Chapter 13:
Fundamentals of Casting

DeGarmo’s Materials and Processes in Manufacturing

13.1 Introduction

- Products go through a series of processes before they are produced
    - Design
    - Material selection
    - Process selection
    - Manufacture
    - Inspection and evaluation
    - Feedback
- Materials processing is the science and technology that converts a material into a product of a desired shape in the desired quantity

Shape-Producing Processes

- Four basic categories
  - Casting processes
  - Material removal processes
  - Deformation processes
  - Consolidation processes
- Decisions should be made after all alternatives and limitations are investigated

Shape-Producing Processes

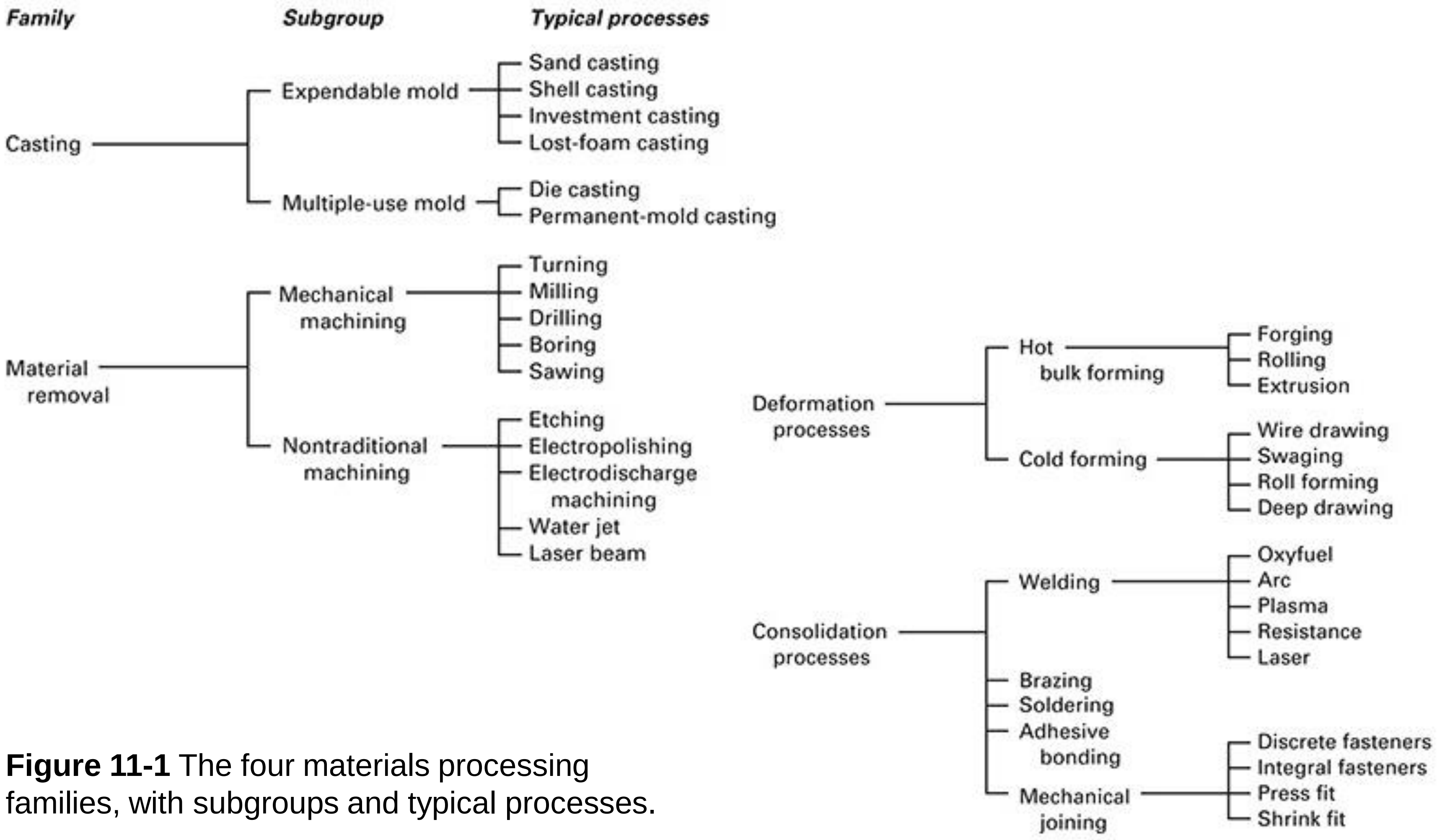


Figure 11-1 The four materials processing families, with subgroups and typical processes.

13.2 Introduction to Casting

- Casting process
  - Material is melted
  - Heated to proper temperature
  - Treated to modify its chemical makeup
  - Molten material is poured into a mold
  - Solidifies
- Casting can produce a large variety of parts

Advantages of Casting

- Complex shapes
- Parts can have hollow sections or cavities
- Very large parts
- Intricate shaping of metals that are difficult to machine
- Different mold materials can be used
  - Sand, metal, or ceramics
- Different pouring methods

Basic Requirements of Casting Processes

- Six basic steps of casting
  - 1. Mold cavity is produced having the desired shape and size of the part
    - Takes shrinkage into account
    - Single-use or permanent mold
  - 2. Melting process
    - Provides molten material at the proper temperature
  - 3. Pouring technique
    - Molten metal is poured into the mold at a proper rate to ensure that erosion and or defects are minimized

Six Basic Steps of Casting

- 4. Solidification process
  - Controlled solidification allows the product to have desired properties
  - Mold should be designed so that shrinkage is controlled
- 5. Mold removal
  - The casting is removed from the mold
    - Single-use molds are broken away from the casting
    - Permanent molds must be designed so that removal does not damage the part
- 6. Cleaning, finishing, and inspection operations
  - Excess material along parting lines may have to be machined

13.3 Casting Terminology

- Pattern- approximate duplicate of the part to be cast
- Molding material- material that is packed around the pattern to provide the mold cavity
- Flask- rigid frame that holds the molding aggregate
- Cope- top half of the pattern
- Drag- bottom half of the pattern
- Core- sand or metal shape that is inserted into the mold to create internal features

Casting Terminology

- Mold cavity- combination of the mold material and cores
- Riser-additional void in the mold that provides additional metal to compensate for shrinkage
- Gating system- network of channels that delivers the molten metal to the mold
- Pouring cup- portion of the gating system that controls the delivery of the metal
- Sprue- vertical portion of the gating system
- Runners- horizontal channels
- Gates- controlled entrances

Casting Terminology

- Parting line- separates the cope and drag
- Draft- angle or taper on a pattern that allows for easy removal of the casting from the mold
- Casting- describes both the process and the product when molten metal is poured and solidified

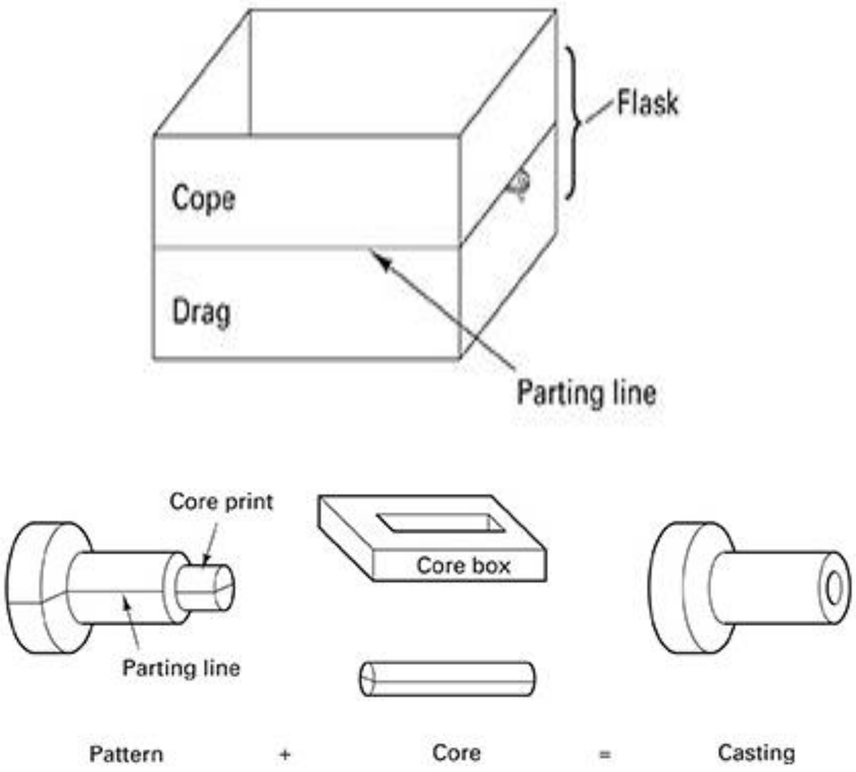


Figure 11-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

Cross Section of a Mold

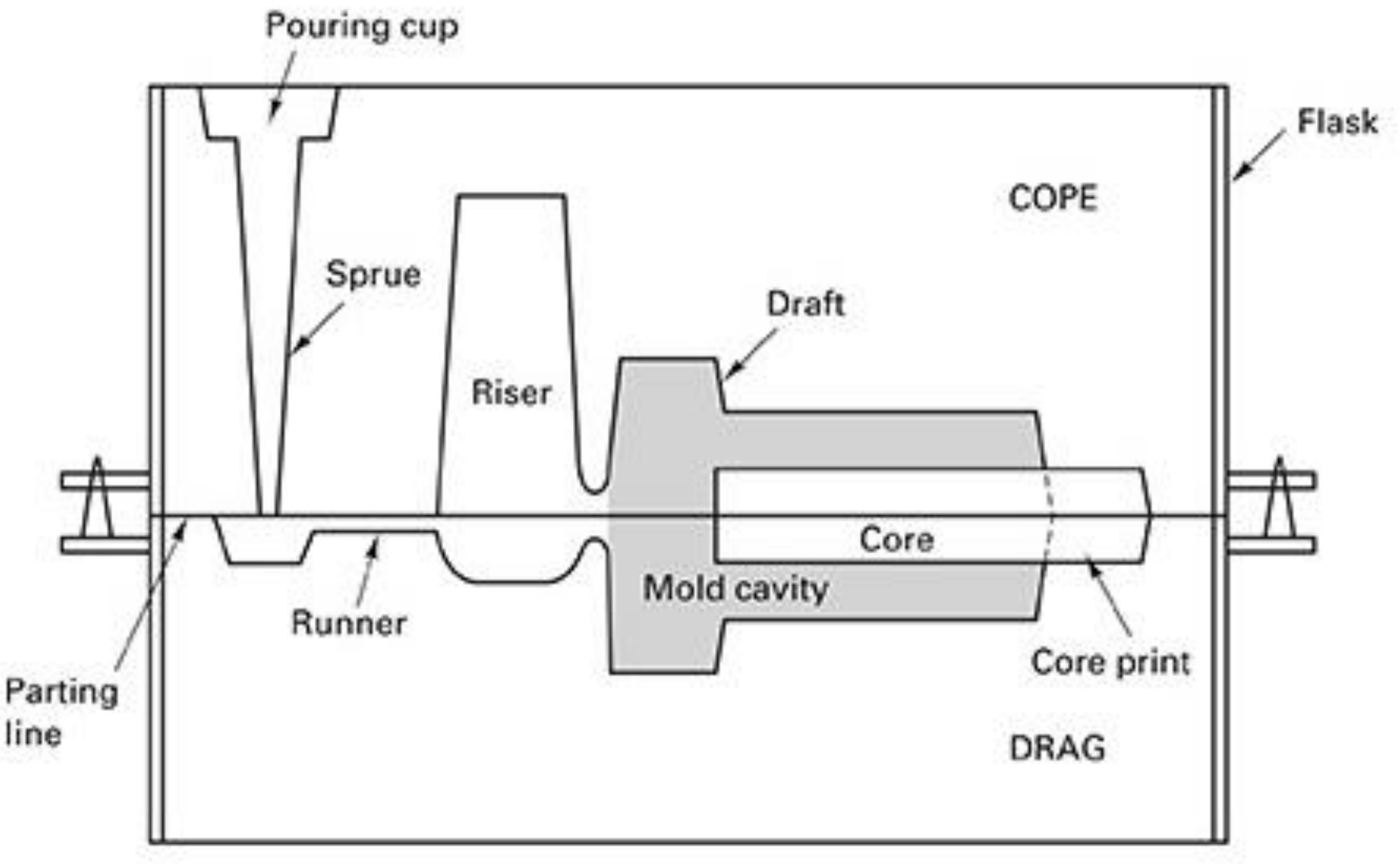
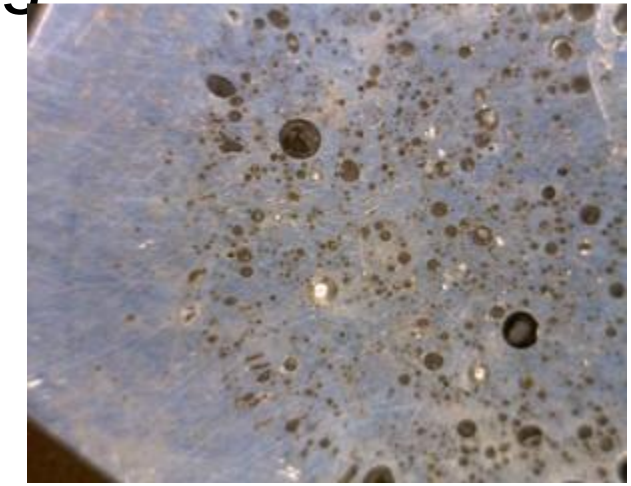


Figure 11-2

13.4 The Solidification Process

- Molten material is allowed to solidify into the final shape
- Casting defects occur during solidification
  - Gas porosity
  - Shrinkage
- Two stages of solidification
  - Nucleation
  - Growth



Nucleation

- Stable particles form from the liquid metal
- Occurs when there is a net release of energy from the liquid
- Undercooling is the difference between the melting point and the temperature at which nucleation occurs
- Each nucleation event produces a grain
  - Nucleation is promoted (more grains) for enhanced material properties
  - Inoculation or grain refinement is the process of introducing solid particles to promote nucleation

Grain Growth

- Occurs as the heat of fusion is extracted from the liquid
- Direction, rate, and type of growth can be controlled
  - Controlled by the way in which heat is removed
  - Rates of nucleation and growth control the size and shape of the crystals
  - Faster cooling rates generally produce finer grain sizes

Cooling Curves

- Useful for studying the solidification process
- Cooling rate is the slop of the cooling curve
- Solidification can occur over a range of temperatures in alloys
- Beginning and end of solidification are indicated by changes in slope

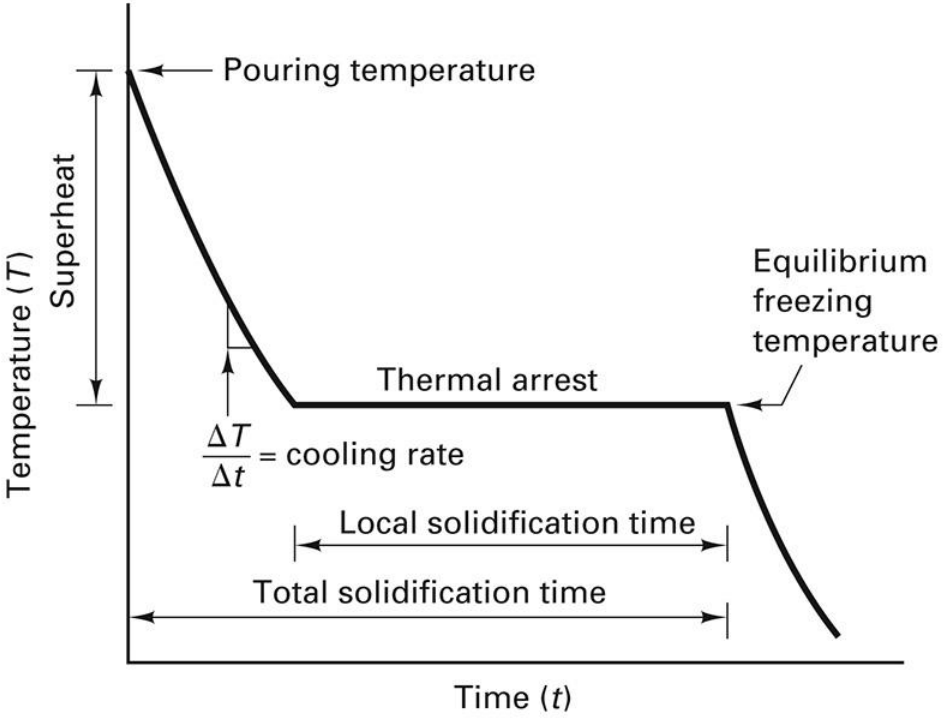


Figure 11-3 Cooling curve for a pure metal or eutectic-composition alloy (metals with a distinct freezing point), indicating major features related to solidification.

Cooling Curves

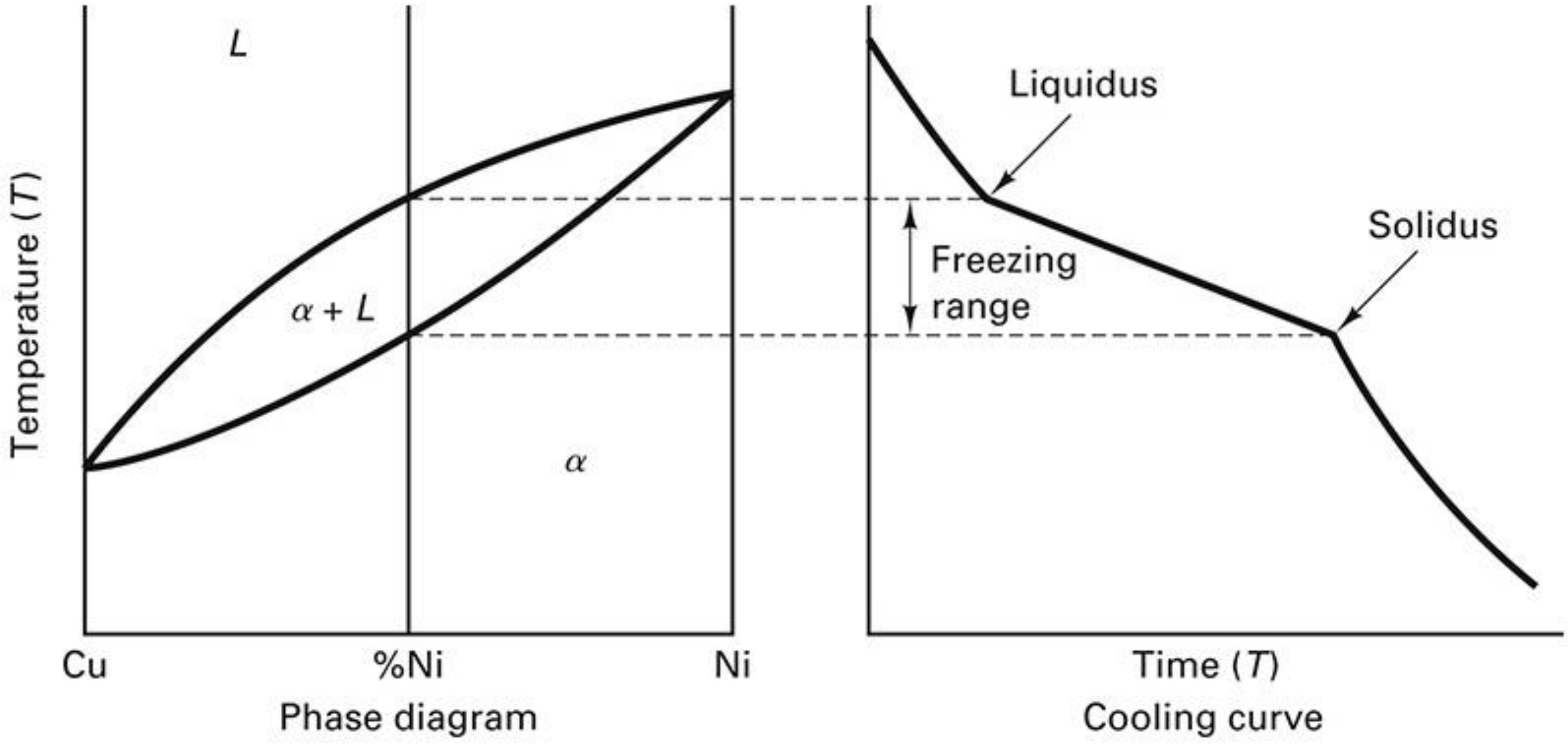


Figure 11-4 Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes indicate the onset and termination of solidification.

Prediction of Solidification Time: Chvorinov’s Rule

- Ability to remove heat from a casting is related to the surface area through which the heat is removed and the environment that it is rejecting heat to
- Chvorinov’s Rule:
  - $t_s=B(V/A)^n$ where n=1.5 to 2.0
- t_s is the time from pouring to solidification
- B is the mold constant
- V is the volume of the casting
- A is the surface area through which heat is rejected

Cast Structure

- Three distinct regions or zones
  - Chill zone
    - Rapid nucleation that occurs when the molten metal comes into contact with the cold walls of the mold
    - Forms a narrow band of randomly oriented crystals on the surface of a casting
  - Columnar zone
    - Rapid growth perpendicular to the casting surface
    - Long and thin
    - Highly directional
  - Equiaxed zone
    - Crystals in the interior of the casting
    - Spherical, randomly oriented crystals

Cast Structure

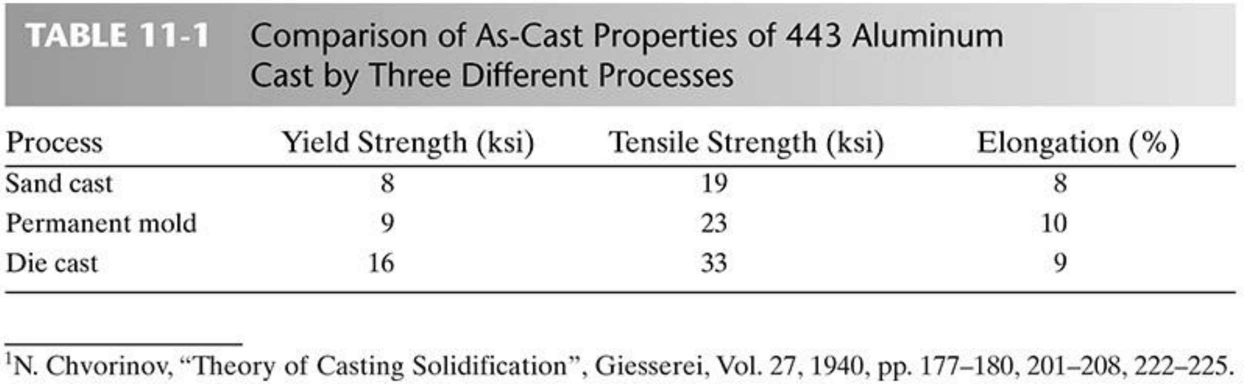


TABLE 11-1 Comparison of As-Cast Properties of 443 Aluminum Cast by Three Different Processes

Process	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
Sand cast	8	19	8
Permanent mold	9	23	10
Die cast	16	33	9

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[1] N. Chvorinov, "Theory of Casting Solidification", Giesserei, Vol. 27, 1940, pp. 177–180, 201–208, 222–225.

Figure 11-5 Internal structure of a cast metal bar showing the chill zone at the periphery, columnar grains growing toward the center, and a central shrinkage cavity.

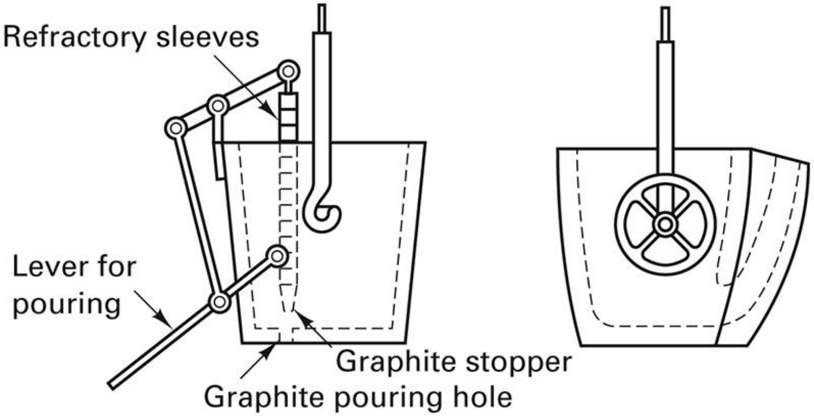
Molten Metal Problems

- Chemical reactions can occur between molten metal and its surroundings
- Reactions can lead to defects in the final castings
  - Metal oxides may form when molten metal reacts with oxygen
  - Dross or slag is the material that can be carried with the molten metal during pouring and filling of the mold
    - Affects the surface finish, machinability, and mechanical properties

Molten Metal Problems

- Gas porosity
  - Gas that is not rejected from the liquid metal may be trapped upon solidification
  - Several techniques to prevent gas porosity
    - Prevent the gas from initially dissolving in the liquid
      - Melting can be done in a vacuum
      - Melting can be done in environments with low-solubility gases
      - Minimize turbulence
    - Vacuum degassing removes the gas from the liquid before it is poured into the castings
    - Gas flushing- passing inert gases or reactive gases through the liquid metal

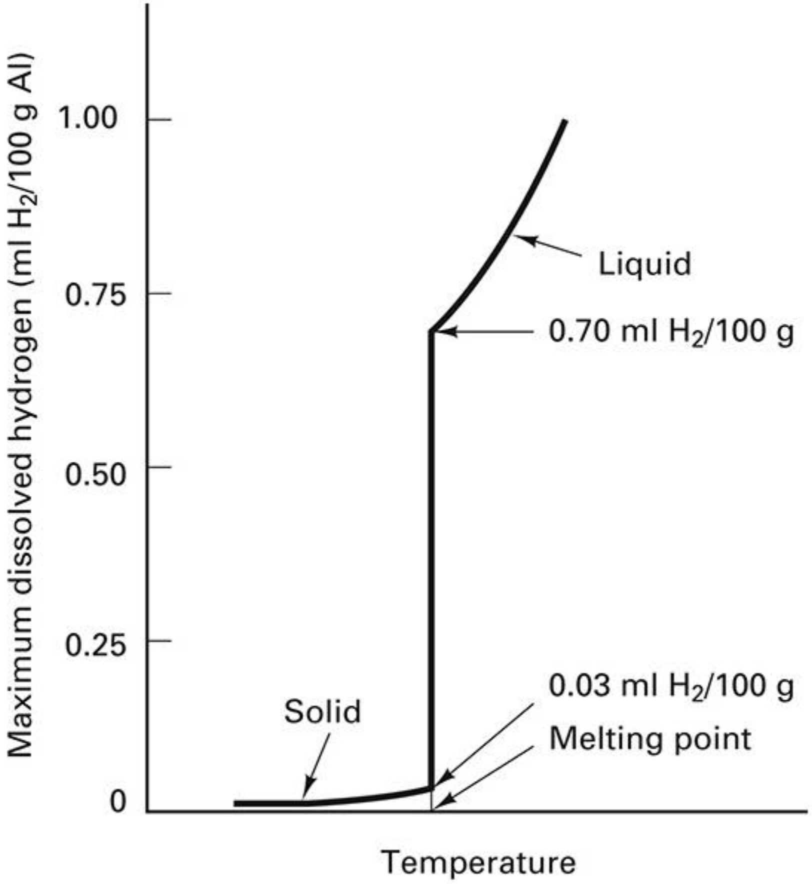
Molten Metal Problems



Bottom – pour ladle **Tea pot ladle**

Figure 11-6 Two types of ladles used to pour castings. Note how each extracts molten material from the bottom, avoiding transfer of the impure material from the top of the molten pool.

Figure 11-7 (Below) The maximum solubility of hydrogen in aluminum as a function of temperature.



