

CUTTING-TOOL TECHNOLOGY AND RELATED TOPICS

1. Tool life
2. Tool materials
3. Tool geometry
4. Cutting fluids
5. Machinability
6. Machining economics

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Cutting Tool Technology

Two principal aspects: R1

1. Tool material
2. Tool geometry

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R2

Three Modes of Tool Failure

1. Fracture failure
   - Cutting force becomes excessive and/or dynamic, leading to brittle fracture
2. Temperature failure
   - Cutting temperature is too high for the tool material
3. Gradual wear
   - Gradual wearing of the cutting tool

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Preferred Mode: Gradual Wear

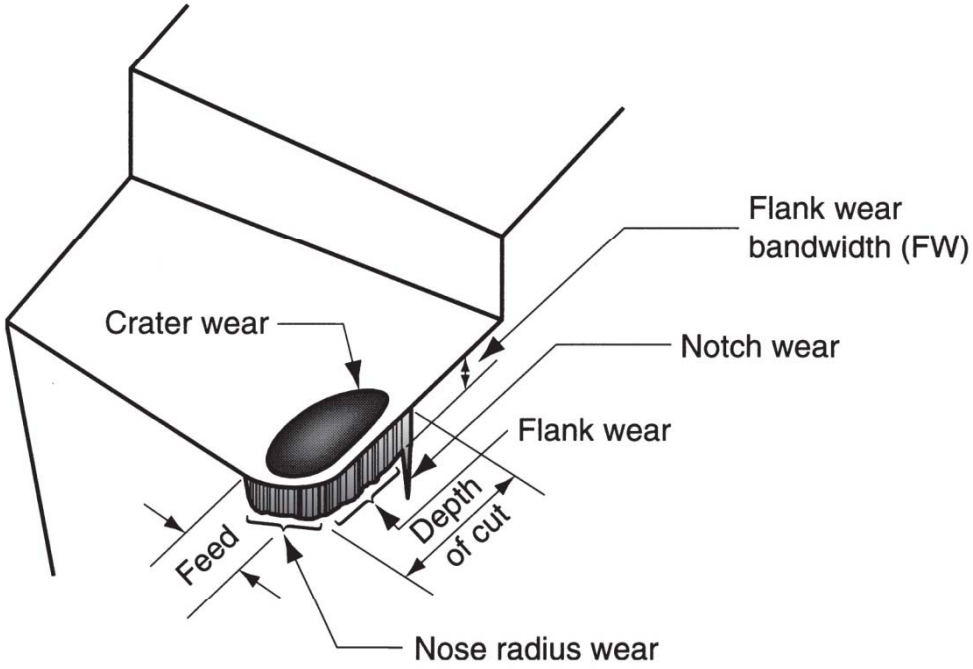
- Fracture and temperature failures are premature failures
- Gradual wear is preferred because it leads to the longest possible use of the tool
- Gradual wear occurs at two locations on a tool: R3
  - Crater wear – occurs on top rake face
  - Flank wear – occurs on flank (side of tool)

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Tool Wear

- Worn cutting tool, showing the principal locations and types of wear that occur

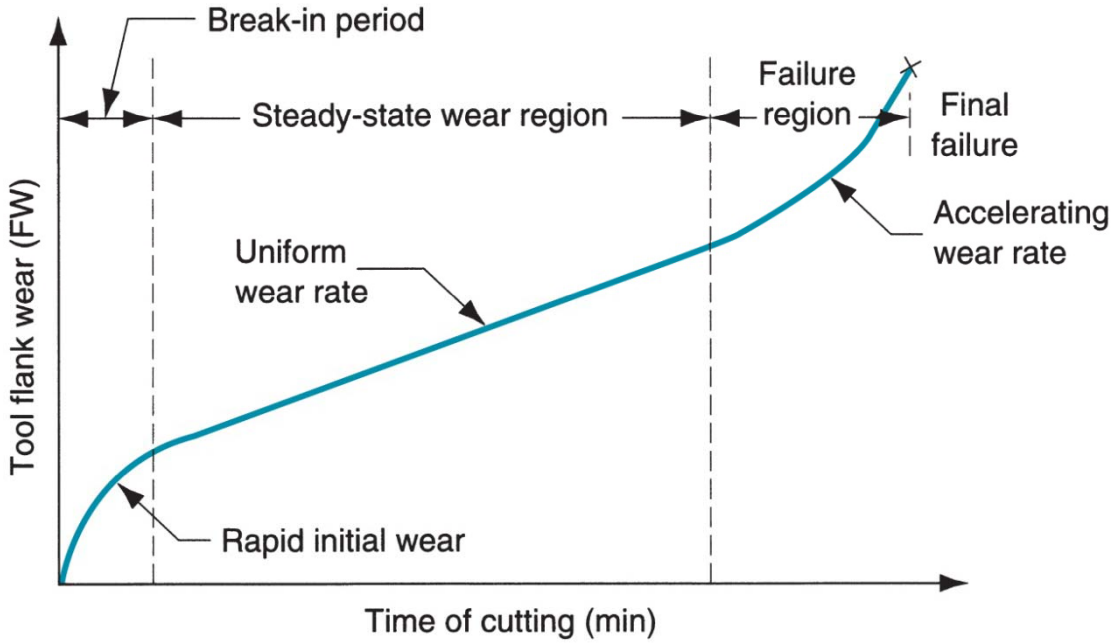


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Tool Wear vs. Time

- Tool wear (flank wear) as a function of cutting time



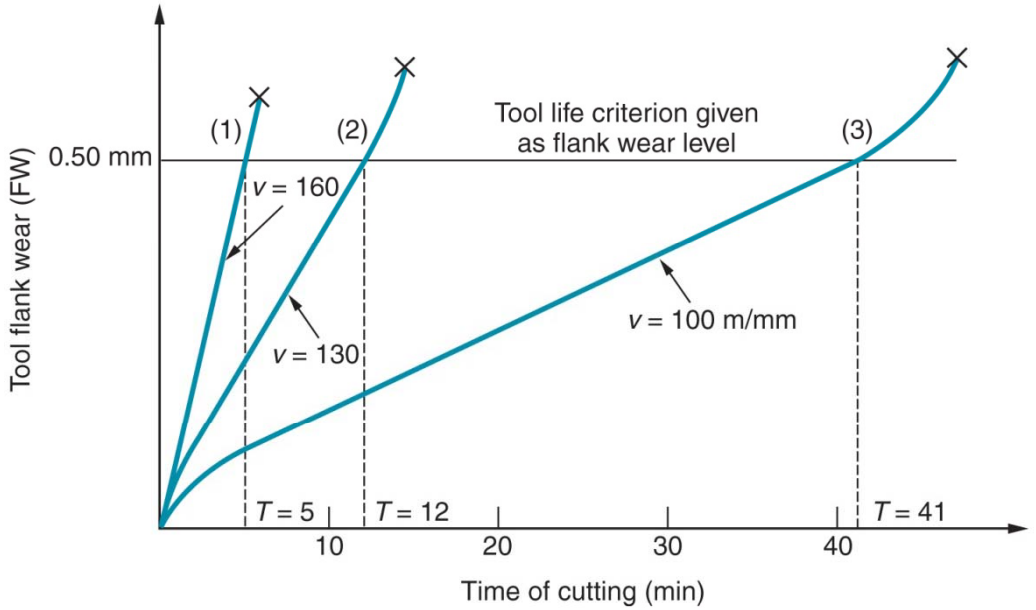
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Effect of Cutting Speed

