CUTTING-TOOL TECHNOLOGY

Cutting-Tool

- Machining operations are accomplished using cutting tools.
- The high forces and temperatures during machining create a very harsh environment for the tool.
- If cutting force becomes too high, the tool fractures.
- If cutting temperature becomes too high, the tool material softens and fails.
- If neither of these conditions causes the tool to fail, continual wear of the cutting edge ultimately leads to failure.
- Cutting tool technology has two principal aspects: tool material and tool geometry.
- The first is concerned with developing materials that can withstand the forces, temperatures, and wearing action in the machining process.
- The second deals with optimizing the geometry of the cutting tool for the tool material and for a given operation.

TOOL LIFE

- There are three possible modes by which a cutting tool can fail in machining:

  1. Fracture failure. This mode of failure occurs when the cutting force at the tool point becomes excessive, causing it to fail suddenly by brittle fracture.

  2. Temperature failure. This failure occurs when the cutting temperature is too high for the tool material, causing the material at the tool point to soften, which leads to plastic deformation and loss of the sharp edge.

  3. Gradual wear. Gradual wearing of the cutting edge causes loss of tool shape, reduction in cutting efficiency, an acceleration of wearing as the tool becomes heavily worn, and finally tool failure in a manner similar to a temperature failure.

TOOL WEAR

- Gradual wear occurs at two principal locations on a cutting tool: the top rake face and the flank.
- Accordingly, two main types of tool wear can be distinguished: crater wear and flank wear, illustrated in Figures

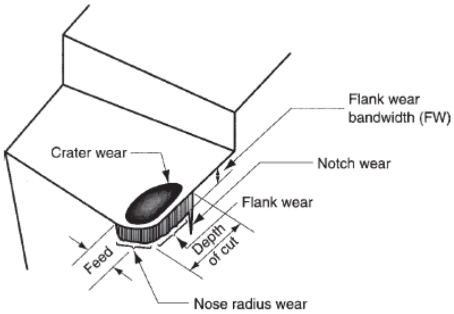
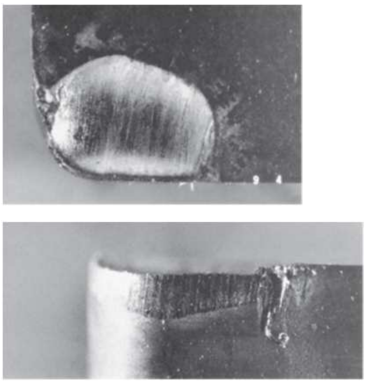


Diagram of worn cutting tool, showing the principal locations and types of wear that occur.



(a) Crater wear and (b) flank wear on a cemented carbide tool, as seen through a toolmaker’s microscope.

TOOL WEAR

- The mechanisms that cause wear at the tool–chip and tool–work interfaces in machining can be summarized as follows:
  - ➢ **Abrasion**. This is a mechanical wearing action caused by hard particles in the work material gouging and removing small portions of the tool. This abrasive action occurs in both flank wear and crater wear; it is a significant cause of flank wear.
  - ➢ **Adhesion**. When two metals are forced into contact under high pressure and temperature, adhesion or welding occur between them. These conditions are present between the chip and the rake face of the tool. As the chip flows across the tool, small particles of the tool are broken away from the surface, resulting in attrition of the surface.
  - ➢ **Diffusion**. This is a process in which an exchange of atoms takes place across a close contact boundary between two materials. In the case of tool wear, diffusion occurs at the tool–chip boundary, causing the tool surface to become depleted of the atoms responsible for its hardness. As this process continues, the tool surface becomes more susceptible to abrasion and adhesion. Diffusion is believed to be a principal mechanism of crater wear.

TOOL WEAR

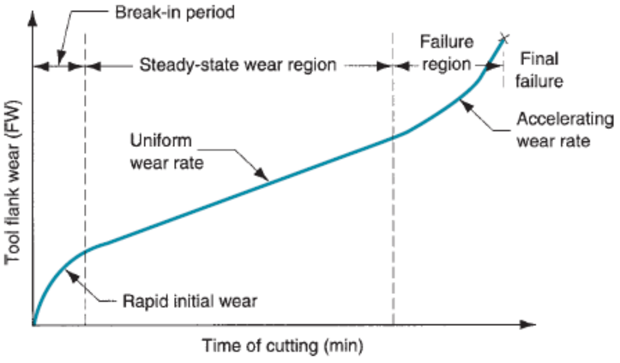
- ➢ **Chemical reactions**. The high temperatures and clean surfaces at the tool–chip interface in machining at high speeds can result in chemical reactions, in articular, oxidation, on the rake face of the tool. The oxidized layer, being softer than the parent tool material, is sheared away, exposing new material to sustain the reaction process.
- ➢ **Plastic deformation**. Another mechanism that contributes to tool wear is plastic deformation of the cutting edge. The cutting forces acting on the cutting edge at high temperature cause the edge to deform plastically, making it more vulnerable to abrasion of the tool surface. Plastic deformation contributes mainly to flank wear.

