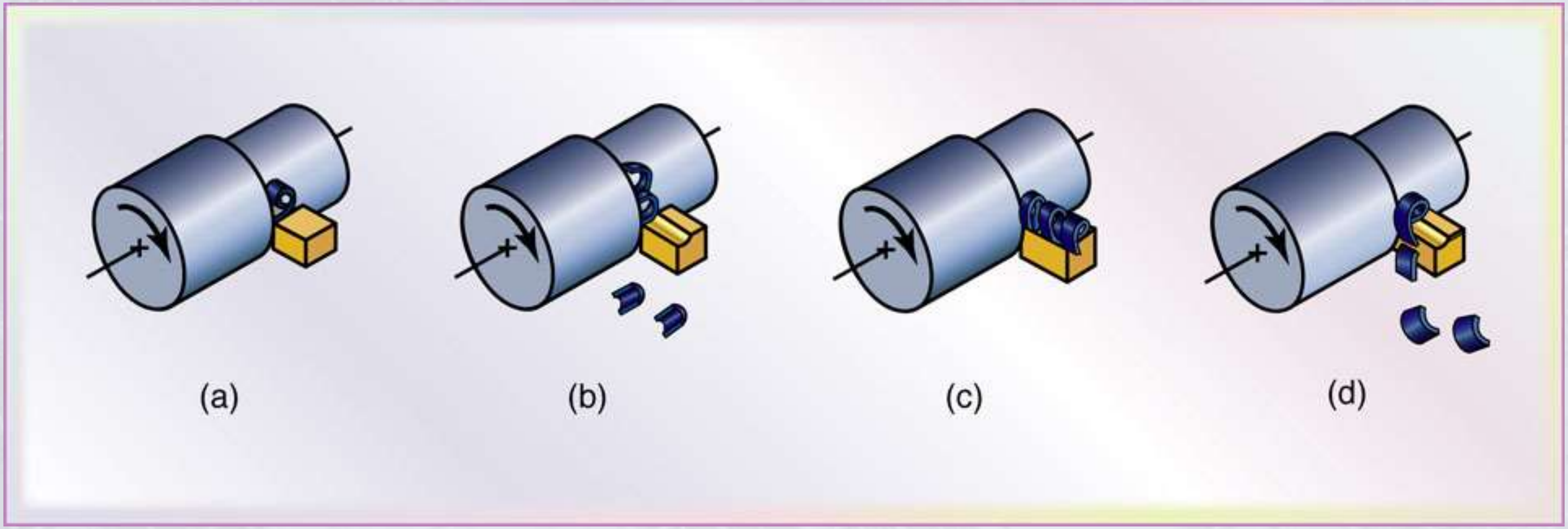


(a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip and eventually breaks it.

(b) Chip breaker clamped on the rake face of a cutting tool.

(c) Grooves in cutting tools acting as chip breakers. Most cutting tools used now are *inserts* with built-in chip breaker features.

انواع براده در تراشکاری



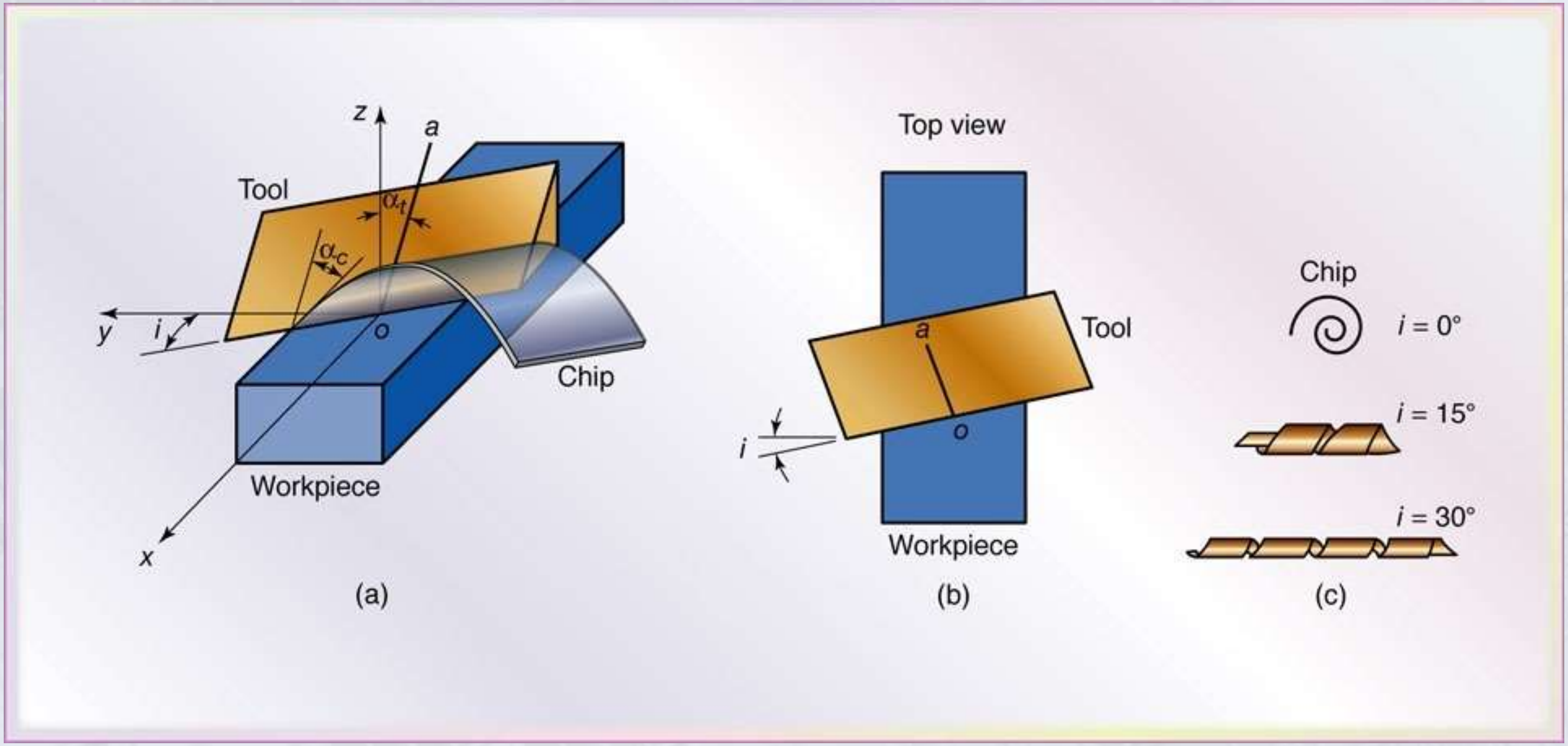
(a) tightly curled chip;

(b) chip hits workpiece and breaks;

(c) continuous chip moving radially away from work-piece; and

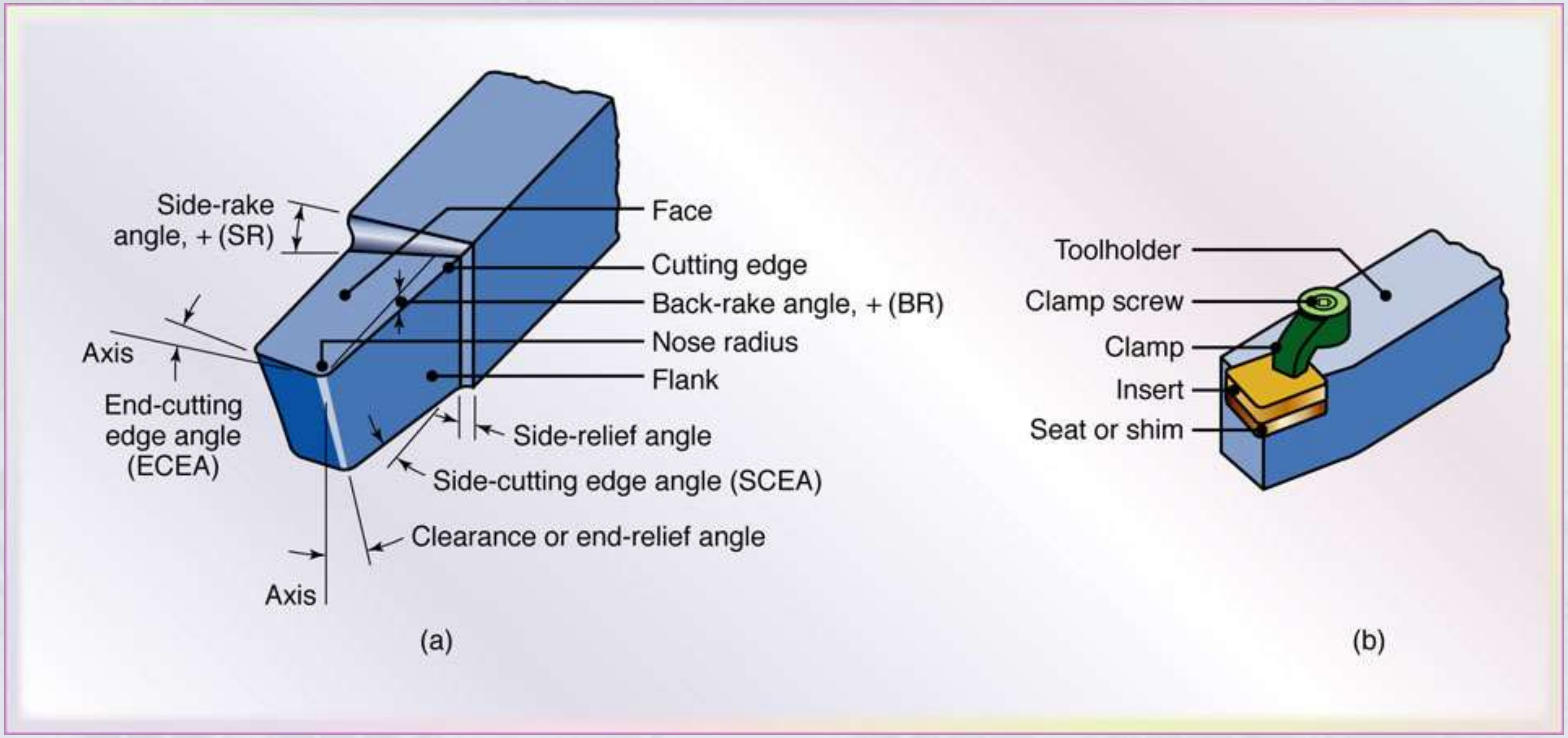
(d) chip hits tool shank and breaks off.

(oblique cutting) برش مایل



- **(a) Schematic illustration of cutting with an oblique tool. Note the direction of chip movement.**
- **(b) Top view, showing the inclination angle, *i*,.**
- **(c) Types of chips produced with tools at increasing inclination angles.**

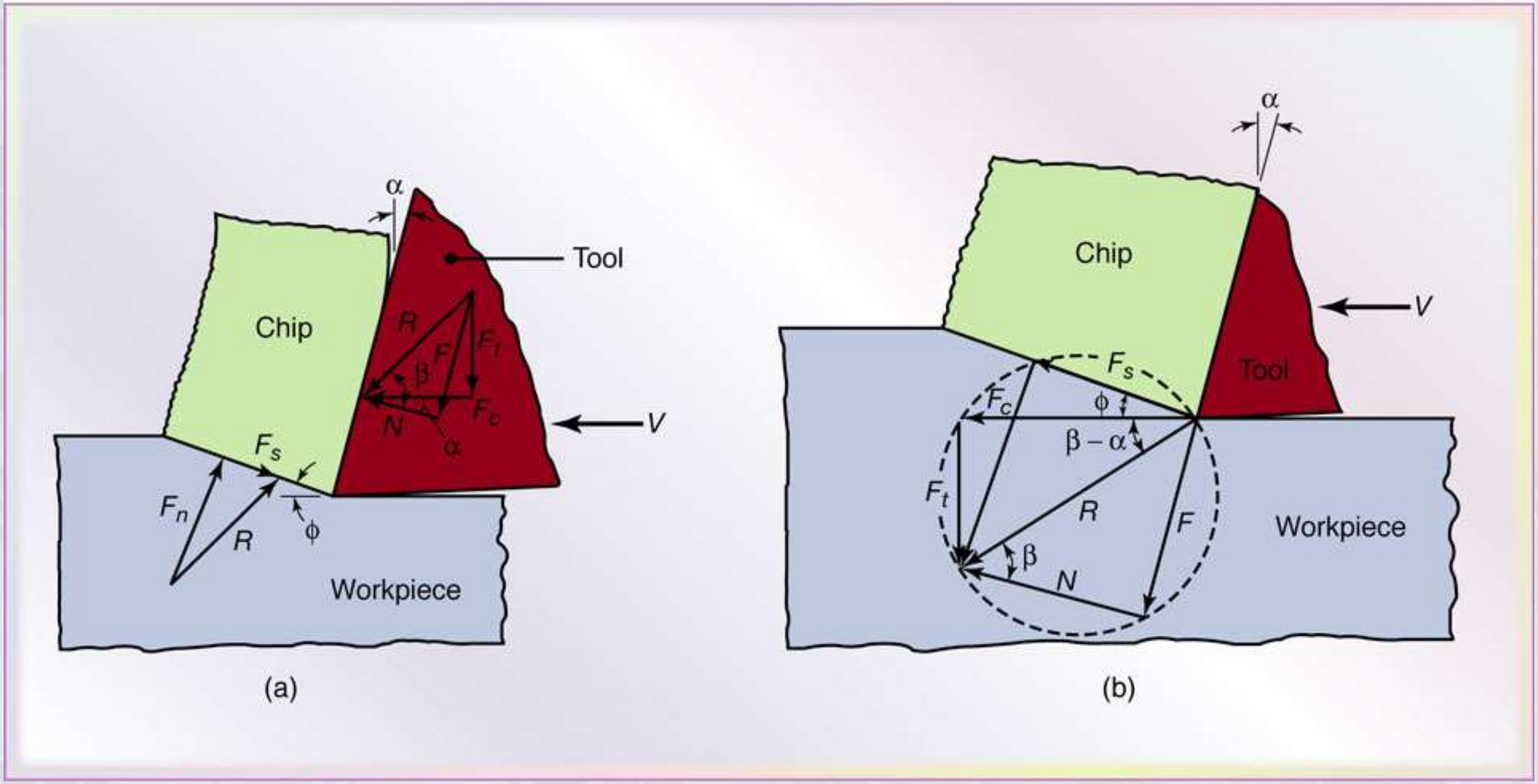
قلم برش راست و الماسه



(a) Schematic illustration of right-hand cutting tool. The various angles on these tools and their effects on machining are described in Section 23.3.1 Although these tools traditionally have been produced from solid tool-steel bars, they have been replaced largely with

(b) inserts made of carbides and other materials of various shapes and sizes.

نیروهای برش (cutting forces)



(a) Forces acting on a cutting tool during two-dimensional cutting.

(b) Force circle to determine various forces acting in the cutting zone.