- Effect of cutting speed on tool flank wear (FW) for three cutting speeds, using tool life criterion of 0.5 mm flank wear

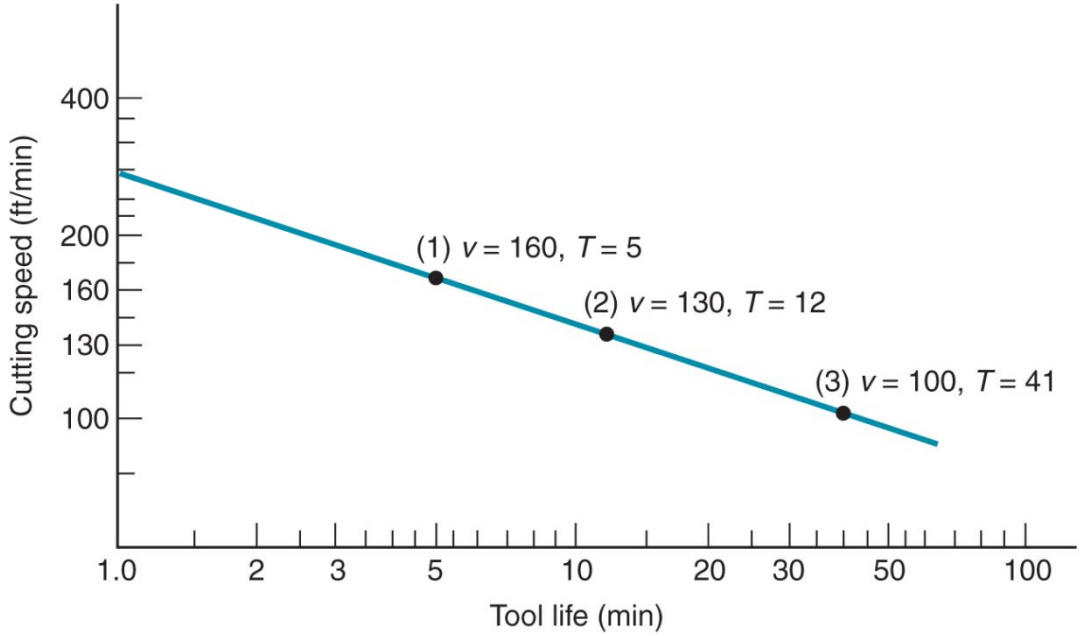


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Tool Life vs. Cutting Speed

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



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Taylor Tool Life Equation

$$vT^n = C$$

where v = cutting speed; T = tool life; and n and C are parameters that depend on feed, depth of cut, work material, tooling material, and the tool life criterion used

- n is the slope of the plot
- C is the intercept on the speed axis at one minute tool life R5
- Relationship credited to Frederick W. Taylor

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Tool Life Criteria in Production R6

1. Visual inspection of wear by the machine operator
2. Degradation of surface finish
3. Workpiece count
4. Cumulative cutting time

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Tool Materials

- Tool failure modes identify the important properties that a tool material should possess
  - Toughness - to avoid fracture failure
  - Hot hardness - ability to retain hardness at high temperatures
  - Wear resistance - hardness is the most important property to resist abrasive wear

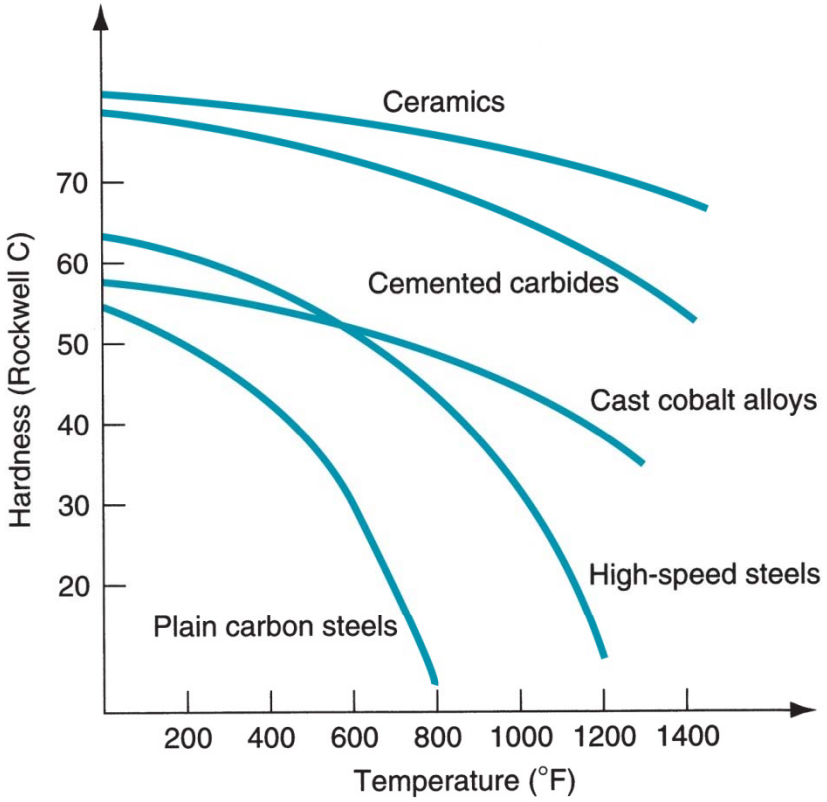
R7

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Hot Hardness

- Typical hot hardness relationships for selected tool materials
- High speed steel is much better than plain C steel
- Cemented carbides and ceramics are significantly harder at elevated temperatures.