Fluidity and Pouring Temperature

- Metal should flow into all regions of the mold cavity and then solidify
- Fluidity is the ability of a metal to flow and fill a mold
  - Affects the minimum section thickness, maximum length of a thin section, fineness of detail, ability to fill mold extremities
  - Dependent on the composition, freezing temperature, freezing range, and surface tension
- Most important controlling factor is pouring temperature

The Role of the Gating System

- Gating system delivers the molten metal to the mold cavity
- Controls the speed of liquid metal flow and the cooling that occurs during flow
- Rapid rates of filling can produce erosion of the mold cavity
  - Can result in the entrapment of mold material in the final casting
  - Cross sectional areas of the channels regulate flows

Gating Systems

- Proper design minimizes turbulence
- Turbulence promotes absorption of gases, oxidation, and mold erosion
- Choke- smallest cross-sectional area in the gating system
- Runner extensions and wells- used to catch and trap the first metal to enter the mold and prevent it from entering the mold cavity
- Filters- used to trap foreign material

Gating System

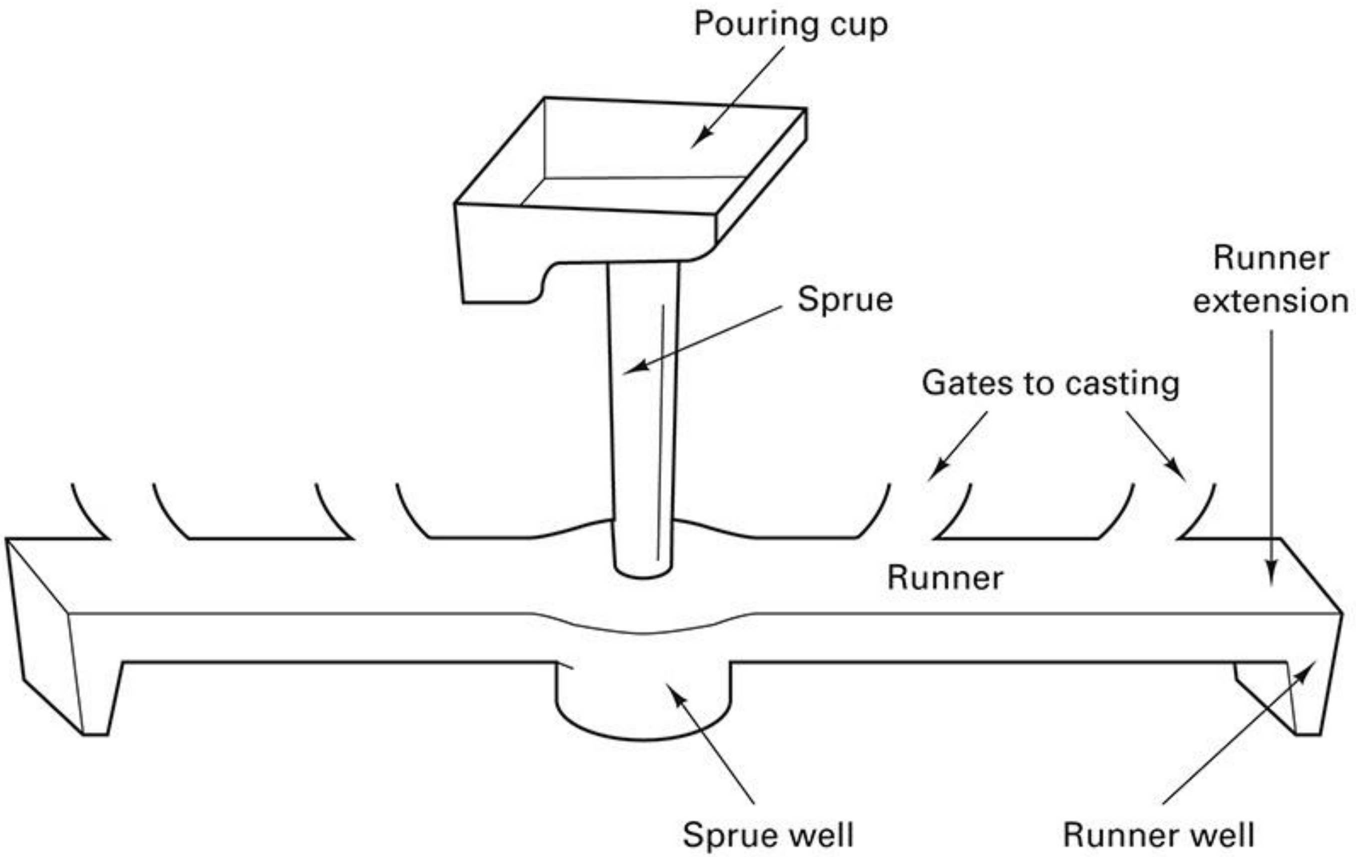


Figure 11-9 Typical gating system for a horizontal parting plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

Filters

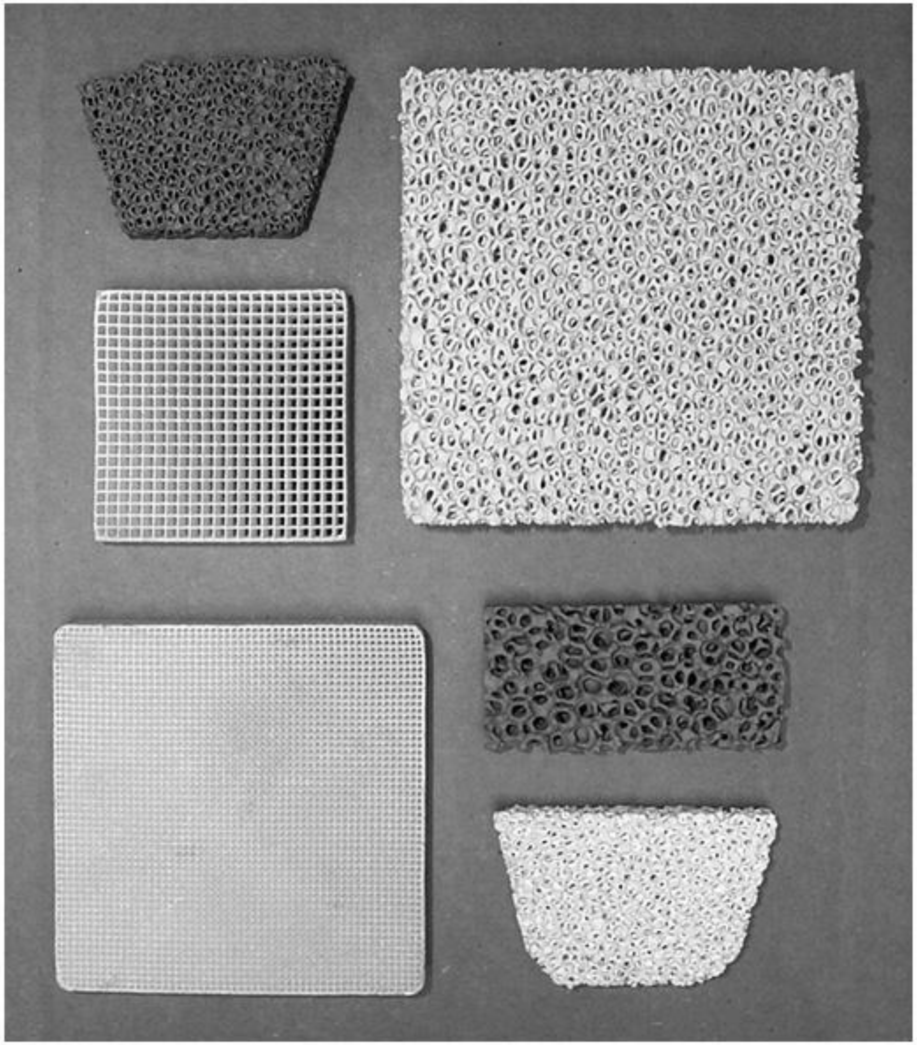


Figure 11-10 Various types of ceramic filters that may be inserted into the gating systems of metal castings.

Solidification Shrinkage

- Most metals undergo noticeable volumetric contraction when cooled
- Three principle stages of shrinkage:
  - Shrinkage of liquid as it cools from the solidification temperature
  - Solidification shrinkage as the liquid turns into solid
  - Solid metal contraction as the solidified metal cools to room temperature

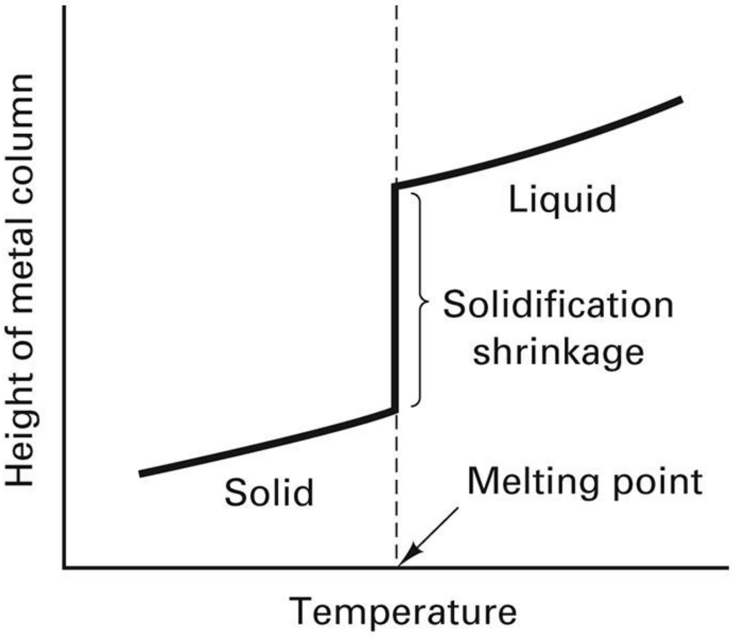


Figure 11-11 Dimensional changes experienced by a metal column as the material cools from a superheated liquid to a room-temperature solid. Note the significant shrinkage that occurs upon solidification.

Solidification Shrinkage

- Amount of liquid metal contraction depends on the coefficient of thermal contraction and the amount of superheat
- As the liquid metal solidifies, the atomic structure normally becomes more efficient and significant amounts of shrinkage can occur
- Cavities and voids can be prevented by designing the casting to have directional solidification
- Hot tears can occur when there is significant tensile stress on the surface of the casting material

Risers and Riser Design

- Risers are reservoirs of liquid metal that feed extra metal to the mold to compensate for shrinkage
- Risers are designed to conserve metal
- Located so that directional solidification occurs from the extremities of the mold toward the riser
- Should feed directly to the thickest regions of the casting
- Blind riser- contained entirely within the mold cavity
- Live riser- receive the last hot metal that enters the mold

Risers and Riser Design

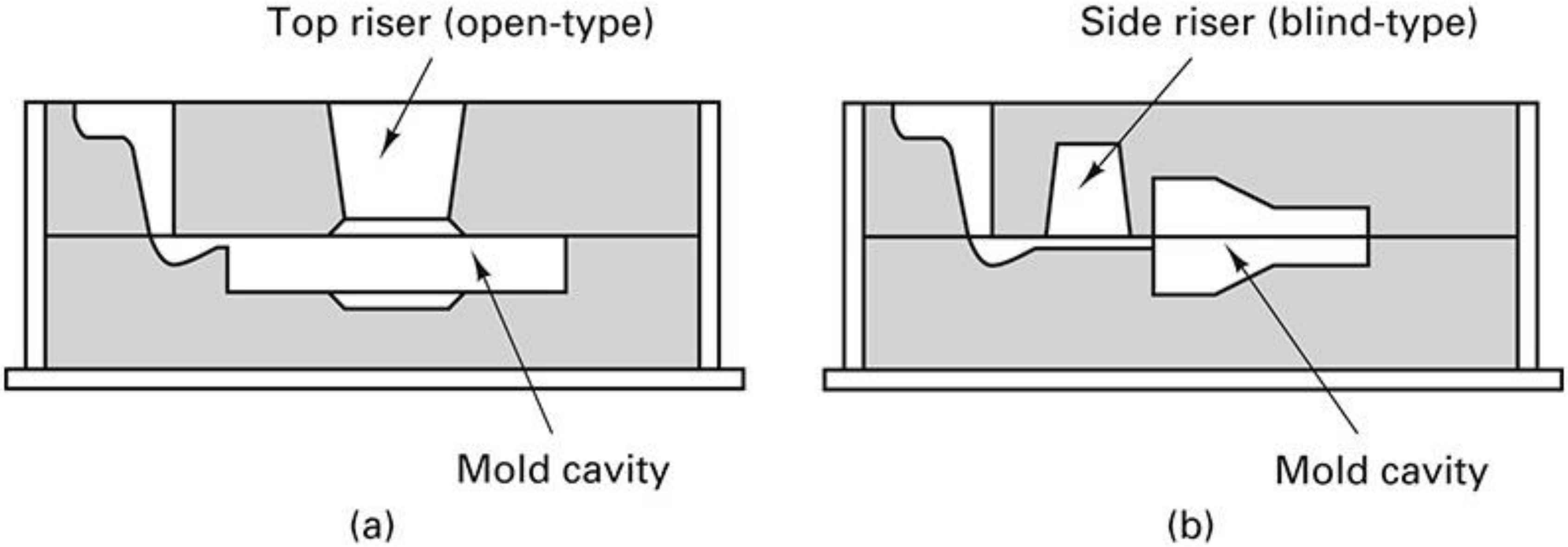


Figure 11-13 Schematic of a sand casting mold, showing a) an open-type top riser and b) a blind-type side riser. The side riser is a live riser, receiving the last hot metal to enter the mold. The top riser is a dead riser, receiving metal that has flowed through the mold cavity.

- Riser must be separated from the casting upon completion so the connection area must be as small as possible

Riser Aids

- Riser’s performance may be enhanced by speeding the solidification of the casting (chills) or slowing down the solidification (sleeves or toppings)
- External chills
  - Masses of high-heat capacity material placed in the mold
  - Absorb heat and accelerate cooling in specific regions
- Internal chills
  - Pieces of metal that are placed in the mold cavity and promote rapid solidification
  - Ultimately become part of the cast part

13.5 Patterns

- Two basic categories for casting processes
  - Expendable mold processes
  - Permanent mold processes
- Patterns are made from wood, metal, foam, or plastic
- Dimensional modification are incorporated into the design (allowances)
  - Shrinkage allowance is the most important
  - Pattern must be slightly larger than the desired part

Dimensional Allowances

- Typical allowances

Cast iron	0.8-1.0%
Steel	1.5-2.0%
Aluminum	1.0-1.3%
Magnesium	1.0-1.3%
Brass	1.5%

- Shrinkage allowances are incorporated into the pattern using shrink rules
- Thermal contraction might not be the only factor for determining pattern size
- Surface finishing operations (machining, etc.) should be taken into consideration

Pattern Removal

- Parting lines are the preferred method
- Damage can be done to the casting at corners or parting surfaces if tapers or draft angles are not used in the pattern
  - Factors that influence the needed draft
    - Size and shape of pattern
    - Depth of mold cavity
    - Method used to withdraw pattern
    - Pattern material
    - Mold material
    - Molding procedure

Design Considerations

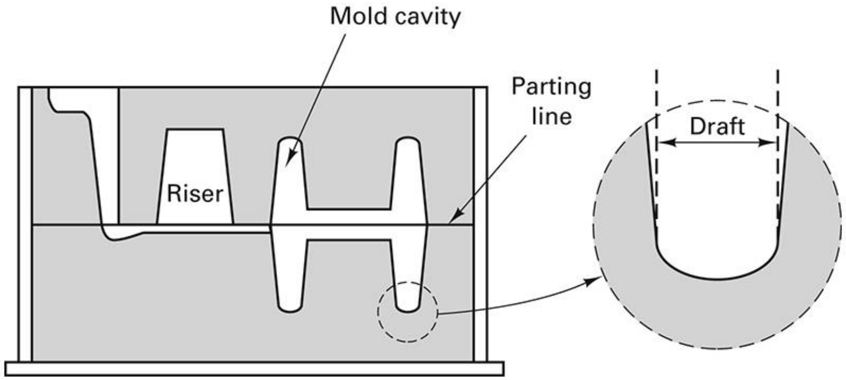


Figure 11-14 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

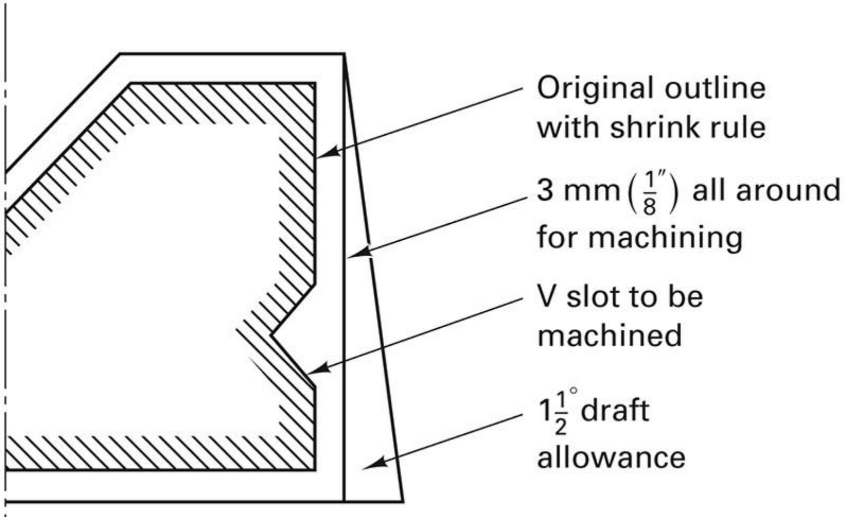


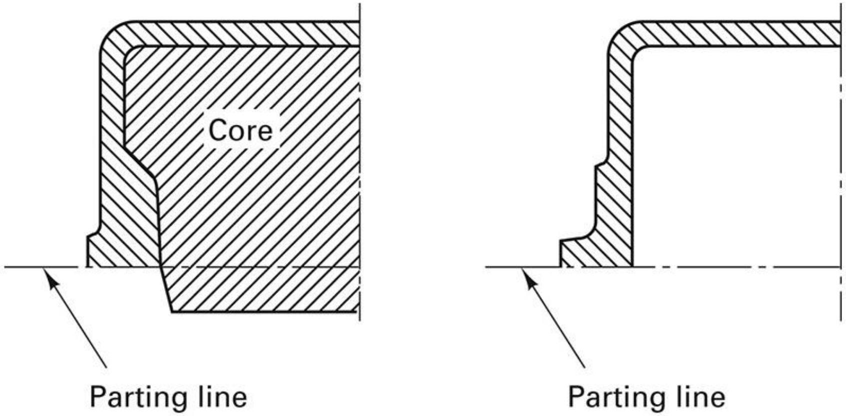
Figure 11-15 Various allowances incorporated into a casting pattern.

13.6 Design Considerations in Castings

- Location and orientation of the parting line is important to castings
- Parting line can affect:
    - Number of cores
    - Method of supporting cores
    - Use of effective and economical gating
    - Weight of the final casting
    - Final dimensional accuracy
    - Ease of molding

Design Considerations

Figure 11-17 (Right) Elimination of a dry-sand core by a change in part design.



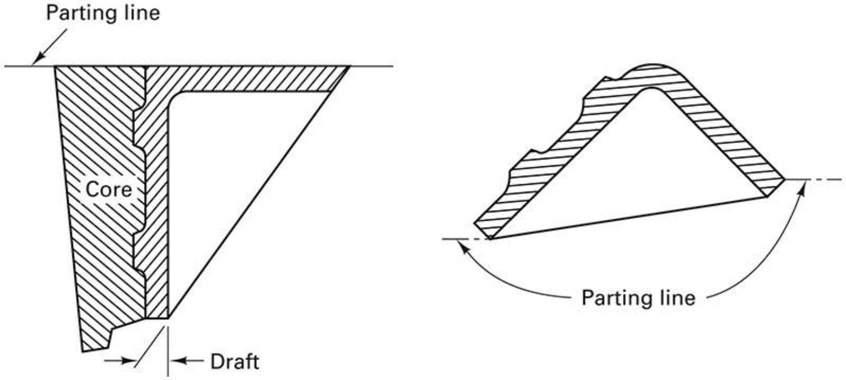
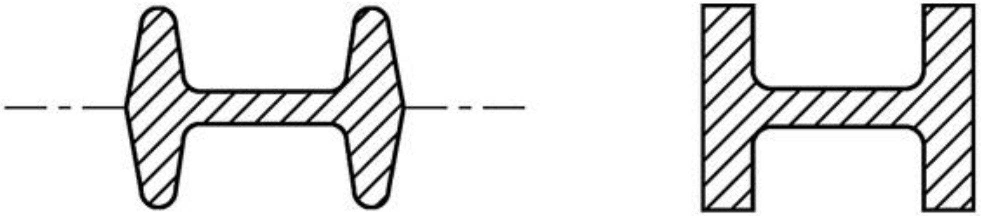


Figure 11-16 (Left) Elimination of a core by changing the location or orientation of the parting plane.

Design Considerations

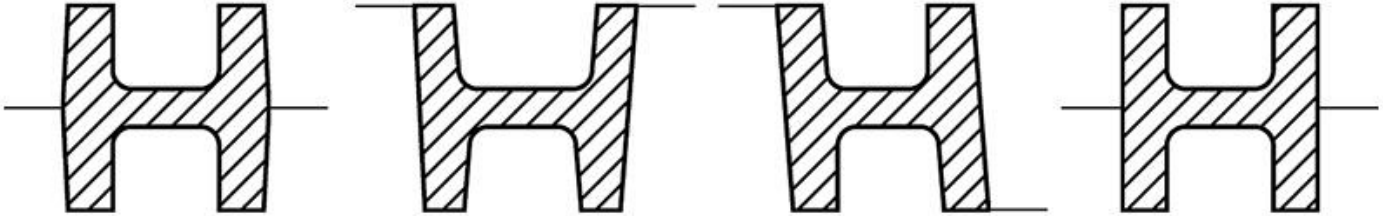
- It is often desirable to minimize the use of cores
- Controlling the solidification process is important to producing quality castings
- Thicker or heavier sections will cool more slowly, so chills should be used
  - If section thicknesses must change, gradual is better
  - If they are not gradual, stress concentration points can be created
    - Fillets or radii can be used to minimize stress concentration points
    - Risers can also be used

Parting Line and Drafts



As shown on drawing

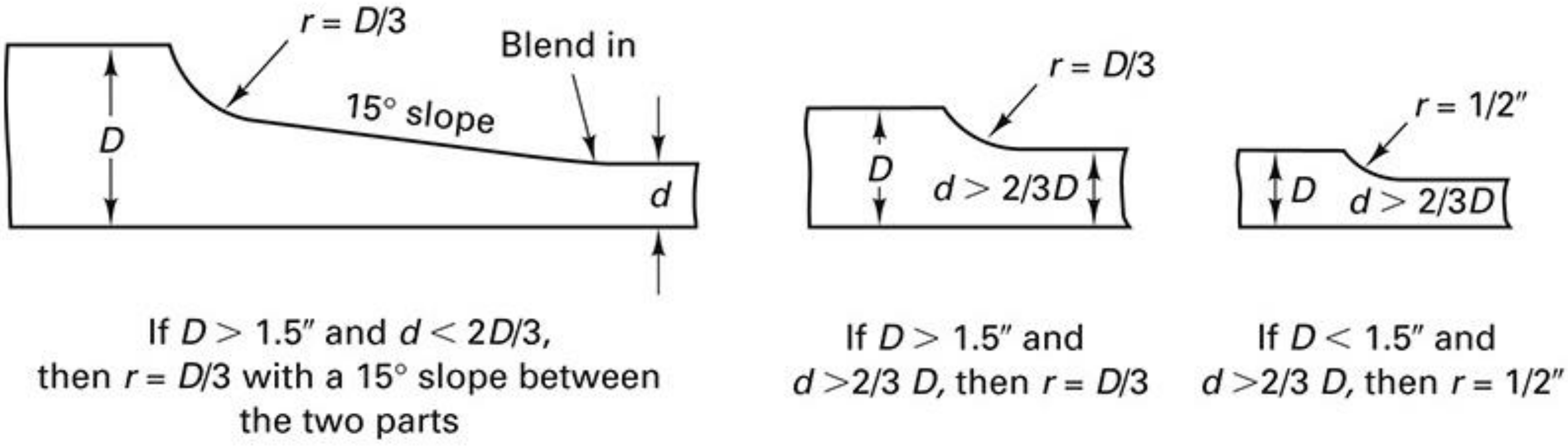
As shown on drawing, with draft permitted by note



Optional results, with and without draft (exaggerated)

Figure 11-18 (Top left) Design where the location of the parting plane is specified by the draft. (Top right) Part with draft unspecified. (Bottom) Various options to produce the top-right part, including a no-draft design.

Section Thicknesses



If $D > 1.5''$ and $d < 2D/3$, then $r = D/3$ with a 15° slope between the two parts

If $D > 1.5''$ and $d > 2/3\ D$, then $r = D/3$

If $D < 1.5''$ and $d > 2/3\ D$, then $r = 1/2''$

Figure 11-19 (Above) Typical guidelines for section change transitions in castings.

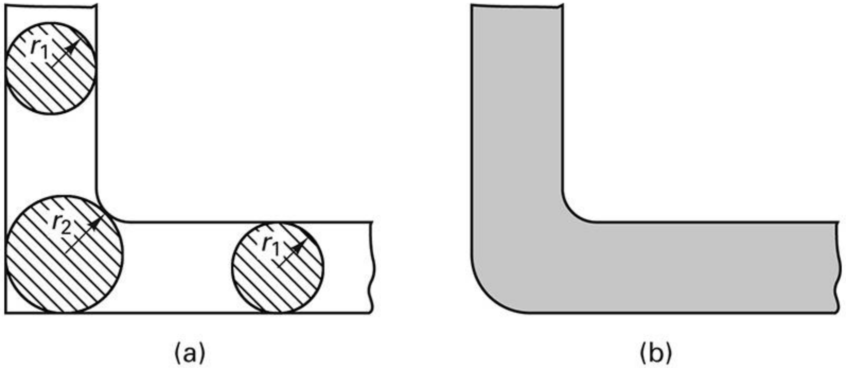


Figure 11-20 a) The “hot spot” at section r_2 is cause by intersecting sections. B) An interior fillet and exterior radius lead to more uniform thickness and more uniform cooling.

Design Modifications

- Hot spots are areas of the material that cool more slowly than other locations
  - Function of part geometry
  - Localized shrinkage may occur

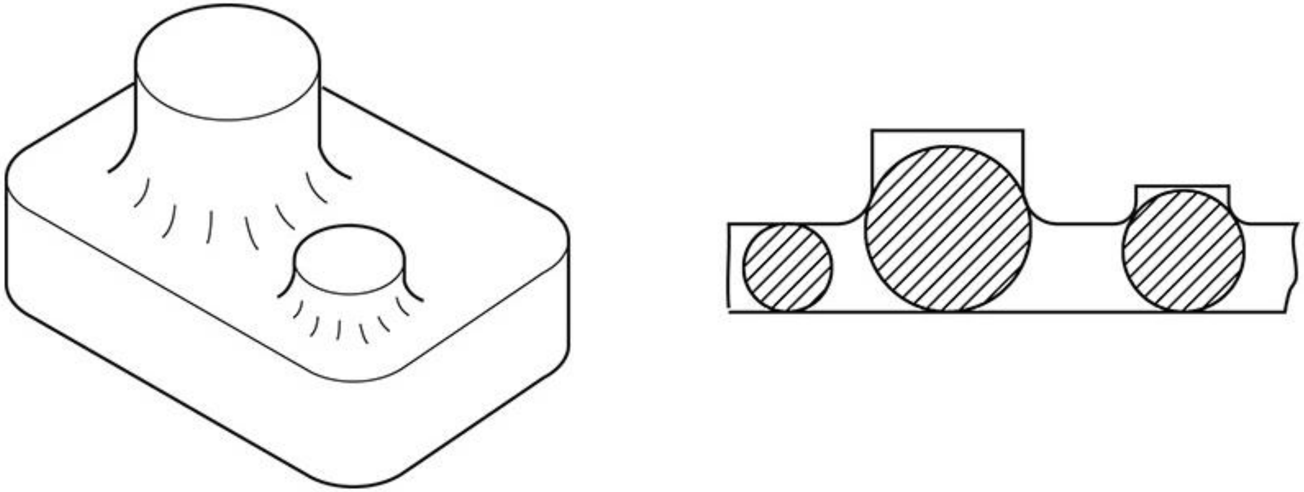
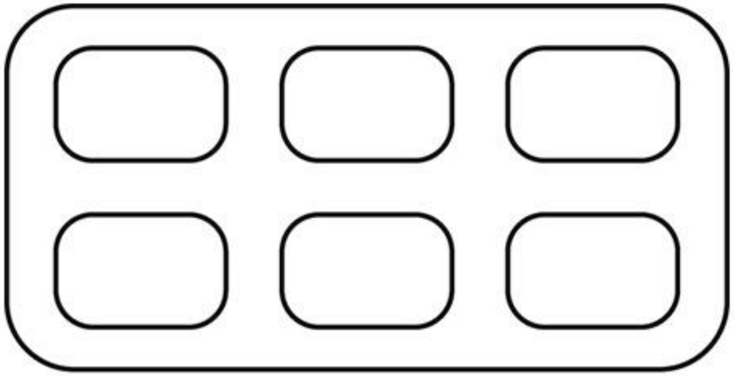


Figure 11-21 Hot spots often result from intersecting sections of various thickness.

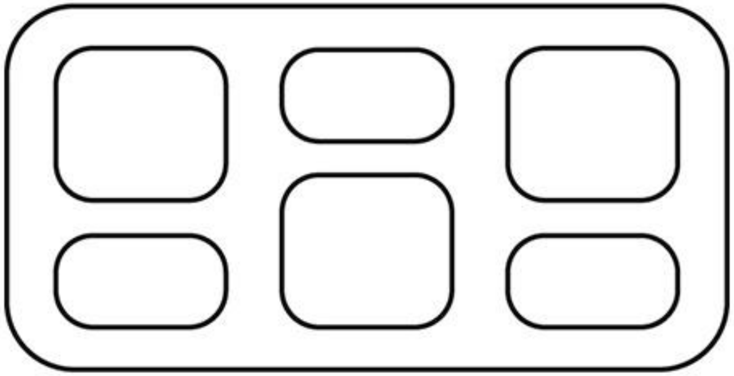
Design Modifications

- Parts that have ribs may experience cracking due to contraction
    - Ribs may be staggered to prevent cracking
- An excess of material may appear around the parting line
    - The parting line may be moved to improve appearance
- Thin-walled castings should be designed with extra caution to prevent cracking

Design Modifications



Bad



Better

Figure 11-23 Using staggered ribs to prevent cracking during cooling.

