Introduction to Manufacturing, AGE-1320

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Fundamentals of Machining part 2 (Chapter 22): Cutting-Tool Materials and Cutting Fluids

Manufacturing Engineering Technology in SI Units, 6th Edition

Chapter Outline

1. Introduction
2. Types of Chips Produced in Metal Cutting
3. Tool Life: Wear and Failure
4. Cutting Tool Materials
5. Cutting Fluids

4. Cutting Tool Materials

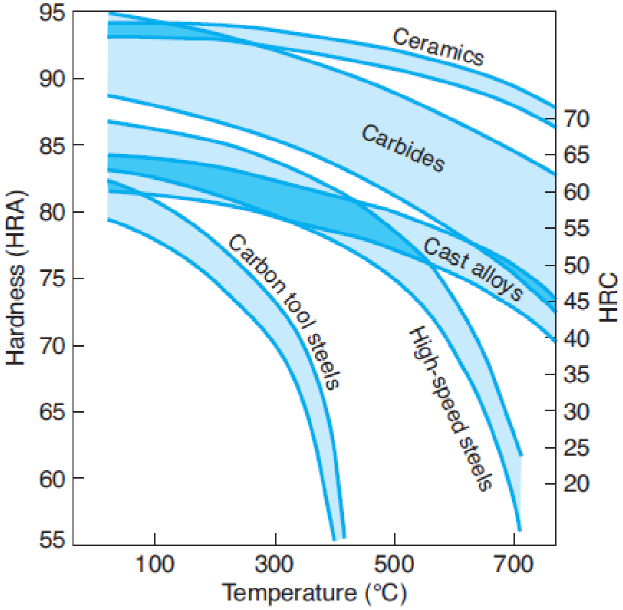
Cutting-Tool Materials

- Cutting tool is subjected to –as mentioned before– :

1. High temperatures,
2. High contact stresses
3. Rubbing along the tool–chip interface and along the machined surface

- Cutting-tool material must possess:

1. **Hot hardness** (see right)
   - compare ceramics vs. carbon steels
2. **Toughness** and **impact strength**
3. **Thermal shock resistance**
4. **Wear resistance**
5. **Chemical stability** and **inertness** (e.g. no adhesion)



Cutting-Tool Materials

- Tool materials -see next 3 slides- may not have all of the desired properties for a particular machining operation:
  - **Hardness, strength**: ensure good mechanical properties of workpiece material
  - **Impact strength**: important for interrupted cuts (e.g. milling)
  - **Melting temperature**: important for tool material due to high temp. generated in cutting zone
  - **Physical properties** (e.g.): ensure tool resistance to thermal fatigue, shock thermal conductivity, coefficient of thermal expansion
  - Compare (for example) in slide 6,
    - High speed steels: high toughness, but low hot hardness
    - Ceramics: high resistance to temp. & wear, but brittle and can chip
    - Diamonds: hardest material, but most expensive

Cutting-Tool Materials

General Characteristics of Tool Materials

Property	High-speed steels	Cast-cobalt alloys	Carbides WC	Carbides TiC	Ceramics	Cubic boron nitride	Single-crystal diamond*
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
Transverse rupture strength, MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
Impact strength, J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	<0.1	<0.5	<0.2
Modulus of elasticity, GPa	200	—	520–690	310–450	310–410	850	820–1050
Density, kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
Volume of hard phase, %	7–15	10–20	70–90	—	100	95	95
Melting or decomposition temperature, °C	1300	—	1400	1400	2000	1300	700
Thermal conductivity, W/m K	30–50	—	42–125	17	29	13	500–2000
Coefficient of thermal expansion, $\times 10^{-6}/°C$	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 for impact strength, which is higher.

Cutting-Tool Materials

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 single-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.

Cutting-Tool Materials

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 roughing 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, 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 thermomechanical 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.

Cutting-Tool Materials

- Tool Materials (also used for dies and molds in casting, forming, and shaping metallic and non-metallic materials):

1. High-speed steels
2. Cast-cobalt alloys
3. Carbides
4. Coated tools
5. Alumina-based ceramics
6. Cubic boron nitride
7. Diamond
8. Whisker-reinforced materials and nanomaterials

- Tools materials are discussed here in terms of:
  - characteristics, applications

Cutting-Tool Materials:
1. High-speed Steels

- High-speed steel (HSS) tools were developed to machine at higher speeds than was previously possible
  - compared to carbon steels (low hot hardness ⇒ low speeds)
- Can be hardened to various depths, have good wear resistance and are inexpensive
- Biggest drawback: low cutting speed *(V)* vs carbide tools