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Typical Values of *n* and *C*

Tool material	n	C (m/min)	C (ft/min)
High speed steel:			
Non-steel work	0.125	120	350
Steel work	0.125	70	200
Cemented carbide			
Non-steel work	0.25	900	2700
Steel work	0.25	500	1500
Ceramic			
Steel work	0.6	3000	10,000

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High Speed Steel (HSS)

Highly alloyed tool steel capable of maintaining hardness at elevated temperatures better than high carbon and low alloy steels

- Especially suited to applications involving complicated tool shapes: drills, taps, milling cutters, and broaches
- Two basic types of HSS (AISI) R8
  1. Tungsten-type, designated T- grades
  2. Molybdenum-type, designated M-grades

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High Speed Steel Composition

- Typical alloying ingredients:
  - Tungsten and/or Molybdenum
  - Chromium and Vanadium
  - Carbon, of course
  - Cobalt in some grades
- Typical composition (Grade T1):
  - 18% W, 4% Cr, 1% V, and 0.9% C

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Cemented Carbides

Class of hard tool material based on tungsten carbide (WC) using powder metallurgy techniques with cobalt (Co) as the binder

- Two basic types: R9
  1. Non-steel cutting grades - only WC-Co
  2. Steel cutting grades - TiC and TaC added to WC-Co

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Cemented Carbides – General Properties

- High compressive strength but low-to-moderate tensile strength
- High hardness (90 to 95 HRA)
- Good hot hardness
- Good wear resistance
- High thermal conductivity
- High elastic modulus - 600 x 10^3 MPa (90 x 10^6 lb/in^2)
- Toughness lower than high speed steel

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Non-steel Cutting Carbide Grades

- Used for nonferrous metals and gray cast iron
- Properties determined by grain size and cobalt content
  - As grain size increases, hardness and hot hardness decrease, but toughness increases
  - As cobalt content increases, toughness improves at the expense of hardness and wear resistance

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Steel Cutting Carbide Grades

- Used for low carbon, stainless, and other alloy steels
- TiC and/or TaC are substituted for some of the WC
- Composition increases crater wear resistance for steel cutting
  - But adversely affects flank wear resistance for non-steel cutting applications

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Cermets

Combinations of TiC, TiN, and titanium carbonitride (TiCN), with nickel and/or molybdenum as binders.

- Some chemistries are more complex
- Applications: high speed finishing and semifinishing of steels, stainless steels, and cast irons
  - Higher speeds and lower feeds than steel-cutting cemented carbide grades
  - Better finish achieved, often eliminating need for grinding

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Coated Carbides

R10

Cemented carbide insert coated with one or more layers of TiC, TiN, and/or Al_2O_3 or other hard materials

- Coating thickness = 2.5 - 13 μm (0.0001 to 0.0005 in)
  - Coating applied by chemical vapor deposition or physical vapor deposition
- Applications: cast irons and steels in turning and milling operations
  - Best applied at high speeds where dynamic force and thermal shock are minimal

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Ceramics

Primarily fine-grained Al_2O_3, pressed and sintered at high pressures and temperatures into insert form with no binder

- Applications: high speed turning of cast iron and steel
- Not recommended for heavy interrupted cuts (e.g. rough milling) due to low toughness
- Al_2O_3 also widely used as an abrasive in grinding

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Synthetic Diamonds

Sintered polycrystalline diamond (SPD) - fabricated by sintering very fine-grained diamond crystals under high temperatures and pressures into desired shape with little or no binder

- Usually applied as coating (0.5 mm thick) on WC-Co insert
- Applications: high speed machining of nonferrous metals and abrasive nonmetals such as fiberglass reinforced polymer, graphite, and wood
  - Not for steel cutting

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Cubic Boron Nitride

- Next to diamond, cubic boron nitride (cBN) is hardest material known
- Fabrication into cutting tool inserts same as SPD: coatings on WC-Co inserts
- Applications: machining steel and nickel-based alloys
- SPD and cBN tools are expensive

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Tool Geometry

Two categories:

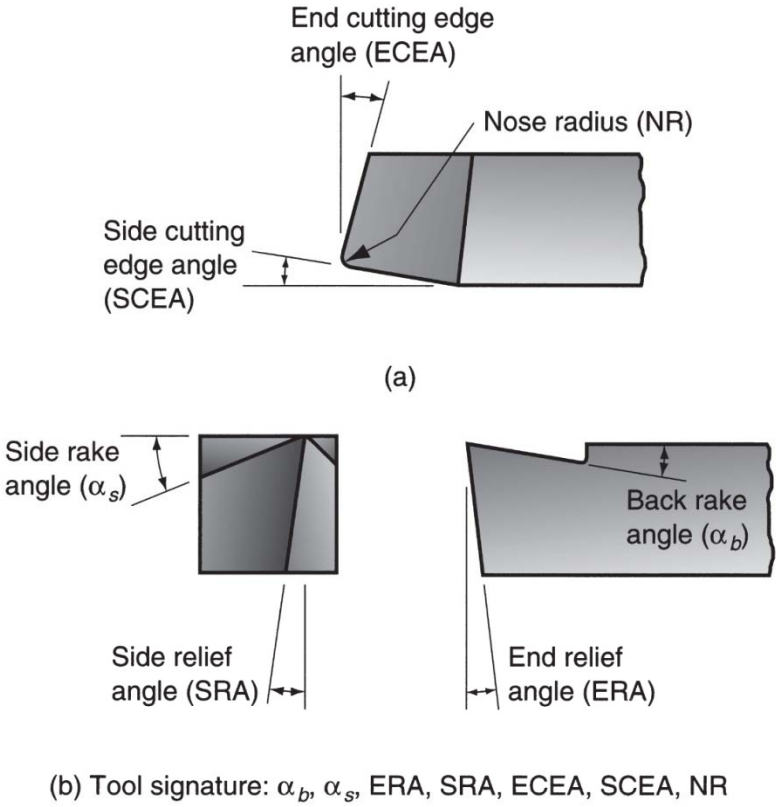
- Single point tools
  - Used for turning, boring, shaping, and planing
- Multiple cutting edge tools
  - Used for drilling, reaming, tapping, milling, broaching, and sawing

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Single-Point Tool Geometry

- (a) Seven elements of single-point tool geometry R11
- (b) Tool signature convention that defines the seven elements