Casting Designs

- May be aided by computer simulation
- Mold filling may be modeled with fluid flow software
- Heat transfer models can predict solidification

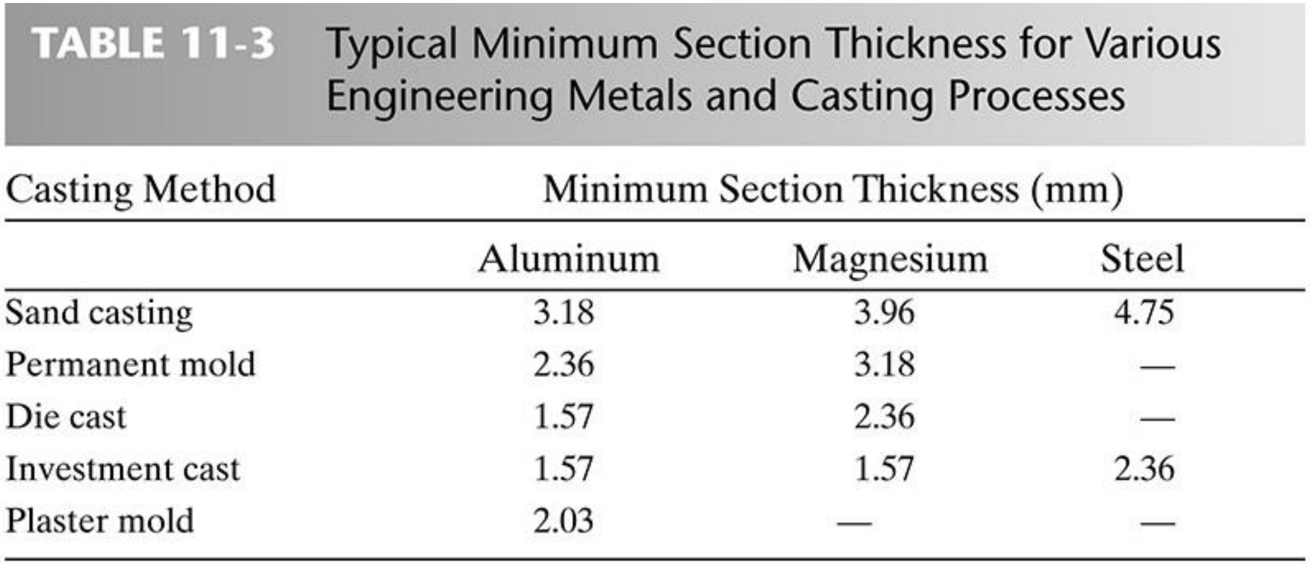


TABLE 11-3 Typical Minimum Section Thickness for Various Engineering Metals and Casting Processes

Casting Method	Minimum Section Thickness (mm)		
	Aluminum	Magnesium	Steel
Sand casting	3.18	3.96	4.75
Permanent mold	2.36	3.18	—
Die cast	1.57	2.36	—
Investment cast	1.57	1.57	2.36
Plaster mold	2.03	—	—

13.7 The Casting Industry

- 14 million pounds of castings are produced every year
- The most common materials cast are gray iron, ductile iron, aluminum alloys, and copper alloys
- 35% of the market is in automotive and light truck manufacturing
- Castings are used in applications ranging from agriculture to railroad equipment and heating and refrigeration

Summary

- A successful casting requires that every aspect of the process be examined
- Every aspect from the desired grain structure to the desired finish of the product should be considered during design stages
- Efforts should be made to minimize cracking and defects
- There are a variety of processes to improve castings and they should all be considered during the design phase

Chapter 14: Expendable-Mold Casting Process

DeGarmo’s Materials and Processes in Manufacturing

14.1 Introduction

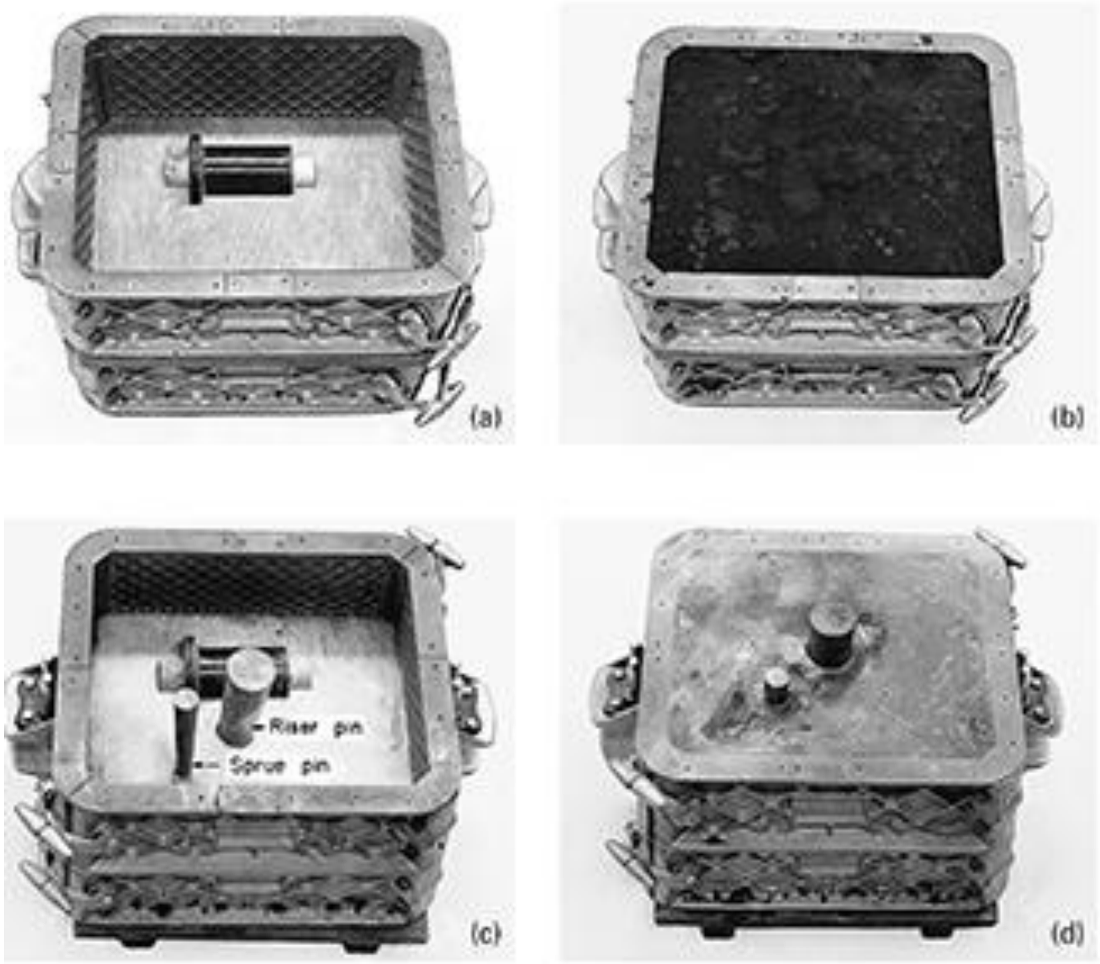
- Factors to consider for castings
  - Desired dimensional accuracy
  - Surface quality
  - Number of castings
  - Type of pattern and core box needed
  - Cost of required mold or die
  - Restrictions due to the selected material
- Three categories of molds
  - Single-use molds with multiple-use patterns
  - Single-use molds with single-use patterns
  - Multiple-use molds

14.2 Sand Casting

- Sand casting is the most common and versatile form of casting
  - Granular material is mixed with clay and water
  - Packed around a pattern
- Gravity flow is the most common method of inserting the liquid metal into the mold
- Metal is allowed to solidify and then the mold is removed

Sand Casting

Figure 12-1 Sequential steps in making a sand casting. a) A pattern board is placed between the bottom (drag) and top (cope) halves of a flask, with the bottom side up. b) Sand is then packed into the bottom or drag half of the mold. c) A bottom board is positioned on top of the packed sand, and the mold is turned over, showing the top (cope) half of pattern with sprue and riser pins in place. d) The upper or cope half of the mold is then packed with sand.



Sand Casting

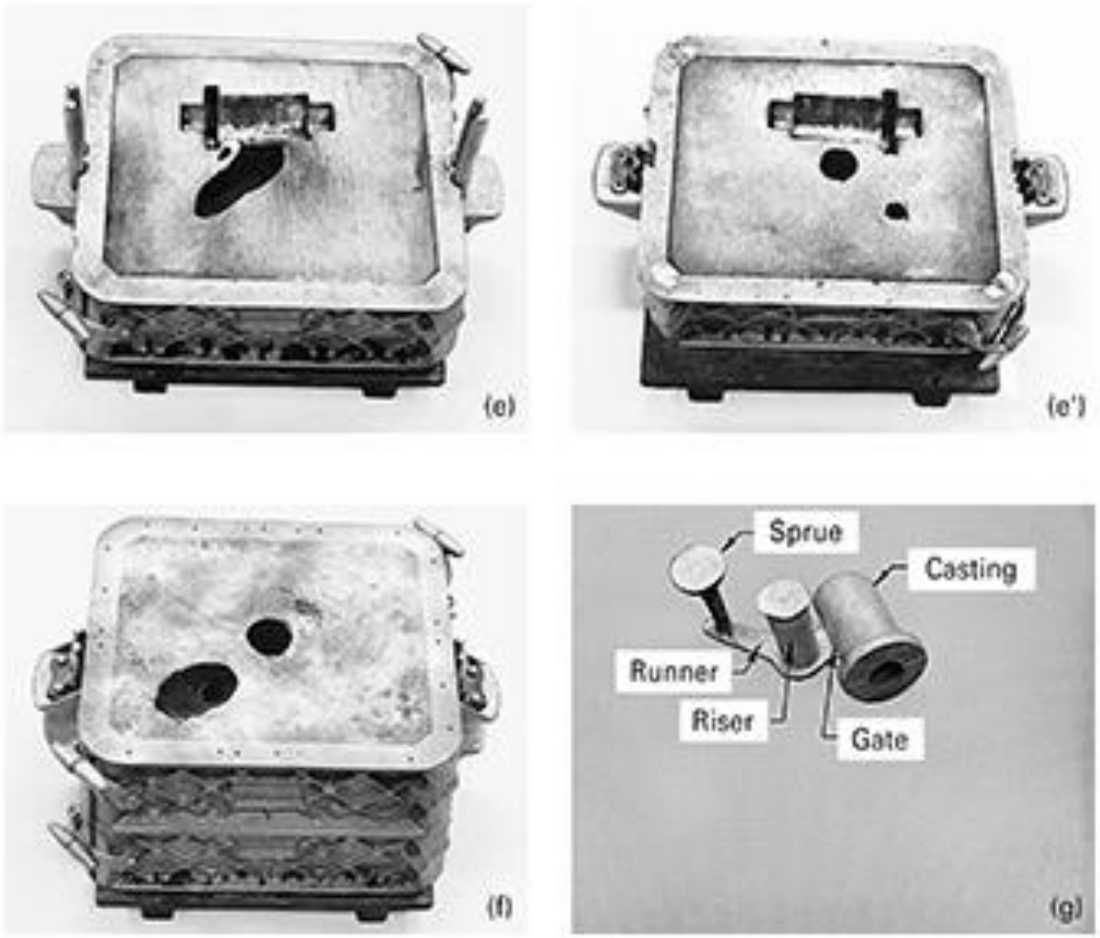


Figure 12-1 e) The mold is opened, the pattern board is drawn (removed), and the runner and gate are cut into the bottom parting surface of the sand. e') The parting surface of the upper or cope half of the mold is also shown with the pattern and pins removed. f) The mold is reassembled with the pattern board removed, and molten metal is poured through the sprue. g) The contents are shaken from the flask and the metal segment is separated from the sand, ready for further processing.

Patterns and Pattern Materials

- First step in casting is to design and construct the pattern
- Pattern selection is determined by the number of castings, size and shape of castings, desired dimensional precision, and molding process
- Pattern materials
  - Wood patterns are relatively cheap, but not dimensionally stable
  - Metal patterns are expensive, but more stable and durable
  - Hard plastics may also be used

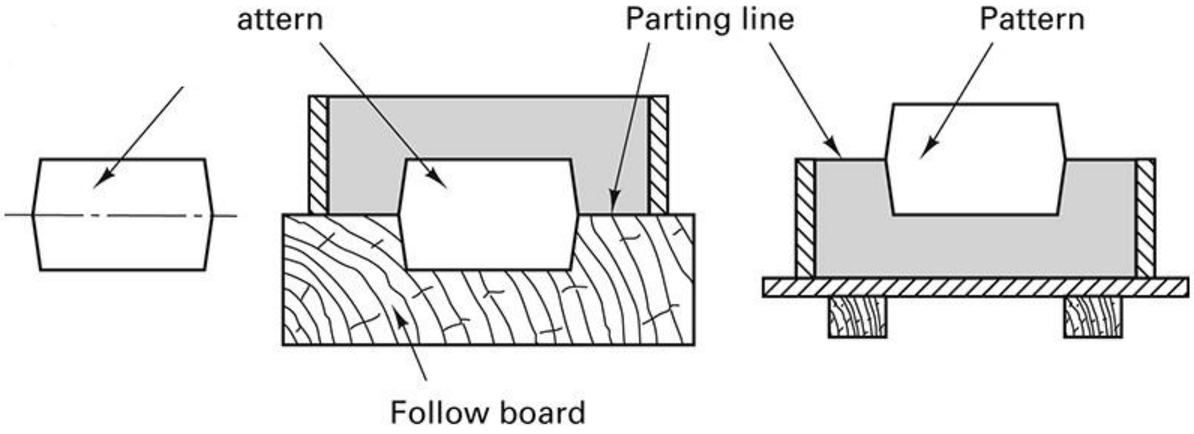
Types of Patterns

- The type of pattern is selected based on the number of castings and the complexity of the part
- One-piece or solid patterns are used when the shape is relatively simple and the number of castings is small
- Split patterns are used for moderate quantities
  - Pattern is divided into two segments

Types of Patterns

Figure 12-2 (Above) Single-piece pattern for a pinion gear.

Figure 12-3 (Below) Method of using a follow board to position a single-piece pattern and locate a parting surface. The final figure shows the flask of the previous operation (the drag segment) inverted in preparation for construction of the upper portion of the mold (cope segment).



Types of Patterns

- Match-plate patterns
  - Cope and drag segments of a split pattern are permanently fastened
  - Pins and guide holes ensure that the cope and drag will be properly aligned on reassembly
- Cope and drag patterns
  - Used for large quantities of castings
  - Multiple castings can occur at once
  - Two or more patterns on each cope and drag

Types of Patterns

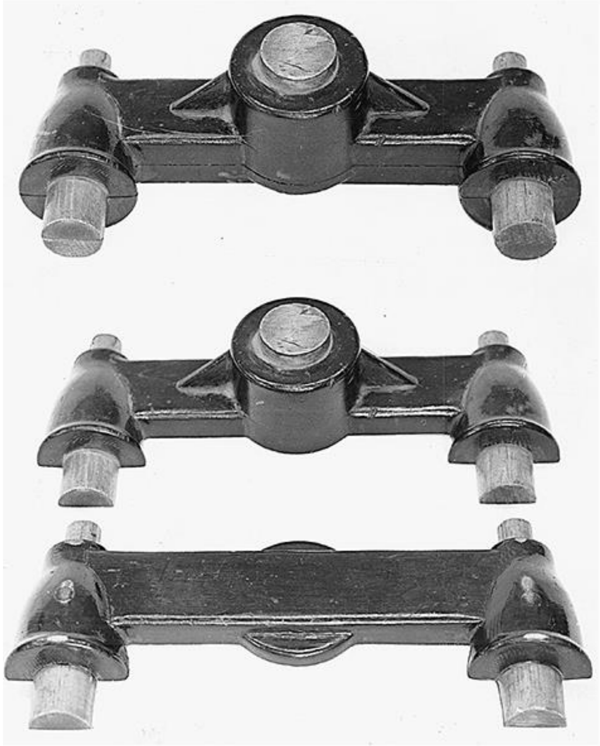


Figure 12-4 Split pattern, showing the two sections together and separated. The light-colored portions are core prints.

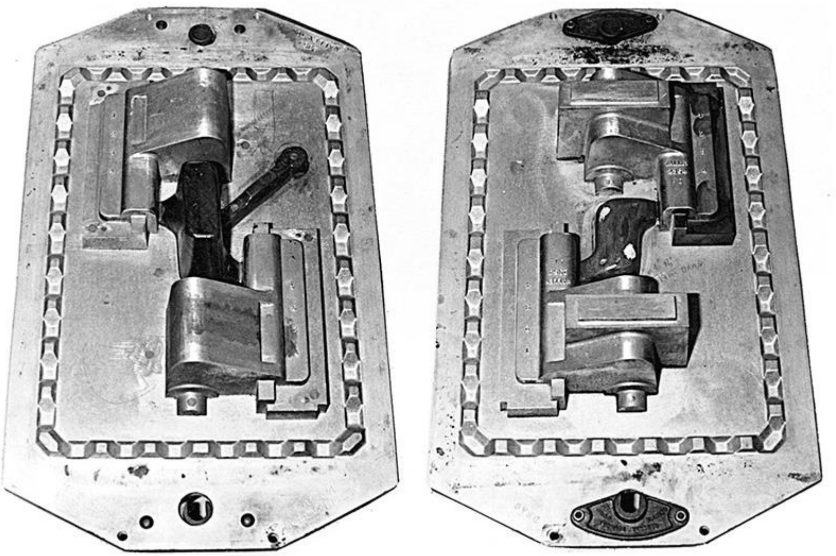


Figure 12-5 Match-plate pattern used to produce two identical parts in a single flask. (Left) Cope side; (right) drag side. (Note: The views are opposite sides of a single-pattern board.

Cope and Drag Patterns

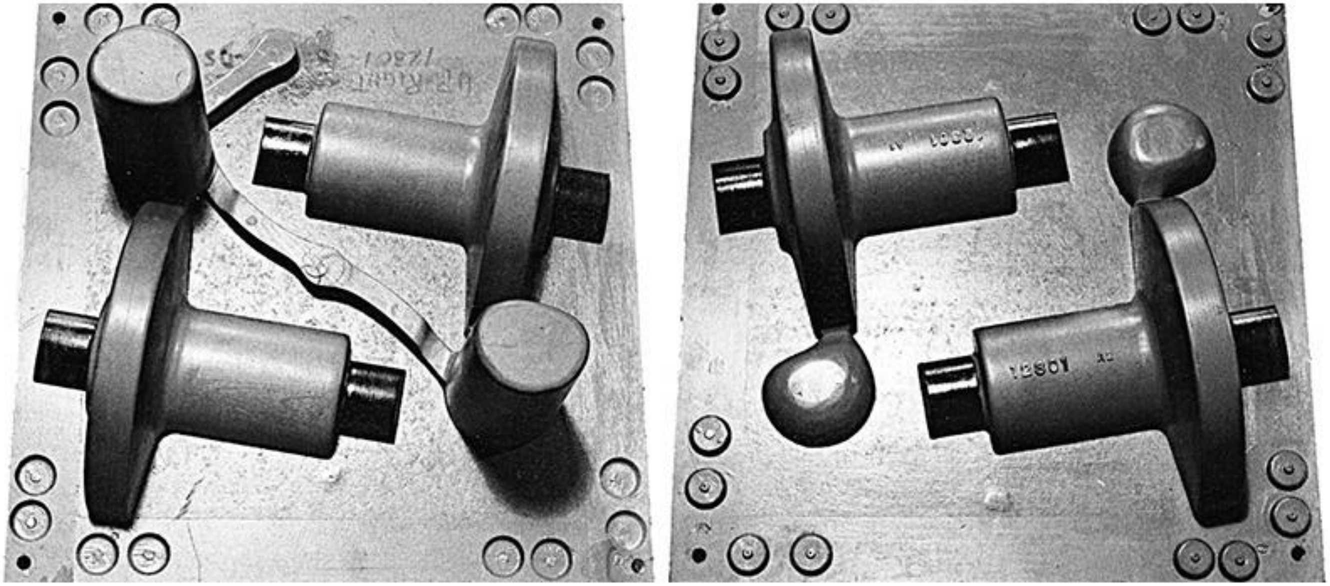


Figure 12-6 Cope-and-drag pattern for producing two heavy parts. (Left) Cope section; (right) drag section. (Note: These are two separate pattern boards.)

Sands and Sand Conditioning

- Four requirements of sand used in casting
  - Refractoriness-ability withstand high temperatures
  - Cohesiveness-ability to retain shape
  - Permeability-ability of a gases to escape through the sand
  - Collapsibility-ability to accommodate shrinkage and part removal
- Size of sand particles, amount of bonding agent, moisture content, and additives are selected to obtain sufficient requirements

Processing of Sand

- Green-sand mixture is 88% silica, 9% clay, and 3% water
- Each grain of sand needs to be coated uniformly with additive agents
- Muller kneads, rolls, and stirs the sand to coat it

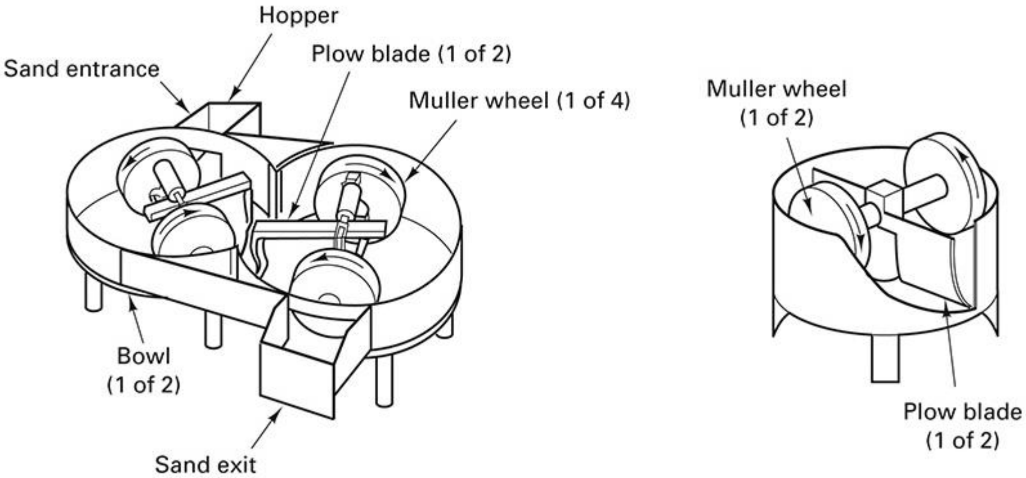


Figure 12-8 Schematic diagram of a continuous (left) and batch-type (right) sand muller. Plow blades move and loosen the sand, and the muller wheels compress and mix the components. (Courtesy of ASM International. Metals Park, OH.)

Sand Testing

- Blended molding sand is characterized by the following attributes
  - Moisture content, clay content, compactibility
- Properties of compacted sand
  - Mold hardness, permeability, strength
- Standard testing
  - Grain size
  - Moisture content
  - Clay content
  - Permeability
  - Compressive strength
  - Ability to withstand erosion
  - Hardness
  - Compactibility

Sand Testing Equipment

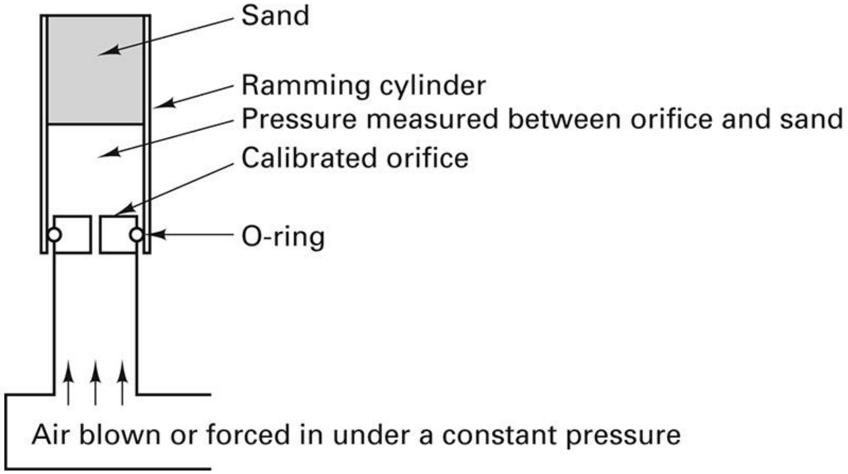
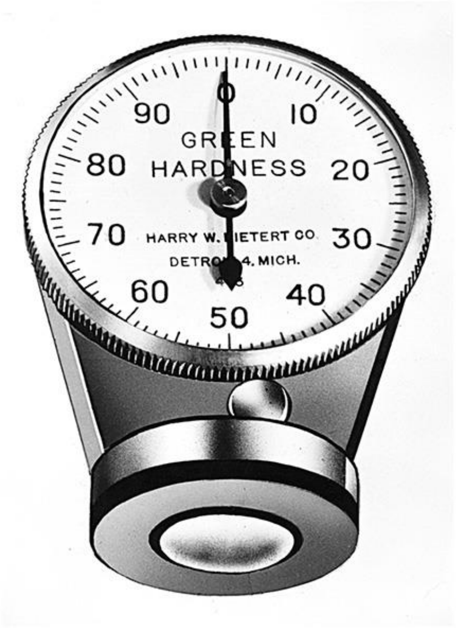


Figure 12-9 Schematic of a permeability tester in operation. A standard sample in a metal sleeve is sealed by an O-ring onto the top of the unit while air is passed through the sand. (Courtesy of Dietert Foundry Testing Equipment Inc, Detroit, MI)

Figure 12-10 Sand mold hardness tester. (Courtesy of Dietert Foundry Testing Equipment Inc., Detroit, MI)



Sand Properties and Sand-Related Defects

- Silica sand
  - Cheap and lightweight but undergoes a phase transformation and volumetric expansion when it is heated to 585°C
- Castings with large, flat surfaces are prone to sand expansion defects
- Trapped or dissolved gases can cause gas-related voids or blows

Sand Properties

- Penetration occurs when the sand grains become embedded in the surface of the casting
- Hot tears or crack occur in metals with large amounts of solidification shrinkage
  - Tensile stresses develop while the metal is still partially liquid and if these stresses do not go away, cracking can occur.

Sand Properties

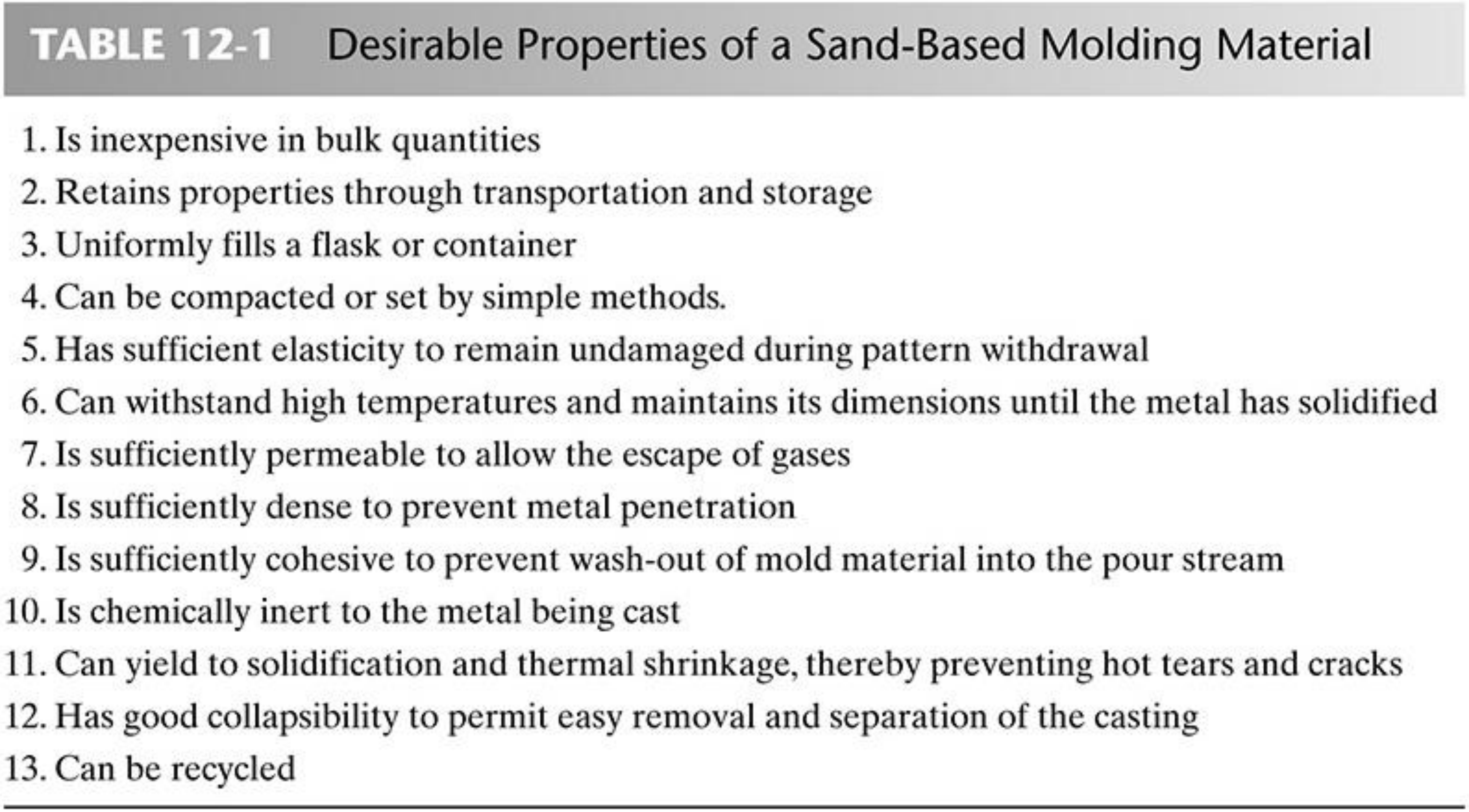


TABLE 12-1 Desirable Properties of a Sand-Based Molding Material

1. Is inexpensive in bulk quantities
2. Retains properties through transportation and storage
3. Uniformly fills a flask or container
4. Can be compacted or set by simple methods.
5. Has sufficient elasticity to remain undamaged during pattern withdrawal
6. Can withstand high temperatures and maintains its dimensions until the metal has solidified
7. Is sufficiently permeable to allow the escape of gases
8. Is sufficiently dense to prevent metal penetration
9. Is sufficiently cohesive to prevent wash-out of mold material into the pour stream
10. Is chemically inert to the metal being cast
11. Can yield to solidification and thermal shrinkage, thereby preventing hot tears and cracks
12. Has good collapsibility to permit easy removal and separation of the casting
13. Can be recycled

The Making of Sand Molds

- Hand ramming is the method of packing sand to produce a sand mold
  - Used when few castings are to be made
  - Slow, labor intensive
  - Nonuniform compaction
- Molding machines
  - Reduce the labor and required skill
  - Castings with good dimensional accuracy and consistency

The Making of Sand Molds

- Molds begin with a pattern and a flask
- Mixed sand is packed in the flask
  - Sand slinger uses rotation to fling sand against the pattern
  - Jolting is a process in which sand is placed over the flask and pattern and they are all lifted and dropped to compact the sand
  - Squeezing machines use air and a diaphragm
- For match plate molding, a combination of jolting and squeezing is used

Methods of Compacting Sand

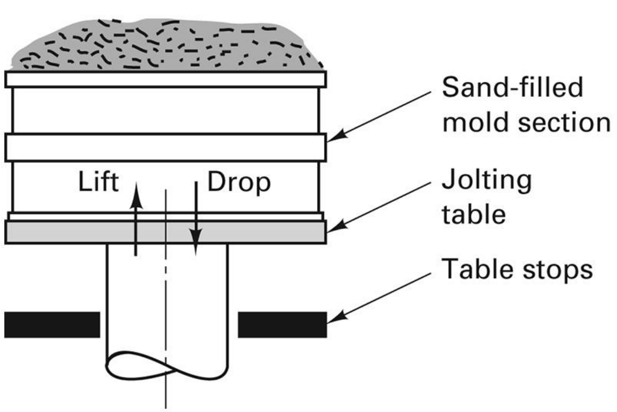


Figure 12-12 (Above) Jolting a mold section. (Note: The pattern is on the bottom, where the greatest packing is expected.)

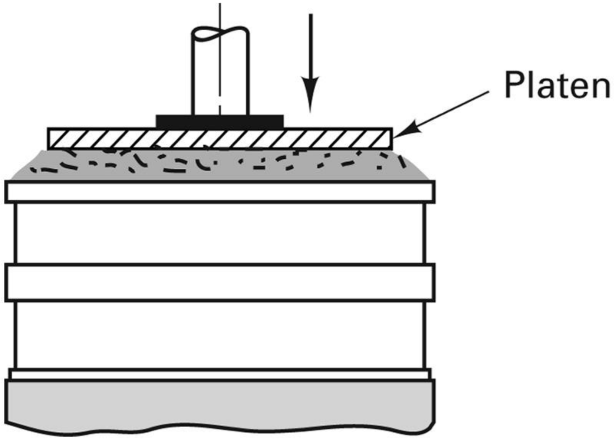


Figure 12-13 (Above) Squeezing a sand-filled mold section. While the pattern is on the bottom, the highest packing will be directly under the squeeze head.