نیروهای و توان برشی

Shear force, $F_s = F_c \cos\phi - F_t \sin\phi$

Normal force, $F_n = F_c \sin\phi + F_t \cos\phi$

Coefficient of friction, $\mu = \frac{F}{N} = \frac{F_t + F_c \tan\alpha}{F_c - F_t \tan\alpha}$

$\text{Power} = F_c V$

Range of Energy Requirements in Cutting Operations

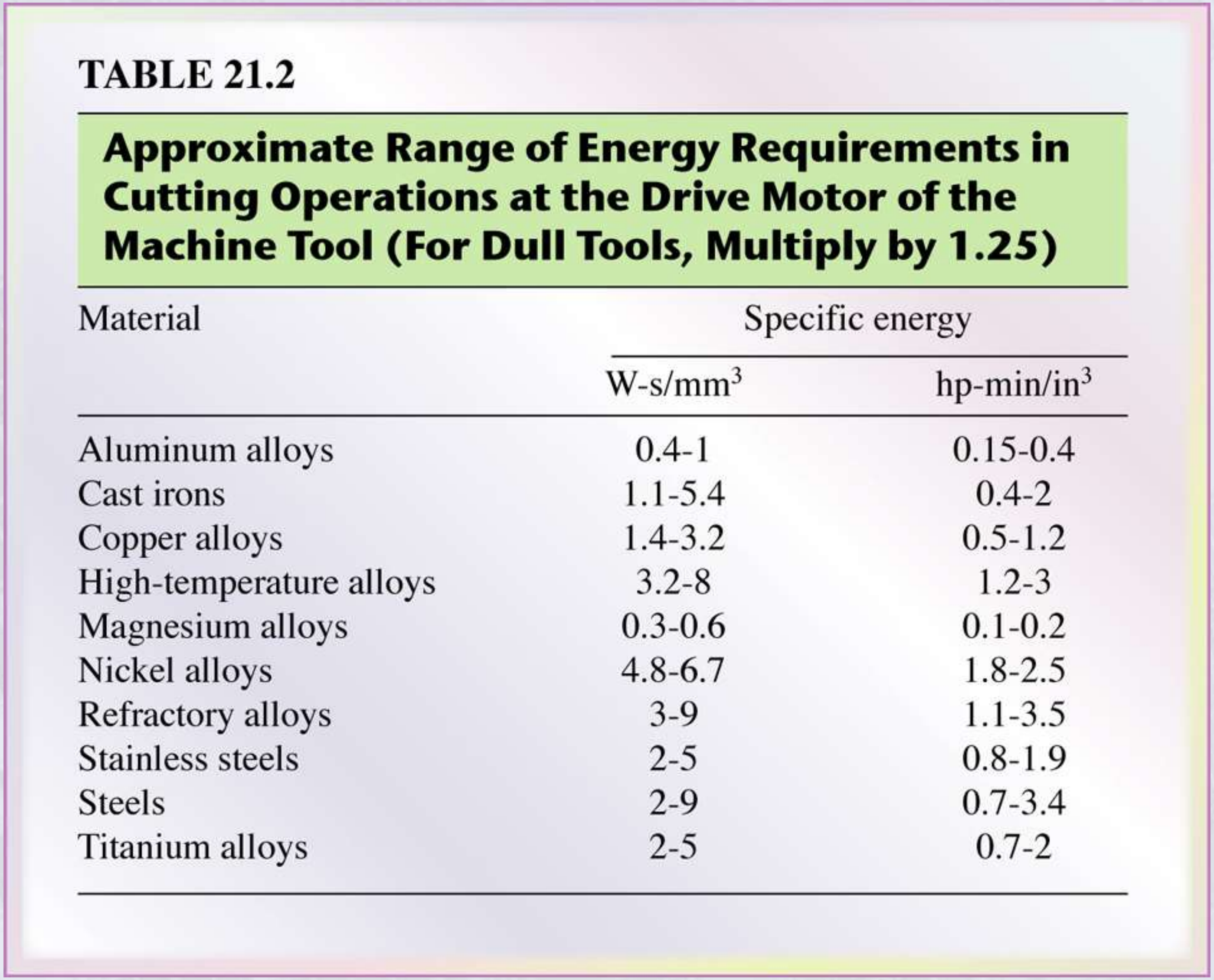


TABLE 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (For Dull Tools, Multiply by 1.25)

Material	Specific energy	
	W-s/mm^3	hp-min/in^3
Aluminum alloys	0.4-1	0.15-0.4
Cast irons	1.1-5.4	0.4-2
Copper alloys	1.4-3.2	0.5-1.2
High-temperature alloys	3.2-8	1.2-3
Magnesium alloys	0.3-0.6	0.1-0.2
Nickel alloys	4.8-6.7	1.8-2.5
Refractory alloys	3-9	1.1-3.5
Stainless steels	2-5	0.8-1.9
Steels	2-9	0.7-3.4
Titanium alloys	2-5	0.7-2

Temperatures in Cutting Zone

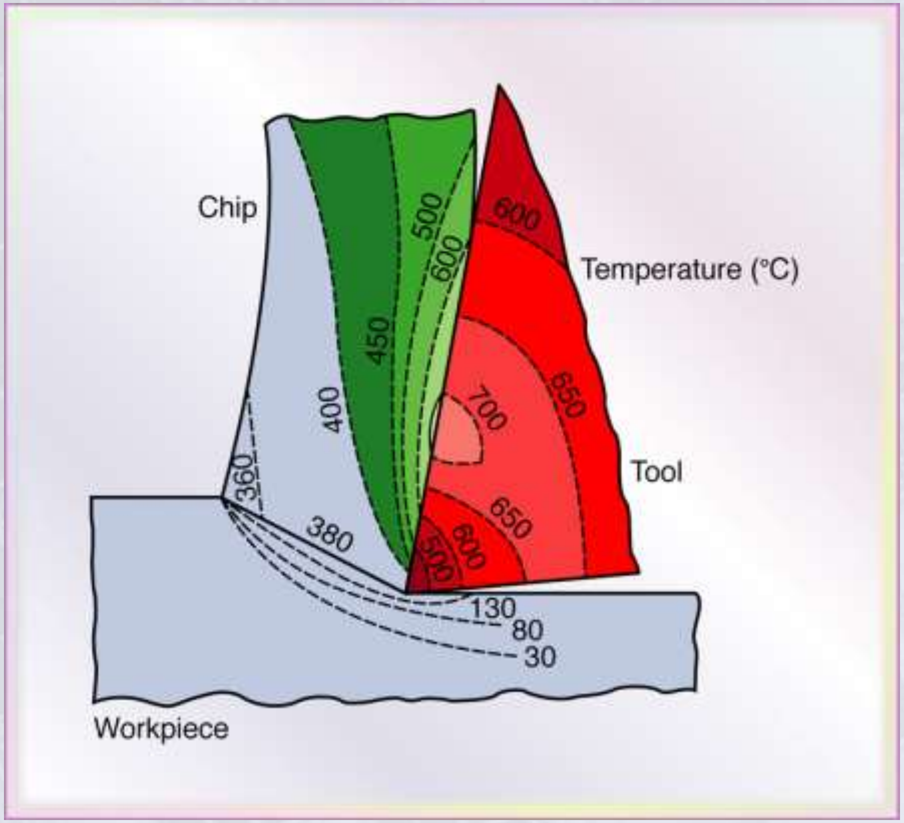


Figure 21.12 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source*: After G. Vieregge.

Mean temperature in cutting:

$$T_{\text{mean}} = \frac{1.2 Y_f}{\rho c \left[\frac{V t_o}{K} \right]^{1/3}}$$

where

$$Y_f = \text{flow stress, psi}$$

$$\rho c = \text{volumetric specific heat, in.-lb/in}^3\text{-°F}$$

$$K = \text{thermal diffusivity}$$

Temperatures Developed in Turning 52100 Steel

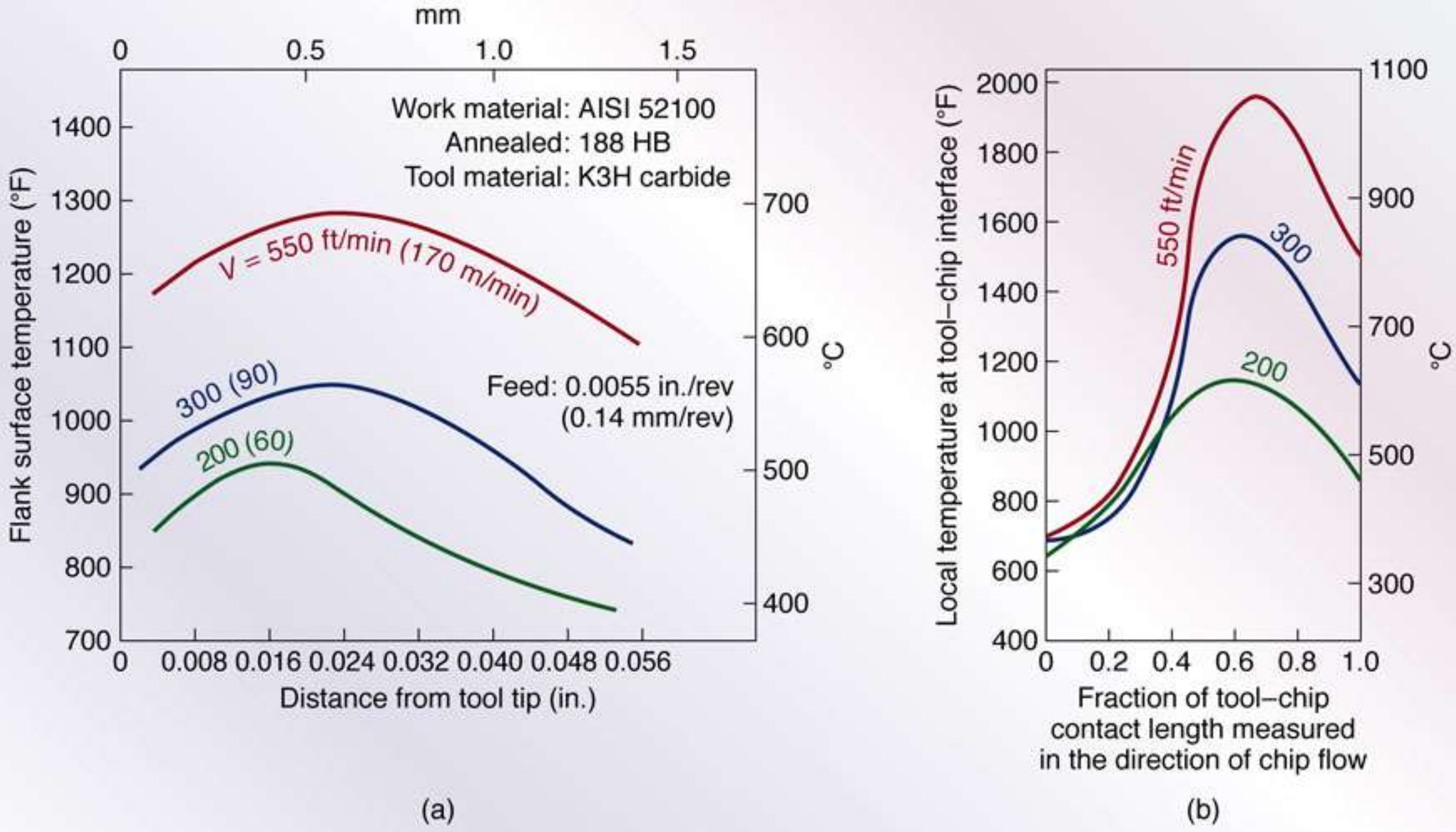


Figure 21.13 Temperatures developed in turning 52100 steel: (a) flank temperature distribution and (b) tool-ship interface temperature distribution. *Source*: After B. T. Chao and K. J. Trigger.

Proportion of Heat from Cutting Transferred as a Function of Cutting Speed

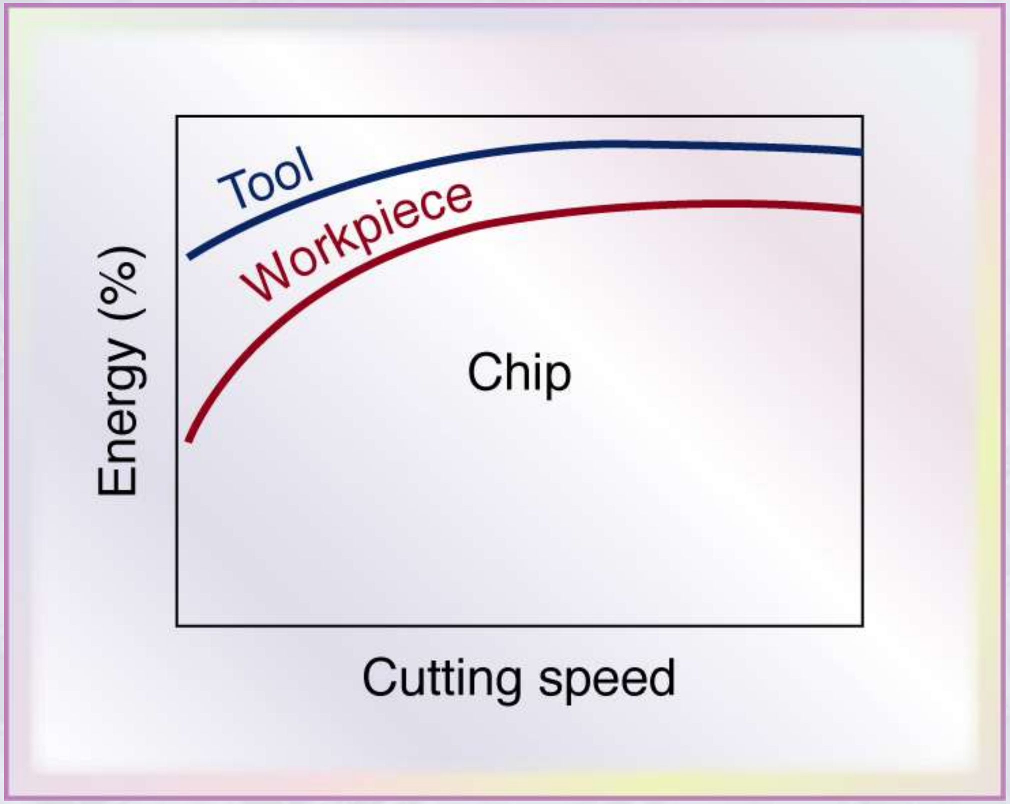


Figure 21.14 Proportion of the heat generated in cutting transferred into the tool, workpiece, and chip as a function of the cutting speed. Note that the chip removes most of the heat.