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

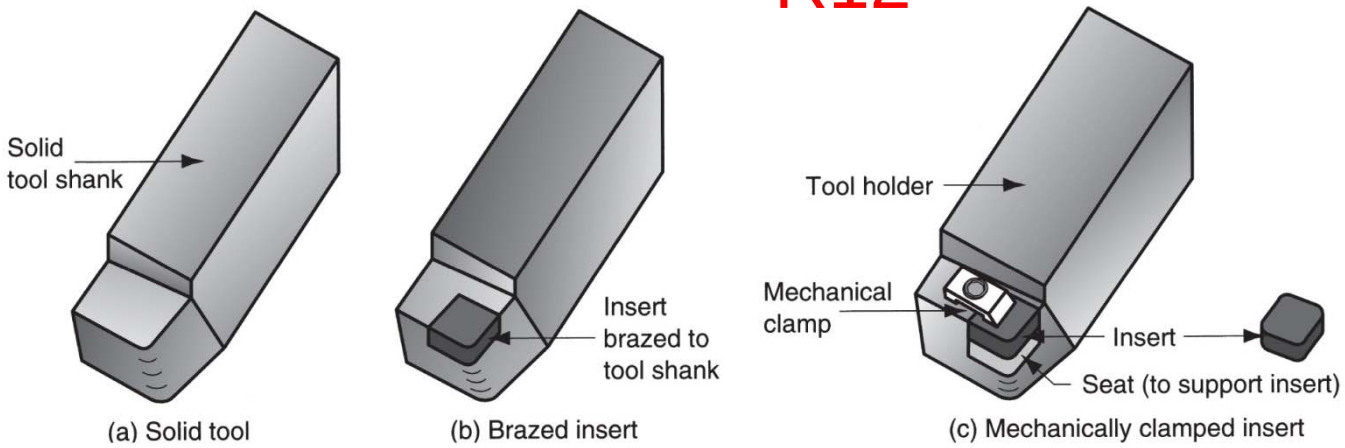
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Holding and Presenting a Single-Point Tool

- (a) Solid shank tool, typical of HSS; (b) brazed cemented carbide insert; and (c) mechanically clamped insert, used for cemented carbides, ceramics, and other very hard tool materials

R12



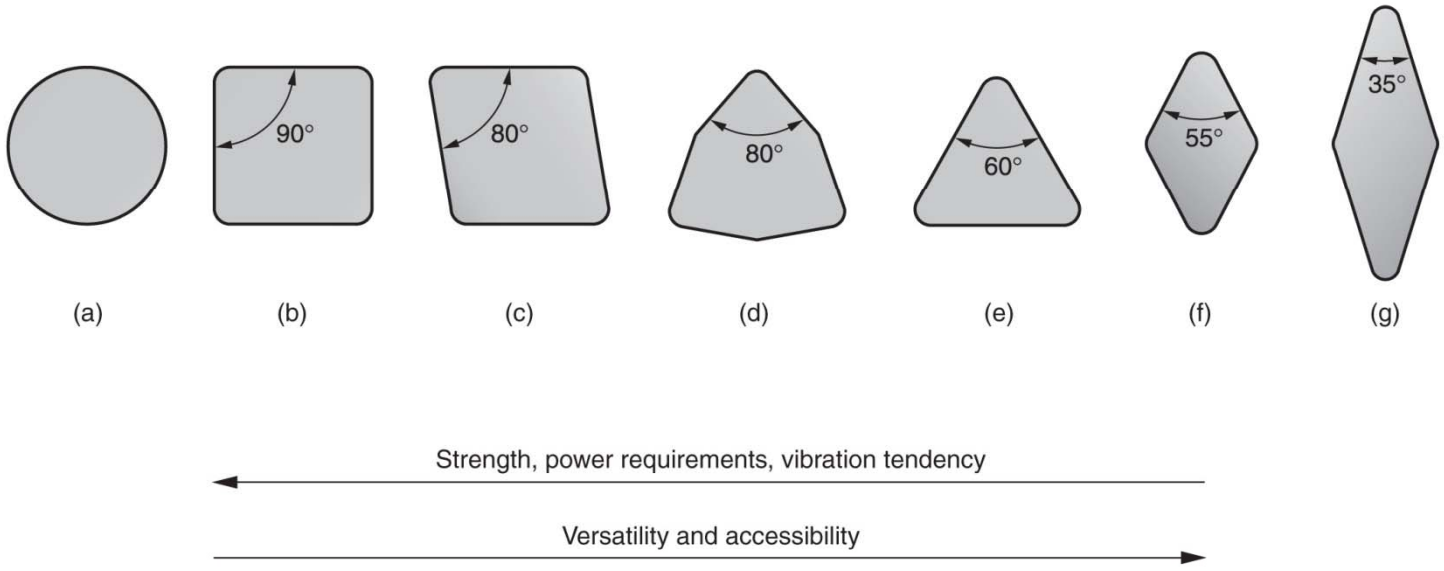
(a) Solid tool (b) Brazed insert (c) Mechanically clamped insert

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Common Insert Shapes

- (a) Round, (b) square, (c) rhombus with 80° point angles, (d) hexagon with 80° point angles, (e) triangle, (f) rhombus with 55° point angles, (g) rhombus with 35° point angles

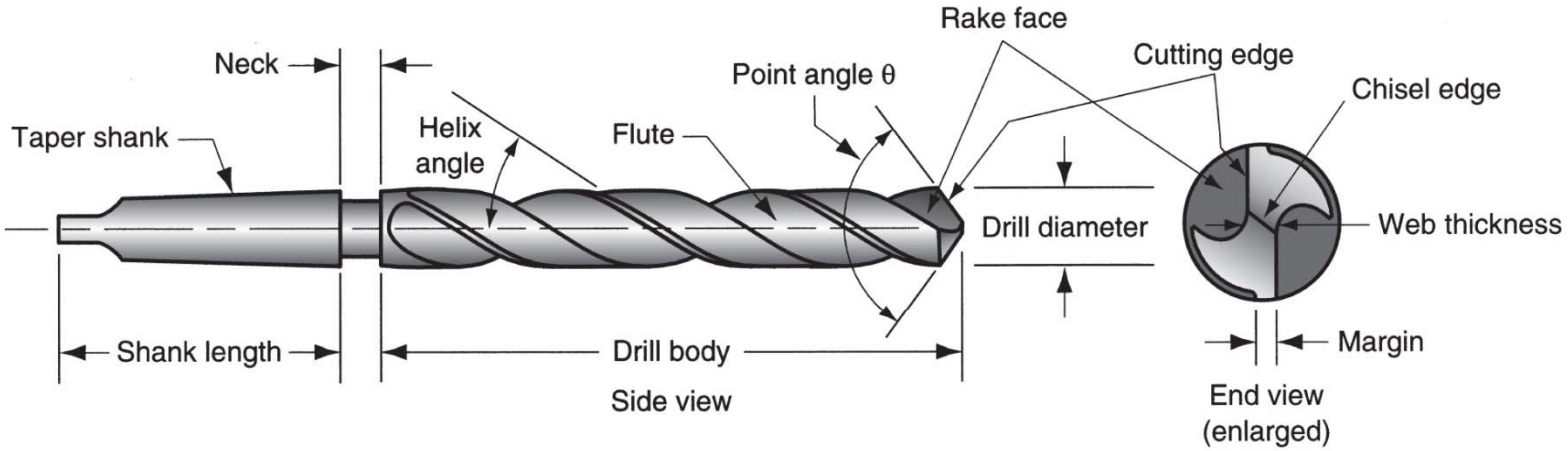


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Twist Drill

- Most common cutting tools for hole-making
- Usually made of high speed steel
- Shown below is standard twist drill geometry