Cutting-Tool Materials:
2. Cast-cobalt Alloys

- Cast-cobalt alloys have,
  - high hardness
  - good wear resistance
  - maintain hardness at elevated temperatures (hot hardness)
- Drawbacks
  - not as tough as HSS
  - sensitive to impact forces
- Applications: used as *Stellite* tools:
  - removing large material
    (little concern for surface finish)

Cast Alloy Lathe Tools

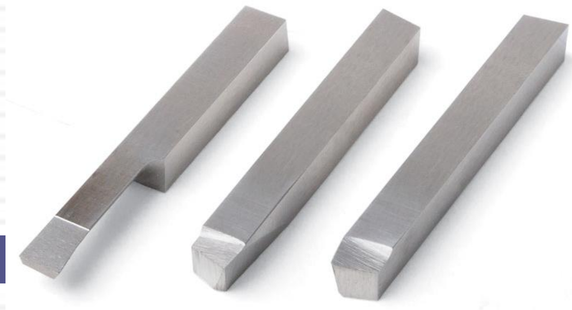
Cutting-Tool Materials:
3. Carbides

- AKA *cemented/sintered carbides* (since 1930's)
- Characteristics of carbides:

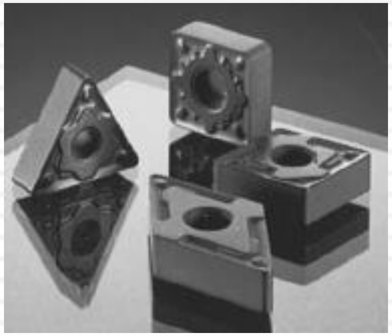
1. High hardness over a wide range of temperatures (&*V*)
2. Versatile
3. Cost-effective tool & die materials for many applications

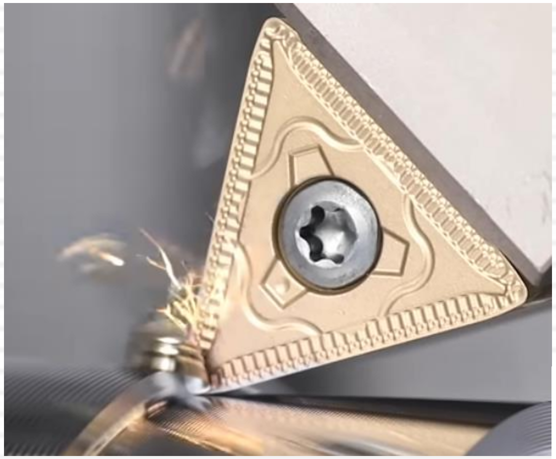
- 2 groups used in machining (AKA uncoated carbides)
  - Tungsten Carbide (WC): sintered into desired "insert" shapes; used for cutting steels, abrasive nonferrous materials
  - Titanium Carbide: used for machining hard materials

Cutting-Tool Materials:
3. Carbides: Inserts

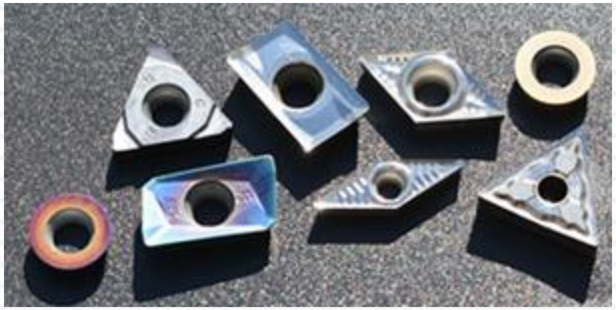


- High-speed steel tools (i.e. traditional tools):
  - 1-piece; shaped for applications: drill bits, milling, gear cutters
  - When cutting edge wears ⇒ tool must be replaced and sharpened, which is a time-consuming and inefficient process
- *Inserts*: individual cutting tools with several cutting points
  - e.g. Square insert: 8 cutting points (how?)
  - Triangular insert: 6 cutting points