Wear Patterns on Tools

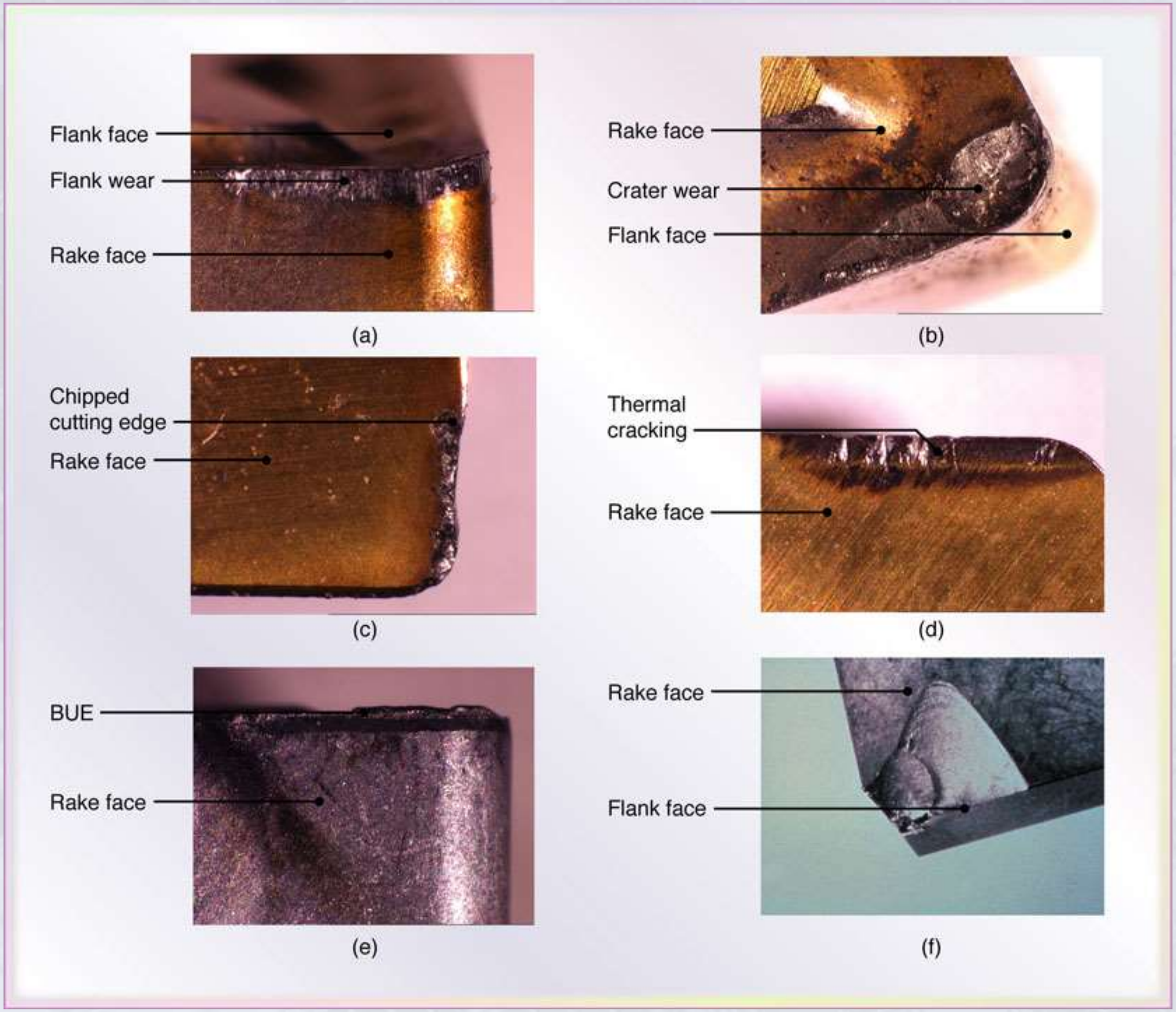


Figure 21.15 (a) Flank wear and crater wear in a cutting tool; the tool moves to the left as in Fig. 21.3. (b) View of the rake face of a turning tool, showing various wear patterns. (c) View of the flank face of a turning tool, showing various wear patterns. (d) Types of wear on a turning tool: 1. flank wear; 2. crater wear; 3. chipped cutting edge; 4. thermal cracking on rake face; 5. built-up edge; 6. catastrophic failure. (See also Fig. 21.18.) *Source*: Courtesy of Kennametal, Inc.

Taylor Tool Lofe Equation

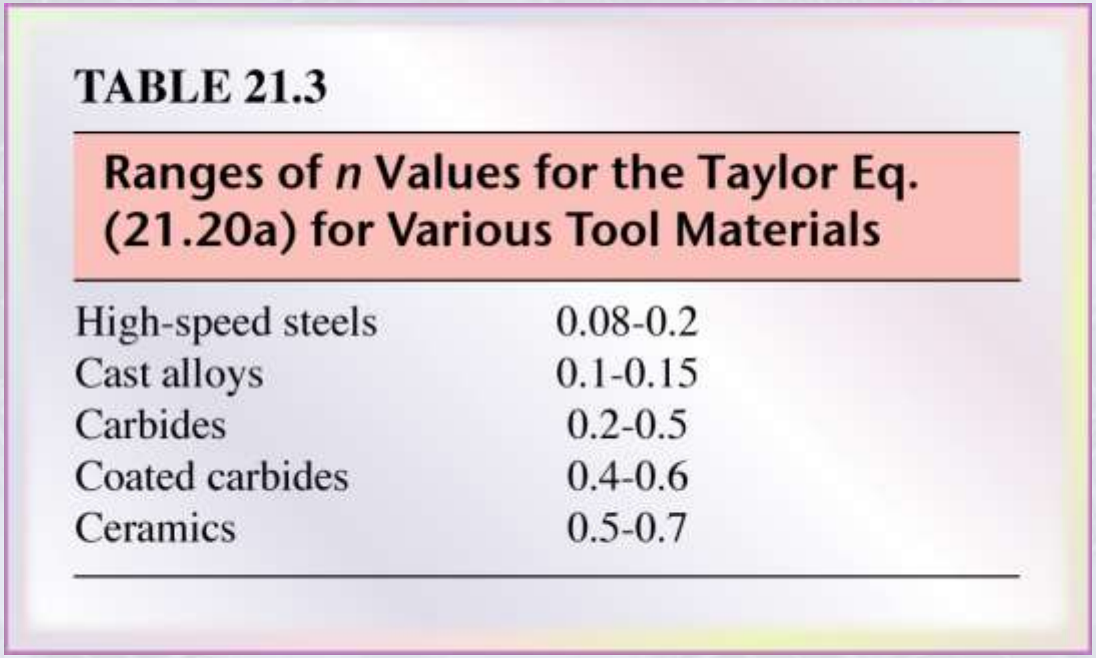


TABLE 21.3

Ranges of *n* Values for the Taylor Eq. (21.20a) for Various Tool Materials

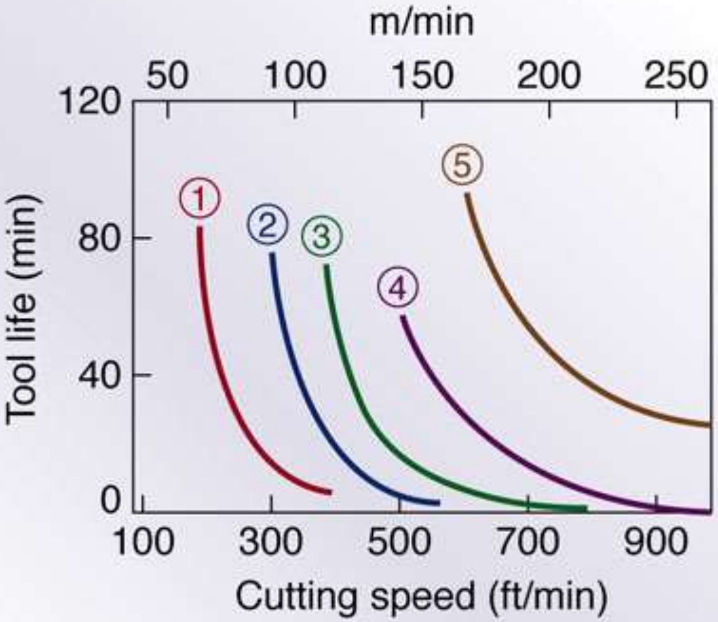
High-speed steels	0.08-0.2
Cast alloys	0.1-0.15
Carbides	0.2-0.5
Coated carbides	0.4-0.6
Ceramics	0.5-0.7

Taylor Equation:

$$VT^n = C$$

$$VT^n d^x f^y = C$$

Effect of Workpiece Hardness and Microstructure on Tool Life



	Hardness (HB)	Ferrite	Pearlite
① As cast	265	20%	80%
② As cast	215	40	60
③ As cast	207	60	40
④ Annealed	183	97	3
⑤ Annealed	170	100	—

Figure 21.16 Effect of workpiece hardness and microstructure on tool life in turning ductile cast iron. Note the rapid decrease in tool life (approaching zero) as the cutting speed increases. Tool materials have been developed that resist high temperatures, such as carbides, ceramics, and cubic boron nitride, as will be described in Chapter 22.

Tool-life Curves

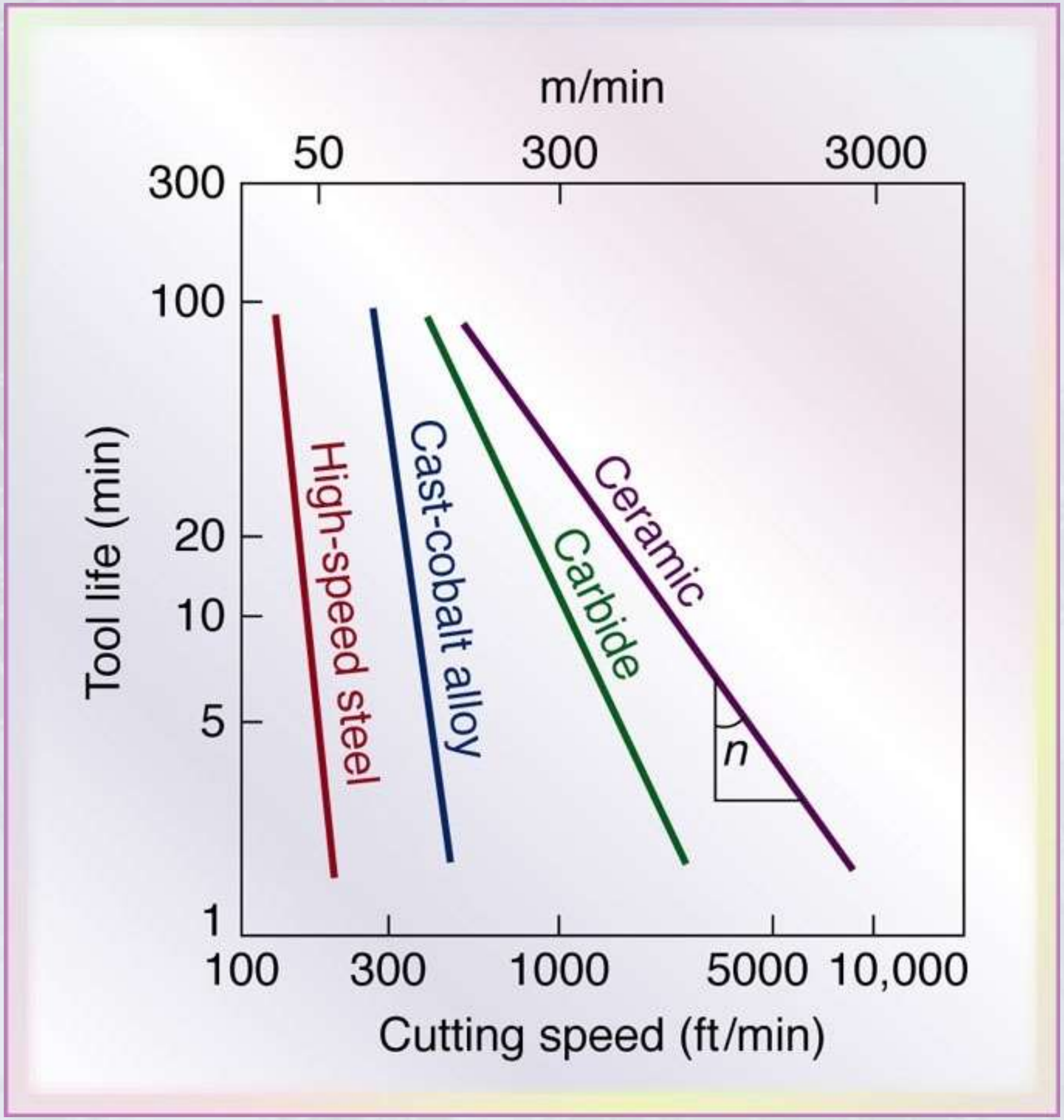


Figure 21.17 Tool-life curves for a variety of cutting-tool materials. The negative inverse of the slope of these curves is the exponent *n* in the Taylor tool-life equation and *C* is the cutting speed at *T* = 1 min, ranging from about 200 to 10,000 ft./min in this figure.

Allowable Average Wear Land for Cutting Tools

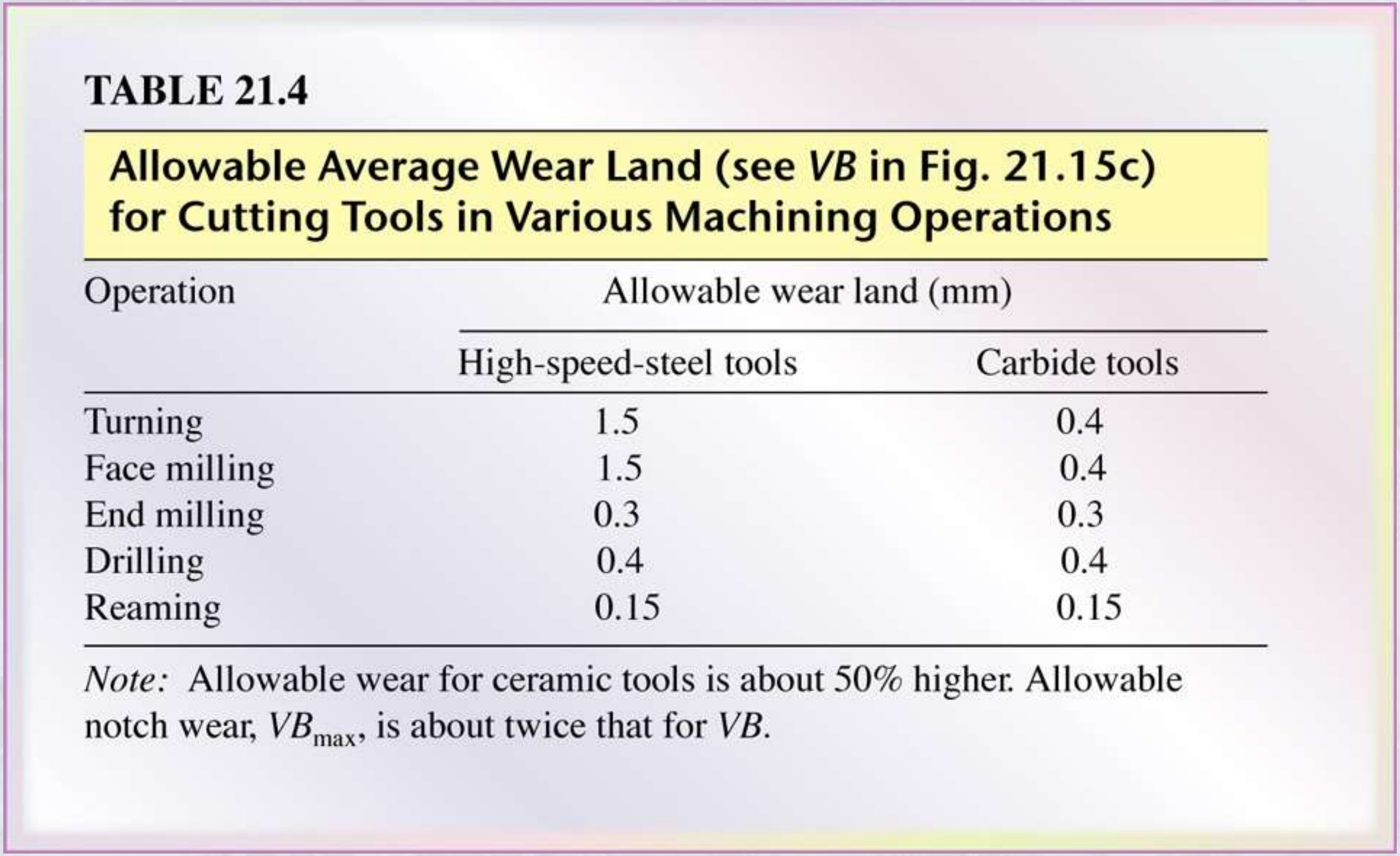


TABLE 21.4

Allowable Average Wear Land (see *VB* in Fig. 21.15c) for Cutting Tools in Various Machining Operations

Operation	Allowable wear land (mm)	
	High-speed-steel tools	Carbide tools
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

Note: Allowable wear for ceramic tools is about 50% higher. Allowable notch wear, $VB_{\max}$, is about twice that for VB.