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Twist Drill Operation

- Rotation and feeding of drill bit result in relative motion between cutting edges and work material to form the chips
  - Cutting speed varies along cutting edges as a function of distance from axis of rotation
  - Relative velocity at drill point is zero, so no cutting takes place
    - Instead, a large thrust force is required to drive the drill forward into the hole

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Twist Drill Operation - Problems

- Chip removal
  - Flutes must provide sufficient clearance to allow chips to move from bottom of hole during cutting
  - Friction makes matters worse
    - Rubbing between outside diameter of drill bit and newly formed hole
    - Delivery of cutting fluid to drill point to reduce friction and heat is difficult because chips are moving in opposite direction

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Milling Cutters

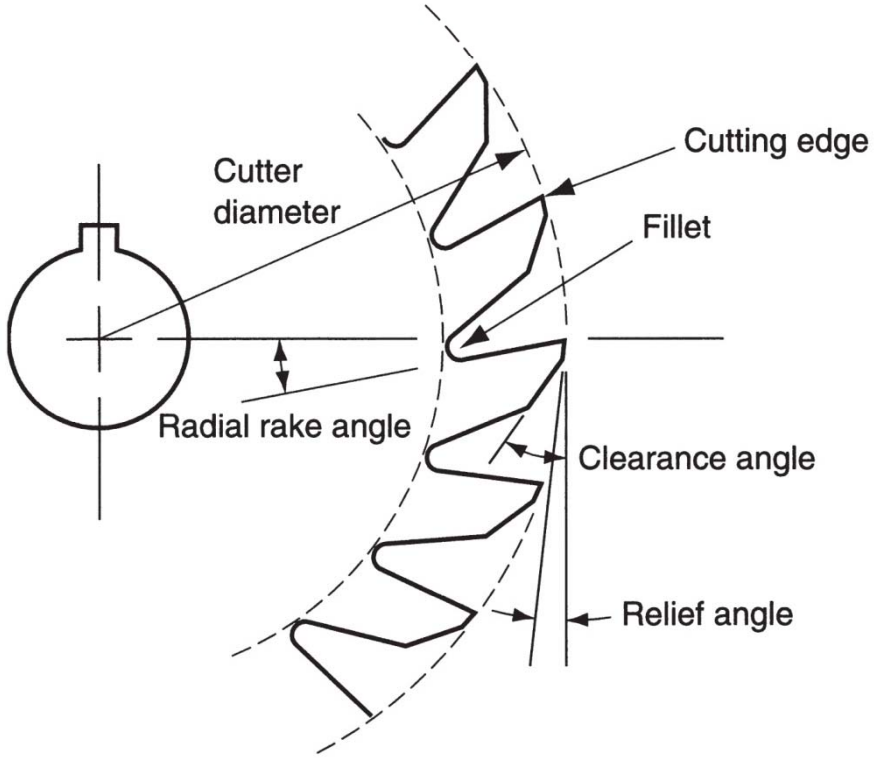
- Principal types:
  - Plain milling cutter
  - Face milling cutter
  - End milling cutter

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Plain Milling Cutter

- Tool geometry elements of an 18-tooth plain milling cutter

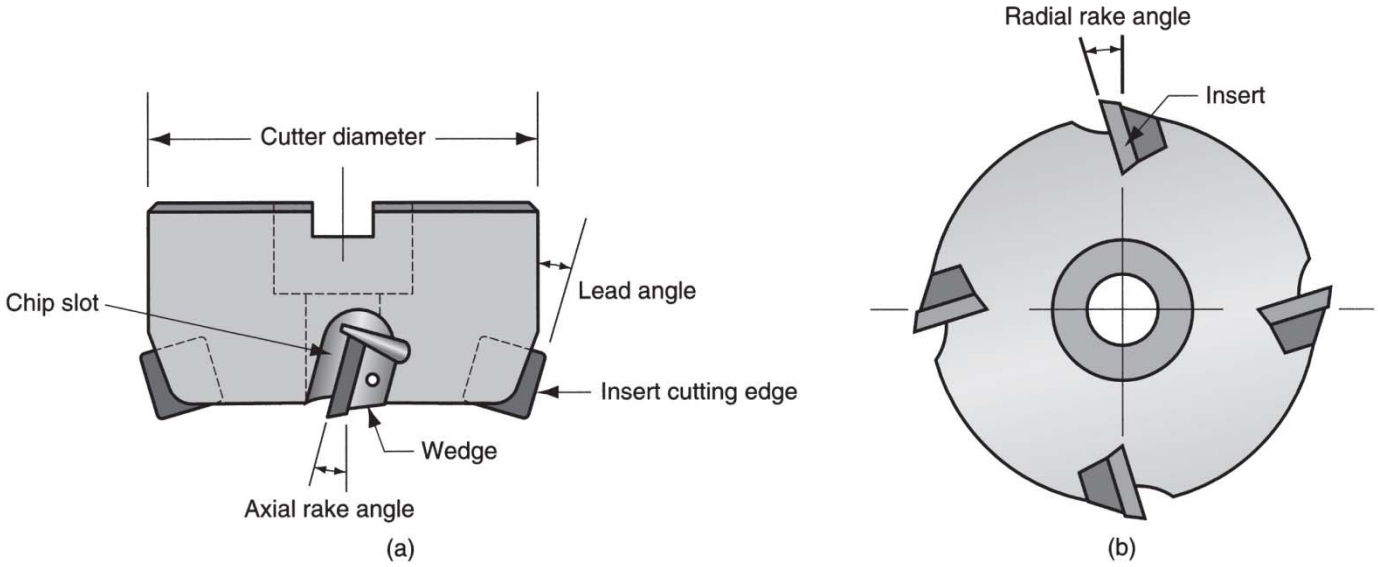


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Face Milling Cutter

- Tool geometry elements of a four-tooth face milling cutter: (a) side view and (b) bottom view



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End Milling Cutter

- Looks like a drill bit but designed for primary cutting with its peripheral teeth
- Applications:
  - Face milling
  - Profile milling and pocketing
  - Cutting slots
  - Engraving
  - Surface contouring
  - Die sinking

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Cutting Fluids

Any liquid or gas applied directly to the machining operation to improve cutting performance

- Two main problems addressed by cutting fluids:
  1. Heat generation at shear and friction zones
  2. Friction at tool-chip and tool-work interfaces

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Cutting Fluids

- Other functions and benefits:
  - Wash away chips (e.g., grinding and milling)
  - Reduce temperature of workpart for easier handling
  - Improve dimensional stability of workpart

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Cutting Fluid Classification R13

Cutting fluids can be classified according to function:

- Coolants - designed to reduce effects of heat in machining
- Lubricants - designed to reduce tool-chip and tool-work friction

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Coolants

- Water used as base in coolant-type cutting fluids
- Most effective at high cutting speeds where heat generation and high temperatures are problems
- Most effective on tool materials that are most susceptible to temperature failures (e.g., HSS)

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Lubricants

- Usually oil-based fluids
- Most effective at lower cutting speeds
- Also reduce temperature in the operation

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Cutting Fluid Contamination

- Tramp oil (machine oil, hydraulic fluid, etc.)
- Garbage (cigarette butts, food, etc.)
- Small chips
- Molds, fungi, and bacteria

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Dealing with Cutting Fluid Contamination

- Replace cutting fluid at regular and frequent intervals
- Use filtration system to continuously or periodically clean the fluid
- Dry machining

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Cutting Fluid Filtration

Advantages:

- Prolong cutting fluid life between changes
- Reduce fluid disposal cost
- Cleaner fluids reduce health hazards
- Lower machine tool maintenance
- Longer tool life

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Dry Machining

- No cutting fluid is used
- Avoids problems of cutting fluid contamination, disposal, and filtration R16
- Problems with dry machining: R17
  - Overheating of tool
  - Operating at lower cutting speeds and production rates to prolong tool life
  - Absence of chip removal benefits of cutting fluids in grinding and milling

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Machinability R18

Relative ease with which a material (usually a metal) can be machined using appropriate tooling and cutting conditions

- Depends not only on work material
  - Type of machining operation, tooling, and cutting conditions are also important factors

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Machinability Criteria in Production R19

- Tool life – longer tool life for the given work material means better machinability
- Forces and power – lower forces and power mean better machinability
- Surface finish – better finish means better machinability
- Ease of chip disposal – easier chip disposal means better machinability

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Machinability Testing

Most tests involve comparison of work materials

- Performance of a test material is measured relative to a base material
- Relative performance is expressed as a machinability rating (MR)
  - MR of base material = 1.00 (100%)
  - MR of test material > 1.00 (100%) means better machinability

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Mechanical Properties and Machinability

- Hardness
  - High hardness means abrasive wear increases so tool life is reduced
- Strength
  - High strength means higher cutting forces, specific energy, and cutting temperature
- Ductility
  - High ductility means tearing of metal to form chip, causing chip disposal problems and poor finish

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Selection of Cutting Conditions

- One of the tasks in process planning
- For each operation, decisions must be made about machine tool, cutting tool(s), and cutting conditions
  - Cutting conditions: depth of cut, feed, speed, and cutting fluid
- These decisions must give due consideration to workpart machinability, part geometry, surface finish, and so forth

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Selecting Depth of Cut

- Depth of cut is often predetermined by workpiece geometry and operation sequence
  - In roughing, depth is made as large as possible to maximize material removal rate, subject to limitations of horsepower, machine tool and setup rigidity, and strength of cutting tool
  - In finishing, depth is set to achieve final part dimensions and surface finish

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Determining Feed R20

- Select feed first, speed second
- Determining feed rate depends on:
  - Tooling – harder tool materials require lower feeds
  - Roughing or finishing?
    - In roughing, limits on feed are imposed by forces, setup rigidity, and maybe horsepower
    - In finishing, select feed to achieve desired finish

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Optimizing Cutting Speed

- Select cutting speed to achieve a balance between high metal removal rate and suitably long tool life
- Mathematical formulas available to determine optimal speed
  - Two alternative objectives in these formulas:
    - Maximum production rate
    - Minimum unit cost

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Maximum Production Rate

- Maximizing production rate is equivalent to minimizing cutting time per unit
- In turning, total production cycle time for one part consists of:
  1. Part handling time per part = T_h
  2. Machining time per part = T_m
  3. Tool change time per part = T_t/n_p, where n_p = number of pieces cut in one tool life

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Maximum Production Rate

- Total time per unit product for operation:

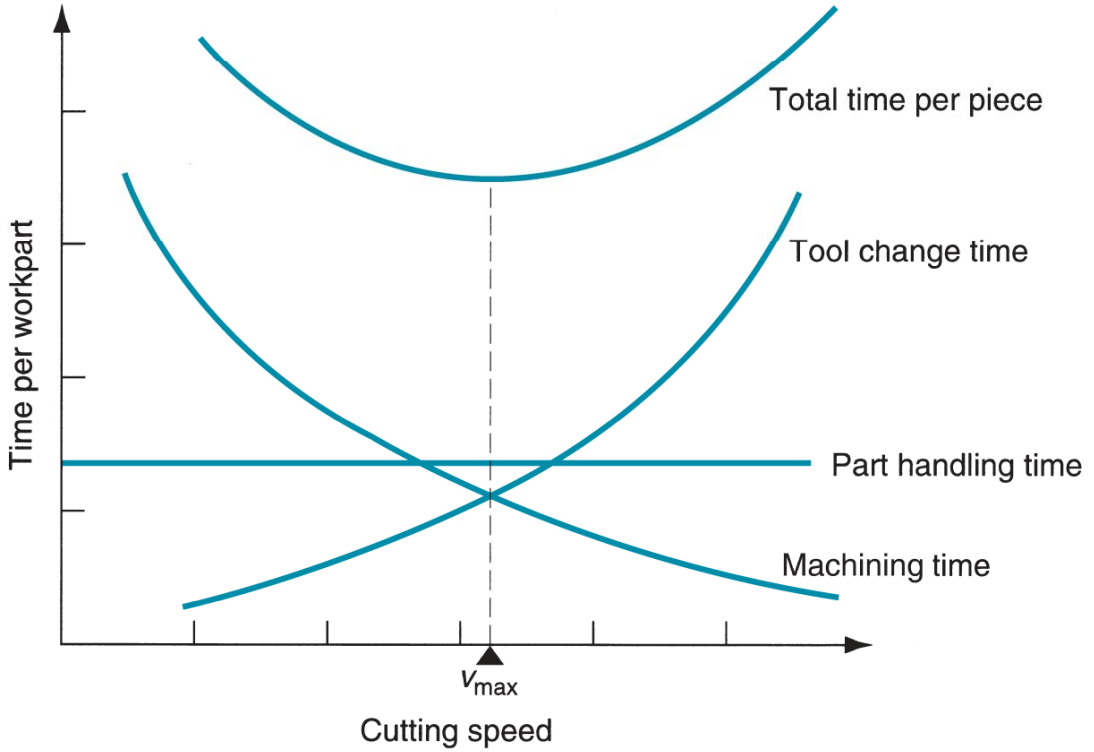
$$T_c = T_h + T_m + T_t/n_p$$

- Cycle time T_c is a function of cutting speed

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Cycle Time vs. Cutting Speed