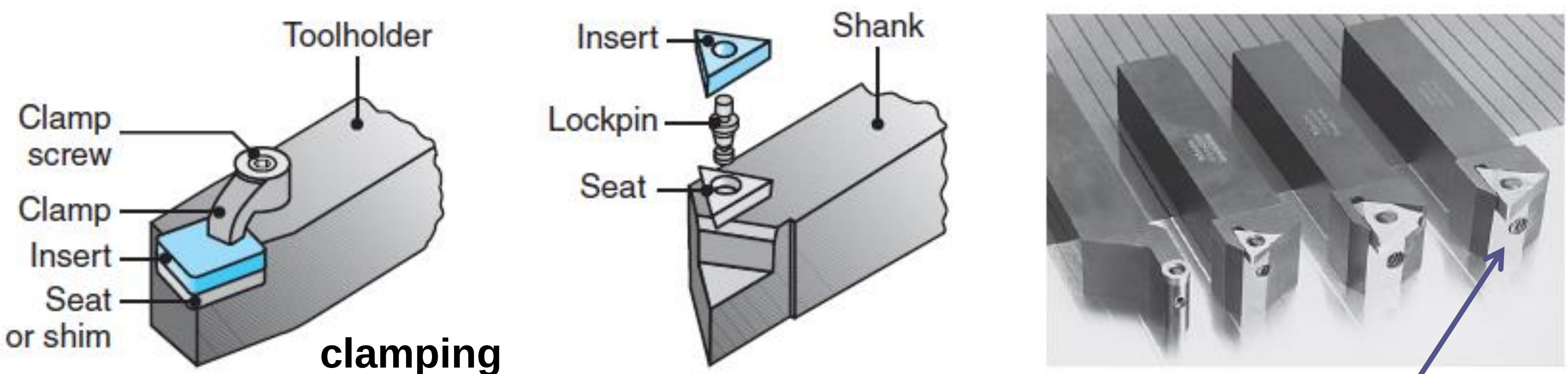


Typical carbide inserts with various shapes and chip-breaker features;
note the complex chip breaking features on inserts



Cutting-Tool Materials: 3. Carbides: Inserts

- Various locking mechanisms for inserts are used (below)
- Clamping is the preferred method of securing an insert
  - A particular edge is first used, then when edge is worn:
  - insert is **indexed** (rotated in its holder) to make another cutting point available



clamping (a)

wing lockpins (b)

(c) **Inserts mounted with threadless lockpins (sidescrews)**

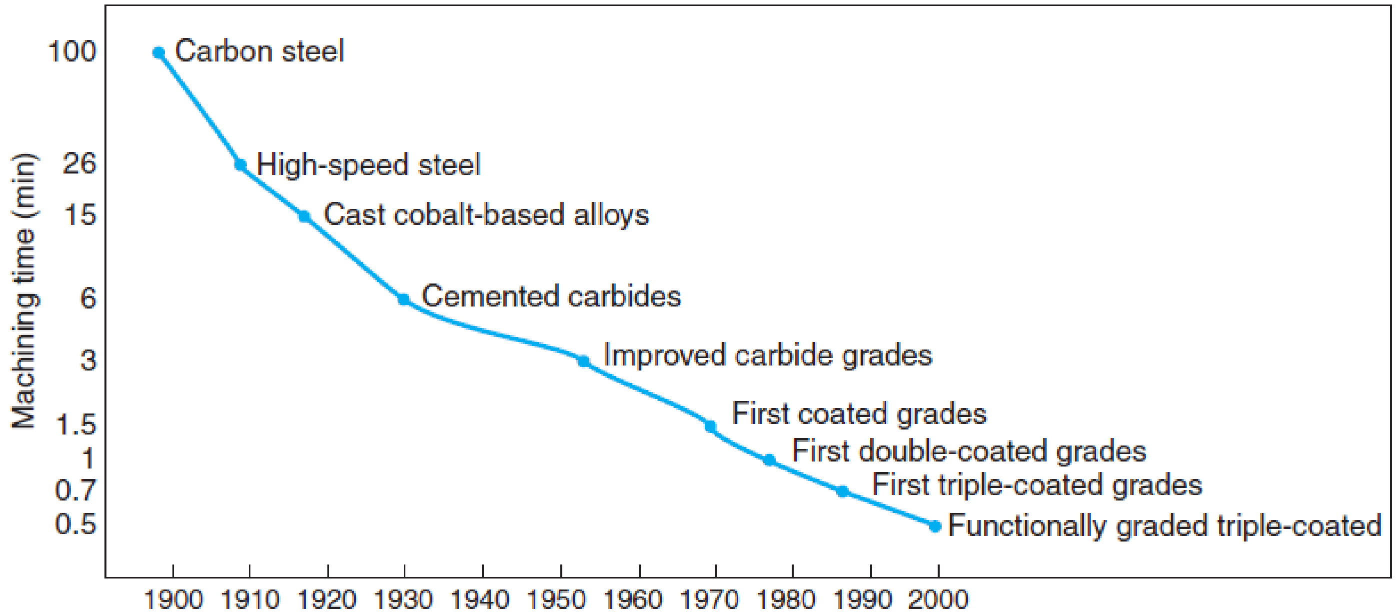
Cutting-Tool Materials:
4. Coated Tools

- New alloys and engineered materials
  - developed to have high strength and toughness (since 1960's)
  - problem: abrasive, chemically reactive with tool materials
  - difficulty in machining these materials ⇒ rise of coated tools
- Coatings have unique properties:

1. Lower friction
2. Higher adhesion (substrate)
3. Higher resistance to wear and cracking
4. Acting as a diffusion barrier
5. Higher hot hardness and impact resistance