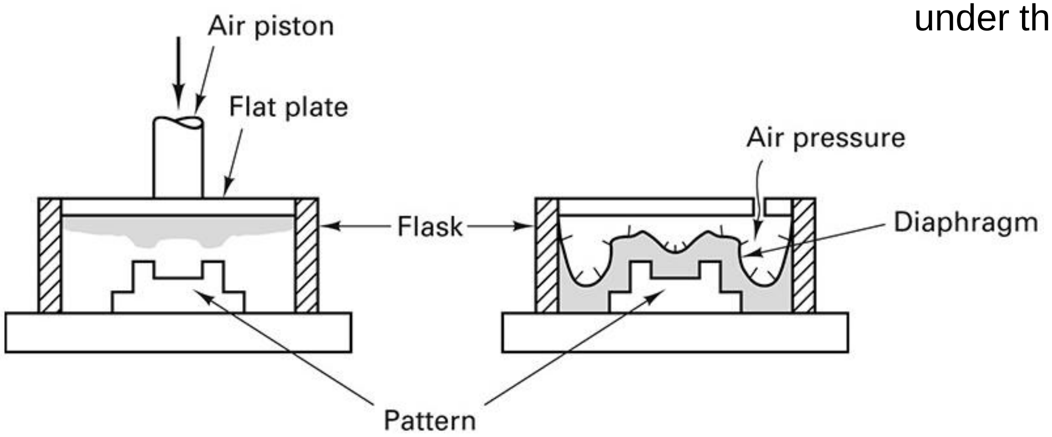


Figure 12-14 (Left) Schematic diagram showing relative sand densities obtained by flat-plate squeezing, where all areas get vertically compressed by the same amount of movement (left) and by flexible-diaphragm squeezing, where all areas flow to the same resisting pressure (right).

Alternative Molding Methods

- Stack molding
  - Molds containing a cope impression on the bottom and a drag impression on the top are stacked on top of one another vertically
  - Common vertical sprue
- Large molds
  - Large flasks can be placed directly on the foundry floor
  - Sand slingers may be used to pack the sand
  - Pneumatic rammers may be used

Green-Sand, Dry-Sand, and Skin-Dried Molds

- Green-sand casting
  - Process for both ferrous and nonferrous metals
  - Sand is blended with clay, water, and additives
  - Molds are filled by a gravity feed
  - Low tooling costs
  - Least expensive
- Design limitations
  - Rough surface finish
  - Poor dimensional accuracy
  - Low strength

Green-Sand Casting

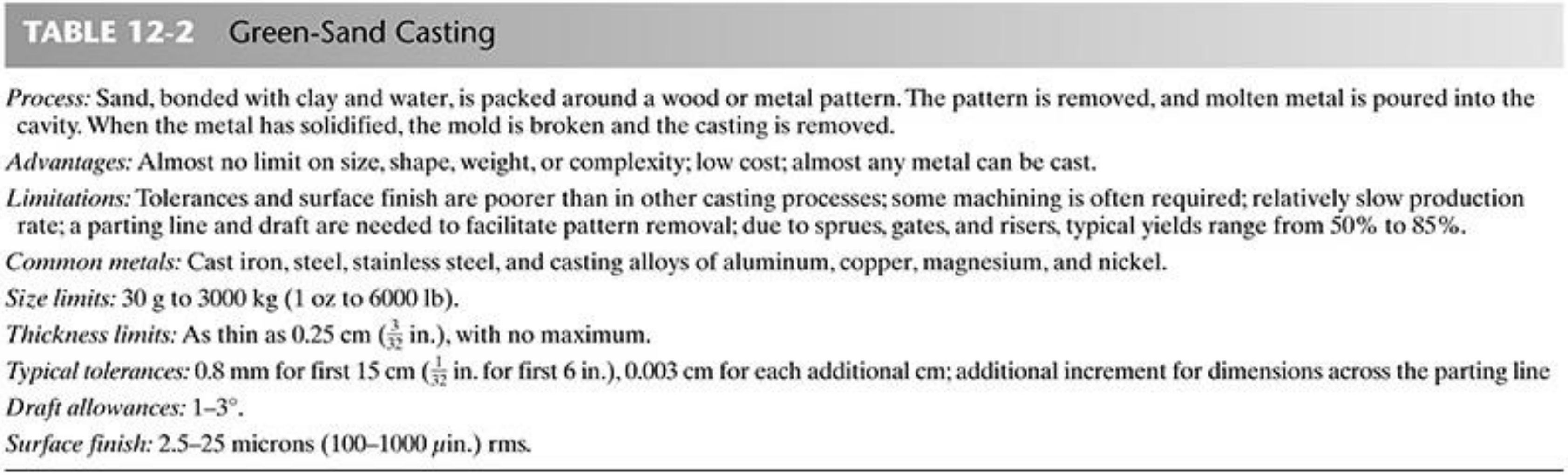


TABLE 12-2 Green-Sand Casting

Process: Sand, bonded with clay and water, is packed around a wood or metal pattern. The pattern is removed, and molten metal is poured into the cavity. When the metal has solidified, the mold is broken and the casting is removed.

Advantages: Almost no limit on size, shape, weight, or complexity; low cost; almost any metal can be cast.

Limitations: Tolerances and surface finish are poorer than in other casting processes; some machining is often required; relatively slow production rate; a parting line and draft are needed to facilitate pattern removal; due to sprues, gates, and risers, typical yields range from 50% to 85%.

Common metals: Cast iron, steel, stainless steel, and casting alloys of aluminum, copper, magnesium, and nickel.

Size limits: 30 g to 3000 kg (1 oz to 6000 lb).

Thickness limits: As thin as 0.25 cm ($\frac{3}{32}$ in.), with no maximum.

Typical tolerances: 0.8 mm for first 15 cm ($\frac{1}{32}$ in. for first 6 in.), 0.003 cm for each additional cm; additional increment for dimensions across the parting line

Draft allowances: 1–3°.

Surface finish: 2.5–25 microns (100–1000 μin.) rms.

Dry-Sand

- Dry-sand molds are durable
  - Long storage life
  - Long time required for drying
- Skin-dried molds
  - Dries only the sand next to the mold cavity
  - Torches may be used to dry the sand
  - Used for large steel parts
  - Binders may be added to enhance the strength of the skin-dried layer

Cast Parts

Figure 12-17 A variety of sand cast aluminum parts. (Courtesy of Bodine Aluminum Inc., St. Louis, MO)

Sodium Silicate-CO_2 Molding

- Molds and cores can receive strength from the addition of 3-6% sodium silicate
- Remains soft and moldable until it is exposed to CO_2
- Hardened sands have poor collapsibility
  - Shakeout and core removal is difficult
- Heating makes the mold stronger

No-Bake, Air-Set, or Chemically Bonded Sands

- Organic and inorganic resin binders can be mixed with the sand before the molding operation
    - Curing reactions begin immediately
- Cost of no-bake molding is about 20-30% more than green-sand molding
- High dimensional precision and good surface finish

No-Bake Sands

- No-bake sand can be compacted by light vibrations
  - Wood, plastic, fiberglass, or Styrofoam can be used as patterns
- System selections are based on the metal being poured, cure time desired, complexity and thickness of the casting, and the possibility of sand reclamation
- Good hot strength
- High resistance to mold-related casting defects
- Mold decomposes after the metal has been poured providing good shakeout

Shell Molding

- Basic steps
  - Individual grains are sand are precoated with a thin layer of thermosetting resin
    - Heat from the pattern partially cures a layer of material
  - Pattern and sand mixture are inverted and only the layer of partially cured material remains
  - The pattern with the shell is placed in an oven and the curing process is completed
  - Hardened shell is stripped from the pattern
  - Shells are clamped or glued together with a thermoset adhesive
  - Shell molds are placed in a pouring jacked and surrounded by sand, gravel, etc. for extra support

Shell Molding

- Cost of a metal pattern is often high
  - Design must include the gate and the runner
  - Expensive binder is required
  - Amount of required material is less
  - High productivity, low labor costs, smooth surfaces, high level of precision

Dump-Box Shell Molding

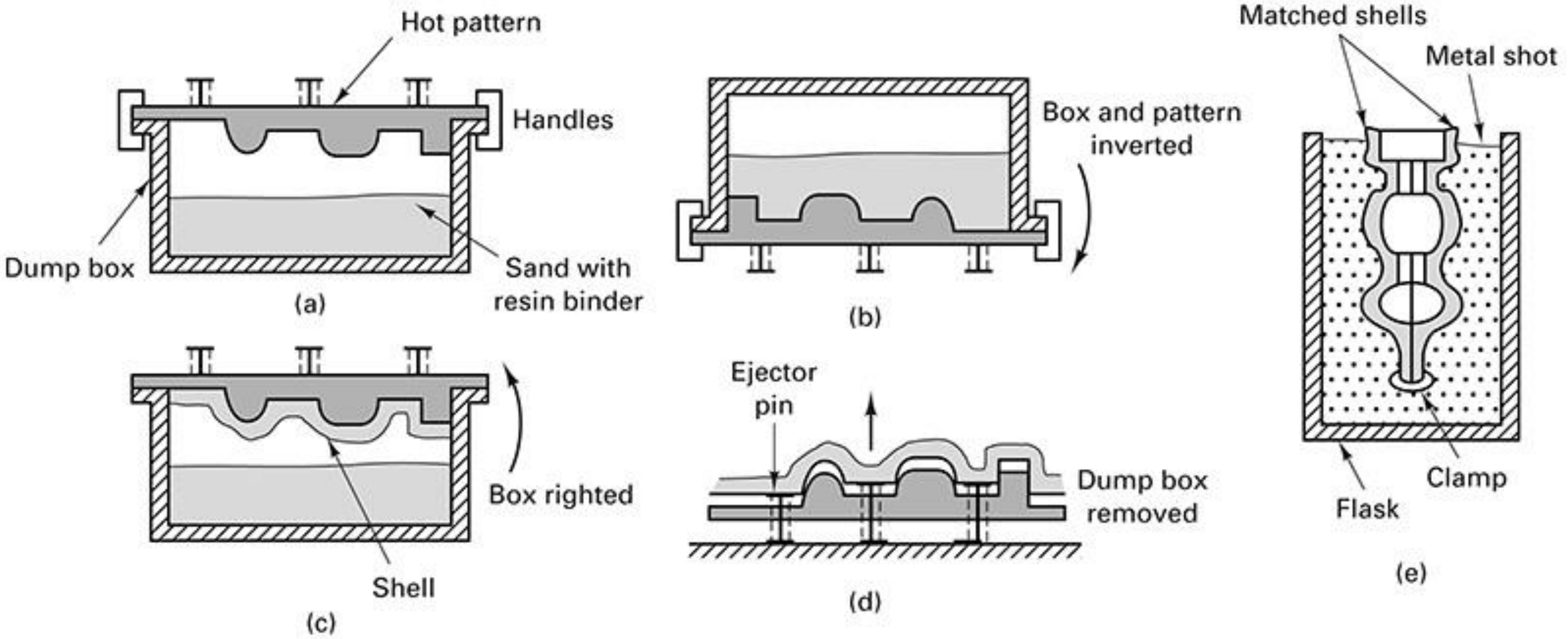


Figure 12-18 Schematic of the dump-box version of shell molding. a) A heated pattern is placed over a dump box containing granules of resin-coated sand. b) The box is inverted, and the heat forms a partially cured shell around the pattern. c) The box is righted, the top is removed, and the pattern and partially cured sand is placed in an oven to further cure the shell. d) The shell is stripped from the pattern. e) Matched shells are then joined and supported in a flask ready for pouring.

Shell-Mold Pattern

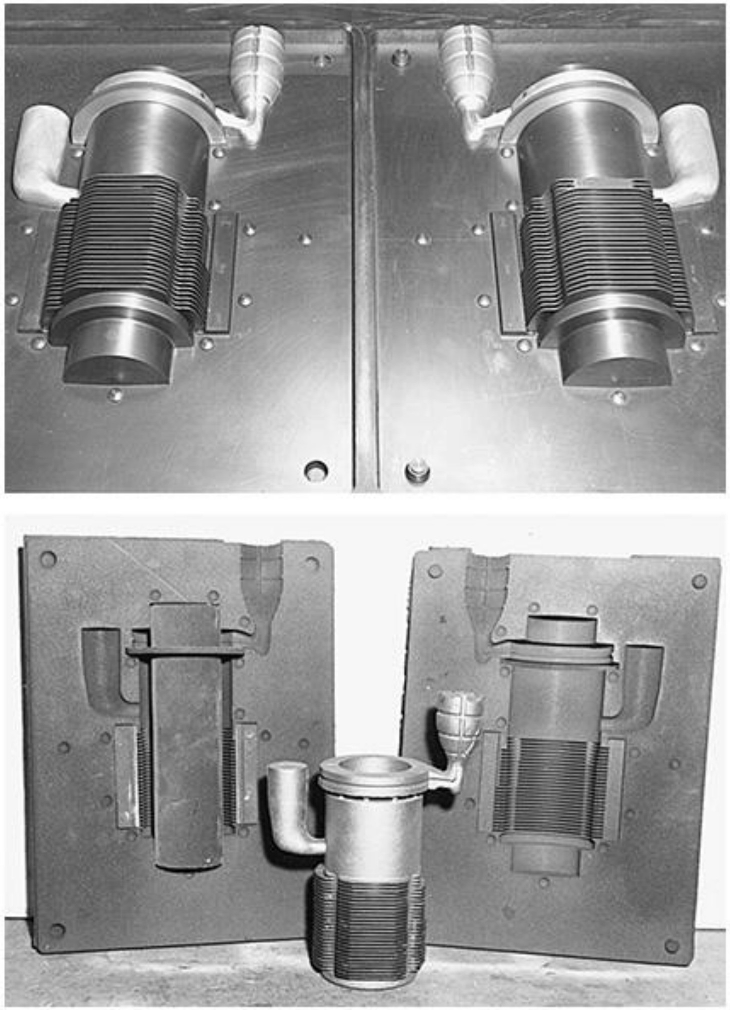


Figure 12-19 (Top) Two halves of a shell-mold pattern. (Bottom) The two shells before clamping, and the final shell-mold casting with attached pouring basin, runner, and riser. (Courtesy of Shalco Systems, Lansing, MI.)

Shell-Mold Casting

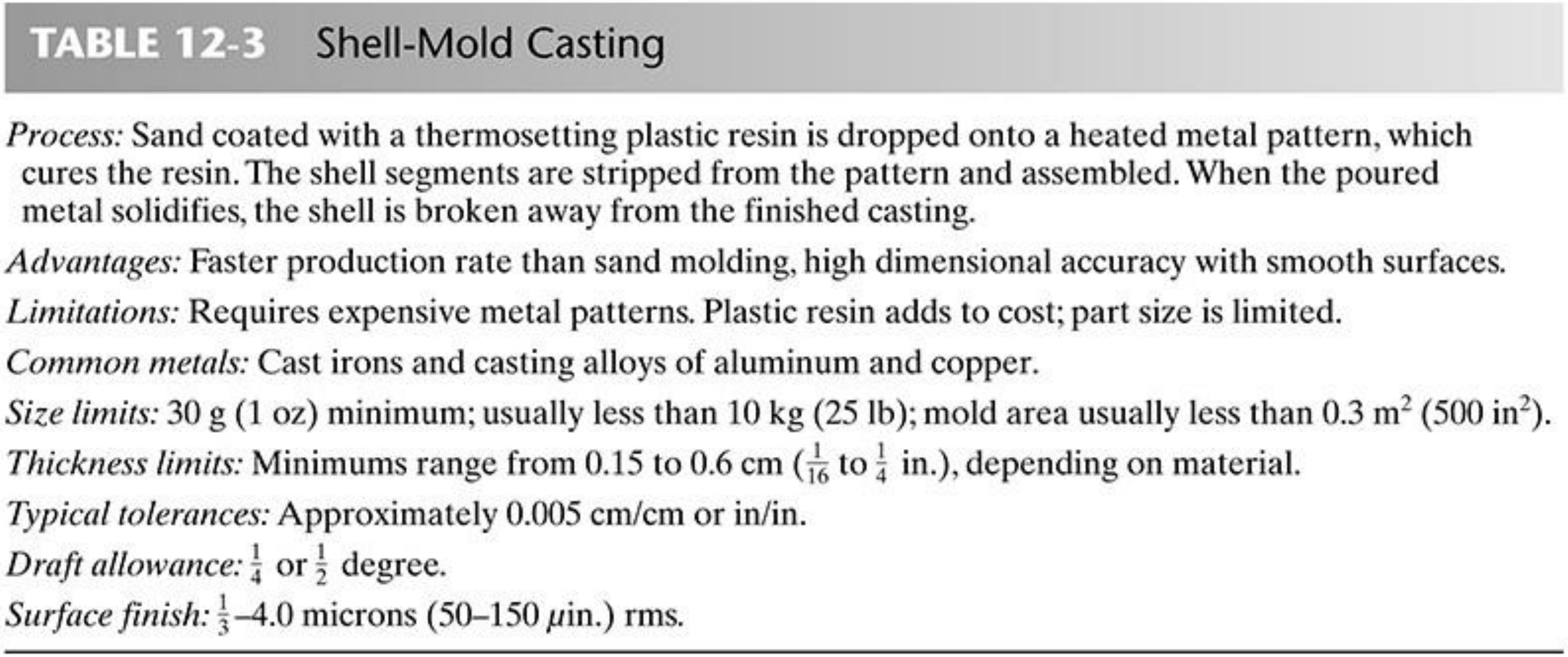


TABLE 12-3 Shell-Mold Casting

Process: Sand coated with a thermosetting plastic resin is dropped onto a heated metal pattern, which cures the resin. The shell segments are stripped from the pattern and assembled. When the poured metal solidifies, the shell is broken away from the finished casting.

Advantages: Faster production rate than sand molding, high dimensional accuracy with smooth surfaces.

Limitations: Requires expensive metal patterns. Plastic resin adds to cost; part size is limited.

Common metals: Cast irons and casting alloys of aluminum and copper.

Size limits: 30 g (1 oz) minimum; usually less than 10 kg (25 lb); mold area usually less than 0.3 m^2 (500 in^2).

Thickness limits: Minimums range from 0.15 to 0.6 cm ($\frac{1}{16}$ to $\frac{1}{4}$ in.), depending on material.

Typical tolerances: Approximately 0.005 cm/cm or in/in.

Draft allowance: $\frac{1}{4}$ or $\frac{1}{2}$ degree.

Surface finish: $\frac{1}{3}$–4.0 microns (50–150 μin.) rms.

Other Sand-Based Molding Methods

- V-process or vacuum molding
  - Vacuum serves as the sand binder
  - Applied within the pattern, drawing the sheet tight to its surface
  - Flask is filled with vibrated dry, unbonded sand
  - Compacts the sand and gives the sand its necessary strength and hardness
  - When the vacuum is released, the pattern is withdrawn

V-Process

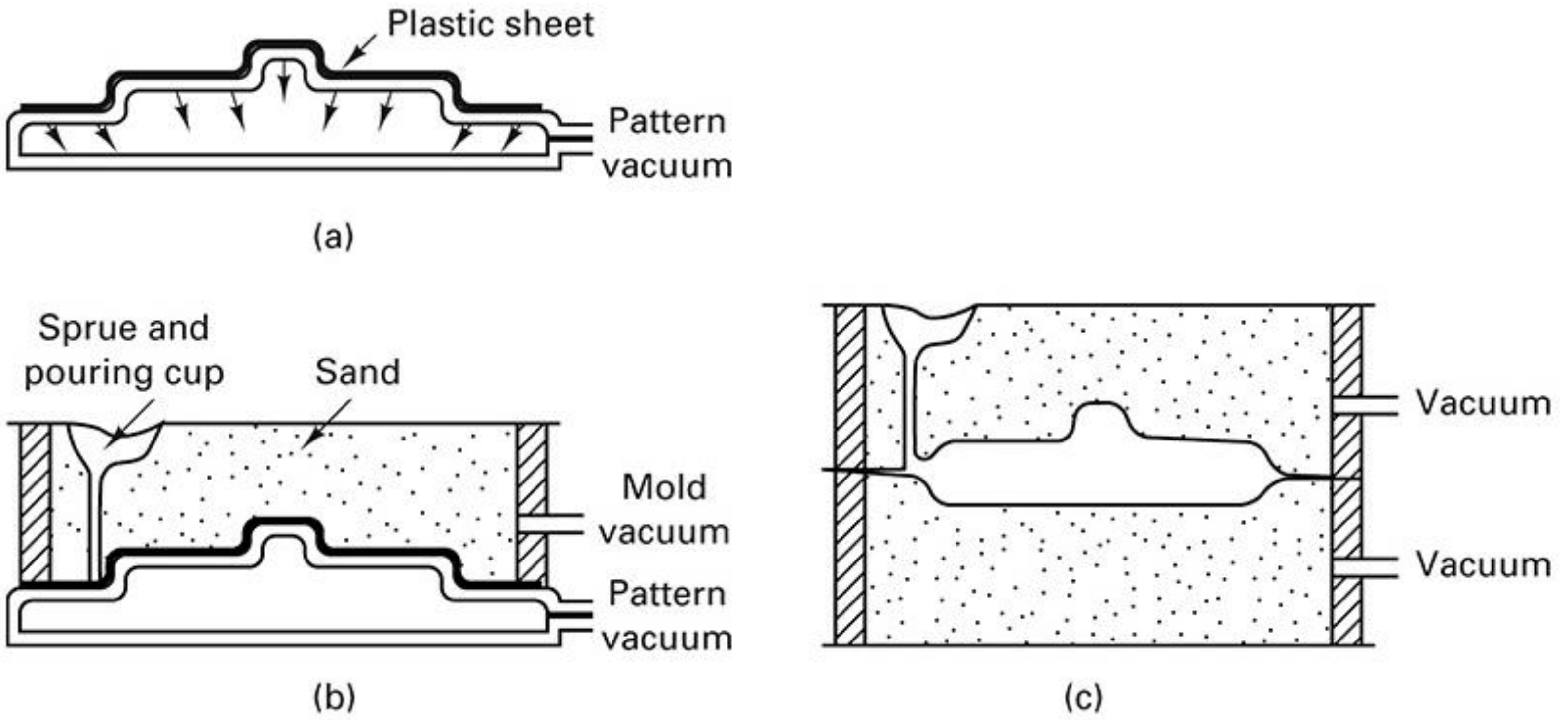


Figure 12-20 Schematic of the V-process or vacuum molding. A) A vacuum is pulled on a pattern, drawing a heated shrink-wrap plastic sheet tightly against it. b) A vacuum flask is placed over the pattern and filled with dry unbonded sand, a pouring basin and sprue are formed; the remaining sand is leveled; a second heated plastic sheet is placed on top; and a mold vacuum is drawn to compact the sand and hold the shape. c) With the mold vacuum being maintained, the pattern vacuum is then broken and the pattern is withdrawn. The cope and drag segments are assembled, and the molten metal is poured.

Advantages and Disadvantages of the V-Process

- Advantages
  - Absence of moisture-related defects
  - Binder cost is eliminated
  - Sand is completely reusable
  - Finer sands can be used
  - Better surface finish
  - No fumes generated during the pouring operation
  - Exceptional shakeout characteristics
- Disadvantages
  - Relatively slow process
  - Used primarily for production of prototypes
  - Low to medium volume parts
  - More than 10 but less than 50,000

Eff-set Process

- Wet sand with enough clay to prevent mold collapse
- Pattern is removed
    - Surface of the mold is sprayed with liquid nitrogen
- Ice that forms serves as a binder
- Molten metal is poured into the mold
- Low binder cost and excellent shakeout

12.3 Cores and Core Making

- Complex internal cavities can be produced with cores
- Cores can be used to improve casting design
- Cores may have relatively low strength
- If long cores are used, machining may need to be done afterwards
- Green sand cores are not an option for more complex shapes

Dry-Sand Cores

- Produced separate from the remainder of the mold
- Inserted into core prints that hold the cores in position
- Dump-core box
  - Sand is packed into the mold cavity
  - Sand is baked or hardened
- Single-piece cores
  - Two-halves of a core box are clamped together

Dry-Sand Cores

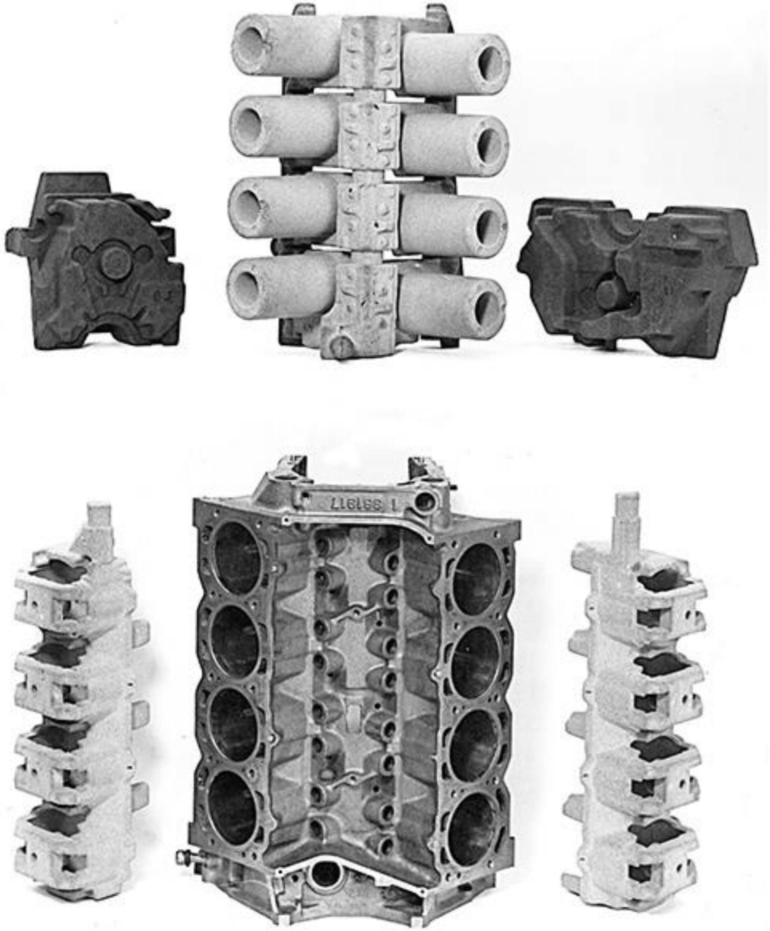


Figure 12-21 V-8 engine block (bottom center) and the five dry-sand cores that are used in the construction of its mold. (Courtesy of General Motors Corporation, Detroit, MI.)

Additional Core Methods

- Core-oil process
  - Sand is blended with oil to develop strength
  - Wet sand is blown or rammed into a simple core box
- Hot-box method
  - Sand is blended with a thermosetting binder
- Cold-box process
  - Binder coated sand is packed and then sealed
  - Gas or vaporized catalyst polymerizes the resin

Additional Core Methods

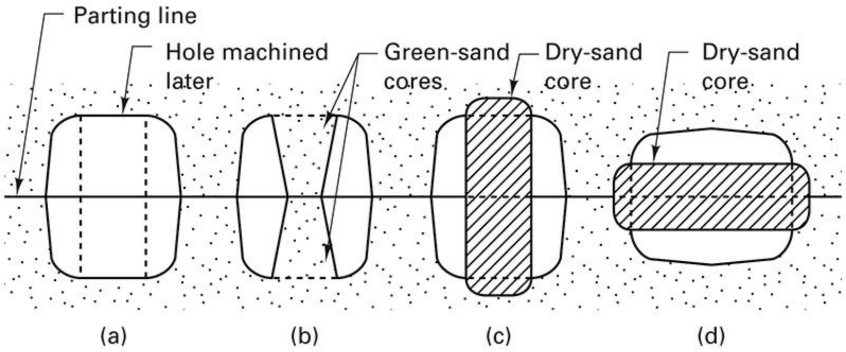


Figure 12-22 (Left) Four methods of making a hole in a cast pulley. Three involve the use of a core.

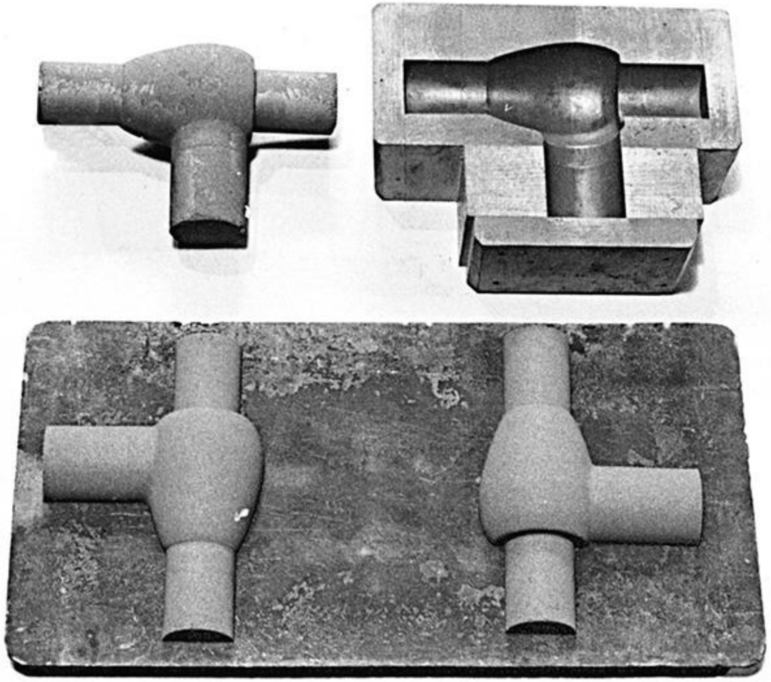


Figure 12-23 (Right) Upper Right; A dump-type core box; (bottom) core halves for baking; and (upper left) a completed core made by gluing two opposing halves together.