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Minimizing Cost per Unit R21

- In turning, total production cycle cost for one part consists of:
  1. Cost of part handling time = $C_o T_h$, where C_o = cost rate for operator and machine
  2. Cost of machining time = $C_o T_m$
  3. Cost of tool change time = $C_o T_t / n_p$
  4. Tooling cost = C_t / n_p , where C_t = cost per cutting edge

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Minimizing Unit Cost

- Total cost per unit product for operation:

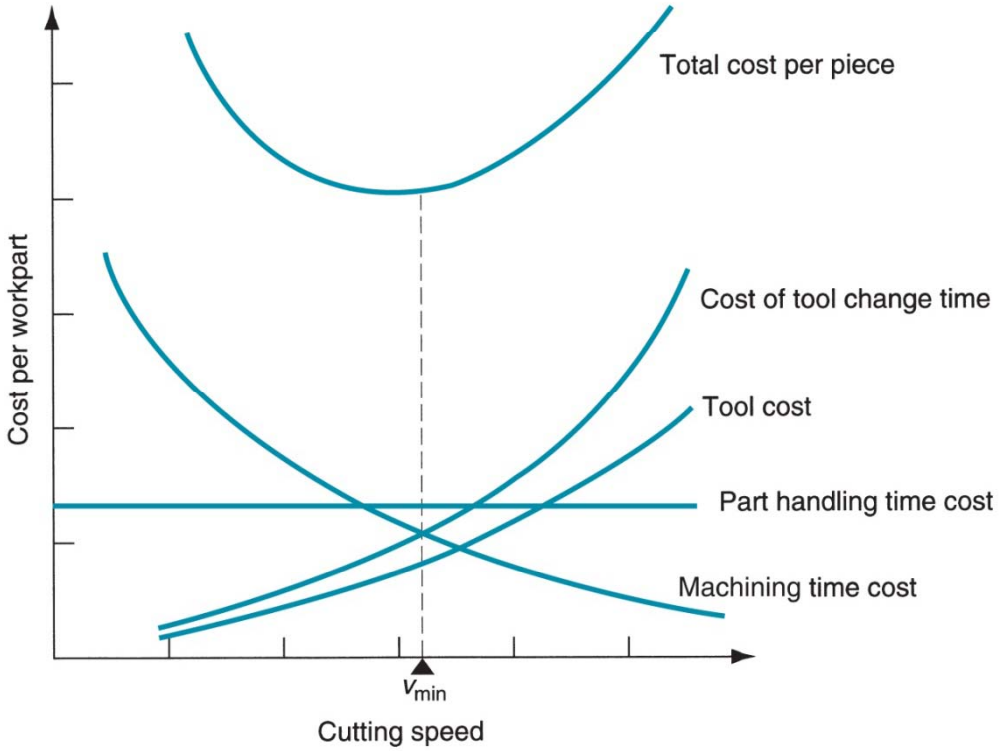
$$C_c = C_o T_h + C_o T_m + C_o T_t / n_p + C_t / n_p$$

- Again, unit cost is a function of cutting speed, just as T_c is a function of v

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Unit Cost vs. Cutting Speed



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Comments on Machining Economics

- As C and n increase in Taylor tool life equation, optimum cutting speed increases
  - Cemented carbides and ceramic tools should be used at speeds significantly higher than for HSS
- v_{max} is always greater than v_{min}
  - The reason: C_t/n_p term in unit cost equation pushes optimum speed to left in the plot of C_c vs. v

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Comments on Machining Economics R22

- As tool change time T_t and/or tooling cost C_t increase, cutting speed should be reduced
  - Tools should not be changed too often if either tool cost or tool change time is high
  - Disposable inserts have an advantage over regrindable tools because tool change time is lower

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17.3 Tool life tests on a lathe have resulted in the following data: (1) at a cutting speed of 375 ft/min, the tool life was 5.5 min; (2) at a cutting speed of 275 ft/min, the tool life was 53 min. (a) Determine the parameters n and C in the Taylor tool life equation. (b) Based on the n and C values, what is the likely tool material used in this operation? (c) Using your equation, compute the tool life that corresponds to a cutting speed of 300 ft/min. (d) Compute the cutting speed that corresponds to a tool life T = 10 min.

(a) $VT^n = C$; Two equations: (1) $375(5.5)^n = C$ and (2) $275(53)^n = C$

$375(5.5)^n = 275(53)^n$

$375/275 = (53/5.5)^n$ $\quad 1.364 = (9.636)^n$

$\ln 1.364 = n \ln 9.636$ $\quad 0.3102 = 2.2655\, n$

$\boldsymbol{n = 0.137}$

$C = 375(5.5)^{0.137} = 375(1.2629)$ $\quad \boldsymbol{C = 474}$

(b) Comparing these values of n and C with those in Table 17.2, the likely tool material is high speed steel.

(c) At v = 300 ft/min, $T = (C/v)^{1/n} = (474/300)^{1/0.137} = (1.579)^{7.305} =$ **28.1 min**

(d) For T = 10 min, $v = C/T^n = 474/10^{0.137} = 474/1.371 =$ **346 ft/min**

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17.18 A high-speed steel tool is used to turn a steel workpart that is 300 mm long and 80 mm in diameter. The parameters in the Taylor equation are: n = 0.13 and C = 75 (m/min) for a feed of 0.4 mm/rev. The operator and machine tool rate = $30.00/hr, and the tooling cost per cutting edge = $4.00. It takes 2.0 min to load and unload the workpart and 3.50 min to change tools. Determine (a) cutting speed for maximum production rate, (b) tool life in min of cutting, and (c) cycle time and cost per unit of product.

(a) C_o = \$30/hr = \$0.50/min

$v_{max} = 75/[(1/0.13 - 1)(3.5)]^{.13} = 75/[6.692 \times 3.5]^{.27}$ = **49.8 m/min**

(b) $T_{max} = (75/49.8)^{1/.13} = (1.506)^{7.692}$ = **23.42 min**

(c) $T_m = \pi DL/fv = \pi(80)(300)/(.4 \times 49.8 \times 10^3)$ = 3.787 min

n_p = 23.42/3.787 = 6.184 pc/tool life Use n_p = 6 pc/tool life

$T_c = T_h + T_m + T_t/n_p$ = 2.0 + 3.787 + 3.5/6 = **6.37 min/pc.**

C_c = 0.50(6.37) + 4.00/6 = **\$3.85/pc**

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17.22 Disposable and regrindable tooling are to be compared. The same grade of cemented carbide tooling is available in two forms for turning operations in a certain machine shop: disposable inserts and brazed inserts. The parameters in the Taylor equation for this grade are: n = 0.25 and C = 300 (m/min) under the cutting conditions considered here. For the disposable inserts, price of each insert = $6.00, there are four cutting edges per insert, and the tool change time = 1.0 min (this is an average of the time to index the insert and the time to replace it when all edges have been used). For the brazed insert, the price of the tool = $30.00 and it is estimated that it can be used a total of 15 times before it must be scrapped. The tool change time for the regrindable tooling = 3.0 min. The standard time to grind or regrind the cutting edge is 5.0 min, and the grinder is paid at a rate = $20.00/hr. Machine time on the lathe costs $24.00/hr. The workpart to be used in the comparison is 375 mm long and 62.5 mm in diameter, and it takes 2.0 min to load and unload the work. The feed = 0.30 mm/rev. For the two tooling cases, compare (a) cutting speeds for minimum cost, (b) tool lives, (c) cycle time and cost per unit of production. Which tool would you recommend?