Cutting-Tool Materials:
4. Coated Tools

- Coated tools:
  - tools lives up to 10X > uncoated tools
  - ⇒ allows higher *V* ⇒ reduced operation time & production costs
  - machining time dropped by < 100 times since 1900 (see ↓)
  - used now in 40-80% of all machining (esp. turning, milling, drilling)

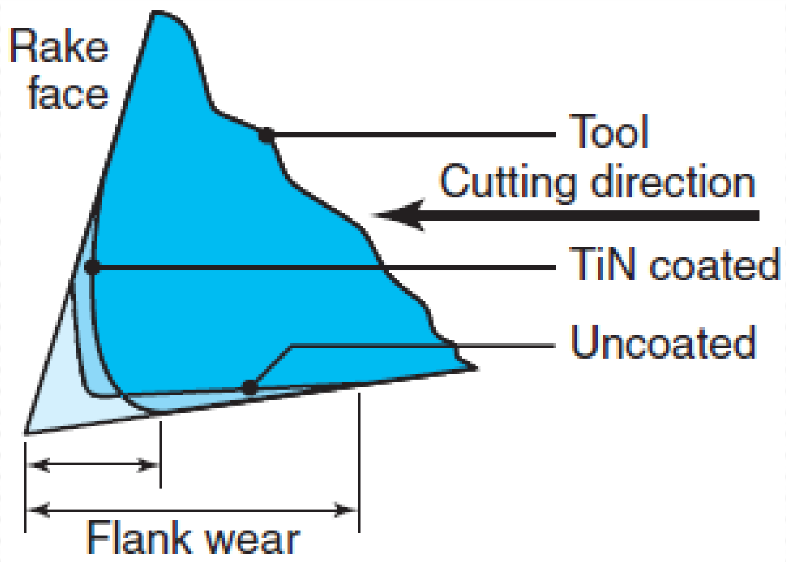


Cutting-Tool Materials:
4. Coated Tools: Coating Materials

- Common coating materials are:

1. Titanium nitride (TiN) – used with HSS/carbide tools
2. Titanium carbide (TiC) – used for abrasive materials
3. Titanium carbonitride (TiCN)
4. Aluminum oxide (Al_2O_3) aka alumina (ceramic) - resists flank and crater wear