Types of Wear seen in Cutting Tools

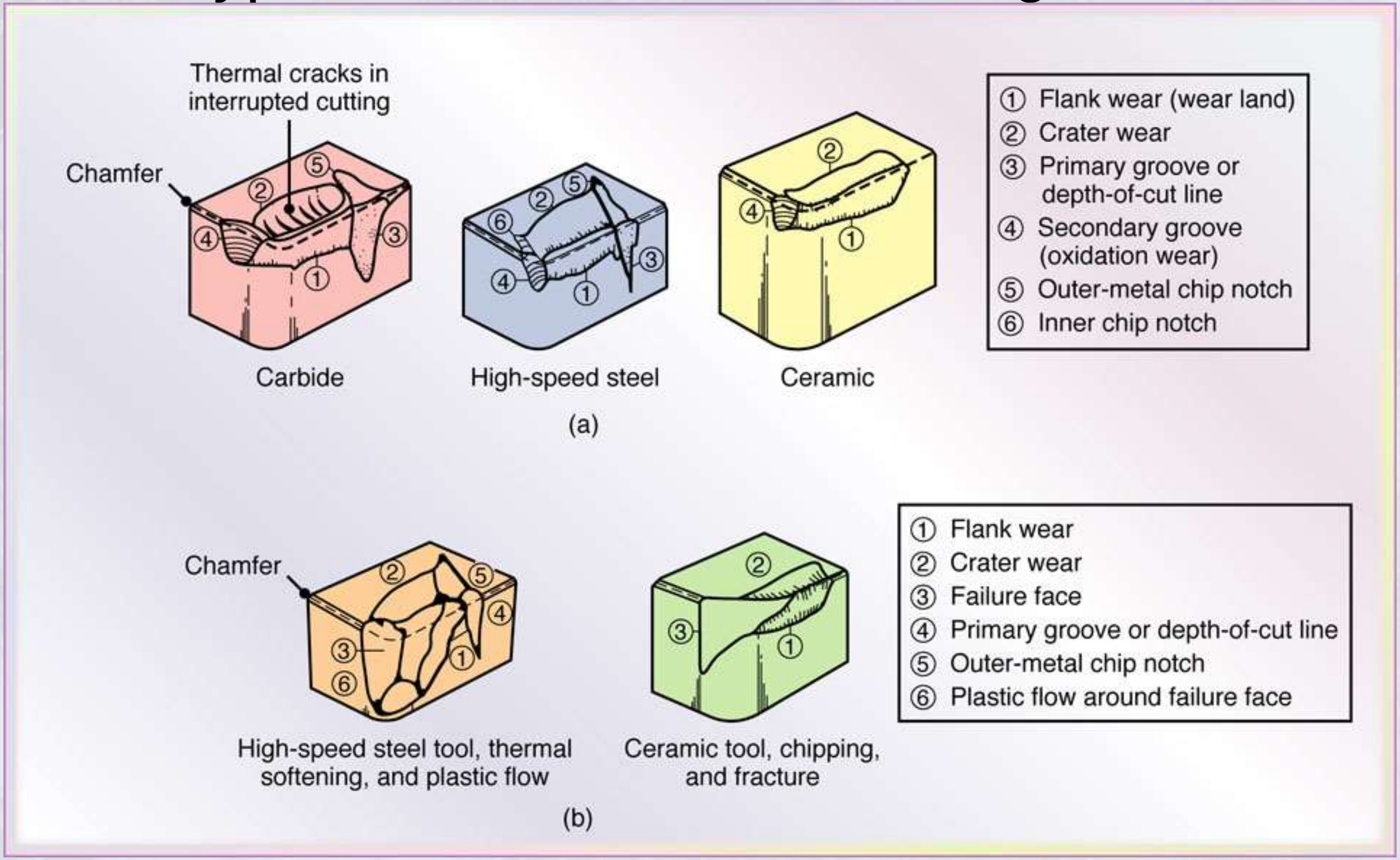


Figure 21.28 (a) Schematic illustration of types of wear observed on various cutting tools. (b) Schematic illustrations of catastrophic tool failures. A wide range of parameters influence these wear and failure patterns. *Source*: Courtesy of V. C. Venkatesh.

Relationship between Crater-Wear Rate and Average Tool-Chip Interface Temperature

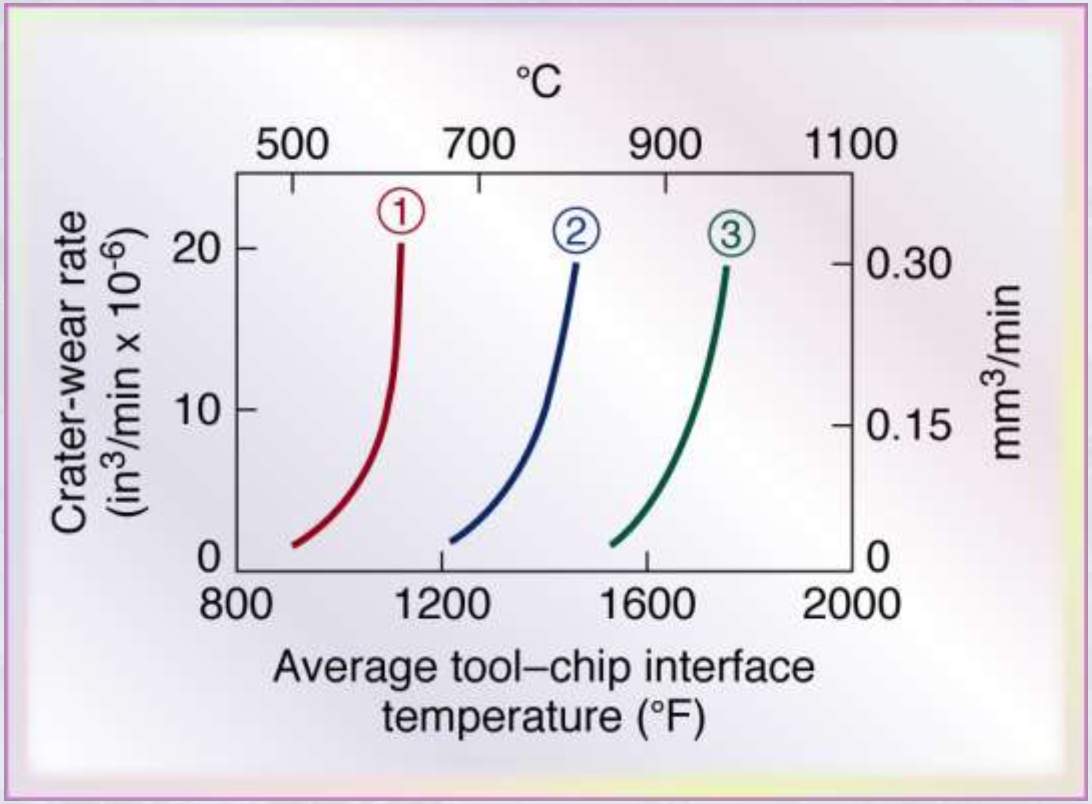


Figure 21.19 Relationship between crater-wear rate and average tool-chip interface temperature: 1) High-speed steel, 2) C-1 carbide, and 3) C-5 carbide (see Table 22.4). Note how rapidly crater-wear rate increases with an incremental increase in temperature. *Source*: After B. T Chao and K. J Trigger.

Cutting Tool Interface and Chip

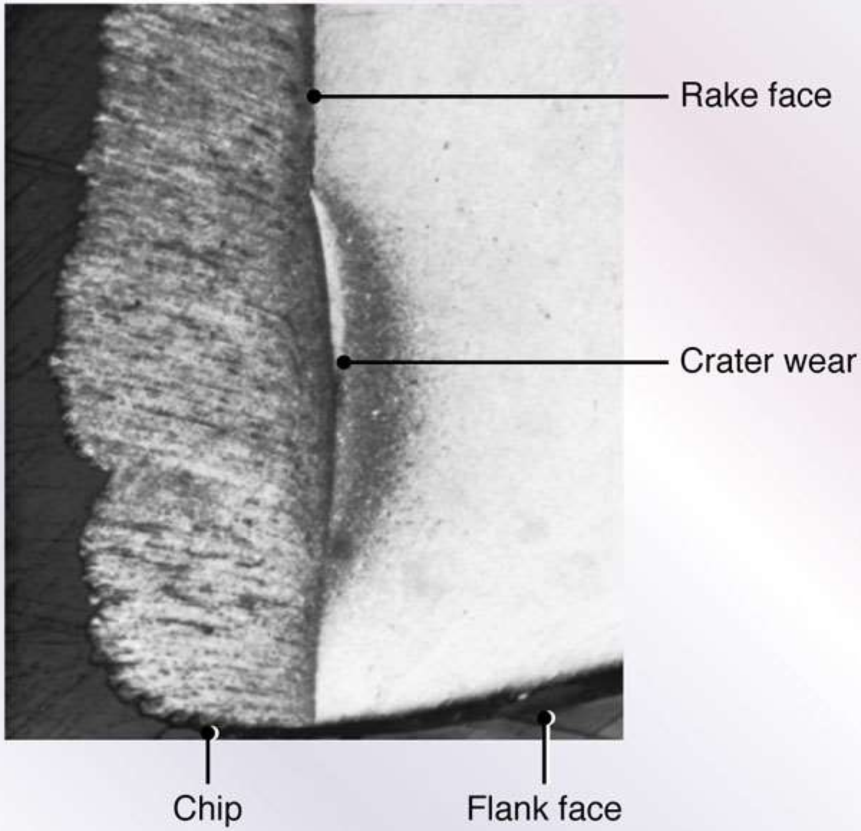
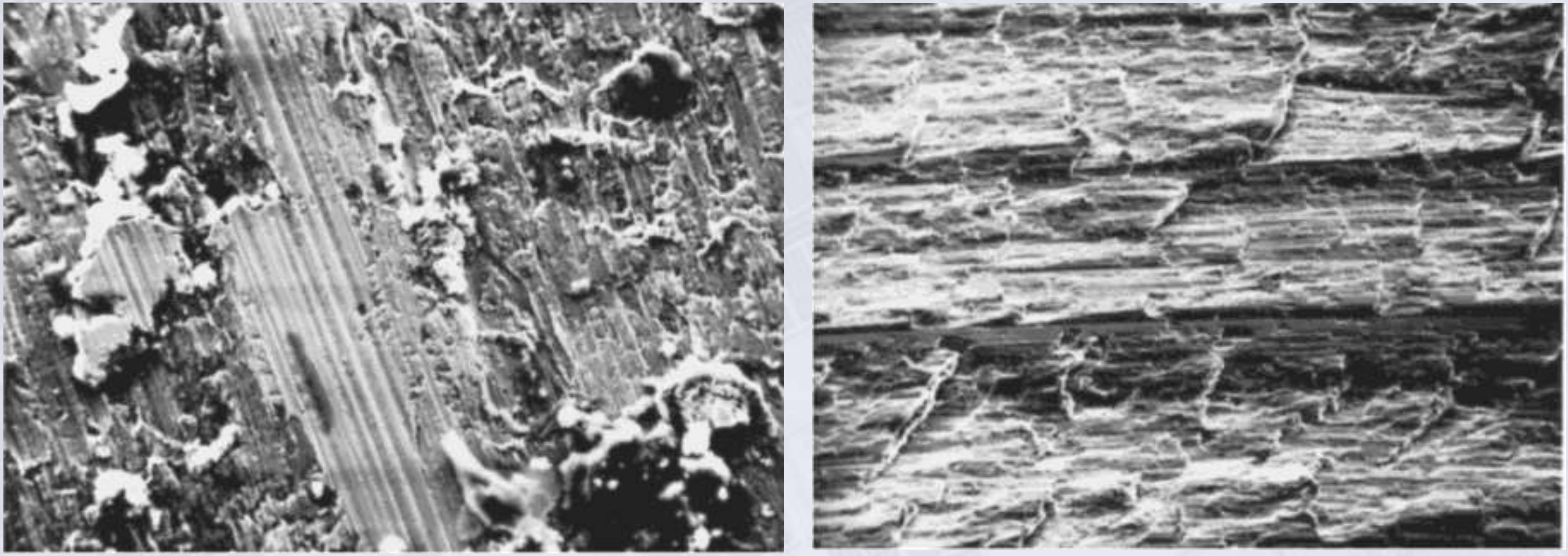


Figure 21.20 Interface of a cutting tool (right) and chip (left) in machining plain-carbon steel. The discoloration of the tool indicates the presence of high temperatures. Compare this figure with the temperature profiles shown in Fig. 21.12. *Source*: Courtesy of P. K. Wright.

Machined Surfaces Produced on Steel



(a) **(b)**

Figure 21.21 Machined surfaces produced on steel (highly magnified), as observed with a scanning electron microscope: (a) turned surface and (b) surface produced by shaping. *Source*: Courtesy of J. T. Black and S. Ramalingam.

Dull Tool in Orthogonal Machining

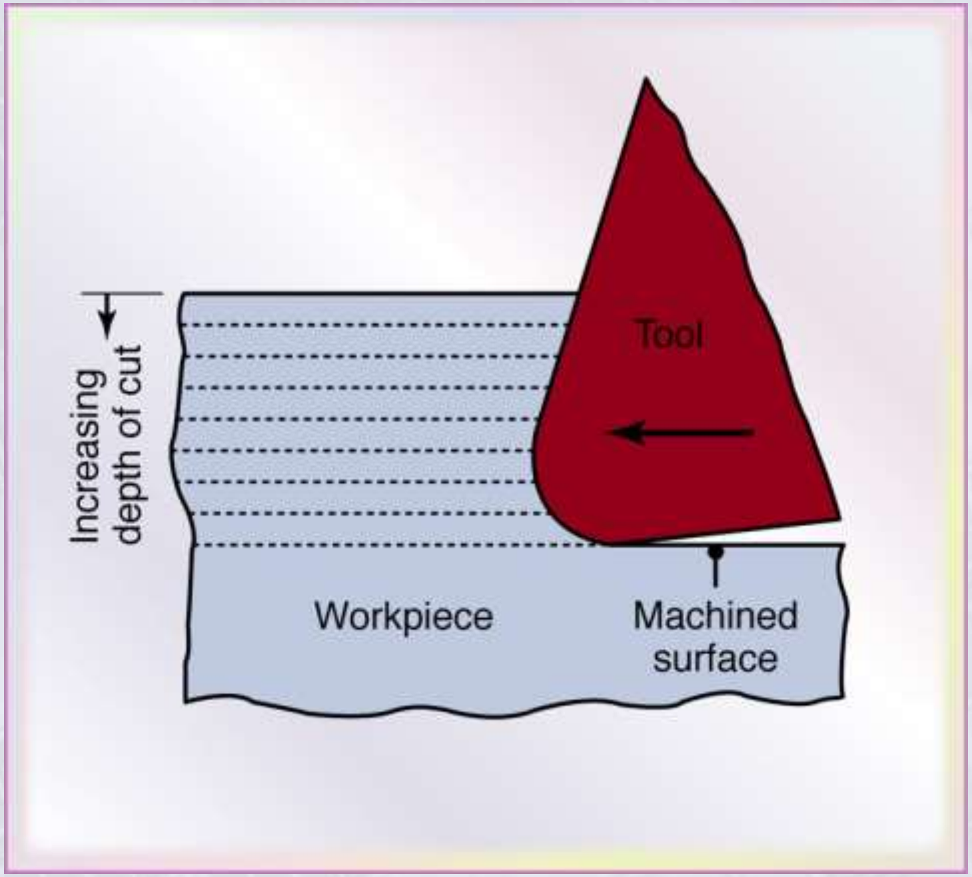


Figure 21.22 Schematic illustration of a dull tool with respect to the depth of cut in orthogonal machining (exaggerated). Note that the tool has a positive rake angle, but as the depth of cut decreases, the rake angle effectively can become negative. The tool then simply rides over the workpiece (without cutting) and burnishes its surface; this action raises the workpiece temperature and causes surface residual stresses.