Most of these tool-wear mechanisms are accelerated at higher cutting speeds and temperatures. Diffusion and chemical reaction are especially sensitive to elevated temperature.

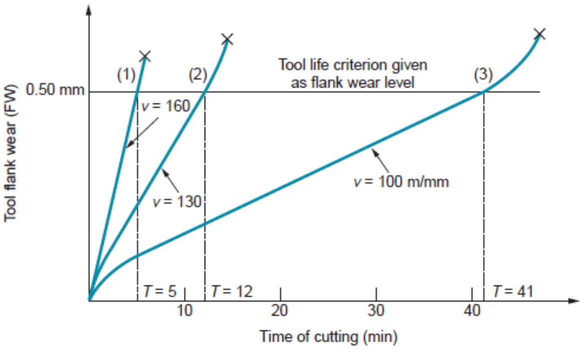
TOOL LIFE

- As cutting proceeds, the various wear mechanisms result in increasing levels of wear on the cutting tool.
- Three regions can usually be identified in the typical wear growth curve.
- The first is the break-in period, in which the sharp cutting edge wears rapidly at the beginning of its use. This first region occurs within the first few minutes of cutting.
- The break-in period is followed by wear that occurs at a fairly uniform rate. This is called the steady-state wear region. This region is pictured as a linear function of time, although there are deviations from the straight line in actual machining.
- Finally, wear reaches a level at which the wear rate begins to accelerate. This marks the beginning of the failure region, in which cutting temperatures are higher, and the general efficiency of the machining process is reduced.
- If allowed to continue, the tool finally fails by temperature failure.

TOOL LIFE



Tool wear as a function of cutting time. Flank wear (FW) is used here as the measure of tool wear. Crater wear follows a similar growth curve.



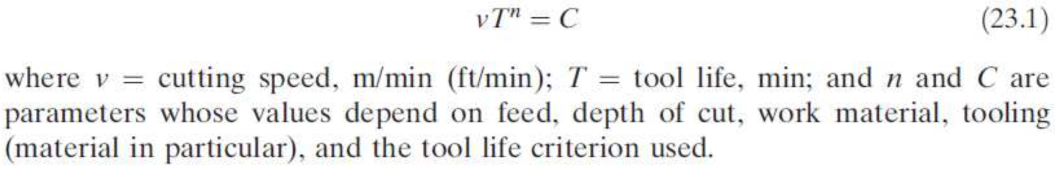
Effect of cutting speed on tool flank wear (FW) for three cutting speeds Hypothetical values of speed and tool life are shown for a tool life criterion of 0.50-mm flank wear.

TOOL LIFE

- The slope of the tool wear curve in the steady-state region is affected by work material and cutting conditions.
- Harder work materials cause the wear rate (slope of the tool wear curve) to increase.
- Increased speed, feed, and depth of cut have a similar effect, with speed being the most important of the three.
- As cutting speed is increased, wear rate increases so the same level of wear is reached in less time.
- **Tool life** is defined as the length of cutting time that the tool can be used. Operating the tool until final catastrophic failure is one way of defining tool life.
- However, in production, it is often a disadvantage to use the tool until this failure occurs because of difficulties in re-sharpening the tool and problems with work surface quality.
- As an alternative, a level of tool wear can be selected as a criterion of tool life, and the tool is replaced when wear reaches that level.
- A convenient tool life criterion is a certain flank wear value, such as 0.5 mm (0.020 in), illustrated as the horizontal line on the graph.

Taylor Tool Life Equation

- If the tool life values are plotted on a natural log–log graph of cutting speed versus tool life, the resulting relationship is a straight line.
- This relationship is expressed by Taylor tool life equation:

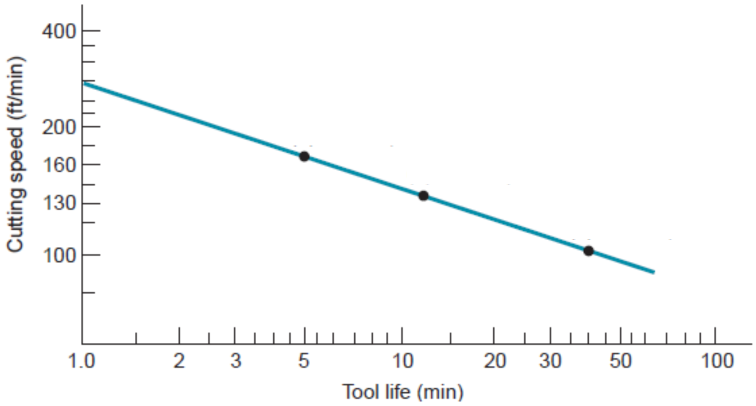


$$vT^n = C \qquad (23.1)$$

where v = cutting speed, m/min (ft/min); T = tool life, min; and n and C are parameters whose values depend on feed, depth of cut, work material, tooling (material in particular), and the tool life criterion used.