- Coatings usually have sizes: 2-15 μm



Cutting-Tool Materials:
4. Coated Tools: Coating Materials

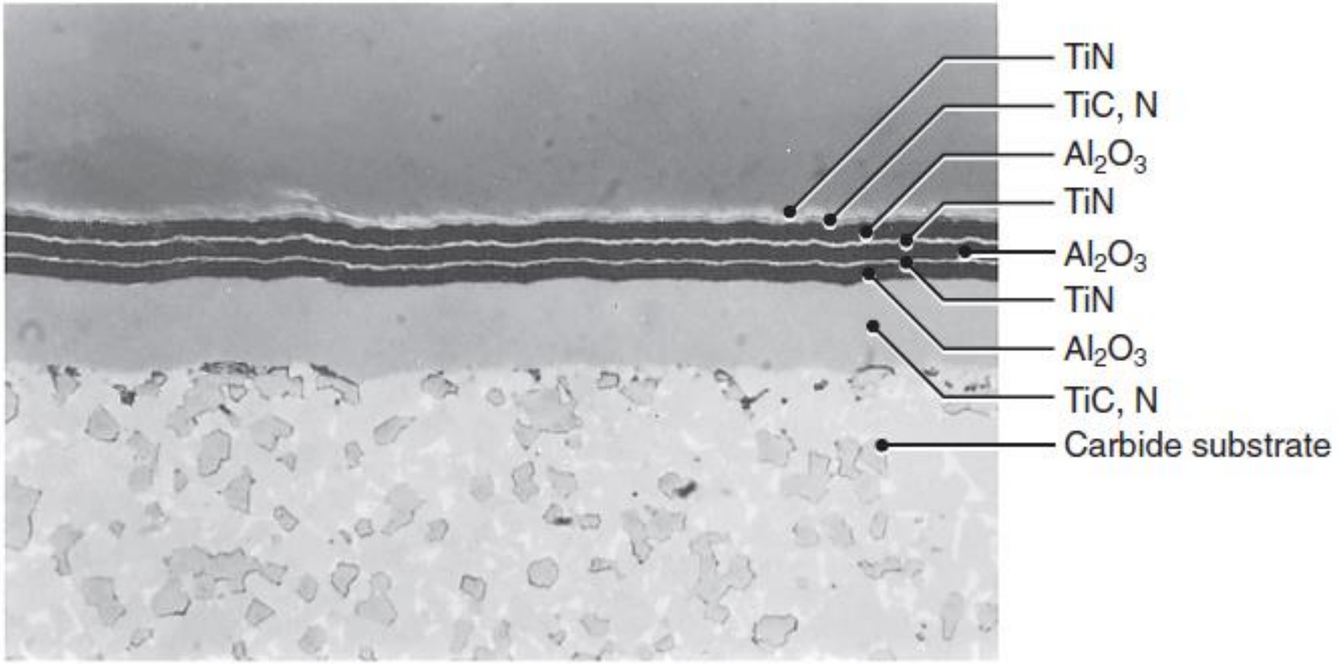
Alternating Multiphase Coatings

- Size of each coating layer: 2-10 μm
- Note, thinner coating ⇒ grain size ↓ ⇒ hardness ↑
- Inserts can have as many as 13 alternating layers

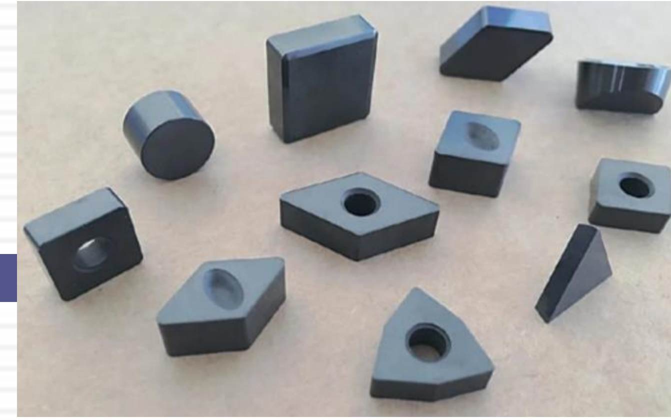
TiN: low friction

Al_2O_3: therm. stability

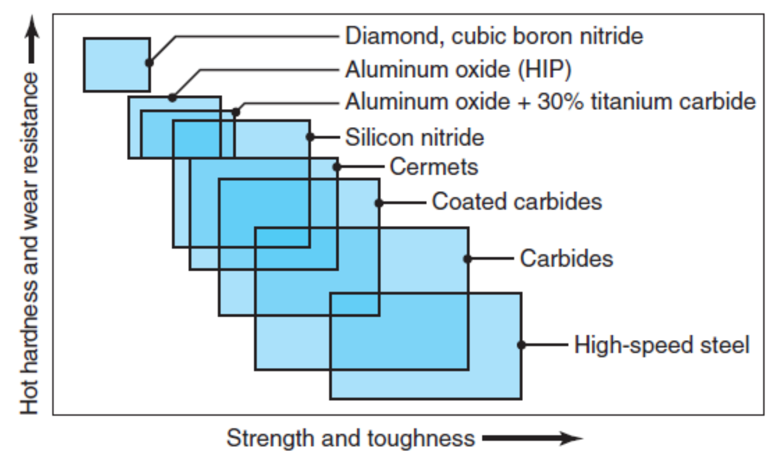
TiC,N: resists flank + crater wear



Cutting-Tool Materials:
5. Ceramics

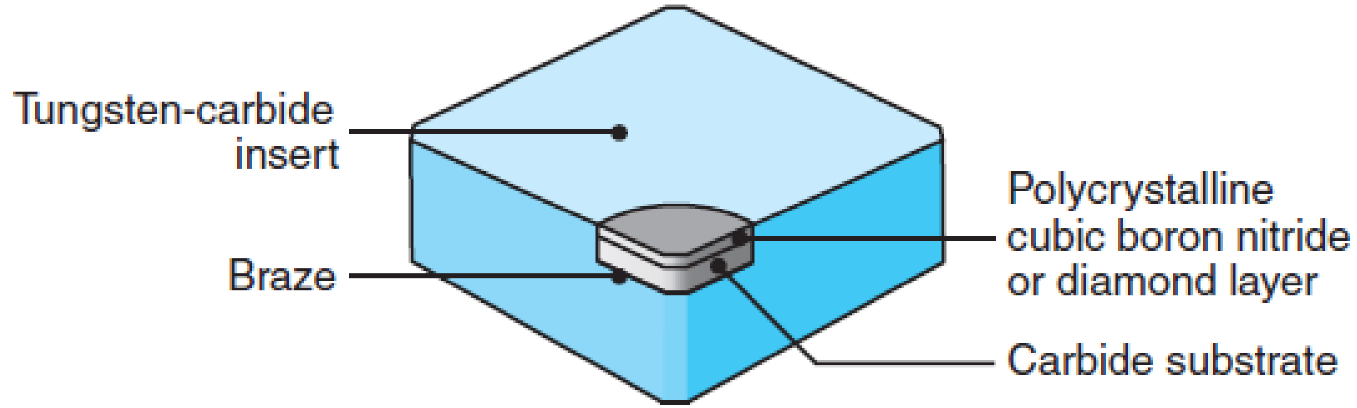


- **Ceramic** tool materials
  - consist of fine-grained and high-purity **aluminum oxide**
  - ceramic inserts: used in high-speed cutting (e.g. turning)
- *Alumina-based ceramic* tools
  - high abrasion resistance and hot hardness (see below)
- *Cermets* (***cer***amic particles in a ***met***allic matrix)
  - expensive; used for high-speed finishing cuts
- *Silicon-nitride (SiN) based ceramic tools*
  - high toughness and hot hardness