Feed Marks on a Turned Surface

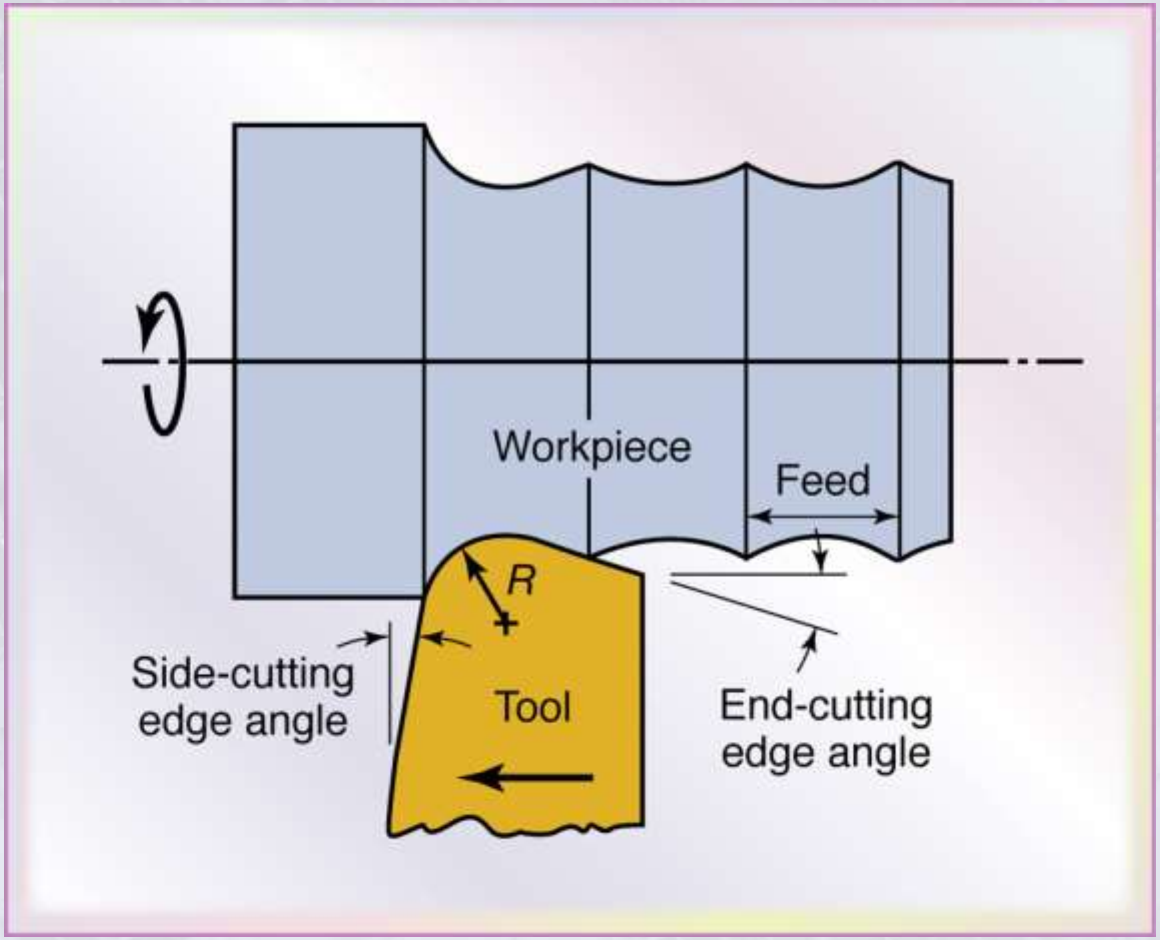


Figure 21.23 Schematic illustration of feed marks on a surface being turned (exaggerated).

Surface roughness:

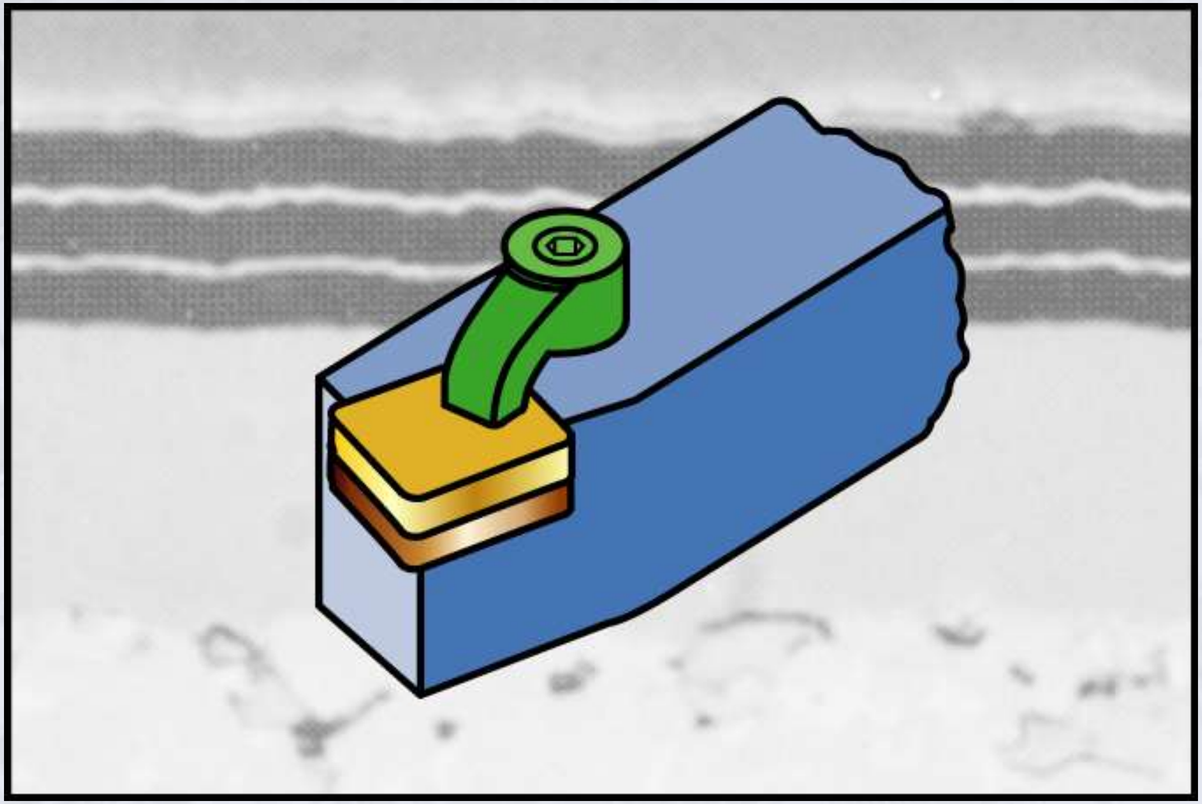
$$R_a = \frac{f^2}{8R}$$

where

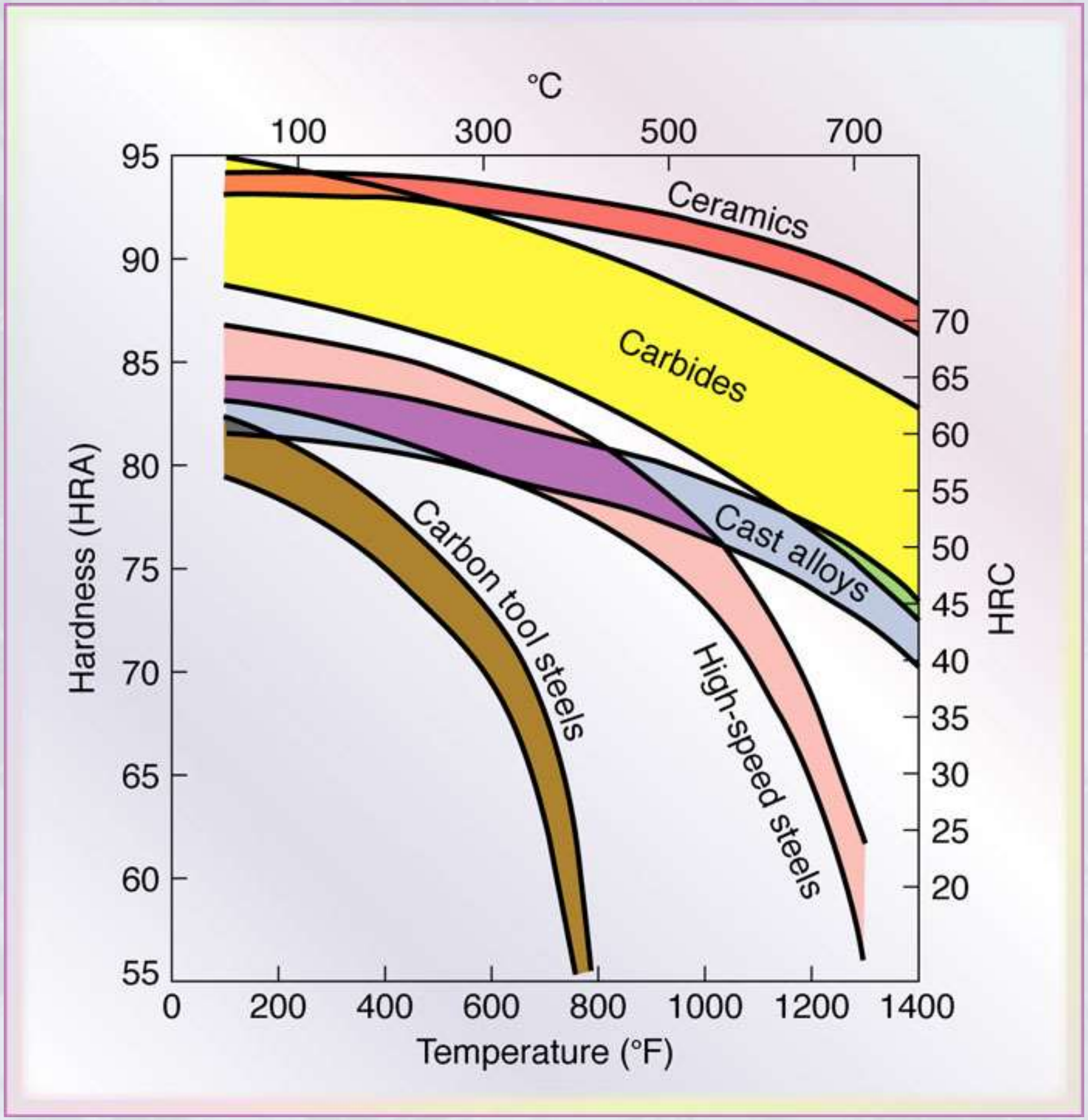
$f = \text{feed}$

$R = \text{tool-nose radius}$

Cutting-Tool Materials and Cutting Fluids



Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid.
ISBN 0-13-148965-8.



Hardness of Cutting Tool Materials as a Function of Temperature

Figure 22.1 The hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of materials is due to the variety of tool compositions and treatments available for that group.

General Properties of Tool Materials

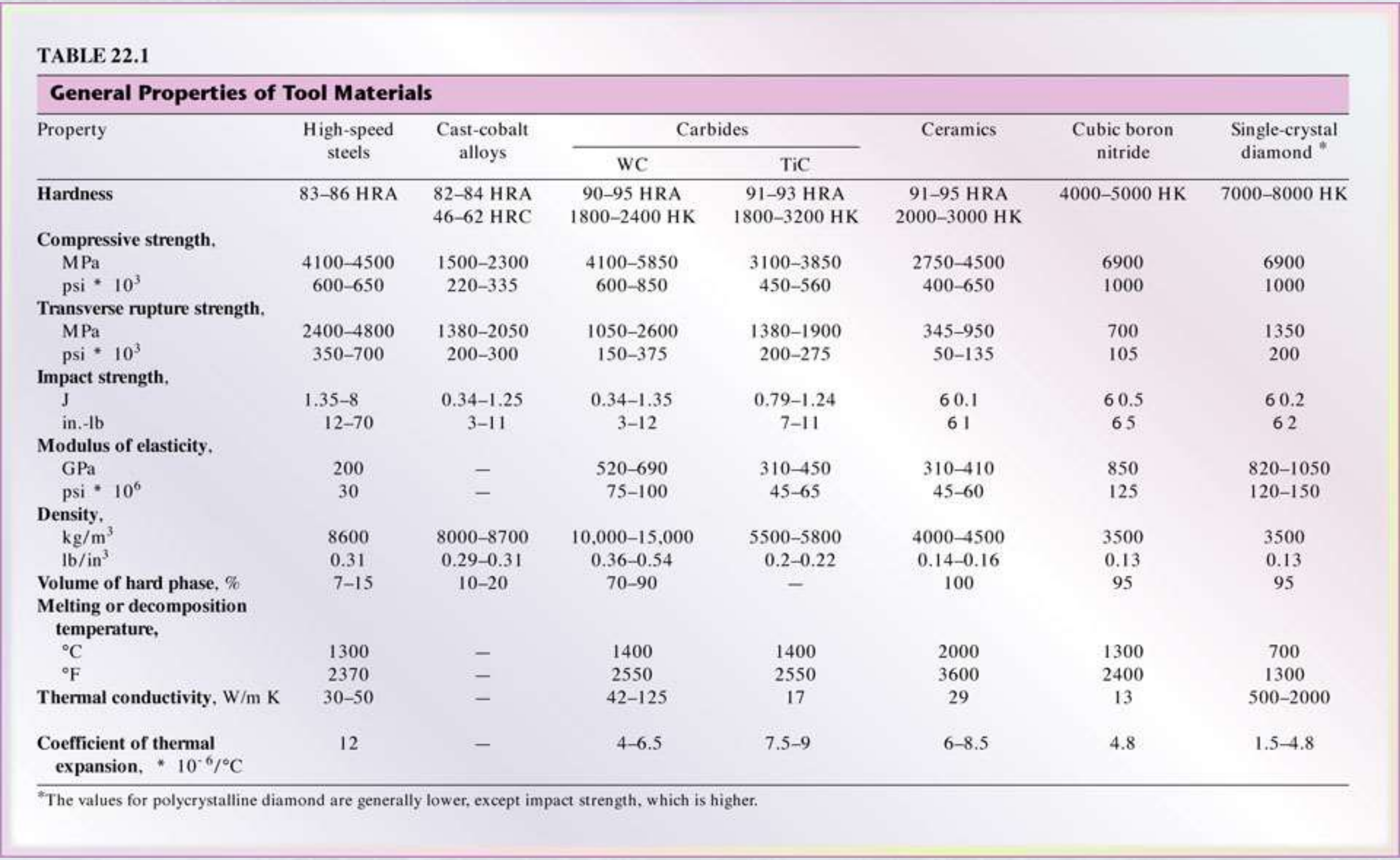


TABLE 22.1

General Properties of Tool Materials

Property	High-speed steels	Cast-cobalt alloys	Carbides		Ceramics	Cubic boron nitride	Single-crystal diamond *
			WC	TiC			
Hardness	83–86 HRA	82–84 HRA 46–62 HRC	90–95 HRA 1800–2400 HK	91–93 HRA 1800–3200 HK	91–95 HRA 2000–3000 HK	4000–5000 HK	7000–8000 HK
Compressive strength,							
MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
psi * 10^3	600–650	220–335	600–850	450–560	400–650	1000	1000
Transverse rupture strength,							
MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
psi * 10^3	350–700	200–300	150–375	200–275	50–135	105	200
Impact strength,							
J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	6 0.1	6 0.5	6 0.2
in.-lb	12–70	3–11	3–12	7–11	6 1	6 5	6 2
Modulus of elasticity,							
GPa	200	—	520–690	310–450	310–410	850	820–1050
psi * 10^6	30	—	75–100	45–65	45–60	125	120–150
Density,							
kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
lb/in^3	0.31	0.29–0.31	0.36–0.54	0.2–0.22	0.14–0.16	0.13	0.13
Volume of hard phase, %	7–15	10–20	70–90	—	100	95	95
Melting or decomposition temperature,							
°C	1300	—	1400	1400	2000	1300	700
°F	2370	—	2550	2550	3600	2400	1300
Thermal conductivity, W/m K	30–50	—	42–125	17	29	13	500–2000
Coefficient of thermal expansion, * 10^{-6}/°C	12	—	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

*The values for polycrystalline diamond are generally lower, except impact strength, which is higher.