- The value of n is relative constant for a given tool material, whereas the value of C depends on tool material, work material, and cutting conditions

Taylor Tool Life Equation



Natural log–log plot of cutting speed vs. tool life.

- The problem with Eq. (23.1) is that the units on the right-hand side of the equation are not consistent with the units on the left-hand side.
- To make the units consistent, the equation should be expressed in the form.

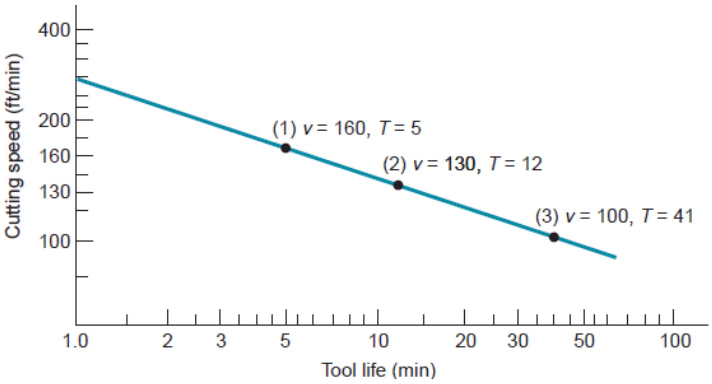
$$vT^n = C\left(T_{\text{ref}}{}^n\right) \tag{23.2}$$

where T_{ref} = a reference value for C. T_{ref} is simply 1 min when m/min (ft/min) and minutes are used for v and T, respectively.

The advantage of Eq. (23.2) is seen when it is desired to use the Taylor equation with units other than m/min (ft/min) and minutes—for example, if cutting speed were expressed as m/sec and tool life as sec. In this case, T_{ref} would be 60 sec and C would therefore be the same speed value as in Eq. (23.1), although converted to units of m/sec. The slope n would have the same numerical value as in Eq. (23.1).

Problem

- Determine the values of C and n in the plot, using two of the three points on the curve and solving simultaneous equations of the form of Eq. (23.1).



Tool Life Criteria in Production

- Tool Life Criteria in Production Although flank wear is the tool life criterion in our previous discussion of the Taylor equation, this criterion is not very practical in a factory environment because of the difficulties and time required to measure flank wear. Following are nine alternative tool life criteria that are more convenient to use in a production machining operation, some of which are admittedly subjective:
    1. Complete failure of the cutting edge (fracture failure, temperature failure, or wearing until complete breakdown of the tool has occurred). This criterion has disadvantages, as discussed earlier.
    2. Visual inspection of flank wear (or crater wear) by the machine operator (without a toolmaker's microscope). This criterion is limited by the operator's judgment and ability to observe tool wear with the naked eye.

Tool Life Criteria in Production

3. Fingernail test across the cutting edge by the operator to test for irregularities.
4. Changes in the sound emitting from the operation, as judged by the operator.
5. Chips become ribbony, stringy, and difficult to dispose of.
6. Degradation of the surface finish on the work.
7. Increased power consumption in the operation, as measured by a wattmeter connected to the machine tool.
8. Workpiece count. The operator is instructed to change the tool after a certain specified number of parts have been machined.
9. Cumulative cutting time. This is similar to the previous workpiece count, except that the length of time the tool has been cutting is monitored. This is possible on machine tools controlled by computer; the computer is programmed to keep data on the total cutting time for each tool.

TOOL MATERIALS

The three modes of tool failure allow us to identify three important properties required in a tool material:

- **Toughness**. To avoid fracture failure, the tool material must possess high toughness. Toughness is the capacity of a material to absorb energy without failing. It is usually characterized by a combination of strength and ductility in the material.
- **Hot hardness**. Hot hardness is the ability of a material to retain its hardness at high temperatures. This is required because of the high-temperature environment in which the tool operates.
- **Wear resistance**. Hardness is the single most important property needed to resist abrasive wear. All cutting-tool materials must be hard. However, wear resistance in metal cutting depends on more than just tool hardness, because of the other tool-wear mechanisms. Other characteristics affecting wear resistance include surface finish on the tool (a smoother surface means a lower coefficient of friction), chemistry of tool and work materials, and whether a cutting fluid is used.

TOOL MATERIALS

- Commercially, the most important tool materials are (1) high-speed steel and (2) cemented carbides, cermets, and coated carbides.
- These two categories account for more than 90% of the cutting tools used in machining operations.
- In addition to hardness as a function of temperature, it is useful to compare the materials in terms of the parameters *n* and *C* in the Taylor tool life equation.