Cutting-Tool Materials: 6. Cubic Boron Nitride

- *Cubic boron nitride (cBN):* hardest material after diamond
  - Carbide (substrate) provides shock resistance
  - cBN layer provides v. high wear resistance & cutting-edge strength
- Suitable for cutting hardened ferrous and high-temp alloys, and for high-speed machining
- But: brittle, so machine must be stiff to resist vibrations



Cutting-Tool Materials: 7. Diamond

- Diamond: hardest of all known substances
- Properties:
  - low friction, high wear resistance
  - ability to maintain a sharp cutting edge (resharpen often)
  - result in good surface finish (light, uninterrupted finishing cuts)
  - used with soft nonferrous alloys, abrasive materials
- *Synthetic* or industrial *diamonds* are used since natural diamond has flaws and performance can be unpredictable

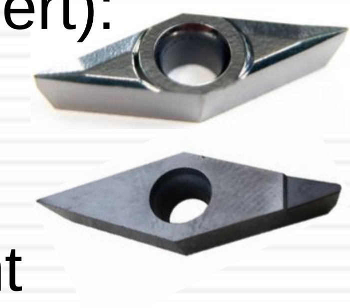
top row: Inserts with polycrystalline cBN tips

bottom row: Solid polycrystalline cBN inserts

Note: these are similar to diamond tools

Cutting-Tool Materials: Tool Costs and Reconditioning of Tools

- *Tool costs* depend on: tool material, size, shape, chip-breaker features and quality; e.g. (12.5-*mm* insert):
  - uncoated carbide: $5-10 (cheapest)
  - diamond-tipped: $90-125 (most expensive)



- Cost of individual insert is relatively insignificant
  - tooling comprises only 2-4% of all machining costs
  - reason: single tool can be indexed and recycled
  - e.g. square insert with 1 edge lasting 30-60 min will last: ?*
- Cutting tools can be **reconditioned** by resharpening
  - carried out manually, or cutter grinders, or comp.-controlled
- Reconditioning of coated tools also done by recoating
  - must make sure dimensions are same as original tool

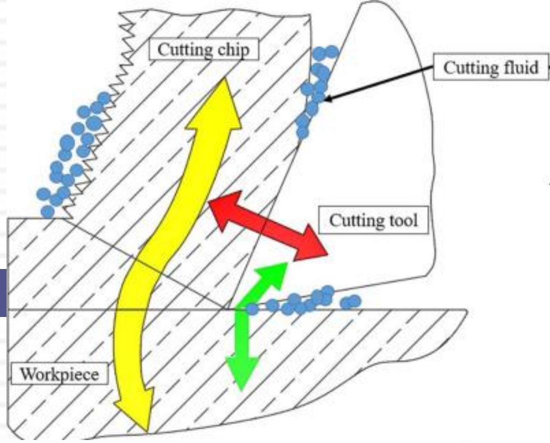
5. Cutting Fluids

Cutting Fluids

- *Cutting fluids* used to:
1. Reduce friction & wear (⇒ improve tool life, surface finish)
2. Cool the cutting zone (⇒ improve tool life, ↓ temperature)
3. Reduce forces and energy consumption
4. Flush chips from cutting zone (important in drilling)
5. Protect machined surface from environmental corrosion

- Cutting fluid used as (depending on machining operation):
  - **coolant**, or **lubricant**, **or** both
  - e.g. water: excellent coolant (i.e. temp ↓); but not effective lubricant (i.e. no ↓ in friction); may also cause oxidation (rust)
- Effectiveness of cutting fluids depends on:
  - machining operation, tool & workpiece materials, cutting speed