Disposable inserts: (a) C_o = \$24/hr = \$0.40/min, C_t = \$6/4 = \$1.50/edge
v_{min} = 300[0.40/((1/0.25 - 1)(0.40 x 1.0 + 1.50))]$^{.25}$ = 300[0.40/(3 x 1.9)]$^{.25}$ = **154.4 m/min**
(b) T_{min} = (1/0.25 - 1)(0.4 + 1.5)/0.4 = 3(1.9/0.4) = **14.25 min**
(c) T_m = π(62.5)(375)/(0.30)(10^{-3})(154.4) = 1.59 min/pc, n_p = 14.25/1.59 = 8.96 pc/tool life, Use n_p = 8 pc/tool
T_c = 2.0 + 1.59 + 1.0/8 = **3.72 min/pc.**
C_c = 0.40(3.72) + 1.50/8 = **\$1.674/pc**

Regrindable tooling: (a) C_o = \$24/hr = \$0.40/min, C_t = \$30/15 + 5(\$20/60) = \$3.67/edge
v_{min} = 300[0.40/((1/0.25 - 1)(0.40 x 3.0 + 3.67))]$^{.25}$ = 300[0.40/(3 x 4.87)]$^{.25}$ = **122.0 m/min**
(b) T_{min} = (1/0.25 - 1)(0.4 x 3 + 3.67)/0.4 = 3(4.87/0.4) = **36.5 min**
(c) T_m = π(62.5)(375)/(0.30)(10^{-3})(122) = 2.01 min/pc, n_p = 36.5/2.01 = 18.16 pc/tool life, use n_p = 18 pc/tool
T_c = 2.0 + 2.01 + 3.0/18 = **4.18 min/pc**
C_c = 0.40(4.18) + 3.67/18 = **\$1.876/pc**

Disposable inserts are recommended. Cycle time and cost per piece are less.

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Disposable inserts: (a) C_o = \$24/hr = \$0.40/min, C_t = \$6/4 = \$1.50/edge
v_{min} = 300[0.40/((1/0.25 - 1)(0.40 x 1.0 + 1.50))]$^{.25}$ = 300[0.40/(3 x 1.9)]$^{.25}$ = **154.4 m/min**
(b) T_{min} = (1/0.25 - 1)(0.4 + 1.5)/0.4 = 3(1.9/0.4) = **14.25 min**
(c) T_m = π(62.5)(375)/(0.30)(10^{-3})(154.4) = 1.59 min/pc, n_p = 14.25/1.59 = 8.96 pc/tool life, Use n_p = 8 pc/tool
T_c = 2.0 + 1.59 + 1.0/8 = **3.72 min/pc.**
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Regrindable tooling: (a) C_o = \$24/hr = \$0.40/min, C_t = \$30/15 + 5(\$20/60) = \$3.67/edge
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(c) T_m = π(62.5)(375)/(0.30)(10^{-3})(122) = 2.01 min/pc, n_p = 36.5/2.01 = 18.16 pc/tool life, use n_p = 18 pc/tool
T_c = 2.0 + 2.01 + 3.0/18 = **4.18 min/pc**
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Disposable inserts are recommended. Cycle time and cost per piece are less.

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17.27 As indicated in Section 17.4, the effect of a cutting fluid is to increase the value of C in the Taylor tool life equation. In a certain machining situation using HSS tooling, the C value is increased from C = 200 to C = 225 due to the use of the cutting fluid. The n value is the same with or without fluid at n = 0.125. Cutting speed used in the operation is v = 125 ft/min. Feed = 0.010 in/rev and depth = 0.100 in. The effect of the cutting fluid can be to either increase cutting speed (at the same tool life) or increase tool life (at the same cutting speed). (a) What is the cutting speed that would result from using the cutting fluid if tool life remains the same as with no fluid? (b) What is the tool life that would result if the cutting speed remained at 125 ft/min? (c) Economically, which effect is better, given that tooling cost = $2.00 per cutting edge, tool change time = 2.5 min, and operator and machine rate = $30/hr? Justify you answer with calculations, using cost per cubic in of metal machined as the criterion of comparison. Ignore effects of workpart handling time.

Cutting dry, the Taylor tool life equation parameters are n = 0.125 and C = 200.
At v = 125 ft/min, tool life $T = (200/125)^{1/.125} = (1.6)^8 = 43$ min
With a cutting fluid, the Taylor tool life equation parameters are n = 0.125 and C = 225.
The corresponding cutting speed for a 43 min tool life $v = 225/43^{0.125}$ = **140.6 ft/min**

(b) Cutting at v = 125 ft/min with a cutting fluid gives a tool life $T = (225/125)^{8.0}$ = **110 min**
(c) Which is better, (1) cutting at a speed of 140.6 ft/min to give a 43 min tool life, or (2) cutting at 125 ft/min to give a 110 min tool life. Use 1.0 in^3 of metal cut as the basis of comparison, with cost and time parameters as follows: C_t = $2.00/cutting edge, T_t = 2.5 min, and C_o = $30/hr = $0.50/min
(1) At v =140.6 ft/min, T_m = 1.0 in^3/R_{MR} = 1.0/(140.6 x 12 x 0.010 x 0.100) = 0.5927 min
For T = 43 min, volume cut per tool life = 43/0.5927 = 72.5 in^3 between tool changes.
•Ignoring work handling time, cost/in^3 = 0.50(.5927) + (0.50 x 2.5 + 2.00)/72.5 = **$0.341/in^3.**
(2) At 125 ft/min, T_m = 1.0 in^3/R_{MR} = 1.0/(125 x 12 x 0.010 x 0.100) = 0.6667 min
For T = 110 min, volume cut per tool life = 110/0.6667 = 164.9 in^3 between tool changes.
Ignoring work handling time, cost/in^3 = 0.50(.6667) + (0.50 x 2.5 + 2.00)/164.9 = **$0.353/in^3.**

Conclusion: it is better to take the benefit of a cutting fluid in the form of increased cutting speed.

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