TOOL MATERIALS

- (1) high-speed steel and its predecessors, plain carbon and low alloy steels; (2) cast cobalt alloys; (3) cemented carbides, cermets, and coated carbides; (4) ceramics; (5) synthetic diamond and cubic boron nitride.

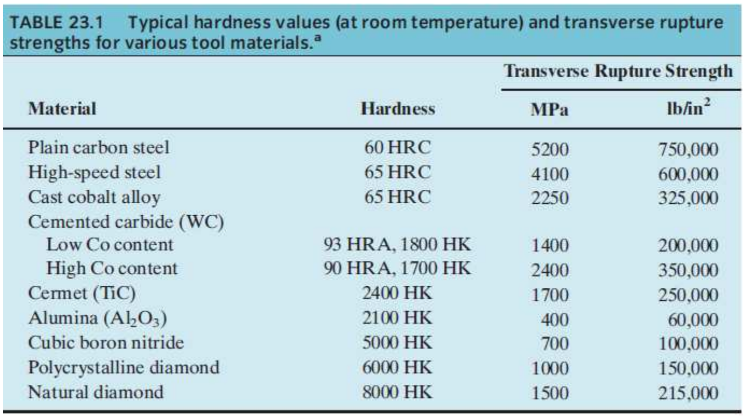
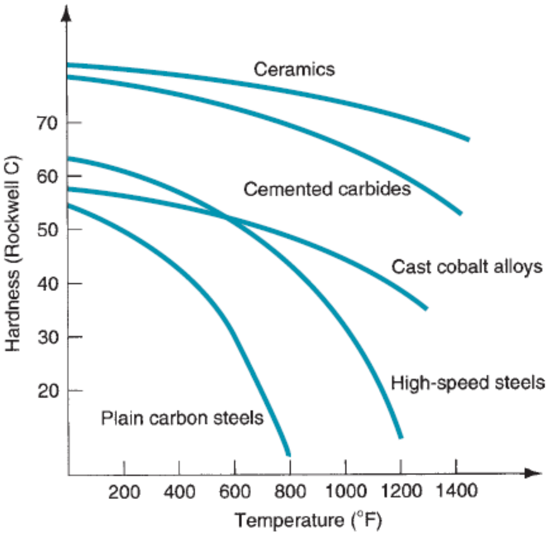


TABLE 23.1 Typical hardness values (at room temperature) and transverse rupture strengths for various tool materials.[a]

		Transverse Rupture Strength	
Material	**Hardness**	**MPa**	**lb/in^2**
Plain carbon steel	60 HRC	5200	750,000
High-speed steel	65 HRC	4100	600,000
Cast cobalt alloy	65 HRC	2250	325,000
Cemented carbide (WC)			
Low Co content	93 HRA, 1800 HK	1400	200,000
High Co content	90 HRA, 1700 HK	2400	350,000
Cermet (TiC)	2400 HK	1700	250,000
Alumina (Al_2O_3)	2100 HK	400	60,000
Cubic boron nitride	5000 HK	700	100,000
Polycrystalline diamond	6000 HK	1000	150,000
Natural diamond	8000 HK	1500	215,000

TOOL MATERIALS



Typical hot hardness relationships for selected tool materials. Plain carbon steel shows a rapid loss of hardness as temperature increases. Highspeed steel is substantially better, whereas cemented carbides and ceramics are significantly harder at elevated temperatures.

TOOL MATERIALS

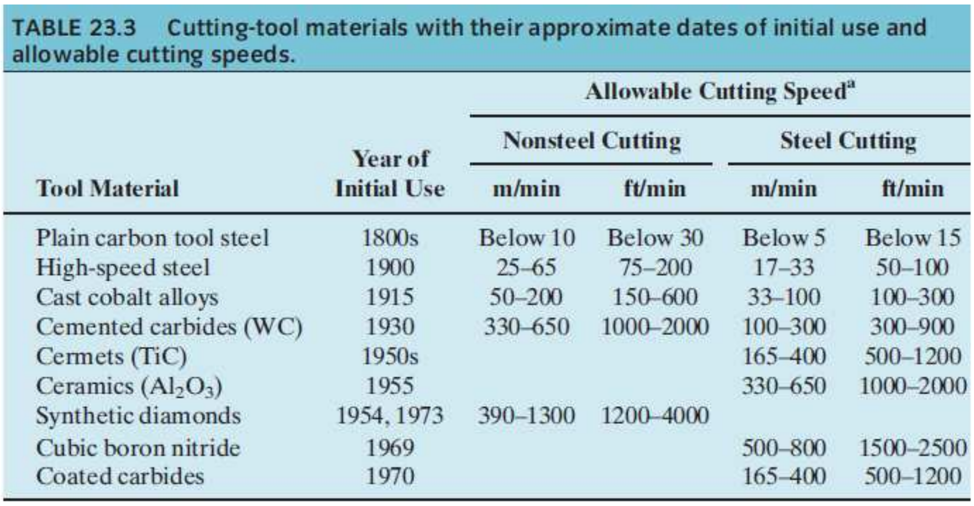


TABLE 23.3 Cutting-tool materials with their approximate dates of initial use and allowable cutting speeds.