Additional Core Considerations

- Air-set or no-bake sands may be used
  - Eliminate gassing operations
  - Reactive organic resin and a curing catalyst
- Shell-molding
  - Core making alternative
  - Produces hollow cores with excellent strength
- Selecting the proper core method is based on the following considerations
  - Production quantity, production rate, required precision, required surface finish, metal being poured

Casting Core Characteristics

- Sufficient strength before hardening
- Sufficient hardness and strength after hardening
- Smooth surface
- Minimum generation of gases
- Adequate permeability
- Adequate refractoriness
- Collapsibility

Techniques to Enhance Core Properties

- Addition of internal wires or rods
- Vent holes
- Cores can be connected to the outer surfaces of the mold cavity
    - Core prints
- Chaplets- small metal supports that are placed between the cores and the mold cavity surfaces and become integral to the final casting

Chaplets

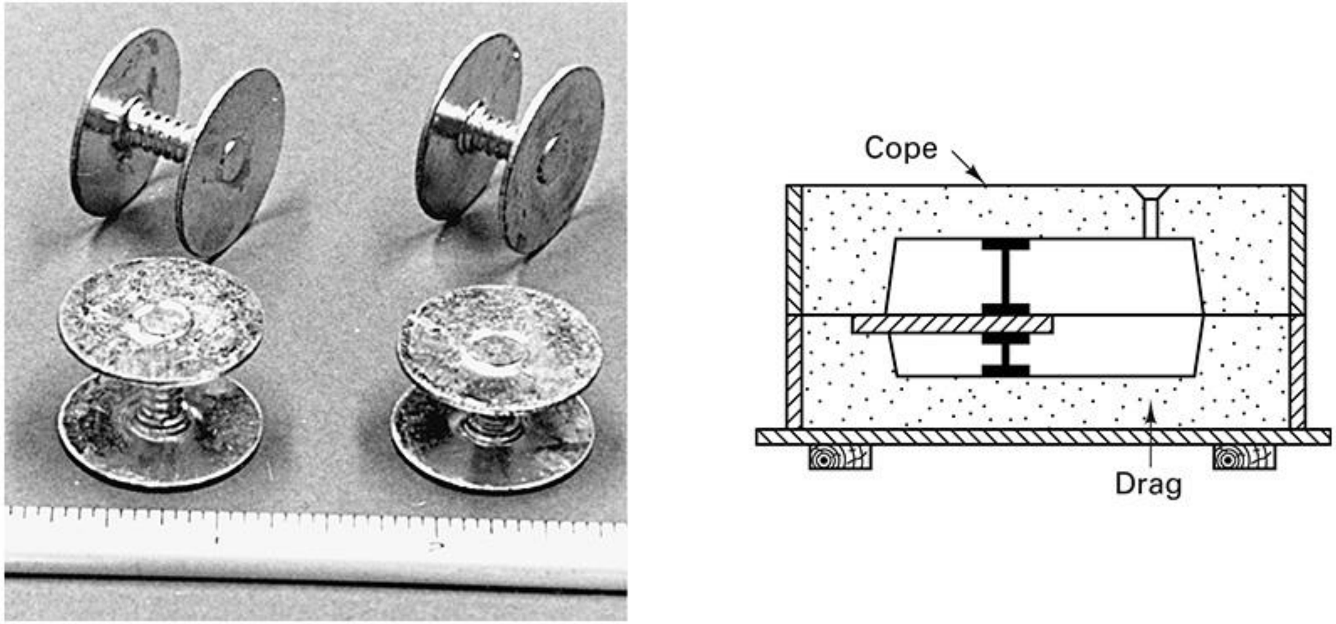


Figure 12-24 (Left) Typical chaplets. (Right) Method of supporting a core by use of chaplets (relative size of the chaplets is exaggerated).

Mold Modifications

- Cheeks are second parting lines that allow parts to be cast in a mold with withdrawable patterns
- Inset cores can be used to improve productivity

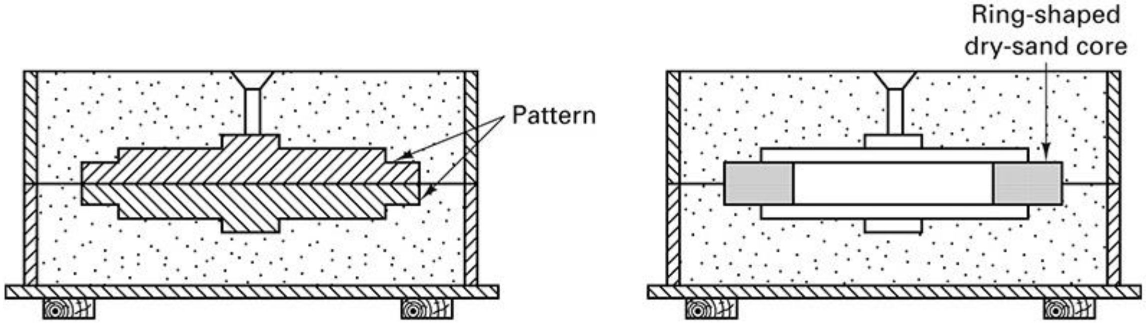


Figure 12-26 (Right) Molding an inset section using a dry-sand core.

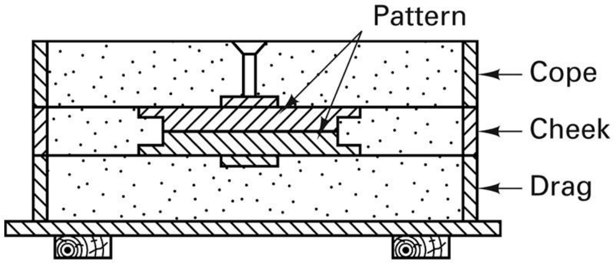


Figure 12-25 (Left) Method of making a reentrant angle or inset section by using a three-piece flask.

14.4 Other Expendable-Mold Processes with Multiple-Use Patterns

- Plaster mold casting
  - Mold material is made out of plaster of paris
  - Slurry is poured over a metal pattern
  - Improved surface finish and dimensional accuracy
  - Limited to the lower-melting-temperature nonferrous alloys
- Antioch process
  - Variation of plaster mold casting
  - 50% plaster, 50% sand

Plaster Molding

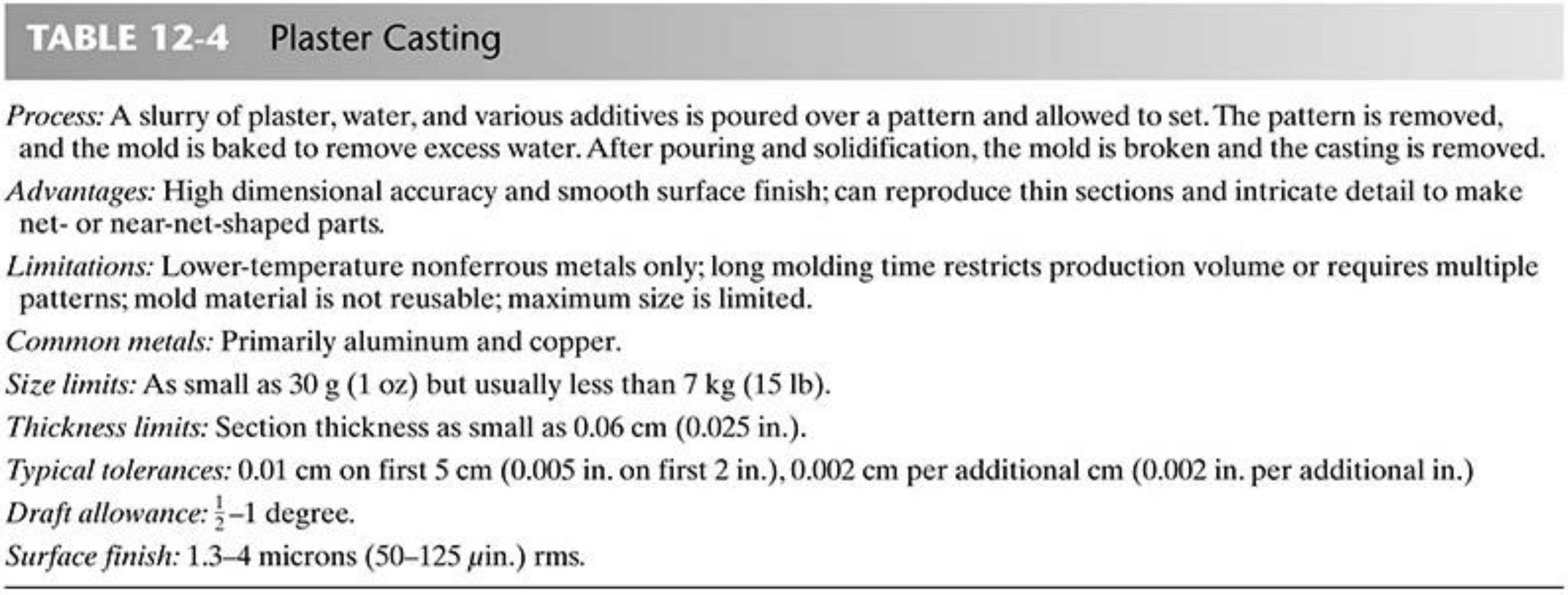


TABLE 12-4 Plaster Casting

Process: A slurry of plaster, water, and various additives is poured over a pattern and allowed to set. The pattern is removed, and the mold is baked to remove excess water. After pouring and solidification, the mold is broken and the casting is removed.

Advantages: High dimensional accuracy and smooth surface finish; can reproduce thin sections and intricate detail to make net- or near-net-shaped parts.

Limitations: Lower-temperature nonferrous metals only; long molding time restricts production volume or requires multiple patterns; mold material is not reusable; maximum size is limited.

Common metals: Primarily aluminum and copper.

Size limits: As small as 30 g (1 oz) but usually less than 7 kg (15 lb).

Thickness limits: Section thickness as small as 0.06 cm (0.025 in.).

Typical tolerances: 0.01 cm on first 5 cm (0.005 in. on first 2 in.), 0.002 cm per additional cm (0.002 in. per additional in.)

Draft allowance: $\frac{1}{2}$–1 degree.

Surface finish: 1.3–4 microns (50–125 μin.) rms.

Ceramic Mold Casting

- Mold is made from ceramic material
- Ceramics can withstand higher temperatures
- Greater mold cost than other casting methods
- Shaw process
  - Reusable pattern inside a slightly tapered flask
  - Mixture sets to a rubbery state that allows the part and flask to be removed
  - Mold surface is then ignited with a torch

Ceramic Mold Casting

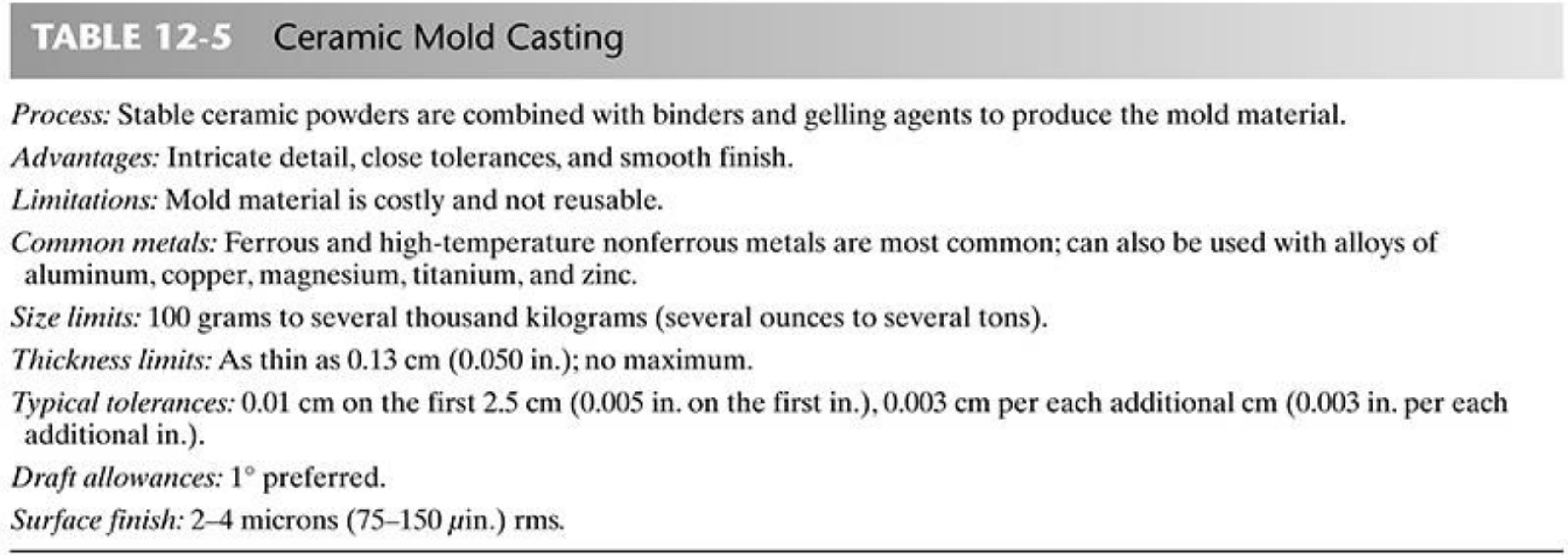


TABLE 12-5 Ceramic Mold Casting

Process: Stable ceramic powders are combined with binders and gelling agents to produce the mold material.

Advantages: Intricate detail, close tolerances, and smooth finish.

Limitations: Mold material is costly and not reusable.

Common metals: Ferrous and high-temperature nonferrous metals are most common; can also be used with alloys of aluminum, copper, magnesium, titanium, and zinc.

Size limits: 100 grams to several thousand kilograms (several ounces to several tons).

Thickness limits: As thin as 0.13 cm (0.050 in.); no maximum.

Typical tolerances: 0.01 cm on the first 2.5 cm (0.005 in. on the first in.), 0.003 cm per each additional cm (0.003 in. per each additional in.).

Draft allowances: 1° preferred.

Surface finish: 2–4 microns (75–150 μin.) rms.

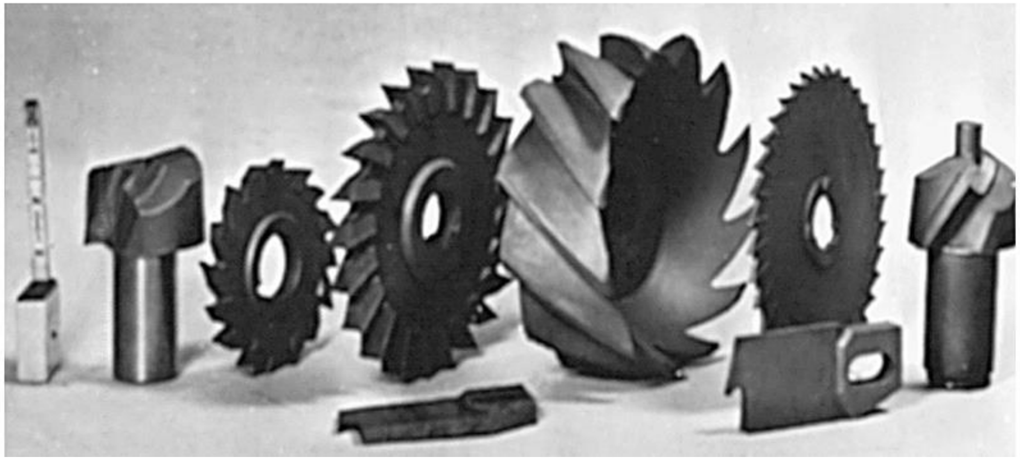


Figure 12-27 Group of intricate cutters produced by ceramic mold casting. (Courtesy of Avnet Shaw Division of Avnet, Inc., Phoenix, AZ)

Other Casting Methods

- Expendable graphite molds
  - Some metals are difficult to cast
    - Titanium
    - Reacts with many common mold materials
  - Powdered graphite can be combined with additives and compacted around a pattern
  - Mold is broken to remove the product
- Rubber-mold casting
  - Artificial elastomers can be compounded in liquid form and poured over the pattern to produce a semirigid mold
  - Limited to small castings and low-melting-point materials

12.5 Expendable-Mold Processes Using Single-Use Patterns

- Investment casting
  - One of the oldest casting methods
  - Products such as rocket components, and jet engine turbine blades
  - Complex shapes
  - Most materials can be casted

Figure 12-30 Typical parts produced by investment casting. (Courtesy of Haynes International, Kokomo, IN.)

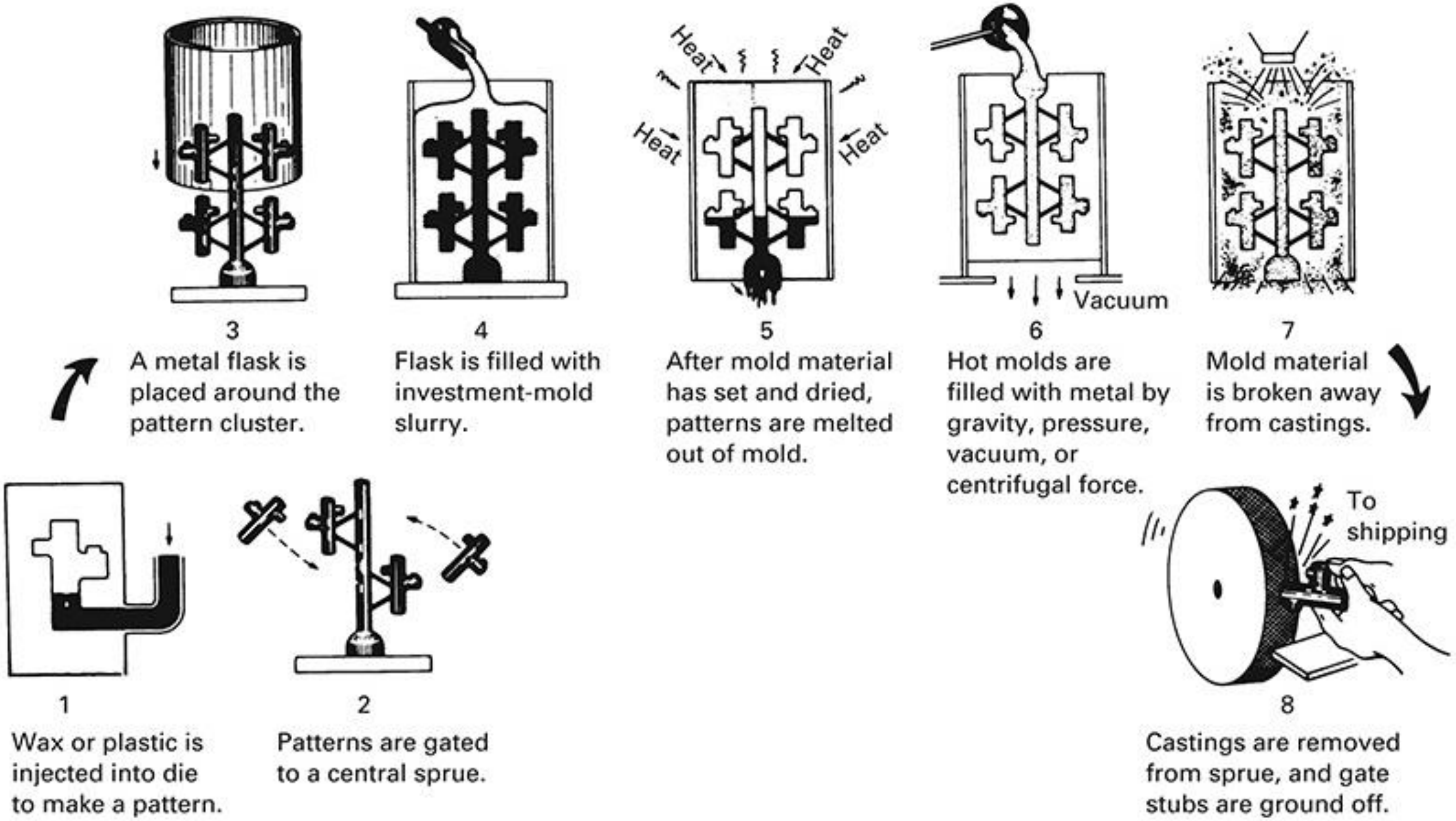
Investment Casting

- Sequential steps for investment casting
  - Produce a master pattern
  - Produce a master die
  - Produce wax patterns
  - Assemble the wax patterns onto a common wax sprue
  - Coat the tree with a thin layer of investment material
  - Form additional investment around the coated cluster
  - Allow the investment to harden
  - Remove the wax pattern from the mold by melting or dissolving
  - Heat the mold
  - Pour the molten metal
  - Remove the solidified casting from the mold

Advantages and Disadvantages of Investment Casting

- Disadvantage
  - Complex process
  - Can be costly
- Advantage
  - Complex shapes can be cast
  - Thin sections can be cast
  - Machining can be eliminated or reduced

Investment Casting



1 Wax or plastic is injected into die to make a pattern.

2 Patterns are gated to a central sprue.

3 A metal flask is placed around the pattern cluster.

4 Flask is filled with investment-mold slurry.

5 After mold material has set and dried, patterns are melted out of mold.

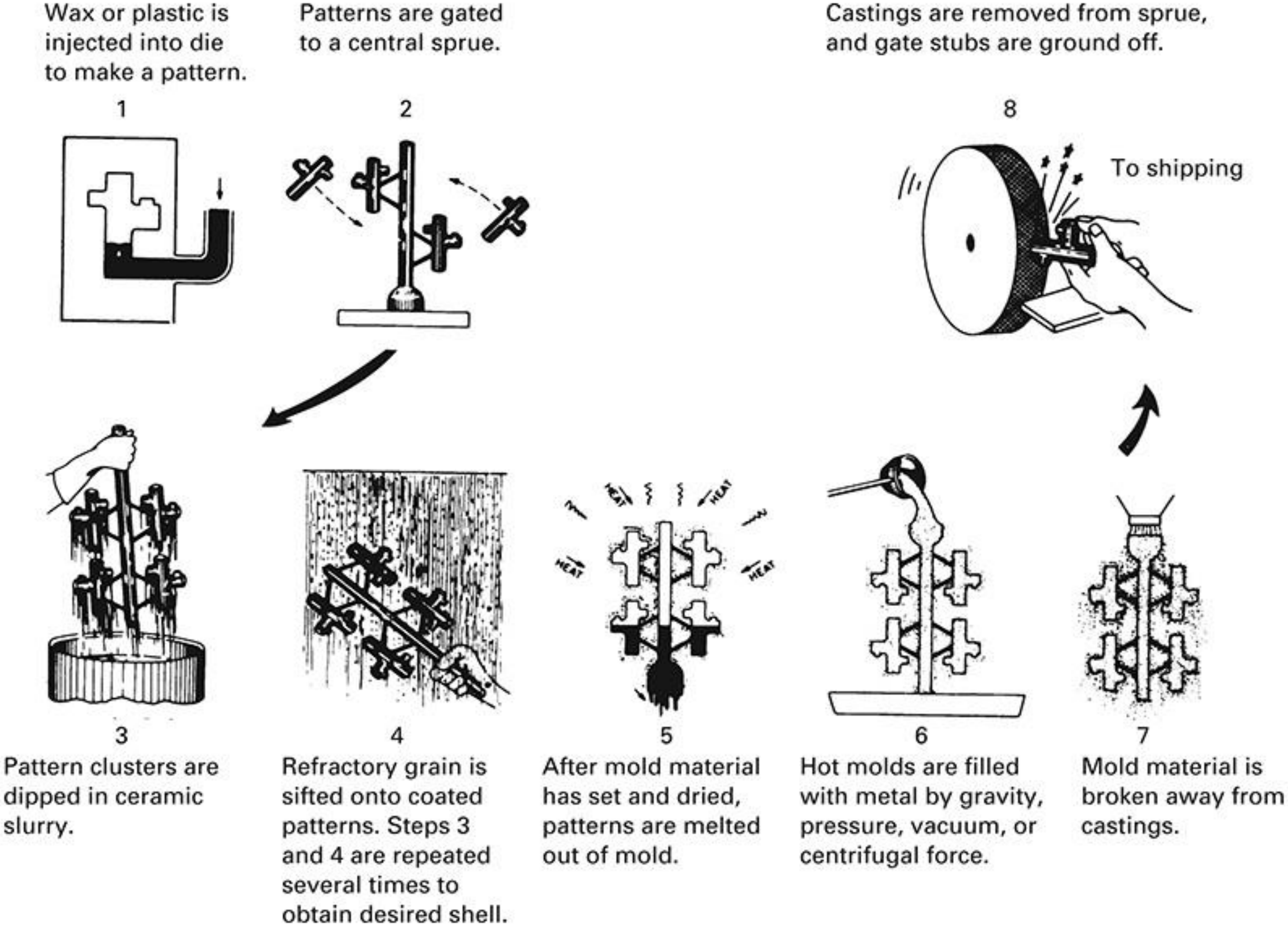
6 Hot molds are filled with metal by gravity, pressure, vacuum, or centrifugal force.

7 Mold material is broken away from castings.

8 Castings are removed from sprue, and gate stubs are ground off.

Figure 12-28 Investment-casting steps for the flask-cast method. (Courtesy of Investment Casting Institute, Dallas, TX.)

Investment Casting



1 Wax or plastic is injected into die to make a pattern.

2 Patterns are gated to a central sprue.

3 Pattern clusters are dipped in ceramic slurry.

4 Refractory grain is sifted onto coated patterns. Steps 3 and 4 are repeated several times to obtain desired shell.

5 After mold material has set and dried, patterns are melted out of mold.

6 Hot molds are filled with metal by gravity, pressure, vacuum, or centrifugal force.

7 Mold material is broken away from castings.

8 Castings are removed from sprue, and gate stubs are ground off.

Figure 12-29 Investment-casting steps for the shell-casting procedure. (Courtesy of Investment Casting Institute, Dallas, TX.)

Investment Casting

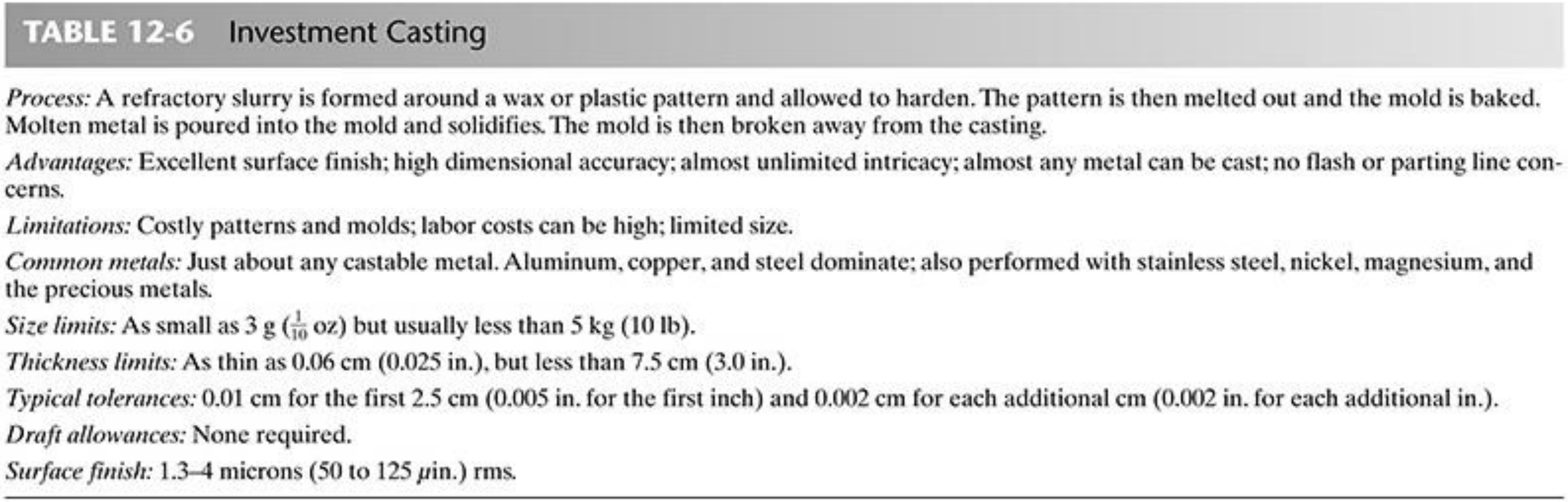


TABLE 12-6 Investment Casting

Process: A refractory slurry is formed around a wax or plastic pattern and allowed to harden. The pattern is then melted out and the mold is baked. Molten metal is poured into the mold and solidifies. The mold is then broken away from the casting.

Advantages: Excellent surface finish; high dimensional accuracy; almost unlimited intricacy; almost any metal can be cast; no flash or parting line concerns.

Limitations: Costly patterns and molds; labor costs can be high; limited size.

Common metals: Just about any castable metal. Aluminum, copper, and steel dominate; also performed with stainless steel, nickel, magnesium, and the precious metals.

Size limits: As small as 3 g ($\frac{1}{10}$ oz) but usually less than 5 kg (10 lb).

Thickness limits: As thin as 0.06 cm (0.025 in.), but less than 7.5 cm (3.0 in.).

Typical tolerances: 0.01 cm for the first 2.5 cm (0.005 in. for the first inch) and 0.002 cm for each additional cm (0.002 in. for each additional in.).

Draft allowances: None required.

Surface finish: 1.3–4 microns (50 to 125 μin.) rms.