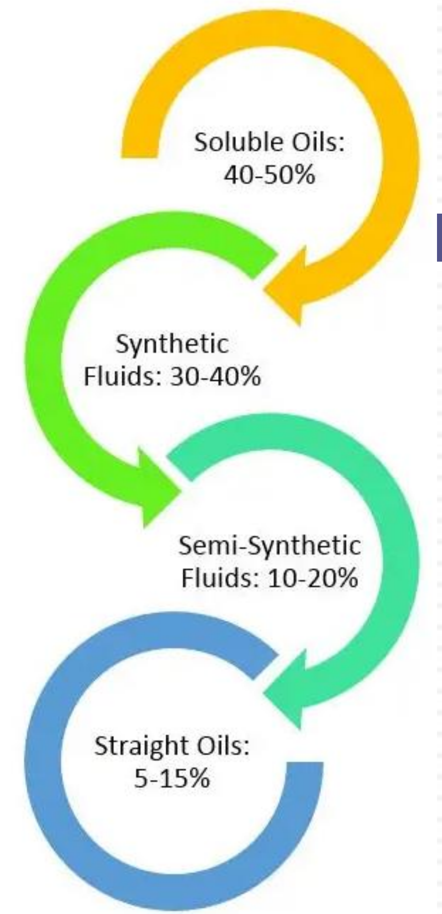
Cutting Fluids



Cutting-fluid Action

- Cutting fluids move to tool-chip interface by
  - seeping (i.e. slow penetration) from sides of the chip
  - capillary action in the unevenness in the interface
- Cutting fluids should thus have
  - small molecular size
  - appropriate "wetting" (high surface tension)
  - e.g. using emulsions, low-weight oils suspended in water
- Discontinuous cutting operations:
  - have easier mechanisms for lubricant application
  - but the tools are more susceptible to thermal shock

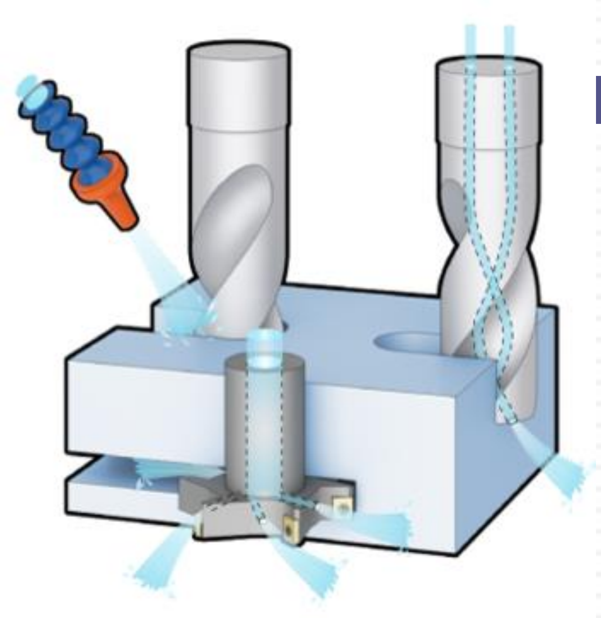
Cutting Fluids



Types of Cutting Fluids (4 general types)

1. **Oils** (AKA *straight oils*)
   - mineral, animal, vegetable
2. **Emulsions** (AKA *soluble oils*)
   - mixture of oil and water and additives
   - water: acts as coolant;
     oils: reduces oxidation caused by water
3. **Semisynthetics**
   - chemical emulsions + little water-diluted mineral oil + additives
4. **Synthetics**
   - chemicals with additives, water-diluted, with no oil

Cutting Fluids



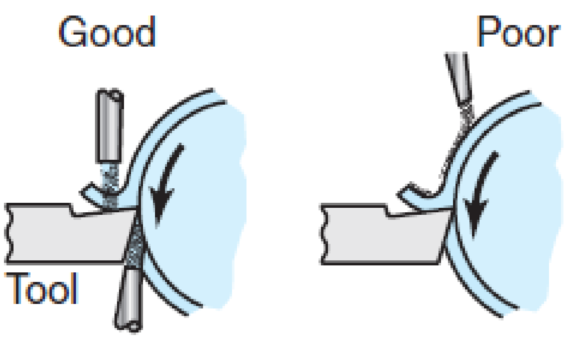
Methods of Cutting-fluid Application

- 4 basic methods:

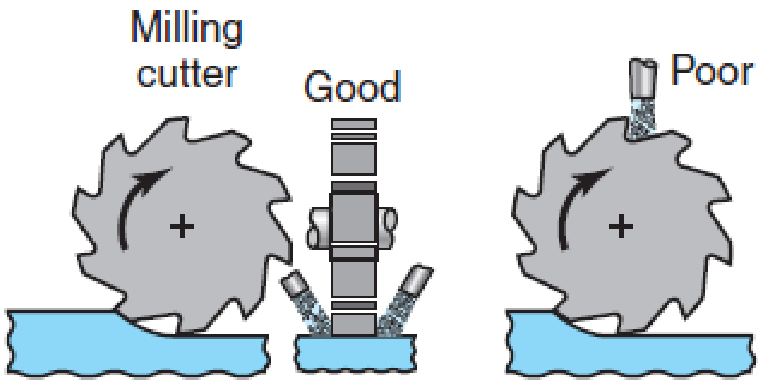
1. **Flooding**
   - Most common method (see next slide)
2. **Mist**
   - Allows better view of machined workpiece (compared to flooding), but has lower cooling capability + hazard (why?)
3. **High-pressure systems**
   - nozzles: direct cutting fluid powerfully into relief (flank) face
4. **Through the cutting tool system**
   - used when difficult to apply cutting fluid into the cutting zone (see figure up)