Tool Material	Year of Initial Use	Allowable Cutting Speed[a] Nonsteel Cutting m/min	Nonsteel Cutting ft/min	Steel Cutting m/min	Steel Cutting ft/min
Plain carbon tool steel	1800s	Below 10	Below 30	Below 5	Below 15
High-speed steel	1900	25–65	75–200	17–33	50–100
Cast cobalt alloys	1915	50–200	150–600	33–100	100–300
Cemented carbides (WC)	1930	330–650	1000–2000	100–300	300–900
Cermets (TiC)	1950s			165–400	500–1200
Ceramics (Al_2O_3)	1955			330–650	1000–2000
Synthetic diamonds	1954, 1973	390–1300	1200–4000		
Cubic boron nitride	1969			500–800	1500–2500
Coated carbides	1970			165–400	500–1200

TOOL MATERIALS

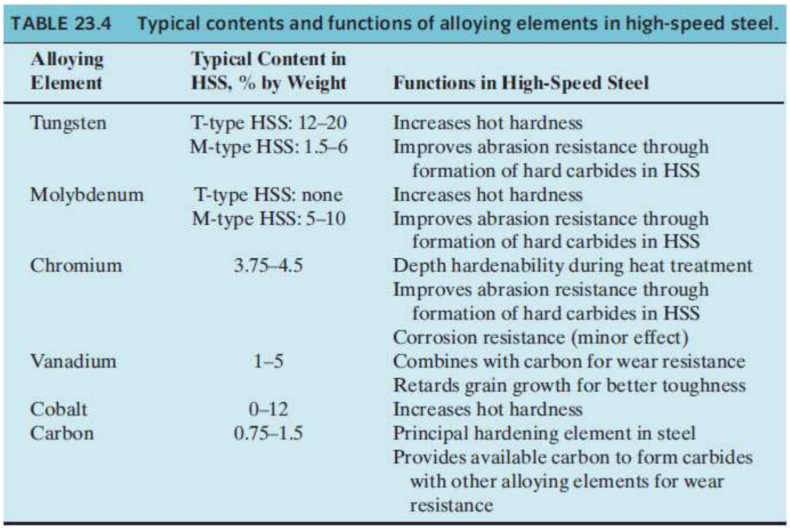


TABLE 23.4 Typical contents and functions of alloying elements in high-speed steel.

Alloying Element	Typical Content in HSS, % by Weight	Functions in High-Speed Steel
Tungsten	T-type HSS: 12–20 M-type HSS: 1.5–6	Increases hot hardness Improves abrasion resistance through formation of hard carbides in HSS
Molybdenum	T-type HSS: none M-type HSS: 5–10	Increases hot hardness Improves abrasion resistance through formation of hard carbides in HSS
Chromium	3.75–4.5	Depth hardenability during heat treatment Improves abrasion resistance through formation of hard carbides in HSS Corrosion resistance (minor effect)
Vanadium	1–5	Combines with carbon for wear resistance Retards grain growth for better toughness
Cobalt	0–12	Increases hot hardness
Carbon	0.75–1.5	Principal hardening element in steel Provides available carbon to form carbides with other alloying elements for wear resistance

PLAIN CARBON STEEL as TOOL MATERIAL

- The plain carbon steels used as cutting tools could be heat-treated to achieve relatively high hardness (Rockwell C 60), because of their fairly high carbon content.
- However, because of low alloying levels, they possess poor hot hardness, which renders them unusable in metal cutting except at speeds too low to be practical by today’s standards.
- Today, these steels are rarely used in industrial machining applications.

HIGH-SPEED STEEL AND ITS PREDECESSORS as TOOL MATERIAL

- **High-speed steel (HSS)** is a highly alloyed tool steel capable of maintaining hardness at elevated temperatures better than high carbon and low alloy steels. Its good hot hardness permits tools made of HSS to be used at higher cutting speeds. Compared with the other tool materials at the time of its development, it was truly deserving of its name ‘‘high speed.’’ A wide variety of high-speed steels are available, but they can be divided into two basic types: (1) tungsten-type, designated T-grades by the American Iron and Steel Institute (AISI); and (2) molybdenum-type, designated M-grades by AISI.
- **Tungsten-type HSS** contains tungsten (W) as its principal alloying ingredient. Additional alloying elements are chromium (Cr), and vanadium (V). One of the original and best known HSS grades is T1, or 18-4-1 high-speed steel, containing 18%W,4%Cr, and 1%V.
- **Molybdenum HSS** grades contain combinations of tungsten and molybdenum(Mo), plus the same additional alloying elements as in the T-grades. Cobalt (Co) is sometimes added to HSS to enhance hot hardness. Of course, high-speed steel contains carbon, the element common to all steels.
- Commercially, high-speed steel is one of the most important cutting-tool materials in use today, despite the fact that it was introduced more than a century ago