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General Characteristics of Cutting-Tool Materials

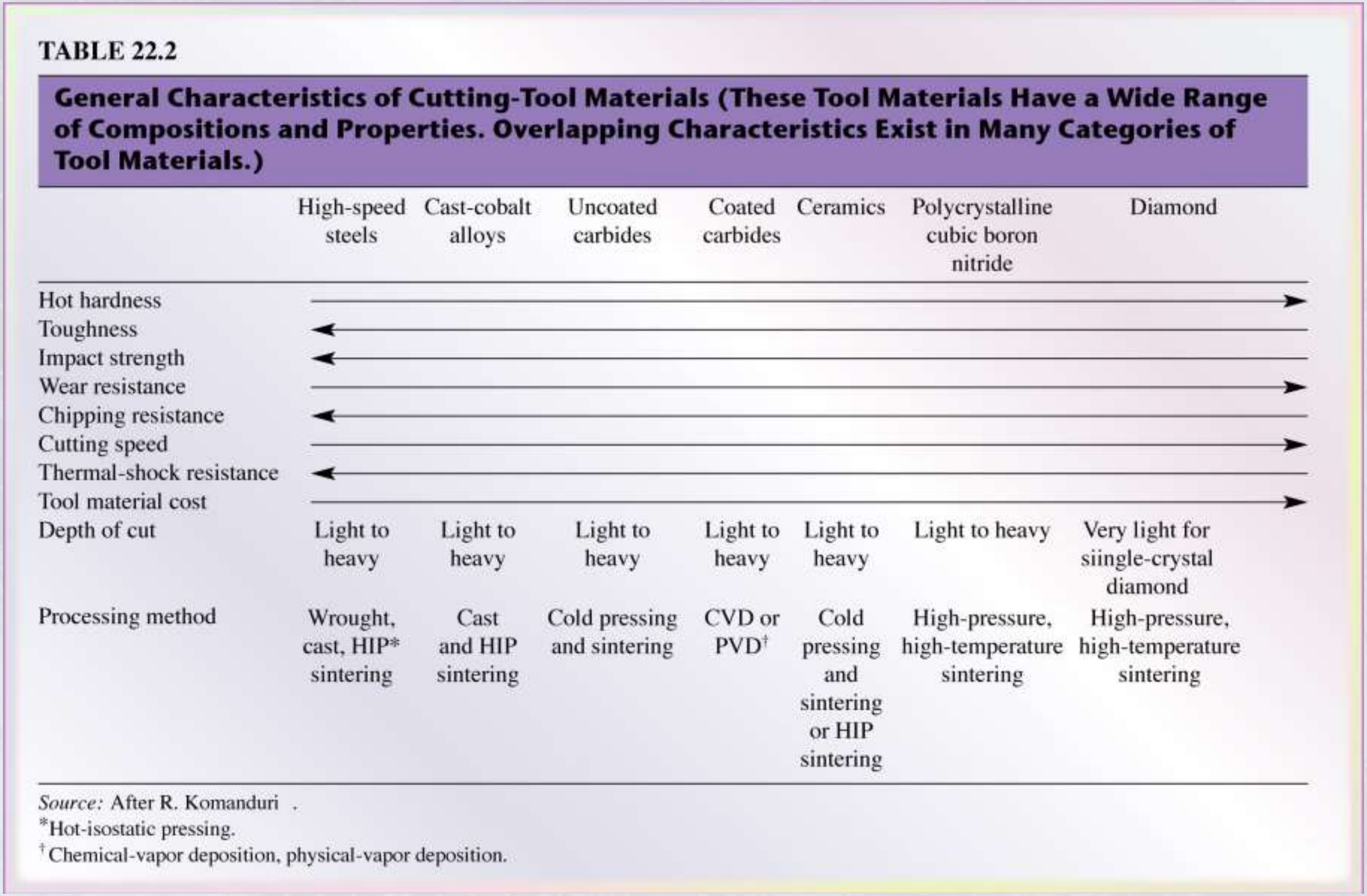

TABLE 22.2

General Characteristics of Cutting-Tool Materials (These Tool Materials Have a Wide Range of Compositions and Properties. Overlapping Characteristics Exist in Many Categories of Tool Materials.)

	High-speed steels	Cast-cobalt alloys	Uncoated carbides	Coated carbides	Ceramics	Polycrystalline cubic boron nitride	Diamond
Hot hardness	→	→	→	→	→	→	→
Toughness	←	←	←	←	←	←	←
Impact strength	←	←	←	←	←	←	←
Wear resistance	→	→	→	→	→	→	→
Chipping resistance	←	←	←	←	←	←	←
Cutting speed	→	→	→	→	→	→	→
Thermal-shock resistance	←	←	←	←	←	←	←
Tool material cost	→	→	→	→	→	→	→
Depth of cut	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Very light for siingle-crystal diamond
Processing method	Wrought, cast, HIP* sintering	Cast and HIP sintering	Cold pressing and sintering	CVD or PVD†	Cold pressing and sintering or HIP sintering	High-pressure, high-temperature sintering	High-pressure, high-temperature sintering

Source: After R. Komanduri .

*Hot-isostatic pressing.

† Chemical-vapor deposition, physical-vapor deposition.

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Operating Characteristics of Cutting-Tool Materials

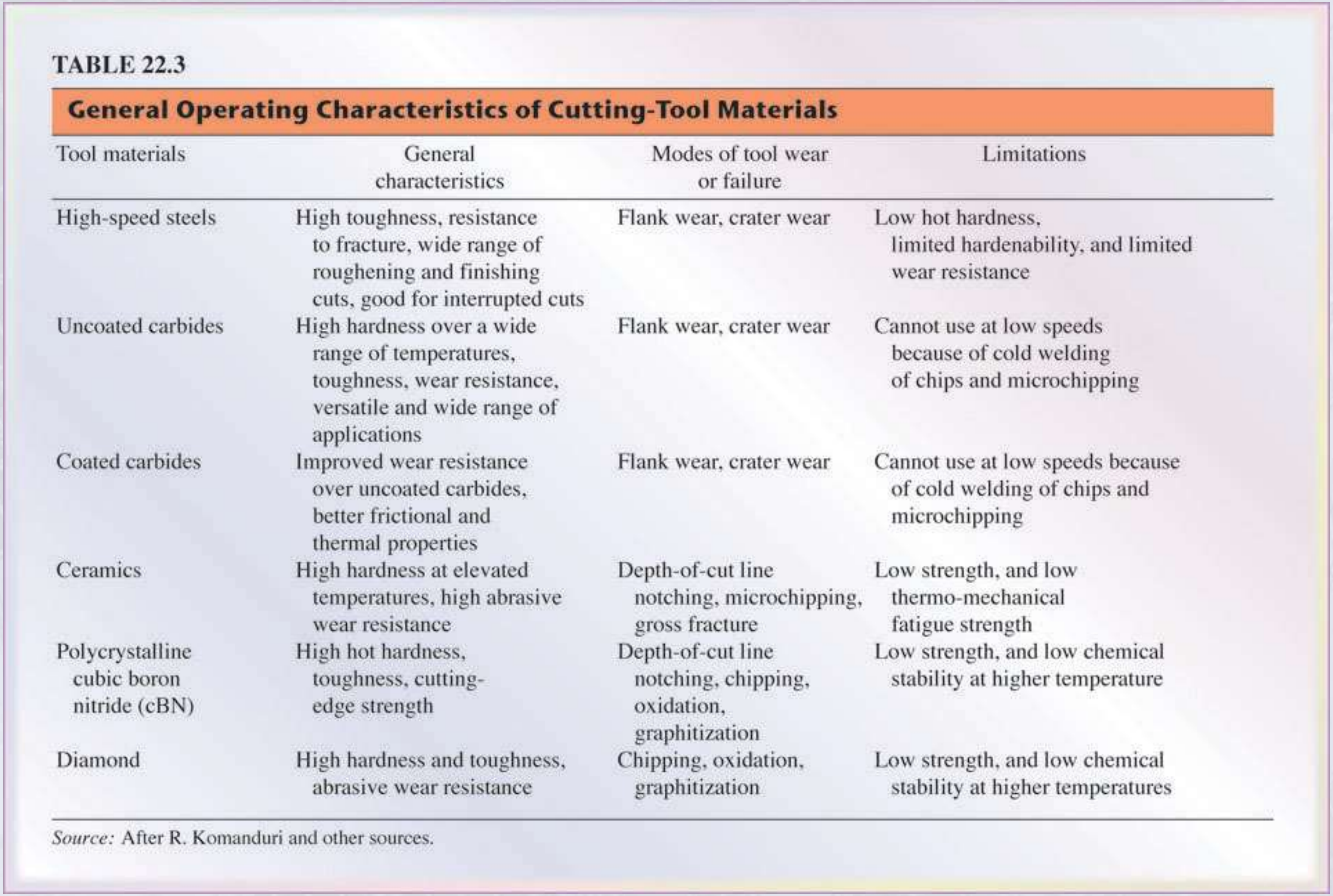

TABLE 22.3

General Operating Characteristics of Cutting-Tool Materials

Tool materials	General characteristics	Modes of tool wear or failure	Limitations
High-speed steels	High toughness, resistance to fracture, wide range of roughening and finishing cuts, good for interrupted cuts	Flank wear, crater wear	Low hot hardness, limited hardenability, and limited wear resistance
Uncoated carbides	High hardness over a wide range of temperatures, toughness, wear resistance, versatile and wide range of applications	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Coated carbides	Improved wear resistance over uncoated carbides, better frictional and thermal properties	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Ceramics	High hardness at elevated temperatures, high abrasive wear resistance	Depth-of-cut line notching, microchipping, gross fracture	Low strength, and low thermo-mechanical fatigue strength
Polycrystalline cubic boron nitride (cBN)	High hot hardness, toughness, cutting-edge strength	Depth-of-cut line notching, chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperature
Diamond	High hardness and toughness, abrasive wear resistance	Chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperatures

Source: After R. Komanduri and other sources.

Inserts and Toolholders

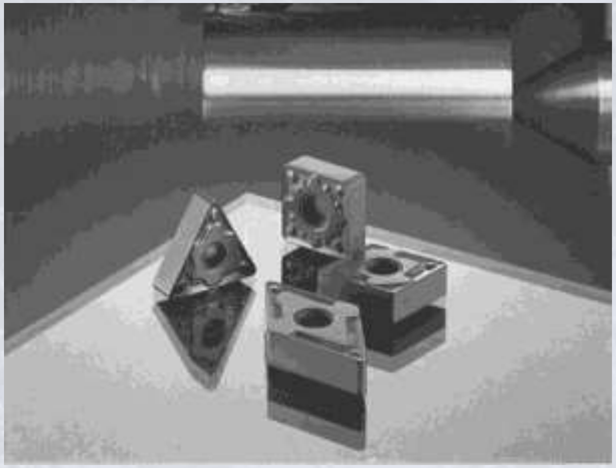

Figure 22.2 Typical carbide inserts with various shapes and chip-breaker features: Round inserts are also available, as can be seen in Figs. 22.3c and 22.4. The holes in the inserts are standardized for interchangeability in toolholders. *Source*: Courtesy of Kyocera Engineered Ceramics, Inc.

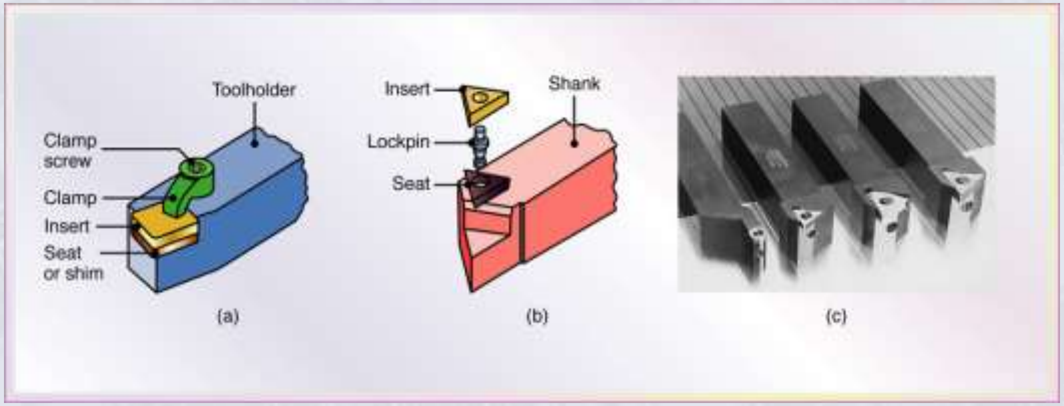

Figure 22.3 Methods of mounting inserts on toolholders: (a) clamping and (b) wing lockpins. (c) Examples of inserts mounted with threadless lockpins, which are secured with side screws. *Source*: Courtesy of Valenite.