Counter-Gravity Investment Casting

- Pouring process is upside down
- Vacuum is used within the chamber
  - Draws metal up through the central sprue and into the mold
- Free of slag and dross
- Low level of inclusions
- Little turbulence
- Improved machinability
- Mechanical properties approach those of wrought material
- Simpler gating systems
- Lower pouring temperatures
- Improved grain structure and better surface finish

Evaporative Pattern (Full-Mold and Lost-Foam) Casting

- Reusable patterns can complicate withdrawal
    - May mandate design modifications
- Evaporative pattern processes
    - Pattern is made of polystyrene or polymethylmethacrylate
        - Pattern remains in the mold until the molten metal melts away the pattern
        - If small quantities are required, patterns may be cut by hand
        - Material is lightweight

Evaporative Patterns

- Metal mold or die is used to mass-produce the evaporative patterns
- For multiple and complex shapes, patterns can be divided into segments or slices
  - Assembled by hot-melt gluing
- Full-mold process
  - Green sand is compacted around the pattern and gating system

Lost Foam Process

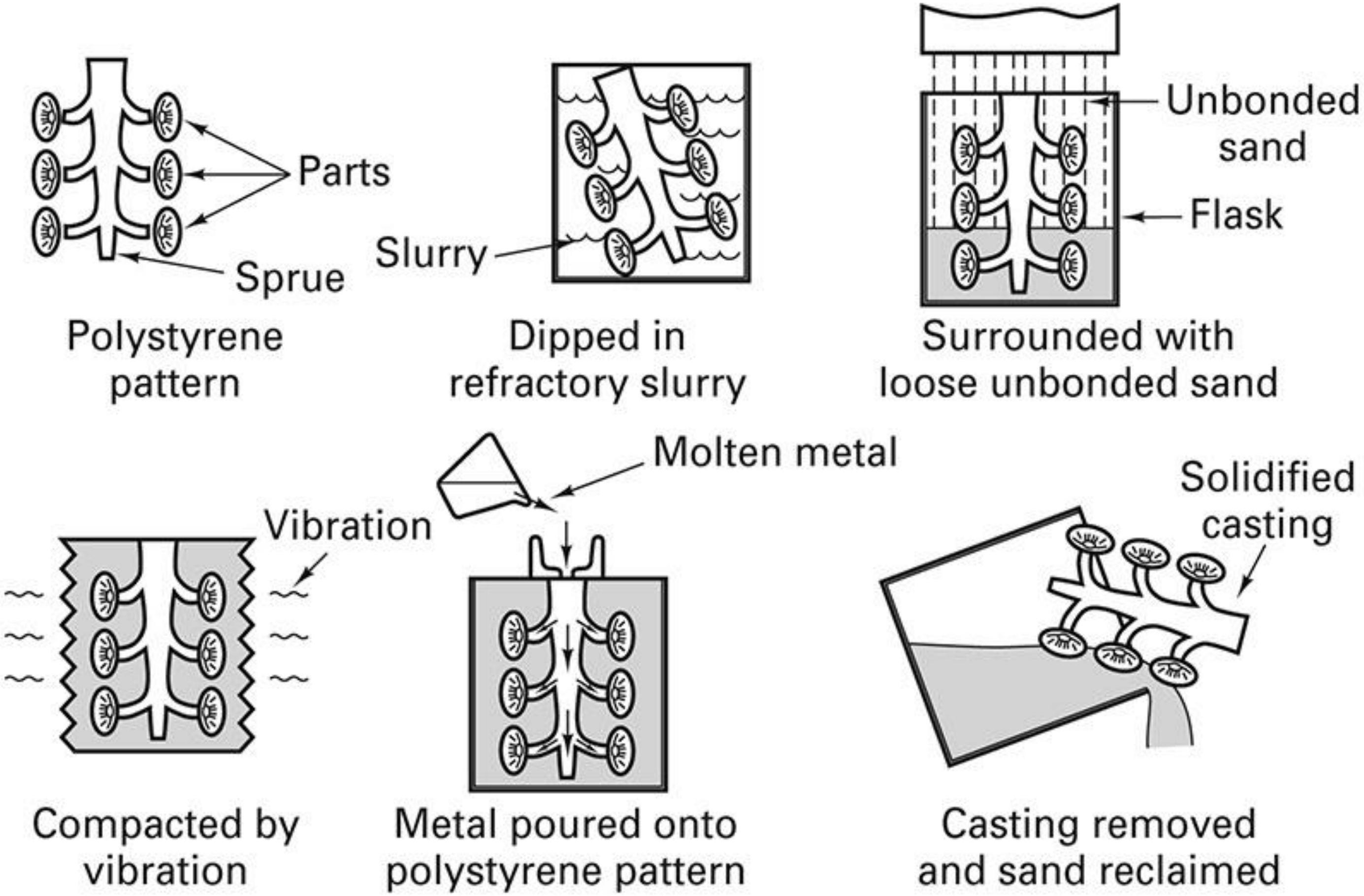


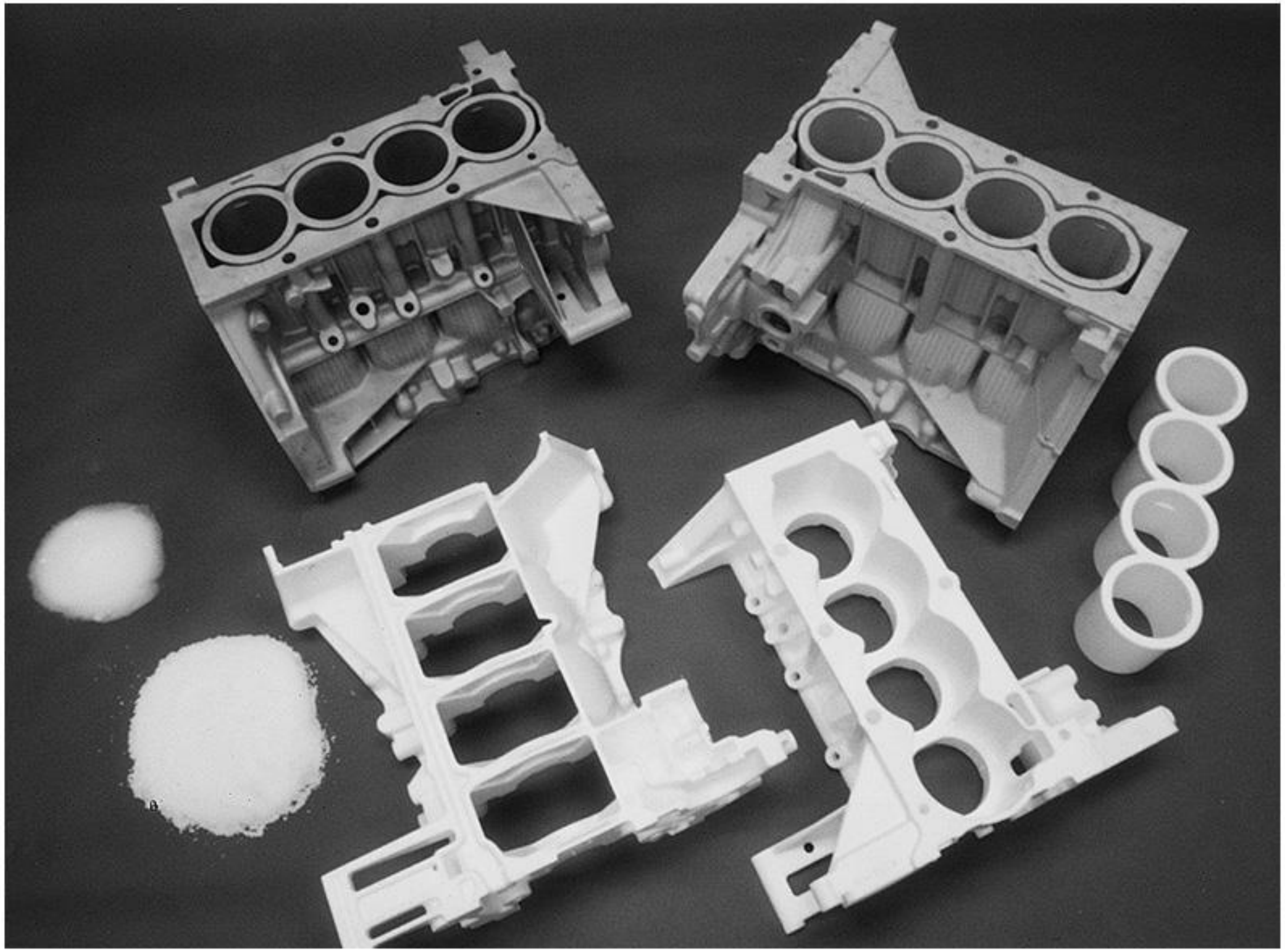
Figure 12-32 Schematic of the lost-foam casting process. In this process, the polystyrene pattern is dipped in a ceramic slurry, and the coated pattern is then surrounded with loose, unbonded sand.

Advantages of the Full-Mold and Lost-Foam Process

- Sand can be reused
- Castings of almost any size
- Both ferrous and nonferrous metals
- No draft is required
- Complex patterns
- Smooth surface finish
- Absence of parting lines

Lost-Foam Casting

Figure 12-33 The stages of lost-foam casting, proceeding counterclockwise from the lower left: polystyrene beads→ expanded polystyrene pellets → three foam pattern segments → an assembled and dipped polystyrene pattern → a finished metal casting that is a metal duplicate of the polystyrene pattern. (Courtesy of Saturn Corporation, Spring Hill, TN.)



Lost-Foam Casting

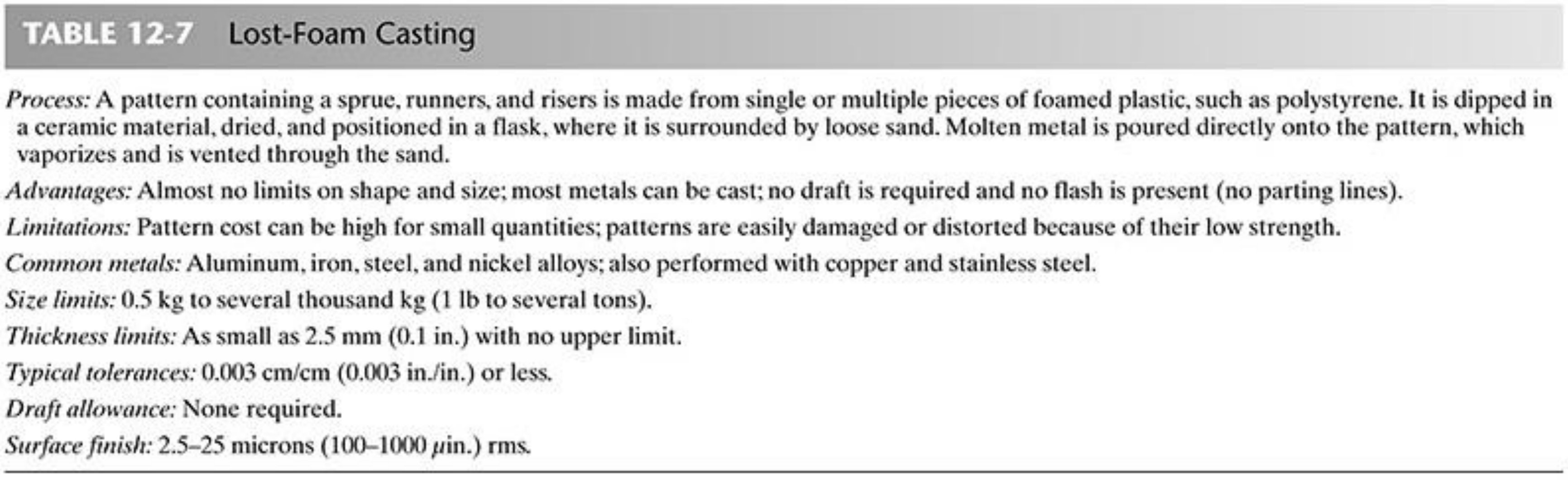


TABLE 12-7 Lost-Foam Casting

Process: A pattern containing a sprue, runners, and risers is made from single or multiple pieces of foamed plastic, such as polystyrene. It is dipped in a ceramic material, dried, and positioned in a flask, where it is surrounded by loose sand. Molten metal is poured directly onto the pattern, which vaporizes and is vented through the sand.

Advantages: Almost no limits on shape and size; most metals can be cast; no draft is required and no flash is present (no parting lines).

Limitations: Pattern cost can be high for small quantities; patterns are easily damaged or distorted because of their low strength.

Common metals: Aluminum, iron, steel, and nickel alloys; also performed with copper and stainless steel.

Size limits: 0.5 kg to several thousand kg (1 lb to several tons).

Thickness limits: As small as 2.5 mm (0.1 in.) with no upper limit.

Typical tolerances: 0.003 cm/cm (0.003 in./in.) or less.

Draft allowance: None required.

Surface finish: 2.5–25 microns (100–1000 μin.) rms.

14.6 Shakeout, Cleaning, and Finishing

- Final step of casting involves separating the molds and mold material
- Shakeout operations
  - Separate the molds and sand from the flasks
- Punchout machines
- Vibratory machines
- Rotary separators
- Blast cleaning

14.7 Summary

- Control of mold shape, liquid flow, and solidification provide a means of controlling properties of the casting
- Each process has unique advantages and disadvantages
- Best method is chosen based on the product shape, material and desired properties

Chapter 15: Multiple-Use-Mold Casting Processes

DeGarmo’s Materials and Processes in Manufacturing

13.1 Introduction

- In expendable mold casting, a separate mold is produced for each casting
  - Low production rate for expendable mold casting
- If multiple-use molds are used, productivity can increase
- Most multiple-use molds are made from metal, so most molds are limited to low melting temperature metals and alloys

13.2 Permanent-Mold Casting

- Also known as gravity die casting
- Mold can be made from a variety of different materials
  - Gray cast iron, alloy cast iron, steel, bronze, or graphite
- Most molds are made in segments with hinges to allow rapid and accurate closing
  - Molds are preheated to improve properties
- Liquid metal flows through the mold cavity by gravity flow

Permanent Mold Casting

- Process can be repeated immediately because the mold is still warm from the previous casting
- Most frequently cast metals
  - Aluminum, magnesium, zinc, lead, copper, and their alloys
  - If steel or iron is to be used, a graphite mold must be used

Advantages of Permanent-Mold Casting

- Near- net shapes
- Little finish machining
- Reusable molds
- Good surface finish
- Consistent dimensions
- Directional solidification

Disadvantages of Permanent Mold Casting

- Limited to lower melting temperature alloys
- High mold costs
  - Mold life is strongly tied to cost
  - Mold life is dependent on the following
    - Alloys being cast
    - Mold material
    - Pouring temperature
    - Mold temperature
    - Mold configuration
  - High production runs can validate high mold costs
- Molds are not permeable
- Limited mold complexity

Permanent Mold Casting

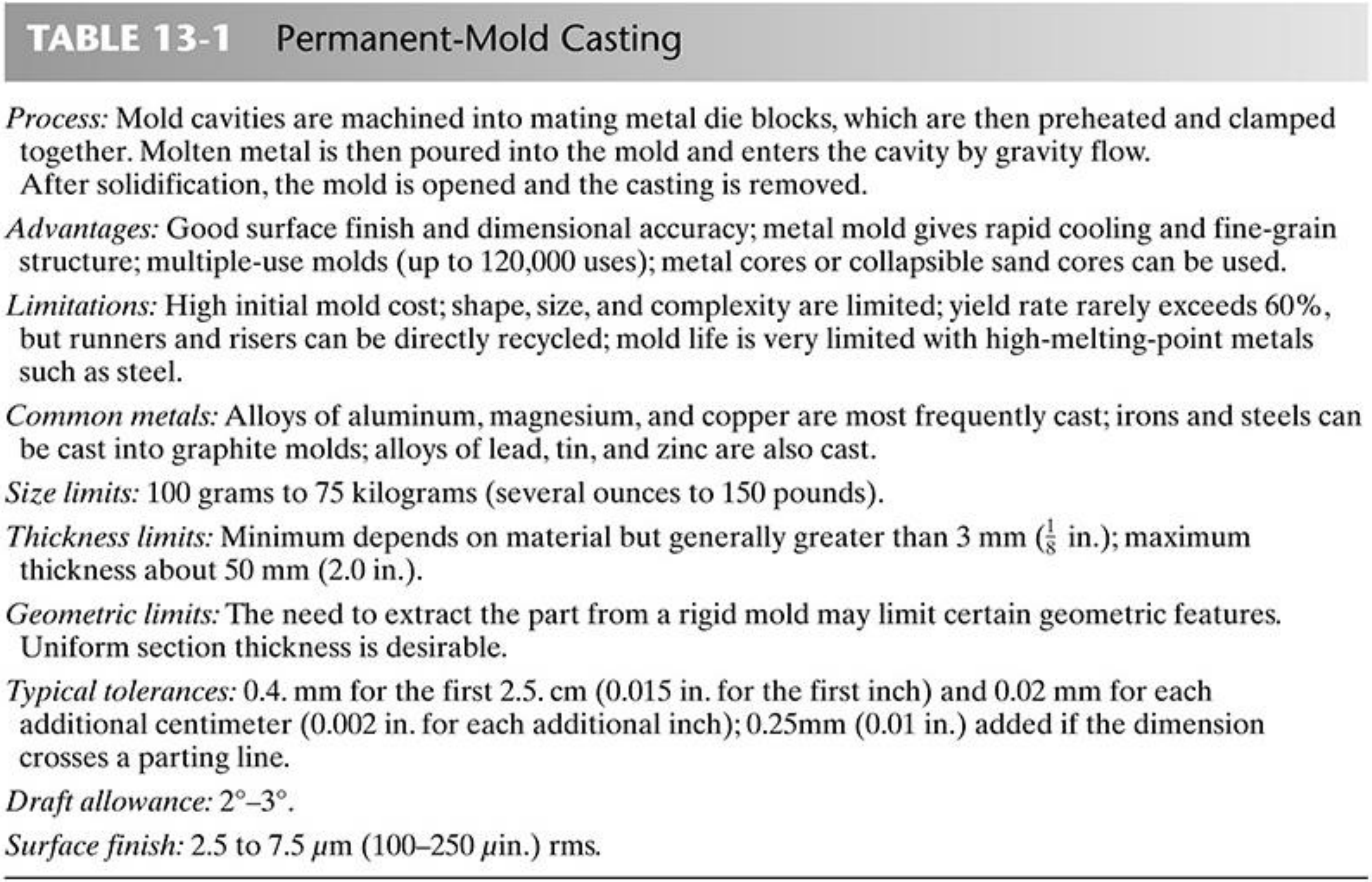


TABLE 13-1 Permanent-Mold Casting

Process: Mold cavities are machined into mating metal die blocks, which are then preheated and clamped together. Molten metal is then poured into the mold and enters the cavity by gravity flow. After solidification, the mold is opened and the casting is removed.

Advantages: Good surface finish and dimensional accuracy; metal mold gives rapid cooling and fine-grain structure; multiple-use molds (up to 120,000 uses); metal cores or collapsible sand cores can be used.

Limitations: High initial mold cost; shape, size, and complexity are limited; yield rate rarely exceeds 60%, but runners and risers can be directly recycled; mold life is very limited with high-melting-point metals such as steel.

Common metals: Alloys of aluminum, magnesium, and copper are most frequently cast; irons and steels can be cast into graphite molds; alloys of lead, tin, and zinc are also cast.

Size limits: 100 grams to 75 kilograms (several ounces to 150 pounds).

Thickness limits: Minimum depends on material but generally greater than 3 mm ($\frac{1}{8}$ in.); maximum thickness about 50 mm (2.0 in.).

Geometric limits: The need to extract the part from a rigid mold may limit certain geometric features. Uniform section thickness is desirable.

Typical tolerances: 0.4. mm for the first 2.5. cm (0.015 in. for the first inch) and 0.02 mm for each additional centimeter (0.002 in. for each additional inch); 0.25mm (0.01 in.) added if the dimension crosses a parting line.

Draft allowance: 2°–3°.

Surface finish: 2.5 to 7.5 μm (100–250 μin.) rms.

Low Pressure Permanent-Mold Casting

- Tilt-pour permanent-mold casting
  - Mold is rotated to force flow into the cavity
- Low pressure permanent-mold casting
  - Mold is upside down and connected to a crucible that contains the molten metal
  - Pressure difference induces upward flow
  - Metals are exceptionally clean because it is fed directly into the mold
  - Little or no turbulence during flow
  - Typical metals cast using low pressure process
    - Aluminum, magnesium, and copper

Low-Pressure and Vacuum Permanent-Mold Casting

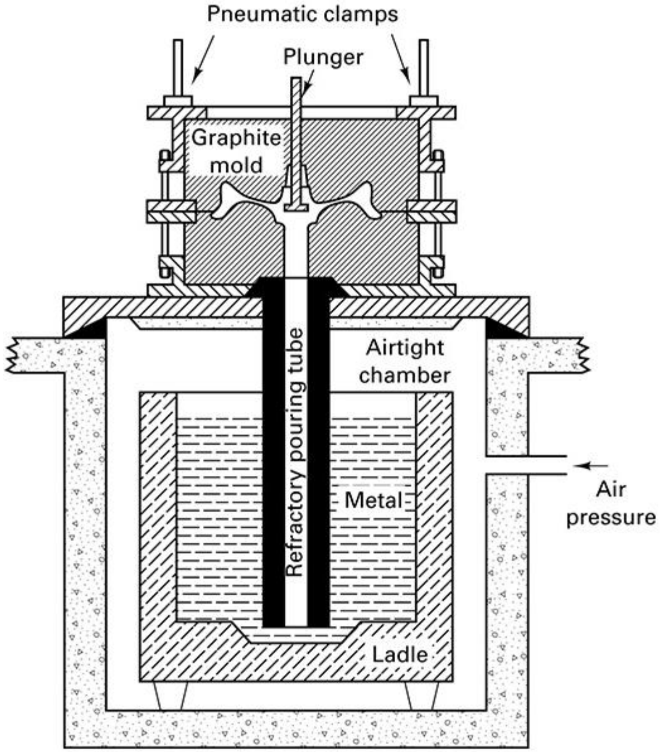


Figure 13-2 Schematic of the low-pressure permanent-mold process. (Courtesy of Amsted Industries, Chicago, IL.)

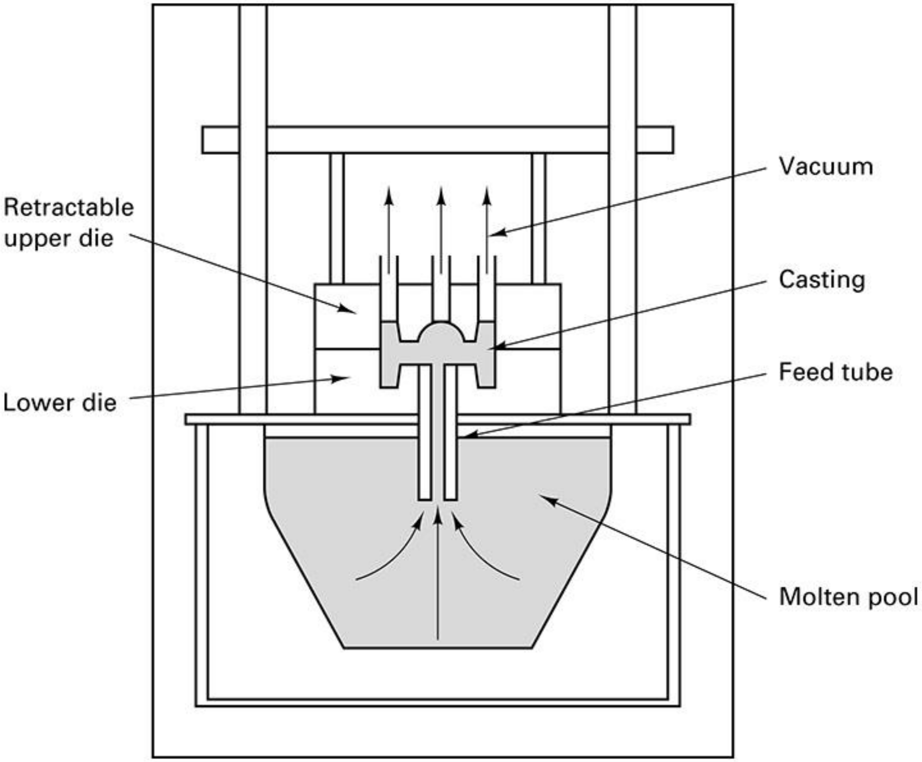


Figure 13-3 Schematic illustration of vacuum permanent-mold casting. Note the similarities to the low-pressure process.

Vacuum Permanent-Mold Casting

- Atmospheric pressure in the chamber forces the metal upward after the vacuum is drawn
- Thin-walled castings can be made
- Excellent surface quality
- Cleaner metals than low pressure
  - Lower dissolved gas content
- Better mechanical properties than low pressure casting

13.3 Die Casting

- Molten metal is forced into the mold under high pressure
- Held under high pressure during solidification
- Castings can have fine sections and complex details
- Long mold life
- Typical metals cast
  - Zinc, copper, magnesium, aluminum, and their alloys

Advantages of Die Casting

- High production rates
- Good strength
- Intricate shapes
- Dimensional precision
- Excellent surface qualities
- Small-medium sized castings

Die Modifications and Die Life

- Die complexity can be improved through the use of
  - Water cooled passages
  - Retractable cores
  - Moving pins to eject castings
- Die life
  - Limited by erosion and usage temperature
  - Surface cracking
  - Heat checking
  - Thermal fatigue

Die-Casting Dies

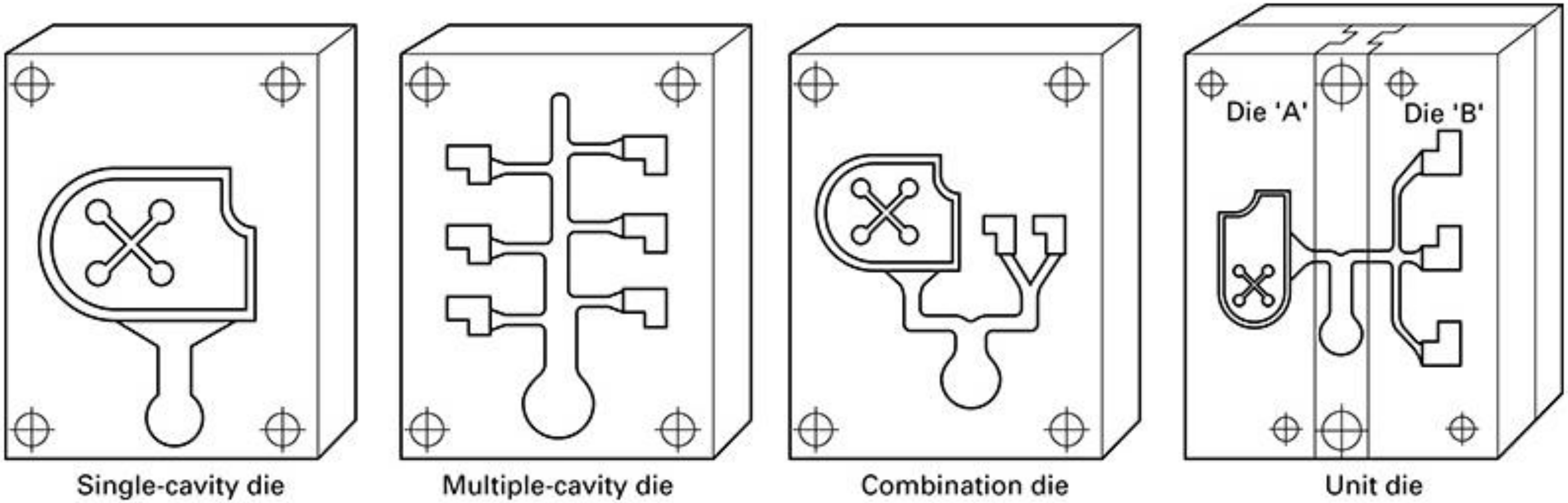


Figure 13-4 Various types of die-casting dies. (Courtesy of American Die Casting Institute, Inc., Des Plaines, IL.)

Basic Types of Die-Casting

- Hot chamber castings
  - Fast cycling times
  - No handling or transfer of molten metal
  - Used with zinc, tin, and lead-based alloys
- Heated-manifold direct injection die casting
  - Molten zinc is forced though a heated manifold
  - Next through heated mini-nozzles directly into the die cavity
  - Eliminates the need for sprues, gates and runners

Basic Types of Die Casting

- Cold-chamber machines
  - Used for materials not suitable for hot chamber machines
  - Typical materials
    - Aluminum, magnesium, copper, and high-aluminum zinc
  - Longer operating cycle than hot-chamber
  - High productivity

Summary of Die Casting

- Dies fill so fast with metal that there is little time for the air in the runner and die to escape
- Molds offer no permeability
    - Air can become trapped and cause defects
- Risers are not used because of the high pressures used
- Sand cores can not be used due to high pressures
    - Cast-in inserts can be used
- High production rates
- Little post casting finishing necessary

Die Casting

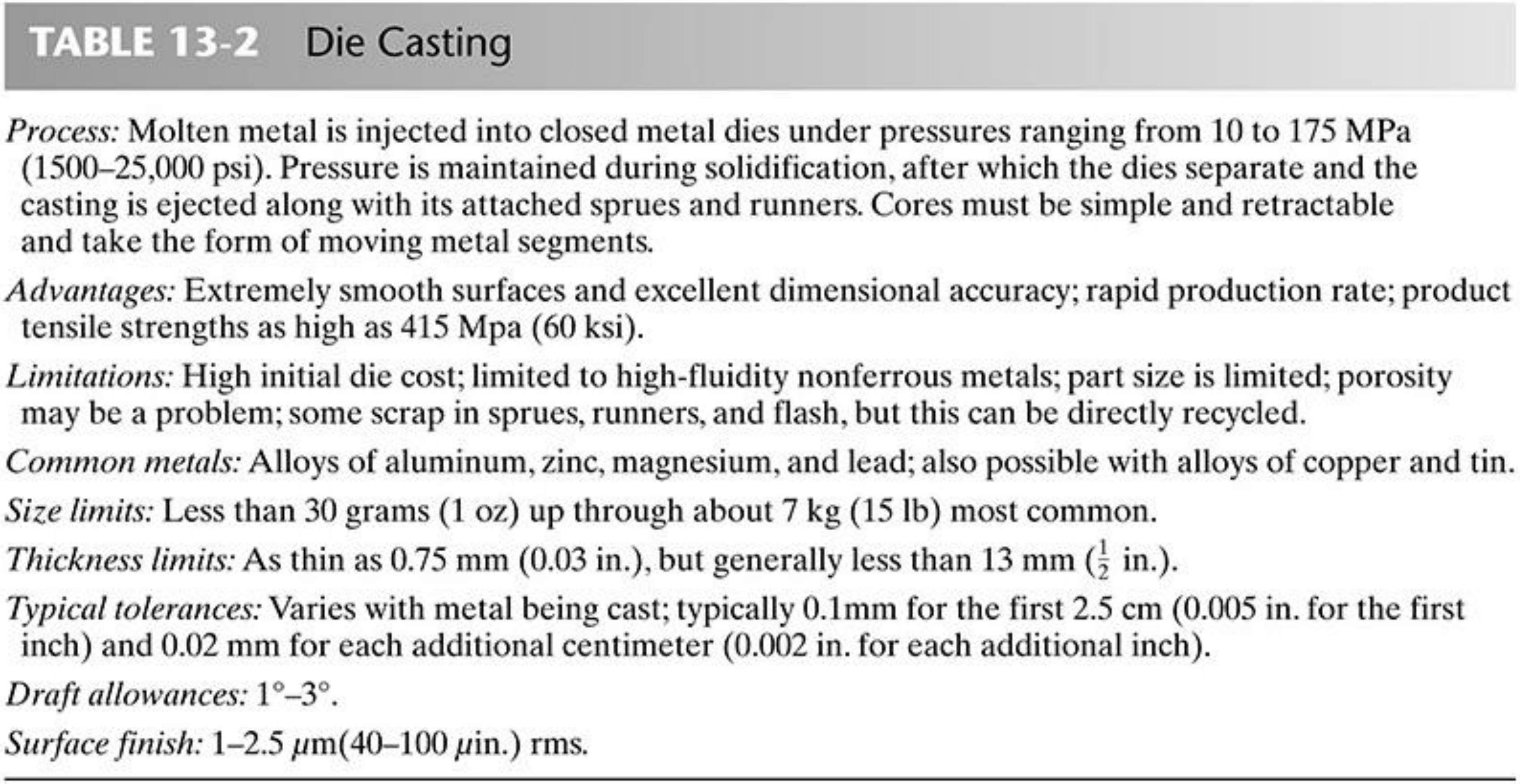


TABLE 13-2 Die Casting

Process: Molten metal is injected into closed metal dies under pressures ranging from 10 to 175 MPa (1500–25,000 psi). Pressure is maintained during solidification, after which the dies separate and the casting is ejected along with its attached sprues and runners. Cores must be simple and retractable and take the form of moving metal segments.

Advantages: Extremely smooth surfaces and excellent dimensional accuracy; rapid production rate; product tensile strengths as high as 415 Mpa (60 ksi).

Limitations: High initial die cost; limited to high-fluidity nonferrous metals; part size is limited; porosity may be a problem; some scrap in sprues, runners, and flash, but this can be directly recycled.