CAST COBALT ALLOYS as TOOL MATERIAL

- Cast cobalt alloy cutting tools consist of cobalt, around 40% to 50%; chromium, about 25% to 35%; and tungsten, usually 15% to 20%; with trace amounts of other elements.
- These tools are made into the desired shape by casting in graphite molds and then grinding to final size and cutting-edge sharpness.
- High hardness is achieved as cast, an advantage over HSS, which requiresheat treatment to achieve its hardness.
- Wear resistance of the cast cobalts is better than high-speed steel, but not as good as cemented carbide.
- Toughness of cast cobalt tools is better than carbides but not as good as HSS.

CEMENTED CARBIDES, CERMETS, AND COATED CARBIDES as TOOL MATERIAL

- Cermets are defined as composites of ceramic and metallic materials.
- Technically speaking, cemented carbides are included within this definition; however, cermets based on WC–Co, including WC–TiC–TaC–Co, are known as carbides (cemented carbides) in common usage.
- In cutting-tool terminology, the term cermet is applied to ceramic-metal composites containing TiC, TiN, and certain other ceramics not including WC.
- One of the advances in cutting-tool materials involves the application of a very thin coating to a WC–Co substrate.
- These tools are called coated carbides.
- Thus, there are important and closely related tool materials to discuss: (1) cemented carbides, (2) cermets, and (3) coated carbides.

CEMENTED CARBIDES, CERMETS, AND COATED CARBIDES as TOOL MATERIAL

- **Cemented Carbides** Cemented carbides (also called sintered carbides) are a class of hard tool material formulated from tungsten carbide (WC) using powder metallurgy techniques with cobalt (Co) as the binder.
- There may be other carbide compounds in the mixture, such as titanium carbide (TiC) and/or tantalum carbide (TaC), in addition to WC.
- Non steel-cutting grades refer to those cemented carbides that are suitable for machining aluminum, brass, copper, magnesium, titanium, and other nonferrous metals; anomalously, gray cast iron is included in this group of work materials.
- Steel-cutting grades are used for low carbon, stainless, and other alloy steels. For these carbide grades, titanium carbide and/or tantalum carbide is substituted for some of the tungsten carbide.

CEMENTED CARBIDES, CERMETS, AND COATED CARBIDES as TOOL MATERIAL

- **Cermets** Although cemented carbides are technically classified as cermet composites, the term cermet in cutting-tool technology is generally reserved for combinations of TiC, TiN, and titanium carbonitride (TiCN), with nickel and/or molybdenum as binders.
- Some of the cermet chemistries are more complex (e.g., ceramics such as Ta_xNb_yC and binders such as Mo_2C).
- However, cermets exclude metallic composites that are primarily based on WC–Co.
- Applications of cermets include high-speed finishing and semi finishing of steels, stainless steels, and cast irons.
- Higher speeds are generally allowed with these tools compared with steel-cutting carbide grades.
- **Coated Carbides** The development of coated carbides around 1970 represented a significant advance in cutting-tool technology.
- Coated carbides are a cemented carbide insert coated with one or more thin layers of wear-resistant material, such as titanium carbide, titanium nitride, and/or aluminum oxide (Al_2O_3).

CERAMICS as TOOL MATERIAL

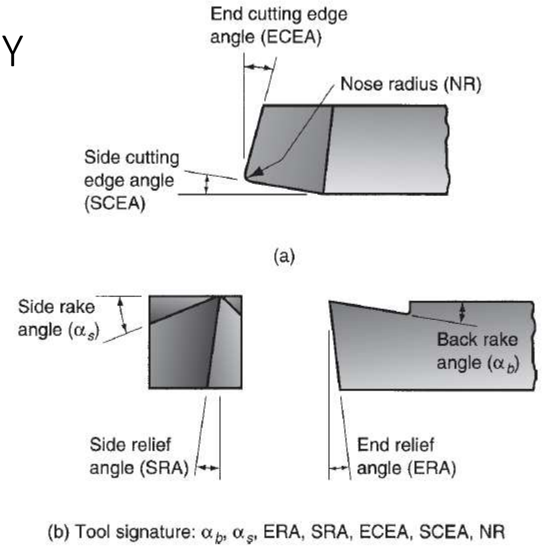
- Today’s ceramic cutting tools are composed primarily of fine-grained aluminum oxide (Al2O3), pressed and sintered at high pressures and temperatures with no binder into insert form.
- The aluminum oxide is usually very pure (99% is typical), although some manufacturers add other oxides (such as zirconium oxide) in small amounts.
- In producing ceramic tools, it is important to use a very fine grain size in the alumina powder, and to maximize density of the mix through high-pressure compaction to improve the material’s low toughness.
- Other commercially available ceramic cutting-tool materials include silicon nitride (SiN), sialon (silicon nitride and aluminum oxide, SiN–Al2O3), aluminum oxide and titanium carbide (Al2O3–TiC), and aluminum oxide reinforced with single crystal whiskers of silicon carbide.