Insert Edge Properties

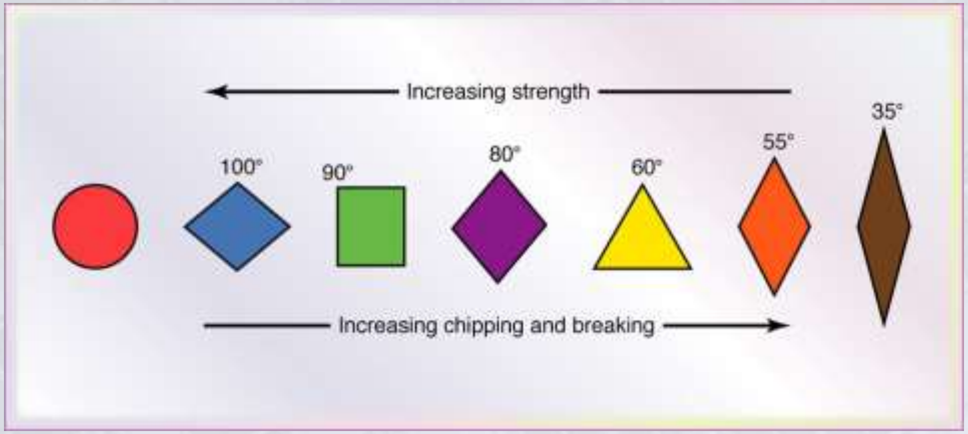

Figure 22.4 Relative edge strength and tendency for chipping of inserts with various shapes. Strength refers to the cutting edge indicated by the included angles. *Source*: Courtesy of Kennametal, Inc.

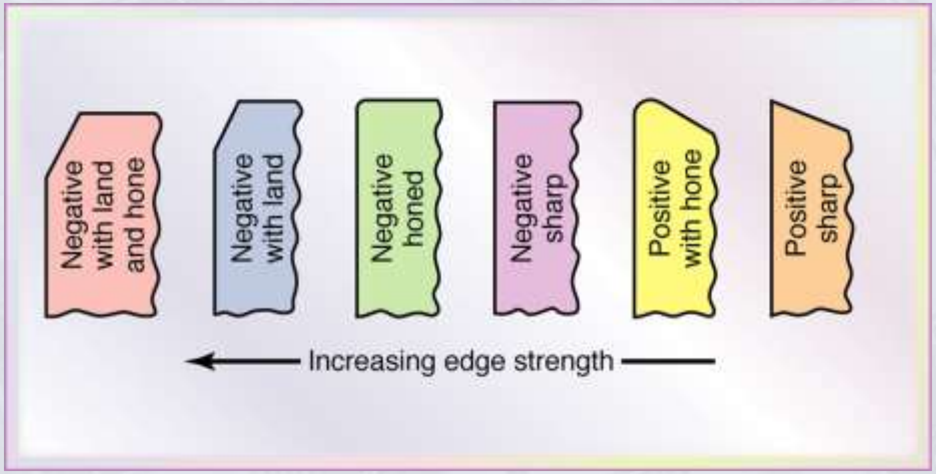

Figure 22.5 Edge preparation for inserts to improve edge strength. *Source*: Courtesy of Kennametal, Inc.

ISO Classification of Carbide Cutting Tools

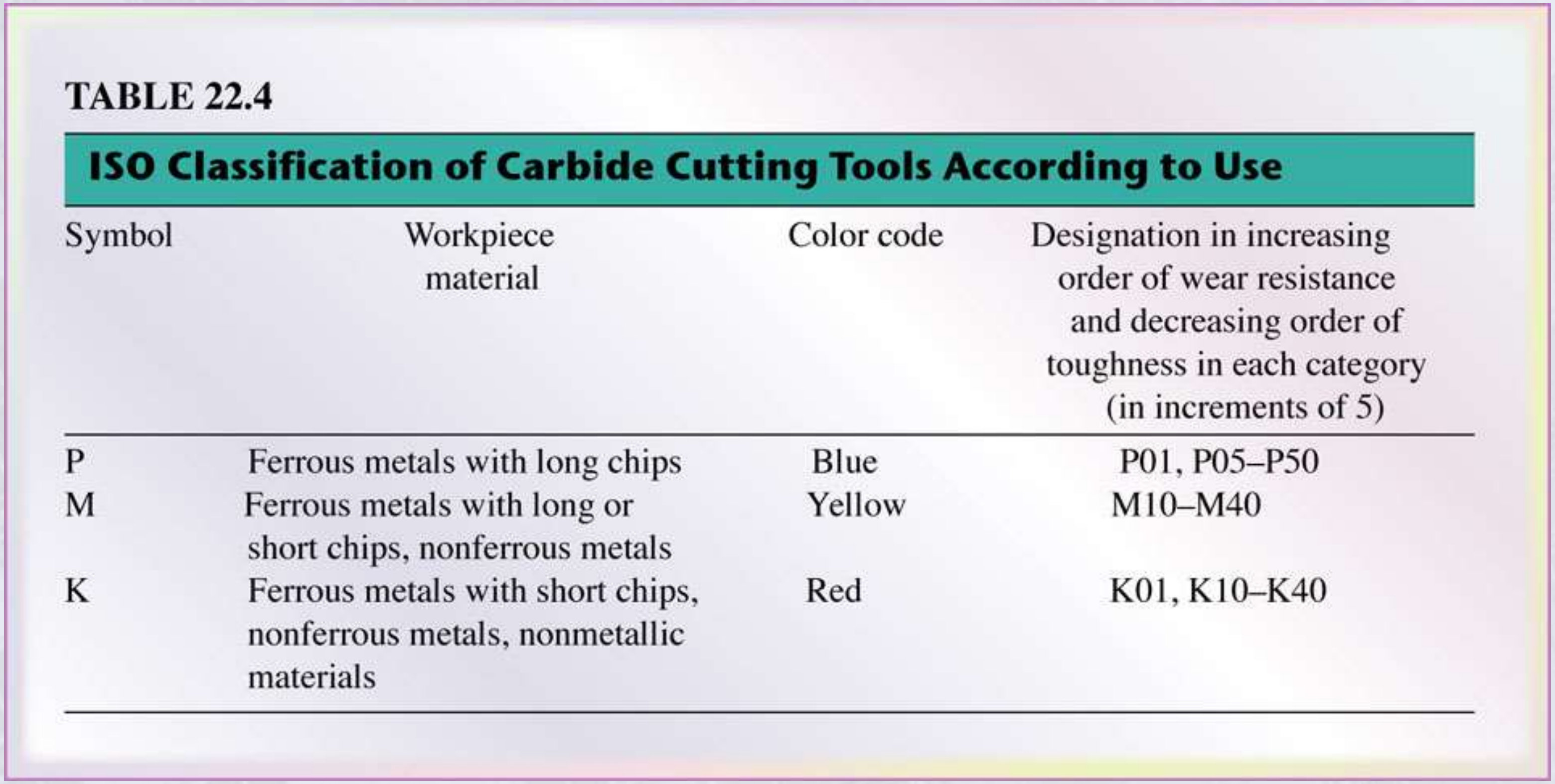

TABLE 22.4

ISO Classification of Carbide Cutting Tools According to Use

Symbol	Workpiece material	Color code	Designation in increasing order of wear resistance and decreasing order of toughness in each category (in increments of 5)
P	Ferrous metals with long chips	Blue	P01, P05–P50
M	Ferrous metals with long or short chips, nonferrous metals	Yellow	M10–M40
K	Ferrous metals with short chips, nonferrous metals, nonmetallic materials	Red	K01, K10–K40

Classification of Tungsten Carbides According to Machining Applications

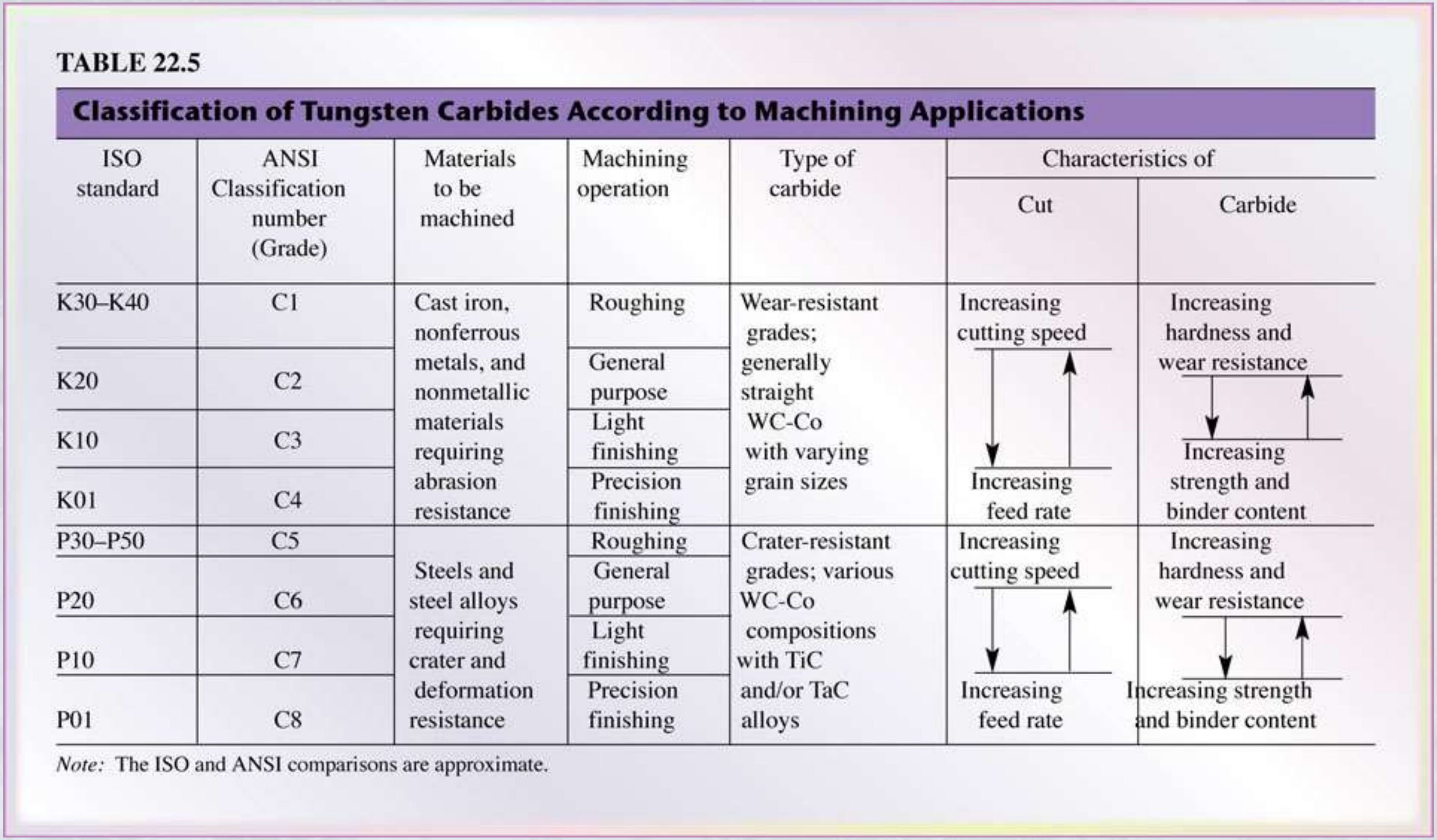

TABLE 22.5

Classification of Tungsten Carbides According to Machining Applications

ISO standard	ANSI Classification number (Grade)	Materials to be machined	Machining operation	Type of carbide	Characteristics of	
					Cut	Carbide
K30–K40	C1	Cast iron, nonferrous metals, and nonmetallic materials requiring abrasion resistance	Roughing	Wear-resistant grades; generally straight WC-Co with varying grain sizes	Increasing cutting speed	Increasing hardness and wear resistance
K20	C2		General purpose			
K10	C3		Light finishing			
K01	C4		Precision finishing		Increasing feed rate	Increasing strength and binder content
P30–P50	C5	Steels and steel alloys requiring crater and deformation resistance	Roughing	Crater-resistant grades; various WC-Co compositions with TiC and/or TaC alloys	Increasing cutting speed	Increasing hardness and wear resistance
P20	C6		General purpose			
P10	C7		Light finishing			
P01	C8		Precision finishing		Increasing feed rate	Increasing strength and binder content

Note: The ISO and ANSI comparisons are approximate.

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Relative Time Required to Machine with Various Cutting-Tool Materials

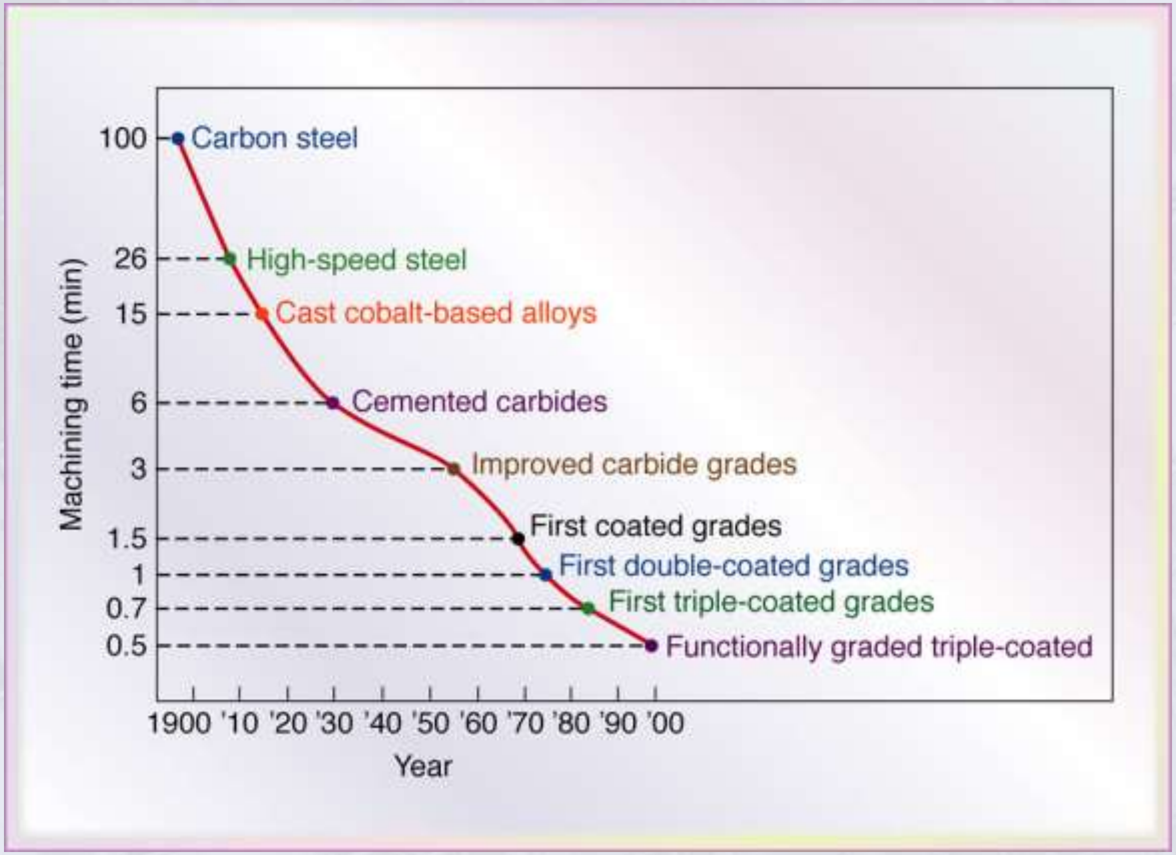

Figure 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced. Note that machining time has been reduced by two orders of magnitude with a hundred years. *Source*: Courtesy of Sandvik.