Cutting Fluids

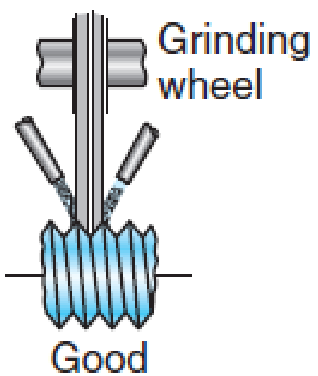
Proper Methods of Applying Flooding (see below)



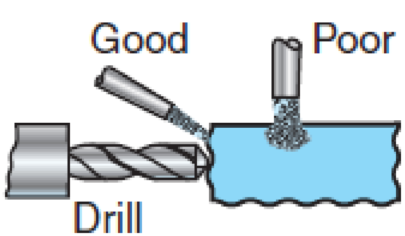
(a) **turning**



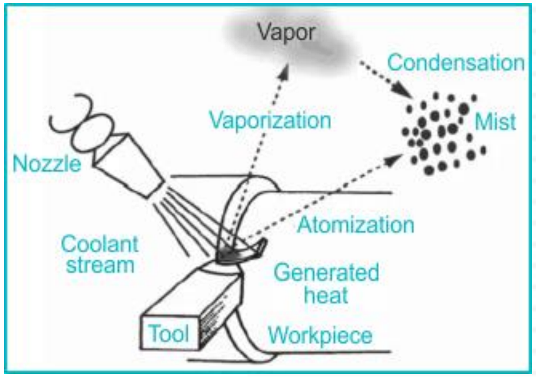
(b) **milling**



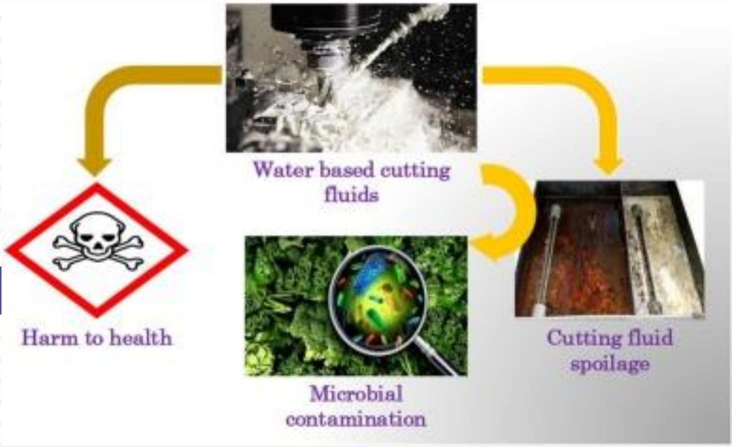
thread grinding (c)



(d) **drilling**



Cutting Fluids



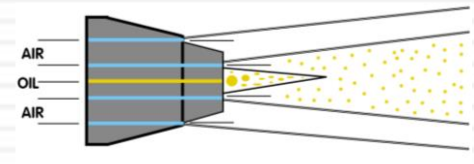
Effects of Cutting Fluids

- Selection of a cutting fluid is based on:

1. Workpiece material and machine tools
   - cutting fluids may react with machine tool components
   - thus, must clean machined parts from cutting fluids residue
2. Biological/Safety considerations
   - health concerns: mist, odors ⇒ skin, respiratory problems
   - progress in safe use of cutting fluids: e.g. dry machining
3. Environment
   - Fluids degrade over time (due to contamination) ⇒ effectiveness ↓
   - Fluid management involves recycling (treatment with additives and biocides), and disposal according to local laws

Cutting Fluids:
Near-dry and Dry Machining

- Trend since mid-1990's to reduce cutting fluid usage
- Thus, rise of near-dry machining; advantages:
  - reducing health, environmental hazards of cutting fluids
  - reducing cost of maintenance, recycling, disposing of CF's
  - improving surface quality



Concentric Oil/ Air Flow Nozzle

- Near-dry cutting/machining (NDM)
  - application of fine mist of air–fluid mixture containing very small amount of cutting fluid (« then used in flooding)
  - also called minimum-quantity lubrication (MQL)

- *Dry machining*
  - effective for turning, milling
  - here chips flushed from cutting zone by pressurized air
  - i.e. air serves limited cooling & flushing, but no lubrication