SYNTHETIC DIAMONDS AND CUBIC BORON NITRIDE as TOOL MATERIAL

- **Sintered polycrystalline diamond (SPD)** is fabricated by sintering fine-grained diamond crystals under high temperatures and pressures into the desired shape.
- Little or no binder is used. The crystals have a random orientation and this adds considerable toughness to the SPD tools compared with single crystal diamonds.
- Next to diamond, cubic boron nitride is the hardest material known, and its fabrication into cutting tool inserts is basically the same as SPD; that is, coatings on WC–Co inserts.
- **Cubic boron nitride (symbolized cBN)** does not react chemically with iron and nickel as SPD does; therefore, the applications of cBN-coated tools are for machining steel and nickel-based alloys.
- Both SPD and cBN tools are expensive, as one might expect, and the applications must justify the additional tooling cost

SINGLE-POINT TOOL GEOMETRY

- In all, there are seven elements of tool geometry for a single-point tool.
- When specified in the following order, they are collectively called the tool geometry signature: back rake angle, side rake angle, end relief angle, side relief angle, end cutting edge angle, side cutting edge angle, and nose radius.
- For example, a single-point tool used in turning might have the following signature: 5, 5, 7, 7, 20, 15, 2/64 in.

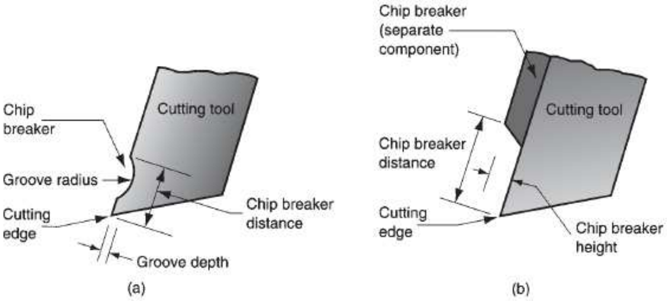


(b) Tool signature: α_b, α_s, ERA, SRA, ECEA, SCEA, NR

(a) Seven elements of single-point tool geometry, and (b) the tool signature convention that defines the seven elements.

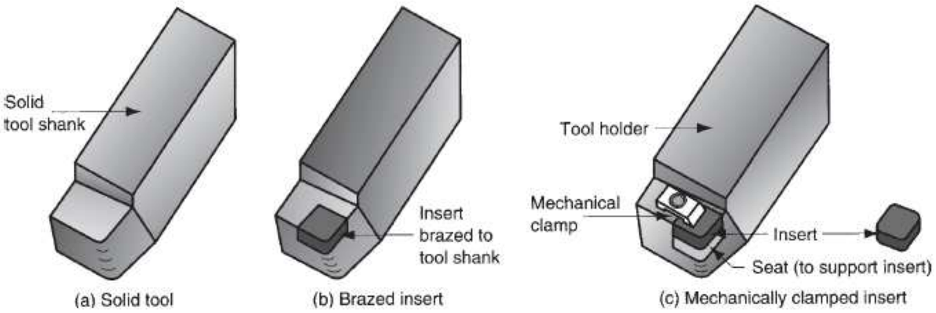
SINGLE-POINT TOOL GEOMETRY

- **Chip Breakers** Chip disposal is a problem that is often encountered in turning and other continuous operations.
- Long, stringy chips are often generated, especially when turning ductile materials at high speeds.
- These chips cause a hazard to the machine operator and the workpart finish, and they interfere with automatic operation of the turning process.
- Chip breakers are frequently used with single-point tools to force the chips to curl more tightly than they would naturally be inclined to do, thus causing them to fracture.