Typical Wear Patterns on High-Speed-Steel Uncoated and Titanium-Nitride Coated Tools

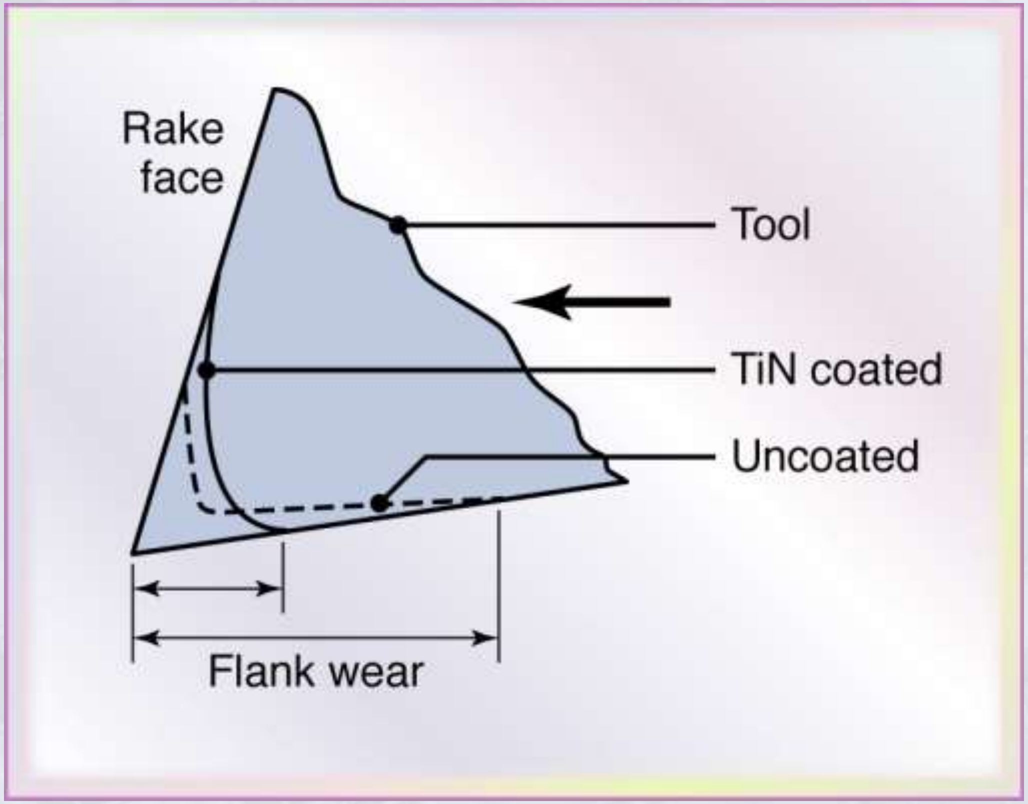

Figure 22.7 Schematic illustration of typical wear patterns of high-speed-steel uncoated and titanium-nitride coated tools. Note that flank wear is significantly lower for the coated tool.

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Multiphase Coatings on a Tungsten-Carbide Substrate

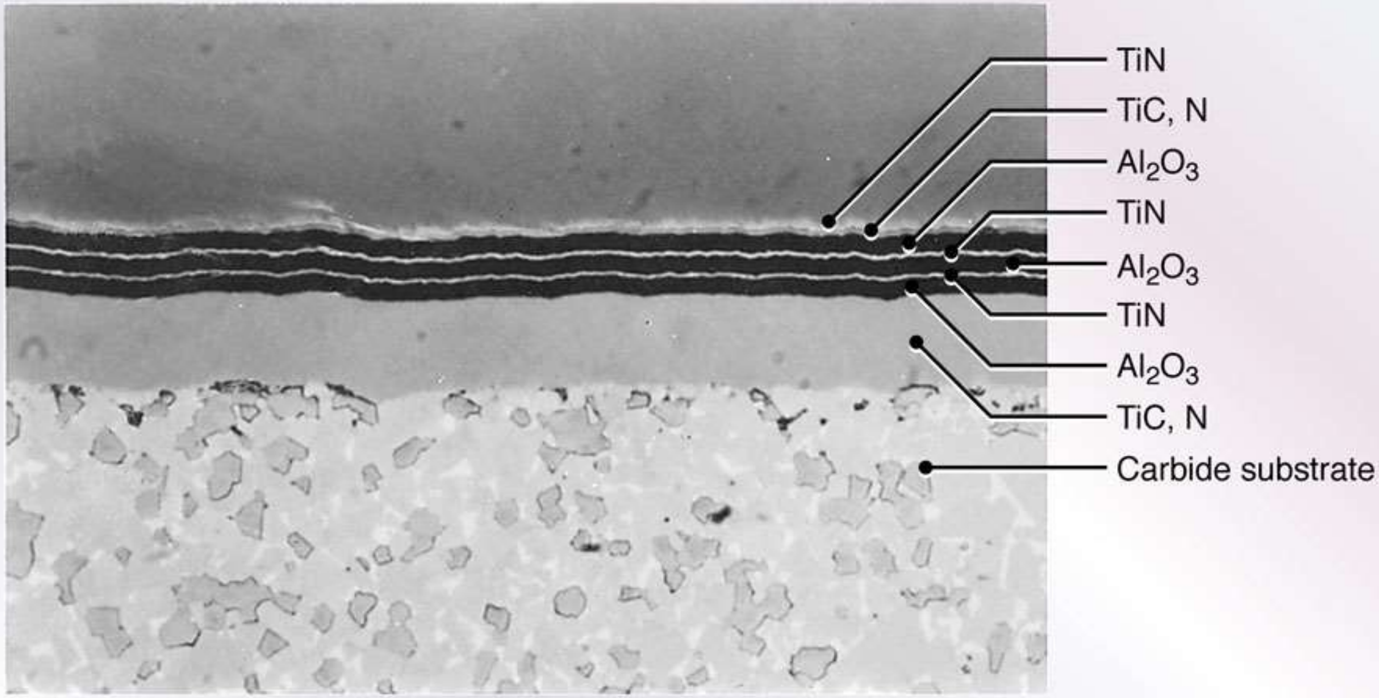

Figure 22.8 Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as thirteen layers of coatings have been made. Coating thicknesses are typically in the range of 2 to 10 μm. *Source*: Courtesy of Kennametal, Inc.

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Ranges of Mechanical Properties for Groups of Tool Materials

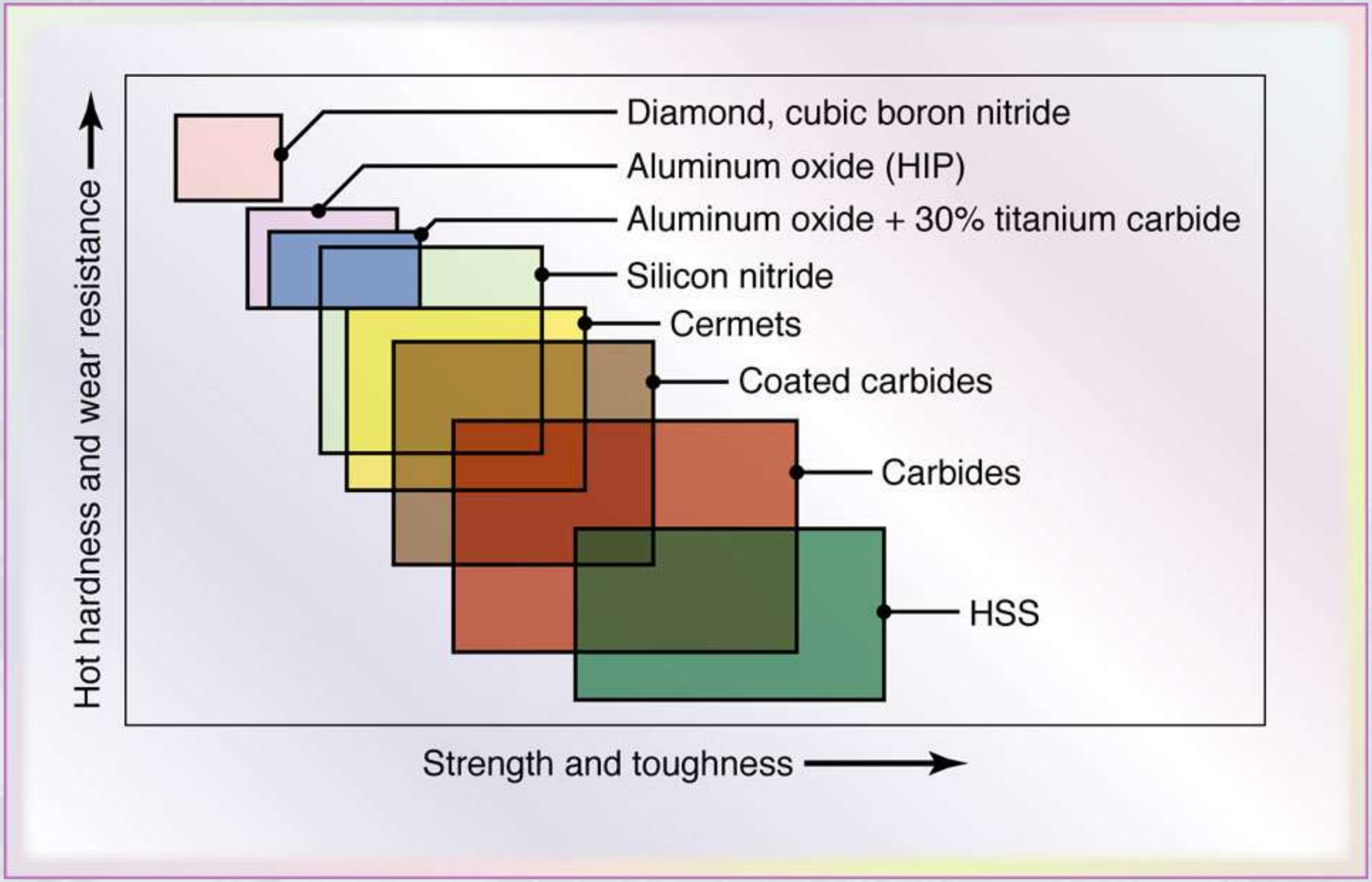

Figure 22.9 Ranges of mechanical properties for various groups of tool materials. See also Tables 22.1 through 22.5.

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Cubic Boron Nitride Inserts

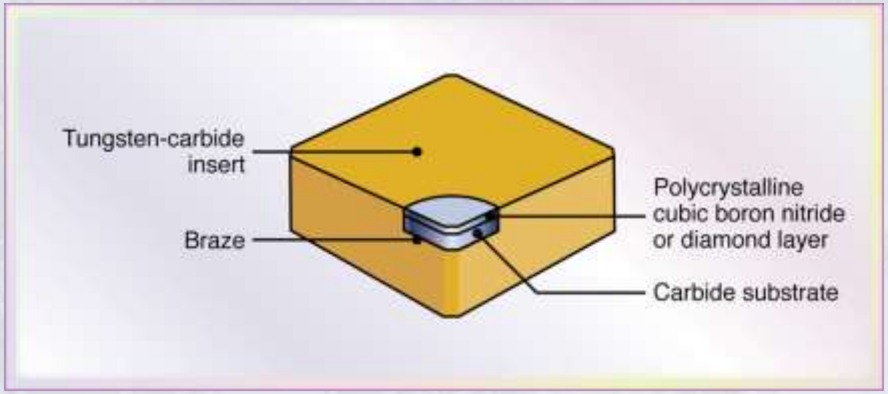

Figure 22.10 An insert of polycrystalline cubic boron nitride or a diamond layer on tungsten carbide.

Figure 22.11 Inserts with polycrystalline cubic boron nitride tips (top row), and solid-polycrystalline cBN inserts (bottom row). *Source*: Courtesy of Valenite.

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Proper Methods of Applying Cutting Fluids

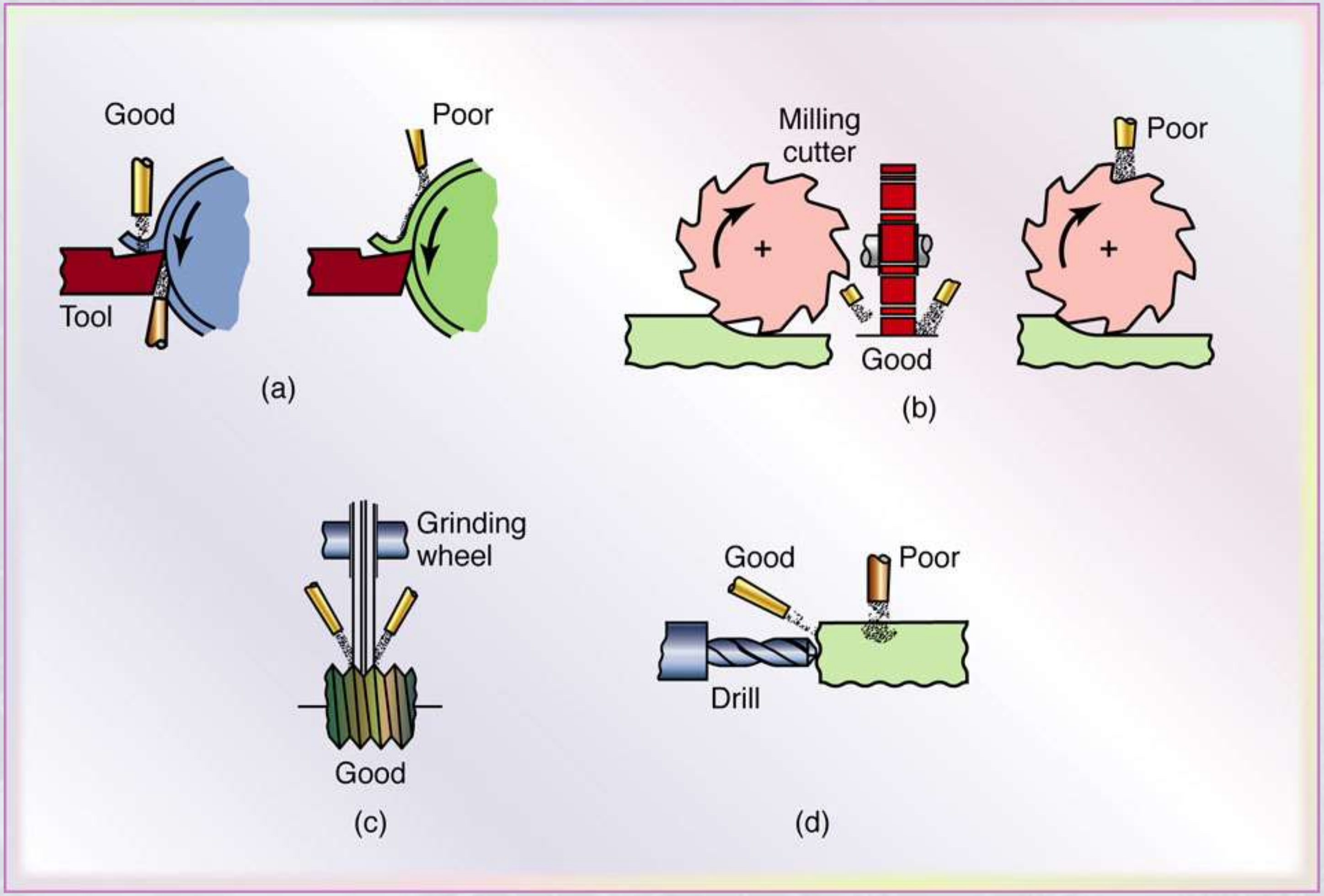

Figure 22.12 Schematic illustration of the proper methods of applying cutting fluids (flooding) in various machining operations: (a) turning, (b) milling, (c) thread grinding, and (d) drilling.

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