Common metals: Alloys of aluminum, zinc, magnesium, and lead; also possible with alloys of copper and tin.

Size limits: Less than 30 grams (1 oz) up through about 7 kg (15 lb) most common.

Thickness limits: As thin as 0.75 mm (0.03 in.), but generally less than 13 mm ($\frac{1}{2}$ in.).

Typical tolerances: Varies with metal being cast; typically 0.1mm for the first 2.5 cm (0.005 in. for the first inch) and 0.02 mm for each additional centimeter (0.002 in. for each additional inch).

Draft allowances: 1°–3°.

Surface finish: 1–2.5 μm(40–100 μin.) rms.

Die Casting

Figure 13-5 (Below) Principal components of a hot-chamber die-casting machine. (Adapted from Metals Handbook, 9th ed., Vol 15, p. 287, ASM International, Metals Park, OH.)

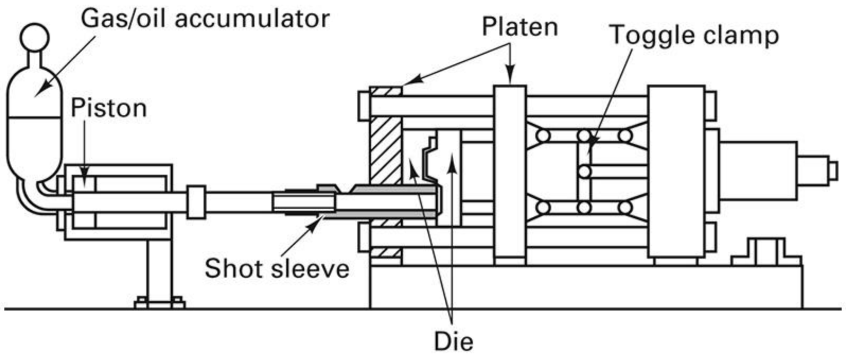
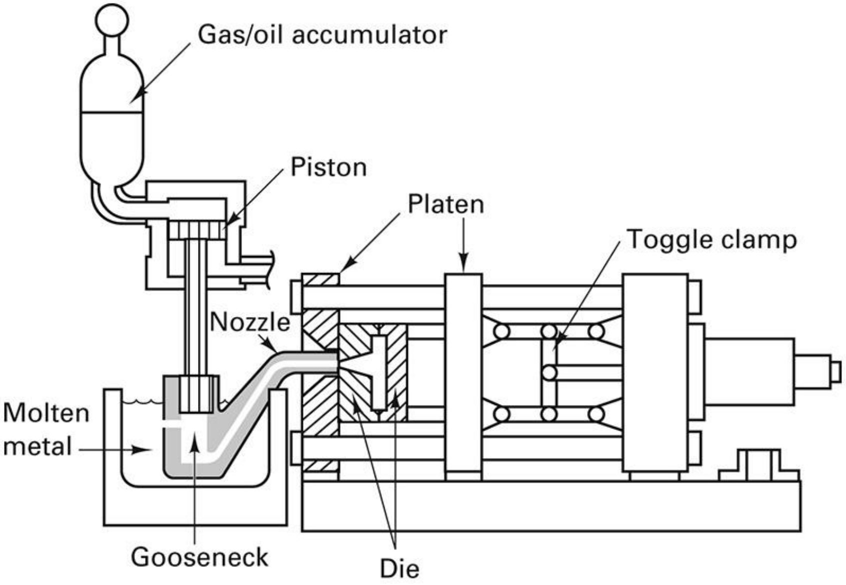


Figure 13-6 (Above) Principal components of a cold-chamber die-casting machine. (Adapted from Metals Handbook, 9th ed., Vol 15, p. 287, ASM International, Metals Park, OH.)



13.4 Squeeze Casting and Semisolid Casting

- Advantages
  - High production
  - Thin-walled parts
  - Good surface finish
  - Dimensional precision
  - Good mechanical properties
- Squeeze Casting
  - Large gate areas and slow metal velocities to avoid turbulence
  - Solidification occurs under high pressure
  - Intricate shapes with good mechanical properties
  - Reduced gas and shrinkage porosity

Rheocasting and Thixocasting

- Rheocasting
  - Molten metal is cooled to semisolid
  - Metal is stirred to break up dendrites
- Thixocasting
  - No handling of molten metal
  - Metal is stirred as in rheocasting and produced into blocks or bars
  - Metal is then reheated to semisolid and can be handled as a solid but processed as a liquid
  - Injection system used is similar to the one used in plastic injection molding

Die Cast Materials

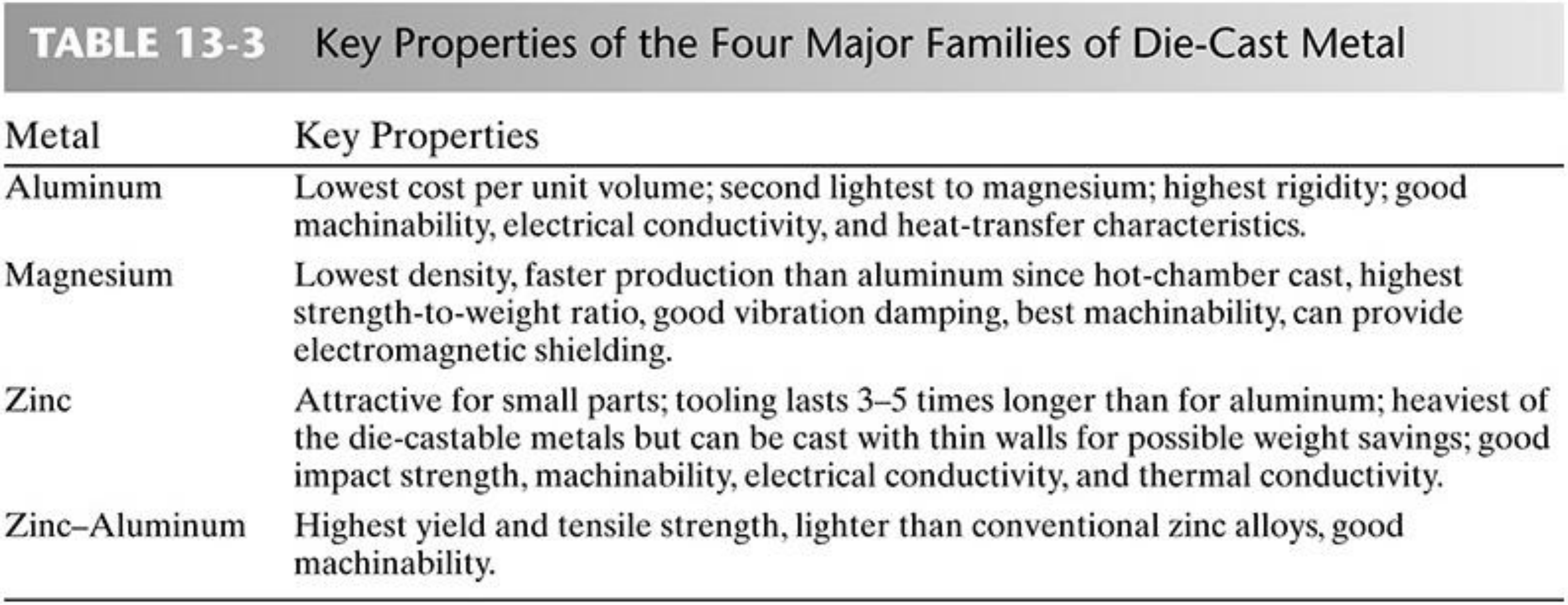


TABLE 13-3 Key Properties of the Four Major Families of Die-Cast Metal

Metal	Key Properties
Aluminum	Lowest cost per unit volume; second lightest to magnesium; highest rigidity; good machinability, electrical conductivity, and heat-transfer characteristics.
Magnesium	Lowest density, faster production than aluminum since hot-chamber cast, highest strength-to-weight ratio, good vibration damping, best machinability, can provide electromagnetic shielding.
Zinc	Attractive for small parts; tooling lasts 3–5 times longer than for aluminum; heaviest of the die-castable metals but can be cast with thin walls for possible weight savings; good impact strength, machinability, electrical conductivity, and thermal conductivity.
Zinc–Aluminum	Highest yield and tensile strength, lighter than conventional zinc alloys, good machinability.

Die Cast Materials

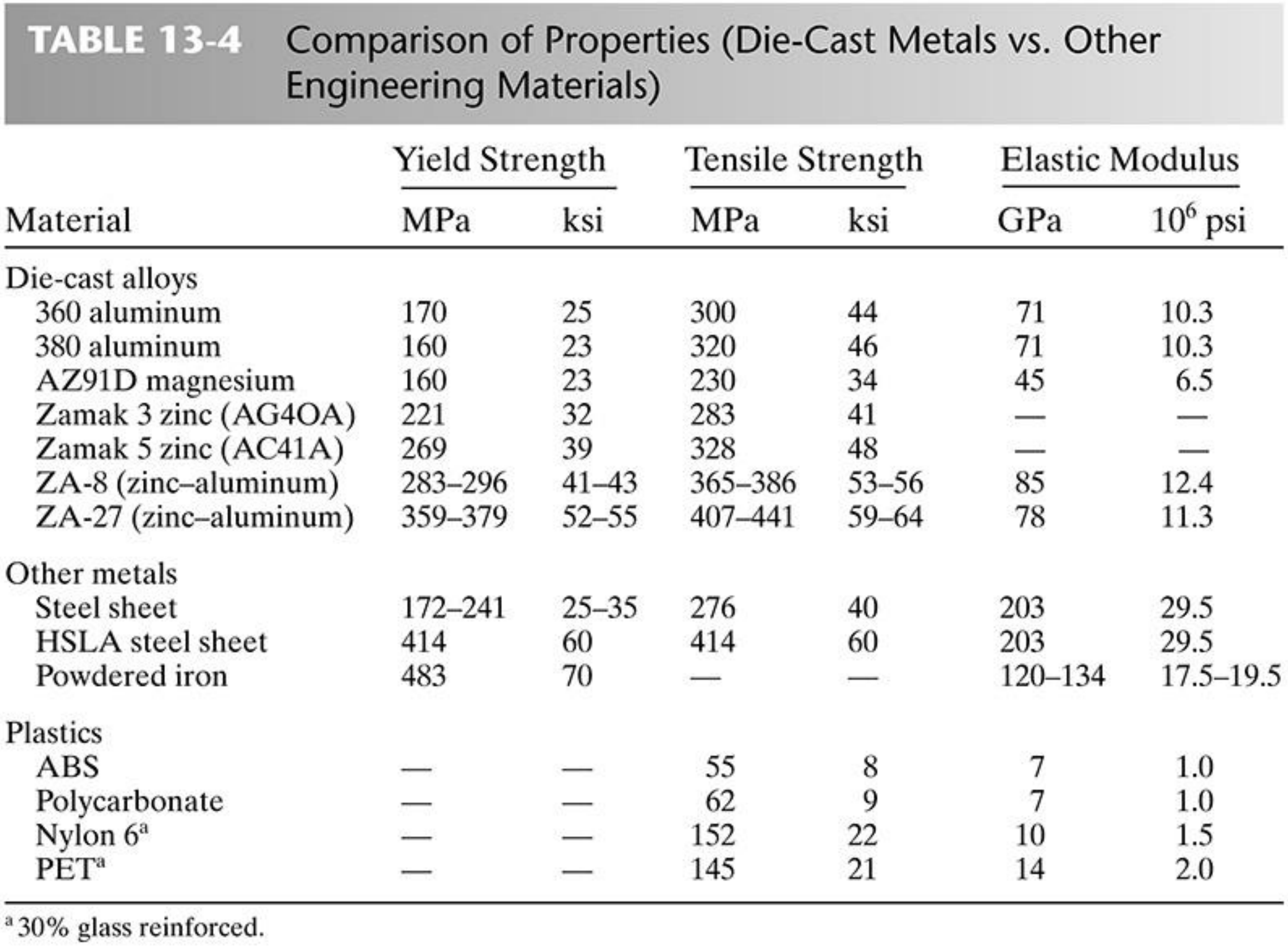


TABLE 13-4 Comparison of Properties (Die-Cast Metals vs. Other Engineering Materials)

	Yield Strength		Tensile Strength		Elastic Modulus	
Material	MPa	ksi	MPa	ksi	GPa	10^6 psi
Die-cast alloys						
360 aluminum	170	25	300	44	71	10.3
380 aluminum	160	23	320	46	71	10.3
AZ91D magnesium	160	23	230	34	45	6.5
Zamak 3 zinc (AG4OA)	221	32	283	41	—	—
Zamak 5 zinc (AC41A)	269	39	328	48	—	—
ZA-8 (zinc–aluminum)	283–296	41–43	365–386	53–56	85	12.4
ZA-27 (zinc–aluminum)	359–379	52–55	407–441	59–64	78	11.3
Other metals						
Steel sheet	172–241	25–35	276	40	203	29.5
HSLA steel sheet	414	60	414	60	203	29.5
Powdered iron	483	70	—	—	120–134	17.5–19.5
Plastics						
ABS	—	—	55	8	7	1.0
Polycarbonate	—	—	62	9	7	1.0
Nylon 6[a]	—	—	152	22	10	1.5
PET[a]	—	—	145	21	14	2.0

[a] 30% glass reinforced.

13.5 Centrifugal Casting

- Inertial forces due to spinning distribute the molten metal into the mold cavity
- True centrifugal casting
  - Dry-sand, graphite or metal mold can be rotated horizontally or vertically
  - Exterior profile of final product is normally round
    - Gun barrels, pipes, tubes
  - Interior of the casting is round or cylindrical
  - If the mold is rotated vertically, the inner surfaces will be parabolic

Centrifugal Casting

- Specialized equipment
- Expensive for large castings
- Long service life
- No sprues, gates, or risers

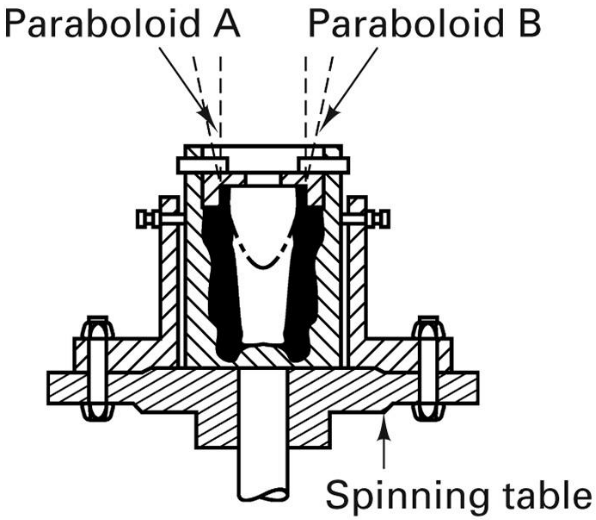


Figure 13-9 (Above) Vertical centrifugal casting, showing the effect of rotational speed on the shape of the inner surface. Parabaloid A results from fast spinning whereas slower spinning will produce parabaloid B.

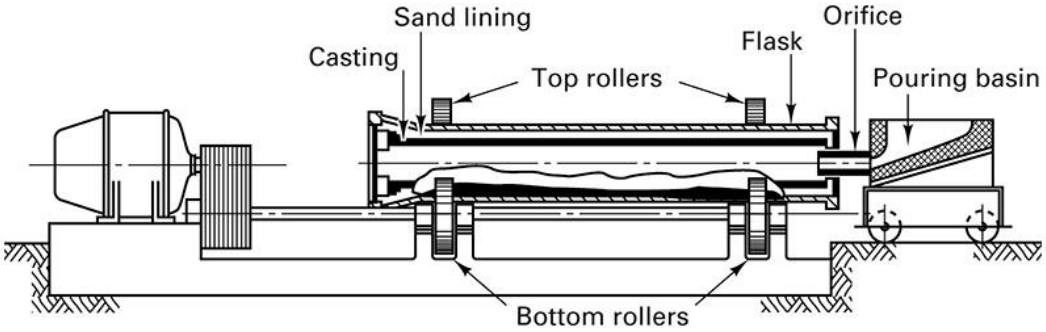


Figure 13-8 (Left) Schematic representation of a horizontal centrifugal casting machine. (Courtesy of American Cast Iron Pipe Company, Birmingham, AL.)

Centrifugal Casting

- Semicentrifugal casting
    - Several molds may be stacked on top of one another
    - Share a common basin and sprue
    - Used for gear blanks, pulley sheaves, wheels, impellers, etc.
- Centrifuging
    - Uses centrifugal acceleration to force metal into mold cavities that are offset from the axis of rotation

Centrifugal Casting

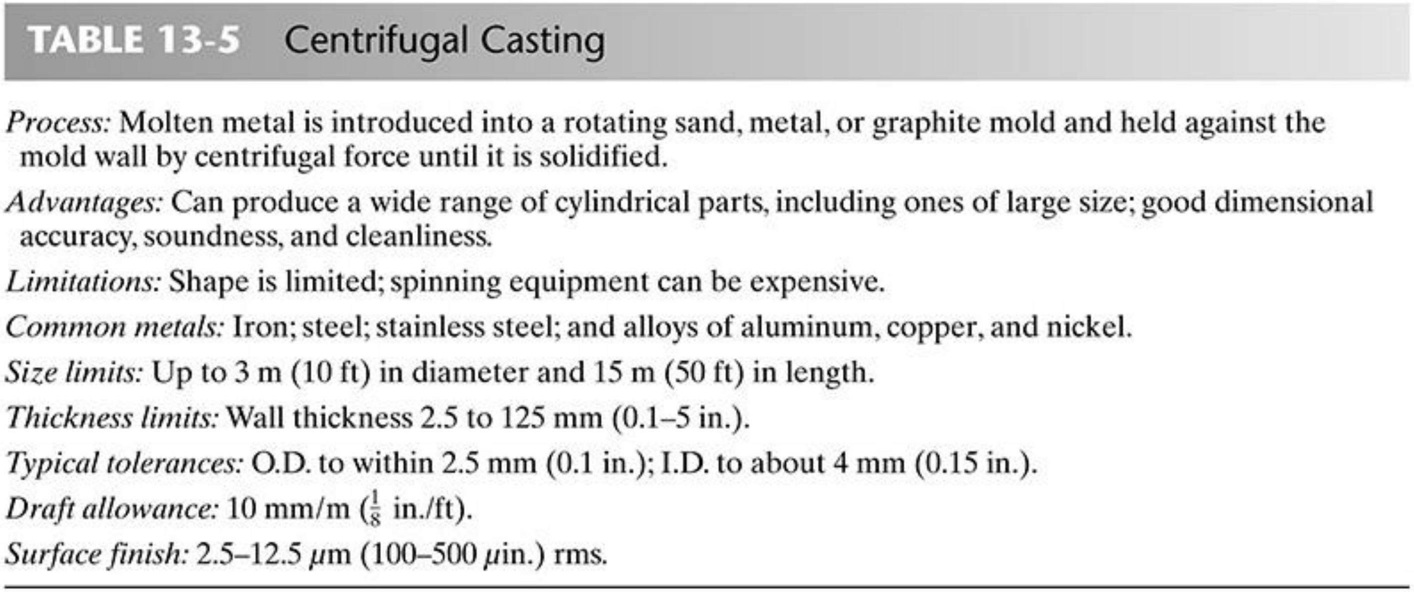


TABLE 13-5 Centrifugal Casting

Process: Molten metal is introduced into a rotating sand, metal, or graphite mold and held against the mold wall by centrifugal force until it is solidified.

Advantages: Can produce a wide range of cylindrical parts, including ones of large size; good dimensional accuracy, soundness, and cleanliness.

Limitations: Shape is limited; spinning equipment can be expensive.

Common metals: Iron; steel; stainless steel; and alloys of aluminum, copper, and nickel.

Size limits: Up to 3 m (10 ft) in diameter and 15 m (50 ft) in length.

Thickness limits: Wall thickness 2.5 to 125 mm (0.1–5 in.).

Typical tolerances: O.D. to within 2.5 mm (0.1 in.); I.D. to about 4 mm (0.15 in.).

Draft allowance: 10 mm/m ($\frac{1}{8}$ in./ft).

Surface finish: 2.5–12.5 μm (100–500 μin.) rms.

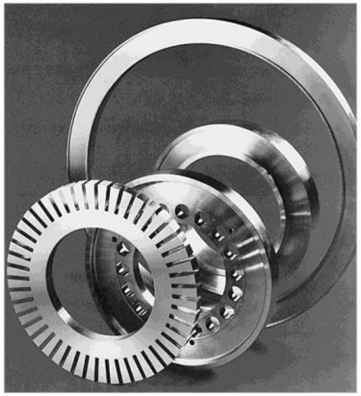
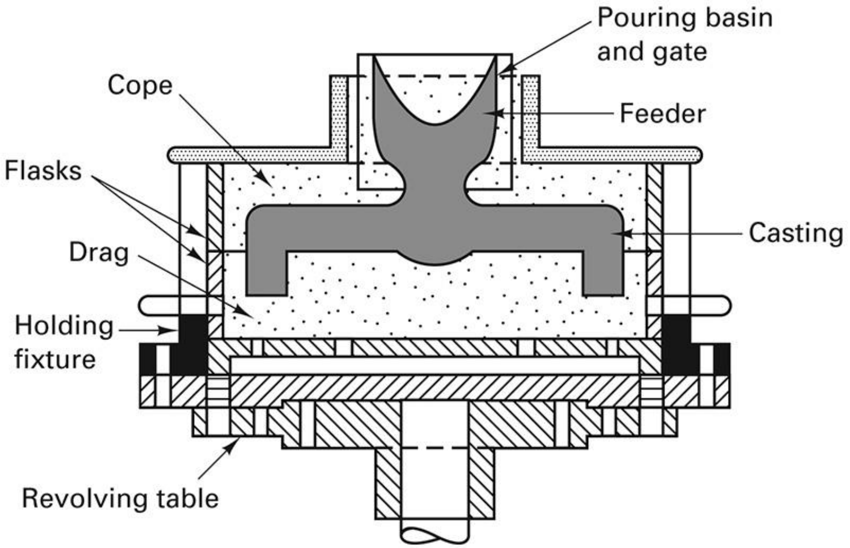


Figure 13-10 Electrical products (collector rings, slip rings, and rotor end rings) that have been centrifugally cast from aluminum and copper. (Courtesy of The Electric Materials Company, North East, PA.)

Centrifuging

Figure 13-11 Schematic of a semicentrifugal casting process.



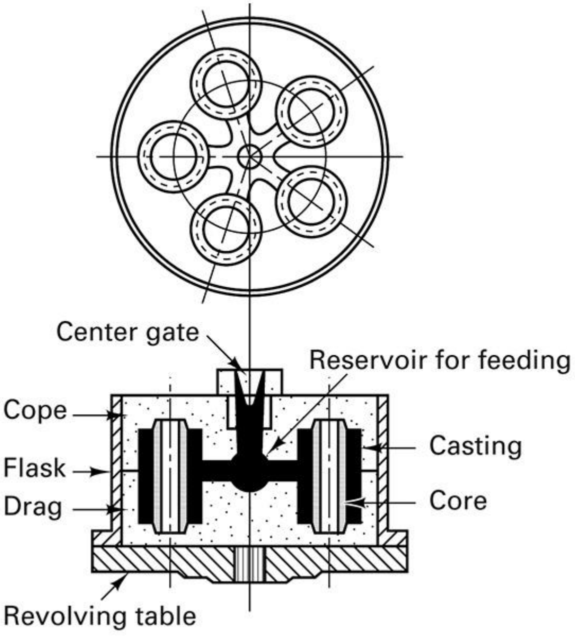


Figure 13-12 (Above) Schematic of a centrifuging process. Metal is poured into the central pouring sprue and spun into the various mold cavities. (Courtesy of American Cast Iron Pipe Company, Birmingham, AL.)

13.6 Continuous Casting

- Used for the solidification of basic shapes for feedstock
- Can be used to produce long lengths of complex cross sections

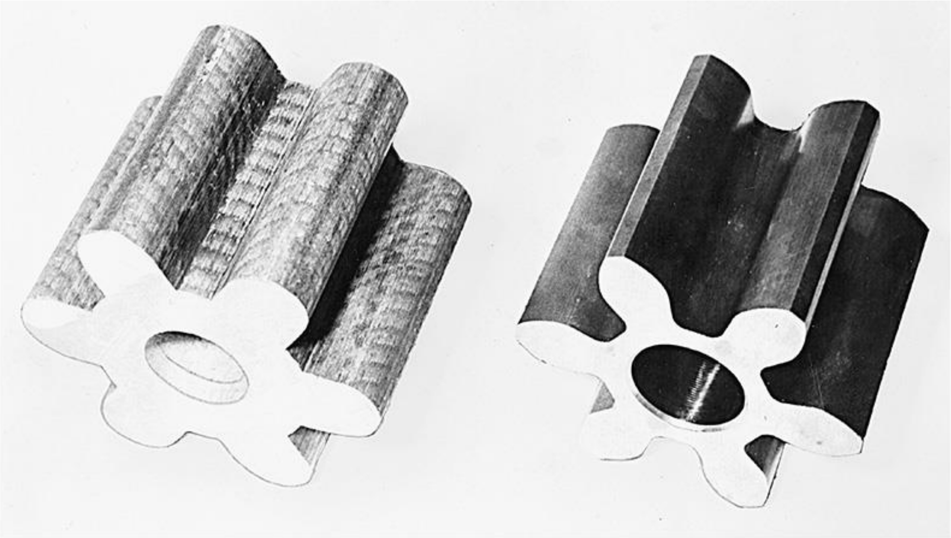


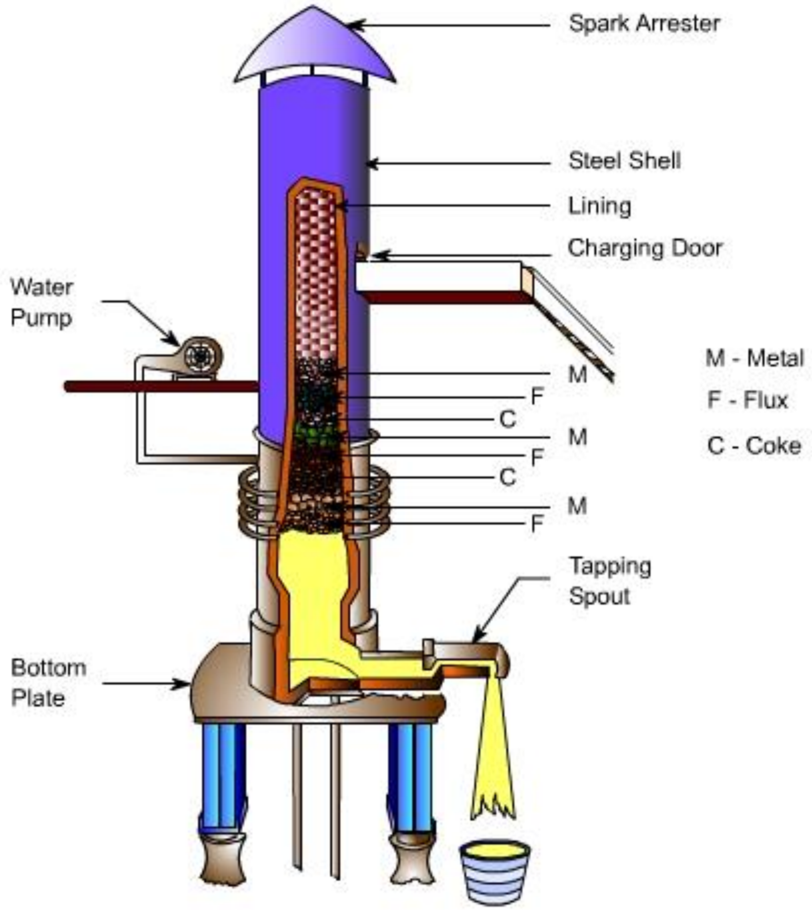
Figure 13-13 Gear produced by continuous casting. (Left) As-cast material; (right) after machining. (Courtesy of ASARCO, Tucson, AZ.)