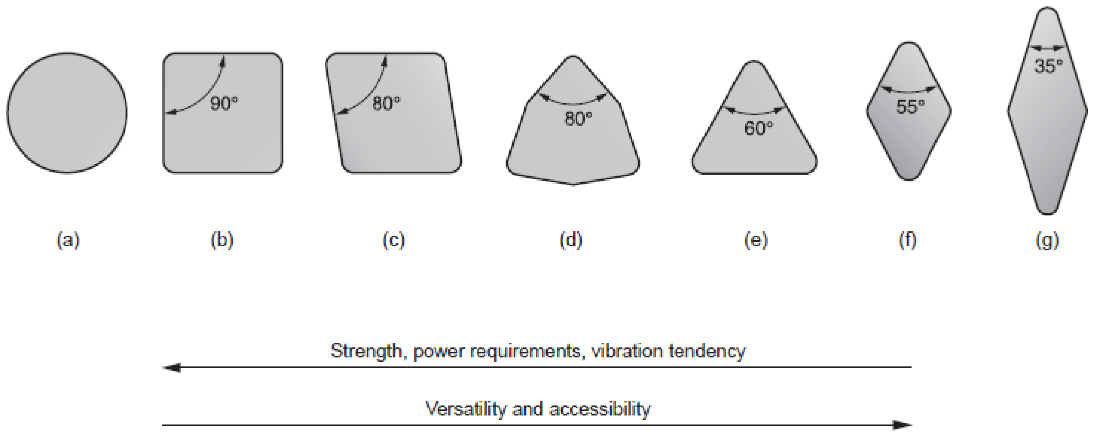


Two methods of chip breaking in single-point tools: (a) groove-type and (b) obstruction-type chip breakers.

The alternative ways of holding and presenting the cutting edge for a single-point tool



Three ways of holding and presenting the cutting edge for a single-point tool: (a) solid tool, typical of high spees steel; (b) brazed insert, one way of holding a cemented carbide insert; and (c) mechanically clamped insert, used for cemented carbides, ceramics, and other very hard tool materials.



Common insert shapes: (a) round, (b) square, (c) rhombus with two 80 point angles, (d) hexagon with three 80 point angles, (e) triangle (equilateral), (f) rhombus with two 55 point angles, (g) rhombus with two 35 point angles. Also shown are typical features of the geometry. Strength, power requirements, and tendency for vibration increase as we move to the left; whereas versatility and accessibility tend to be better with the geometries at the right.

CUTTING FLUIDS

- A cutting fluid is any liquid or gas that is applied directly to the machining operation to improve cutting performance.
- Cutting fluids address two main problems: (1) heat generation at the shear zone and friction zone, and (2) friction at the tool–chip and tool–work interfaces.
- In addition to removing heat and reducing friction, cutting fluids provide additional benefits, such as washing away chips (especially in grinding and milling), reducing the temperature of the workpart for easier handling, reducing cutting forces and power requirements, improving dimensional stability of the workpart, and improving surface finish.

Chemical Formulation of Cutting Fluids

There are four categories of cutting fluids according to chemical formulation: (1) cutting oils, (2) emulsified oils, (3) semichemical fluids, and (4) chemical fluids.

- **Cutting oils** are based on oil derived from petroleum, animal, marine, or vegetable origin. Mineral oils (petroleum based) are the principal type because of their abundance and generally desirable lubricating characteristics. To achieve maximum lubricity, several types of oils are often combined in the same fluid. Chemical additives are also mixed with the oils to increase lubricating qualities. These additives contain compounds of sulfur, chlorine, and phosphorus, and are designed to react chemically with the chip and tool surfaces to form solid films (extreme pressure lubrication) that help to avoid metal-to-metal contact between the two.
- **Emulsified oils** consist of oil droplets suspended in water. The fluid is made by blending oil (usually mineral oil) in water using an emulsifying agent to promote blending and stability of the emulsion. A typical ratio of water to oil is 30:1. Chemical additives based on sulfur, chlorine, and phosphorus are often used to promote extreme pressure lubrication. Because they contain both oil and water, the emulsified oils combine cooling and lubricating qualities in one cutting fluid.
- **Chemical fluids** are chemicals in a water solution rather than oils in emulsion. The dissolved chemicals include compounds of sulfur, chlorine, and phosphorus, plus wetting agents. The chemicals are intended to provide some degree of lubrication to the solution. Chemical fluids provide good coolant qualities but their lubricating qualities are less than the other cutting fluid types.
- **Semichemical fluids** have small amounts of emulsified oil added to increase the lubricating characteristics of the cutting fluid. In effect, they are a hybrid class between chemical fluids and emulsified oils.

REVIEW QUESTIONS

1. What are the two principal aspects of cutting-tool technology?
2. Name the three modes of tool failure in machining.
3. What are the two principal locations on a cutting tool where tool wear occurs?
4. Identify the mechanisms by which cutting tools wear during machining.
5. What is the physical interpretation of the parameter C in the Taylor tool life equation?
6. What are some of the tool life criteria used in production machining operations?
7. Identify three desirable properties of a cutting-tool material.
8. What are the principal alloying ingredients in high speed steel?
9. Identify some of the common compounds that form the thin coatings on the surface of coated carbide inserts.
10. Name the two main categories of cutting fluid according to function.
11. Name the four categories of cutting fluid according to chemistry.
12. Determine the values of C and n in the plot, using two of the three points on the curve and solving simultaneous equations of the form of Eq. (23.1).
13. Tool life tests in turning yield the following data: (1) when cutting speed is 100 m/min, tool life is 10 min; (2) when cutting speed is 75 m/min, tool life is 30 min. (a) Determine the n and C values in the Taylor tool life equation. Based on your equation, compute (b) the tool life for a speed of 110 m/min, and (c) the speed corresponding to a tool life of 15 min.