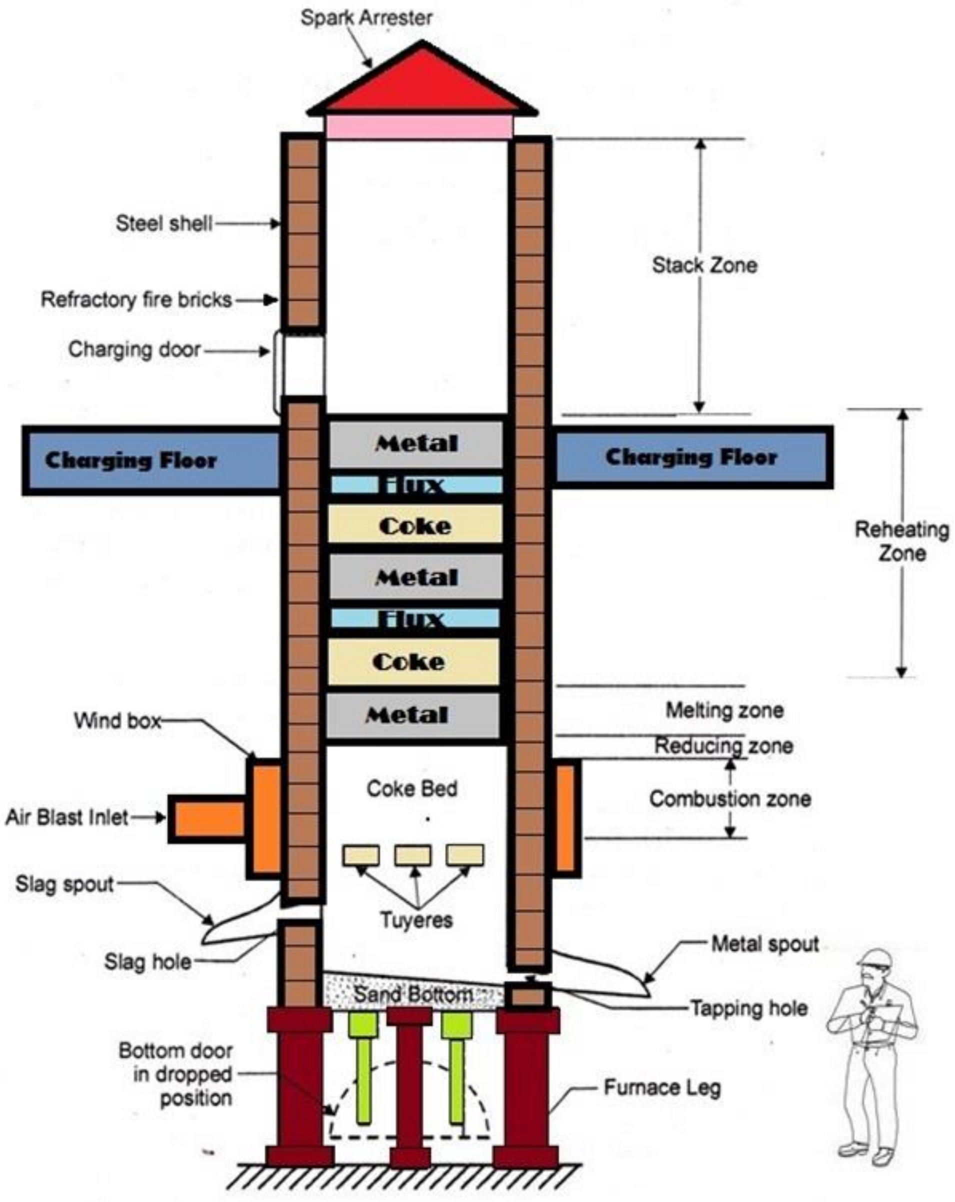
13.7 Melting

- Selection of melting method is based on several factors
  - Temperature needed to melt and superheat the metal
  - Alloy being melted
  - Desired melting rate and quantity
  - Desired quality of metal
  - Availability and cost of fuels
  - Variety of metals or alloys to be melted
  - Batch or continuous
  - Required level of emission control
  - Capital and operating costs

Cupolas

- Cupola- refractory-lined, vertical steel shell
    - Alternating layers of carbon, iron, limeston, and alloy additions
    - Melted under forced air
- Simple and economical
- Melting rate can be increased by using hot-blast cupolas, oxygen-enriched blasts, or plasma torches





Cupola furnace

Types of Furnaces

- Indirect Fuel-Fired Furnace
  - Crucibles or holding pots are heated externally which in turn heats the metal
  - Low capital and operating costs
- Direct Fuel-Fired Furnace
  - Similar to small open-hearth furnaces
  - Flame passes directly over metal

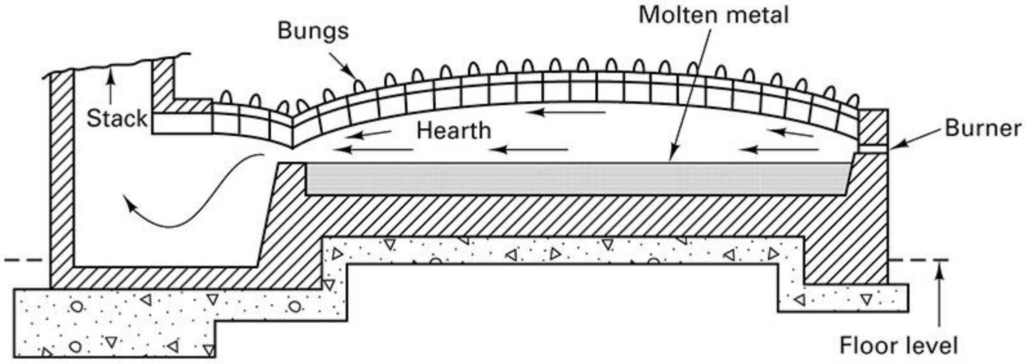


Figure 13-14 Cross section of a direct fuel-fired furnace. Hot combustion gases pass across the surface of a molten metal pool.

Arc Furnaces

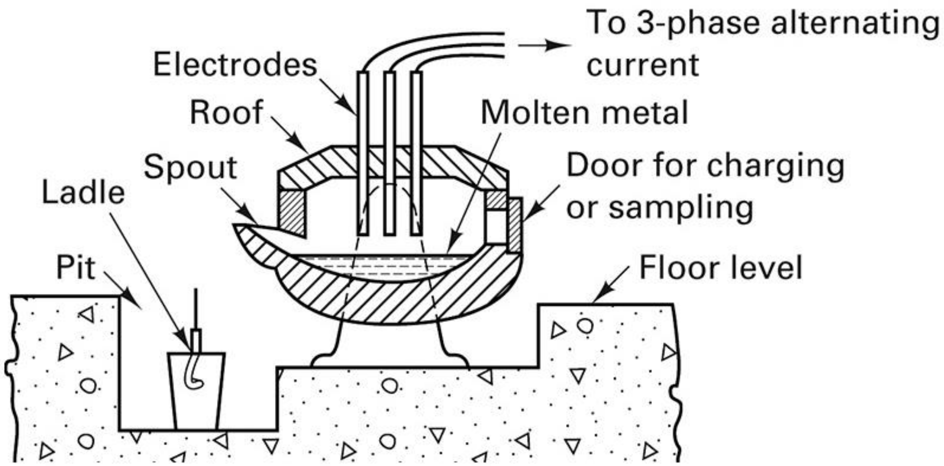


Figure 13-15 Schematic diagram of a three-phase electric-arc furnace.

- Preferred method for most factories
- Rapid melting rates
- Ability to hold molten metal for any period of time
- Greater ease of incorporating pollution control equipment

Induction Furnaces

- Rapid melting rates
- Two basic types of induction furnaces
  - High-frequency (coreless)
    - Contains a crucible surrounded by a water-cooled coil of copper tubing
    - High-frequency electrical current induces an alternating magnetic field
    - The magnetic field, in turn, induces a current in metal being melted
  - Low-frequency (channel-type)
    - Small channel is surrounded by the primary coil and a secondary coil is formed by a loop or channel of molten metal

Induction Furnaces

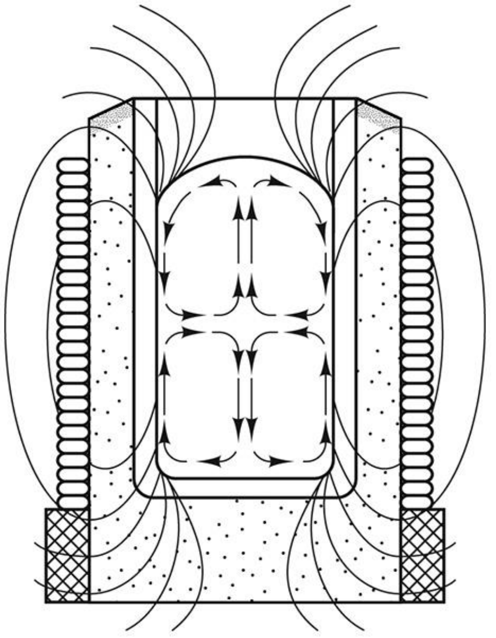
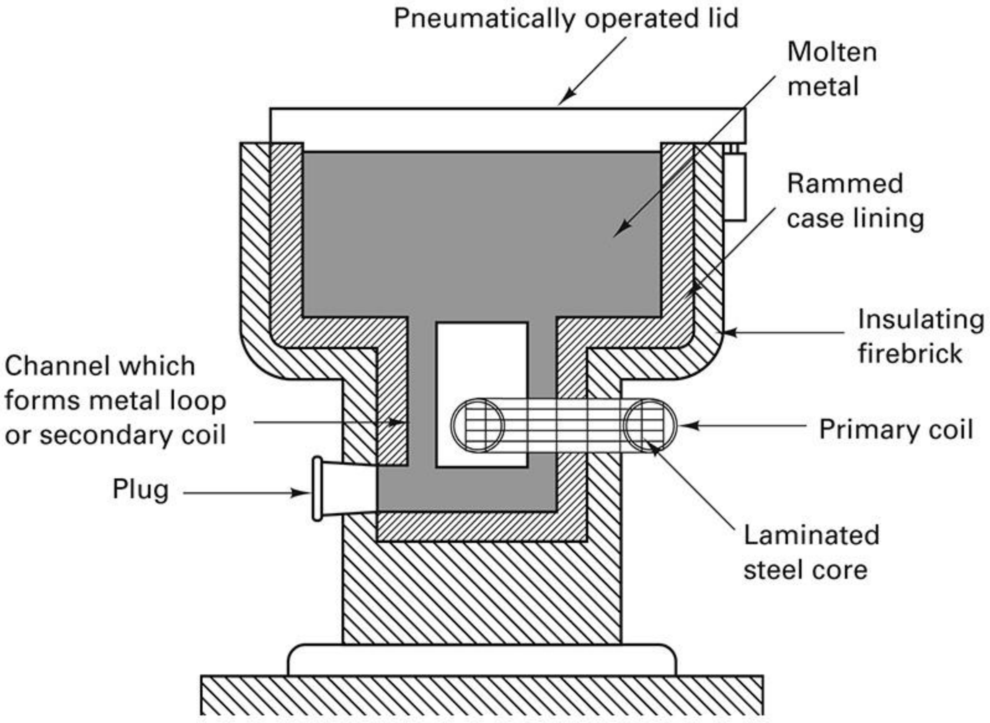


Figure 13-17 (Above) Schematic showing the basic principle of a coreless induction furnace.

Figure 13-18 (Below) Cross section showing the principle of the low-frequency or channel-type induction furnace.



13.8 Pouring Practice

- Ladles are used to transfer the metal from the melting furnace to the mold
- Concerns during pouring
  - Maintain proper metal temperature
  - Ensure that only high-quality metal is transferred
- Pouring may be automated in high-volume, mass-production foundries

Automatic Pouring

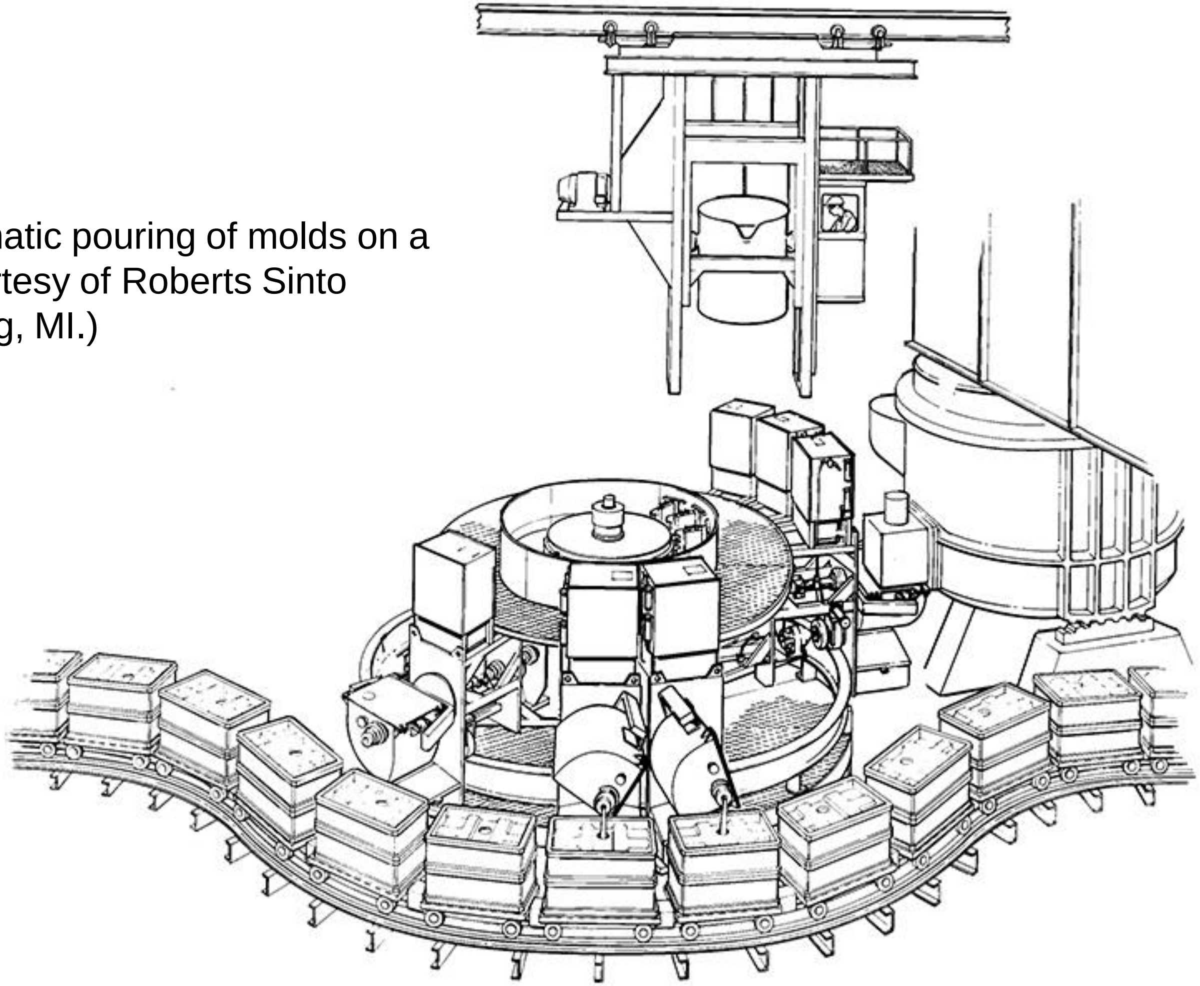


Figure 13-19 Automatic pouring of molds on a conveyor line. (Courtesy of Roberts Sinto Corporation, Lansing, MI.)

13.9 Cleaning, Finishing, and Heat Treating of Castings

- Post-casting operations
  - Removing cores
  - Removing gates and risers
  - Removing fins, flash, and rough surface spots
  - Cleaning the surface
  - Repairing any defects
- Cleaning and finishing may be expensive, so processes should be selected that minimize necessary operations

Cleaning and Finishing

- Sand cores may be removed by mechanical shaking or chemically dissolved
- Flash may be removed by being tumbled in barrels containing abrasive materials
- Manual finishing
    - Pneumatic chisels, grinders, blast hoses
- Porosity at surfaces may be filled with resins (impregnation)
- Pores may also be filled with lower-melting point metals (infiltration)

Heat Treatment and Inspection of Casting

- Heat treatments alter properties while maintaining shape
- Full anneals reduce hardness and brittleness of rapidly cooled castings
  - Reduce internal stresses
- Nonferrous castings may be heat treated to provide chemical homogenization or stress relief
- Prepares materials for further finishing operations

13.10 Automation in Foundries

- Most manufacturing operations may be performed by robots
    - Dry mold, coat cores, vent molds, clean or lubricate dies
    - Plasma torches
    - Grinding and blasting
    - Investment casting
    - Lost foam process
- Casting can be dangerous for workers; by automating these processes, safety is increased

13.11 Process Selection

- Each casting process has advantages and disadvantages
- Typical requirements
  - Size, complexity, dimensional precision, surface finish, quantity, rate of production
  - Costs for materials (dies, equipment, and metal)

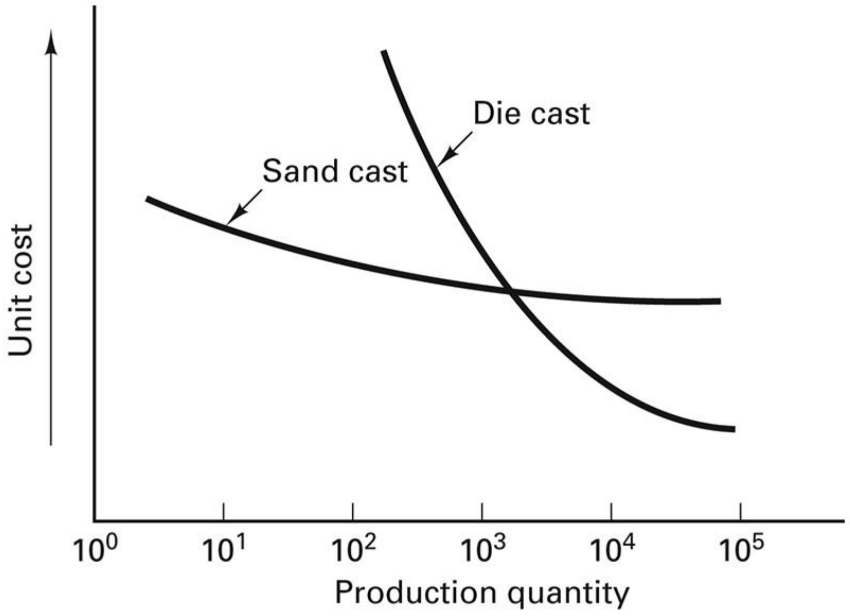


Figure 13-20 Typical unit cost of castings comparing sand casting and die casting. Note how the large cost of a die-casting die diminishes as it is spread over a larger quantity of parts.

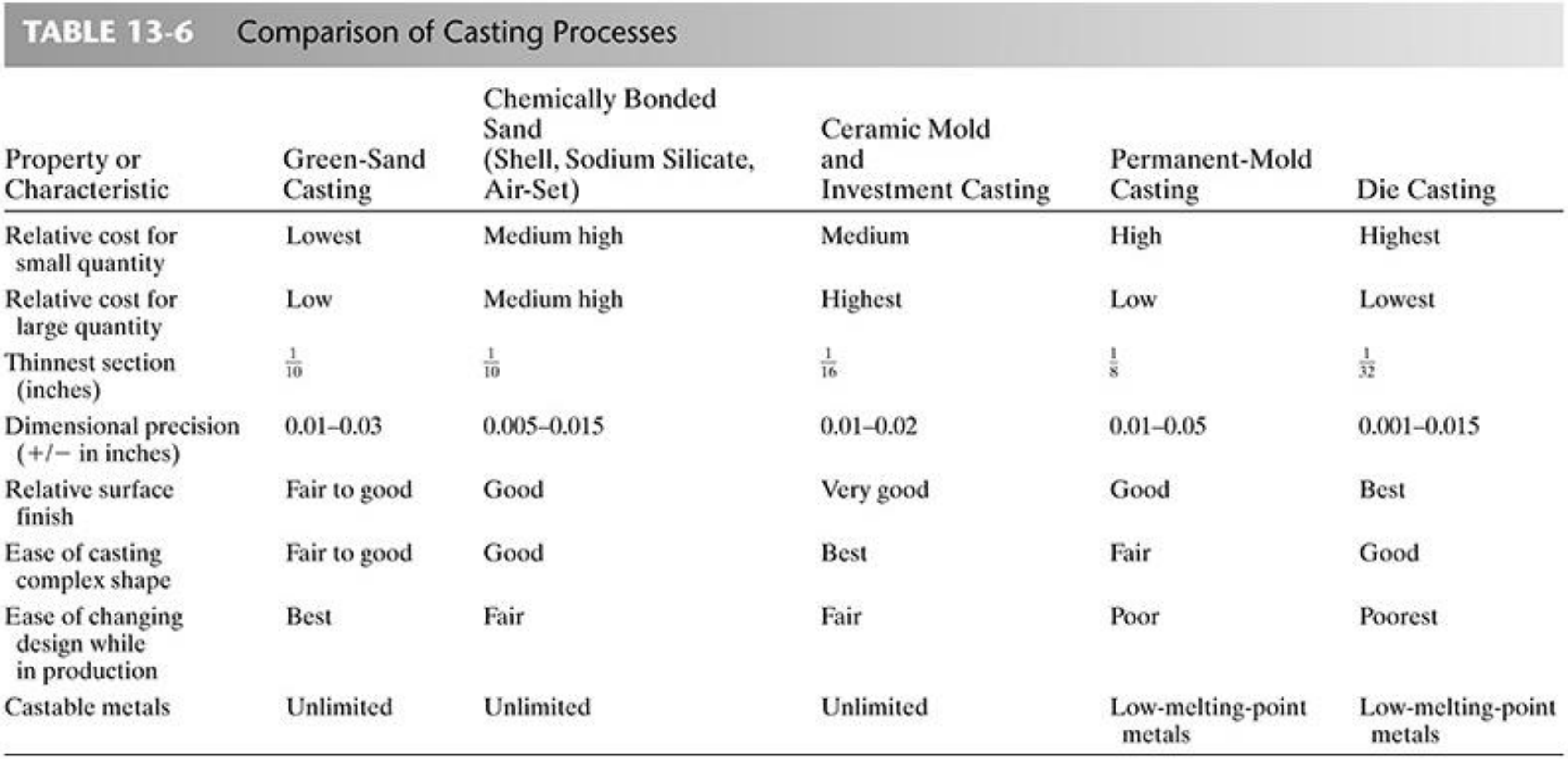


TABLE 13-6 Comparison of Casting Processes

Property or Characteristic	Green-Sand Casting	Chemically Bonded Sand (Shell, Sodium Silicate, Air-Set)	Ceramic Mold and Investment Casting	Permanent-Mold Casting	Die Casting
Relative cost for small quantity	Lowest	Medium high	Medium	High	Highest
Relative cost for large quantity	Low	Medium high	Highest	Low	Lowest
Thinnest section (inches)	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{32}$
Dimensional precision (+/− in inches)	0.01–0.03	0.005–0.015	0.01–0.02	0.01–0.05	0.001–0.015
Relative surface finish	Fair to good	Good	Very good	Good	Best
Ease of casting complex shape	Fair to good	Good	Best	Fair	Good
Ease of changing design while in production	Best	Fair	Fair	Poor	Poorest
Castable metals	Unlimited	Unlimited	Unlimited	Low-melting-point metals	Low-melting-point metals

Summary

- Variety of casting processes
- Each has its own set of characteristics and benefits
- Care should be taken in properly selecting a casting process to minimize cost while maximizing qualities of the finished product
- Most casting processes may be automated, but the process selected determines the quality of the finished product

Chapter 16:
Powder Metallurgy

DeGarmo’s Materials and Processes in Manufacturing

18.1 Introduction

- Powder metallurgy is the name given to the process by which fine powdered materials are blended, pressed into a desired shape, and then heated to bond surfaces
- Typically used when large amounts of small, intricate parts with high precision are required
- Little material waste and unusual mixtures can be utilized
- Used for parts in the automotive industry, household appliances, and recreational equipment (to name a few)

18.2 The Basic Process

- Four basic steps
  - 1. Powder manufacture
  - 2. Mixing or blending
  - 3. Compacting
  - 4. Sintering

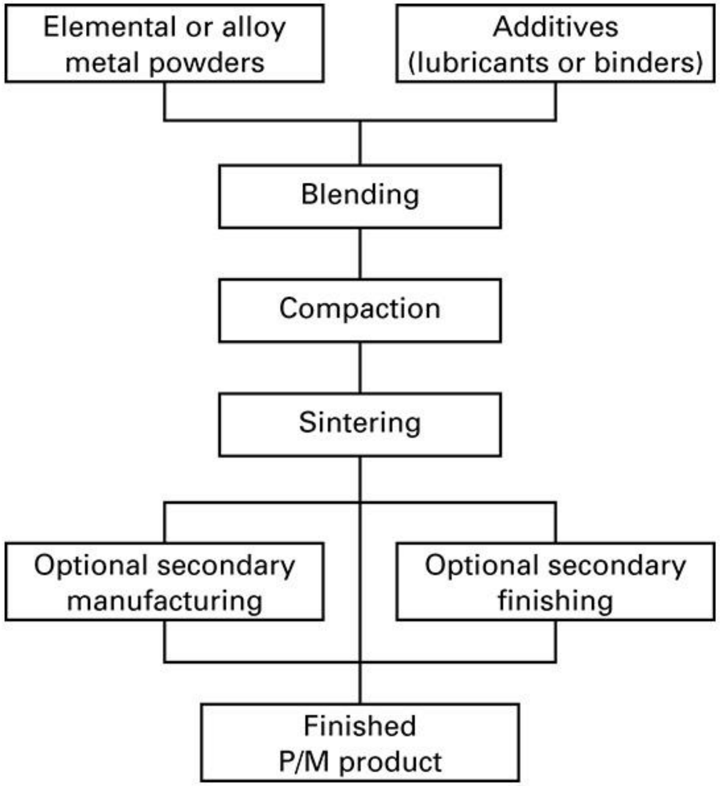


Figure 18-1 Simplified flow chart of the basic powder metallurgy process.

18.3 Powder Manufacture

- Properties of powder metallurgy products are highly dependent on the characteristics of starting powders
- Some important properties and characteristics
  - Chemistry and purity
  - Particle size
  - Size distribution
  - Particle shape
  - Surface texture
- Useful in producing prealloyed powders
  - Each powder particle can have the desired alloy composition

Powder Manufacture

- The majority of commercial powder is produced by some form of melt atomization
  - Atomization is a process where liquid metal is fragmented into small droplets that cool and solidify into particles

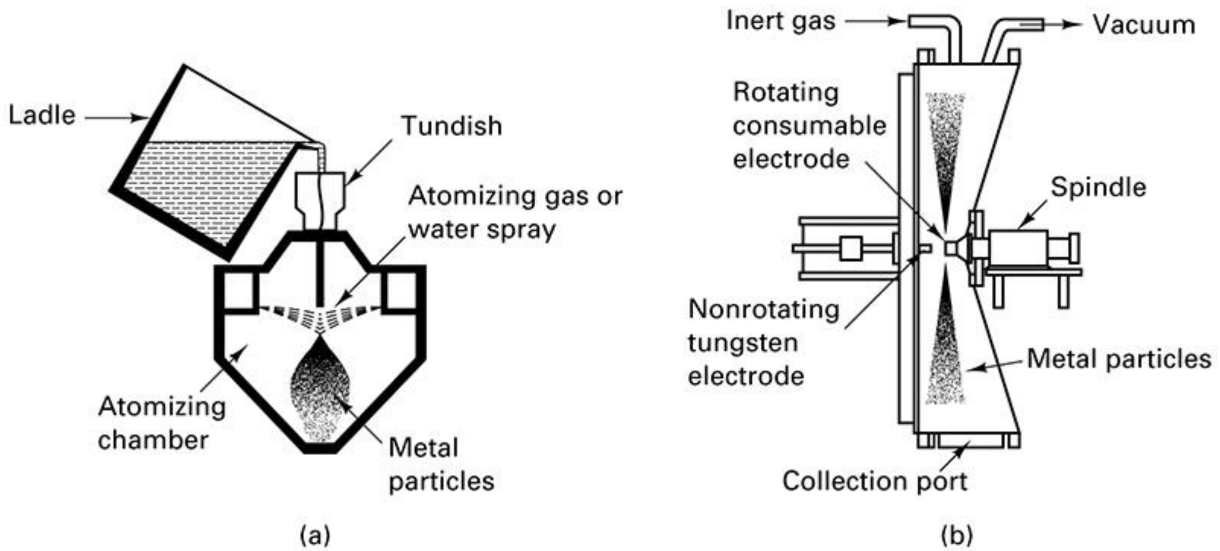


Figure 18-2 Two methods for producing metal powders: (a) melt atomization and (b) atomization from a rotating consumable electrode.

Additional Methods of Powder Manufacture

- Methods
  - Chemical reduction of particulate compounds
  - Electrolytic deposition
  - Pulverization or grinding
  - Thermal decomposition of particulate hydrides
  - Precipitation from solution
  - Condensation of metal vapors
- Almost any metal or alloy can be converted into powder

18.4 Rapidly Solidified Powder (Microcrystalline and Amorphous)

- If the cooling rate of an atomized liquid is increased, ultra-fine or microcrystalline sized grains can form
- Some metals can solidify without becoming crystalline (called amorphous materials)
- amorphous materials can have high strength, improved corrosion resistance, and reduced energy to induce and reverse magnetization

18.5 Powder Testing and Evaluation

- Powders should be evaluated for their suitability for further processing
- *Flow rate* measures the ease with which powder can be fed and distributed into a die
- *Apparent density* is the measure of a powder’s ability to fill available space without external pressure
- *Compressibility* is the effectiveness of applied pressure
- *Green strength* is used to describe the strength of the pressed powder after compacting

18.6 Powder Mixing and Blending

- The majority of powders are mixed with other powders, binders, and lubricants to achieve the desired characteristics in the finished product
- Sufficient diffusion must occur during sintering to ensure a uniform chemistry and structure
- Unique composites can be produced
- Blending or mixing operations can be done either wet or dry

18.7 Compacting

- Loose powder is compacted and densified into a shape, known as green compact
- Most compacting is done with mechanical presses and rigid tools
  - Hydraulic and pneumatic presses are also used

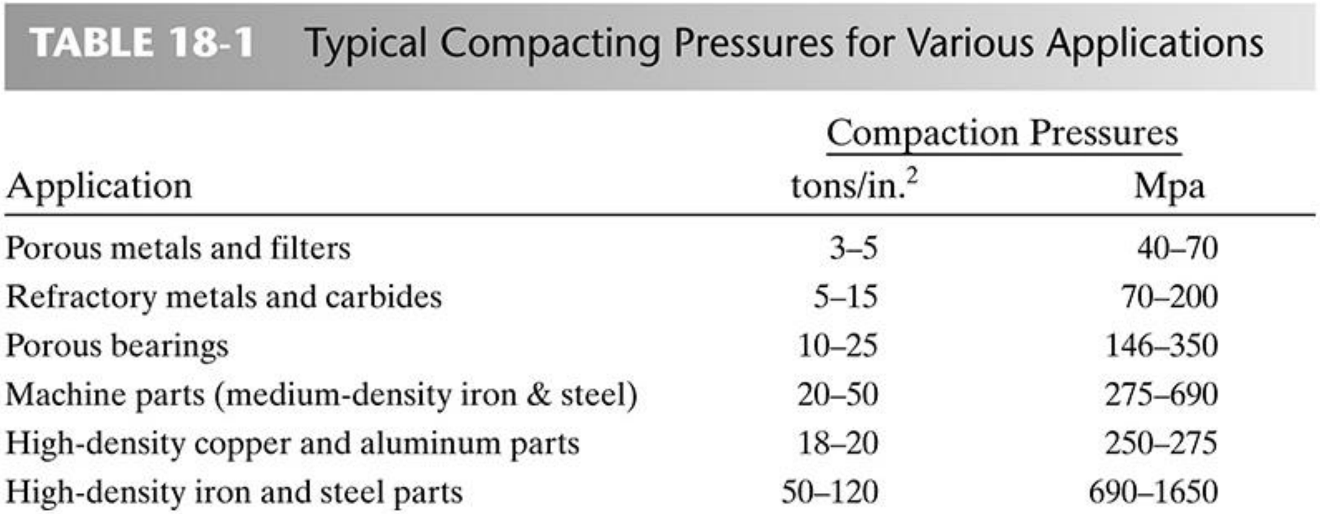


TABLE 18-1 Typical Compacting Pressures for Various Applications

Application	Compaction Pressures tons/in.^{2}	Compaction Pressures Mpa
Porous metals and filters	3–5	40–70
Refractory metals and carbides	5–15	70–200
Porous bearings	10–25	146–350
Machine parts (medium-density iron & steel)	20–50	275–690
High-density copper and aluminum parts	18–20	250–275
High-density iron and steel parts	50–120	690–1650

Figure 18-3 (Left) Typical press for the compacting of metal powders. A removable die set (right) allows the machine to be producing parts with one die set while another is being fitted to produce a second product. (*Courtesy of Alfa Laval, Inc., Warminster, PA*.)

Compaction Sequence

- Powders do not flow like liquid, they simply compress until an equal and opposing force is created
  - This opposing force is created from a combination of (1) resistance by the bottom punch and (2) friction between the particles and die surface

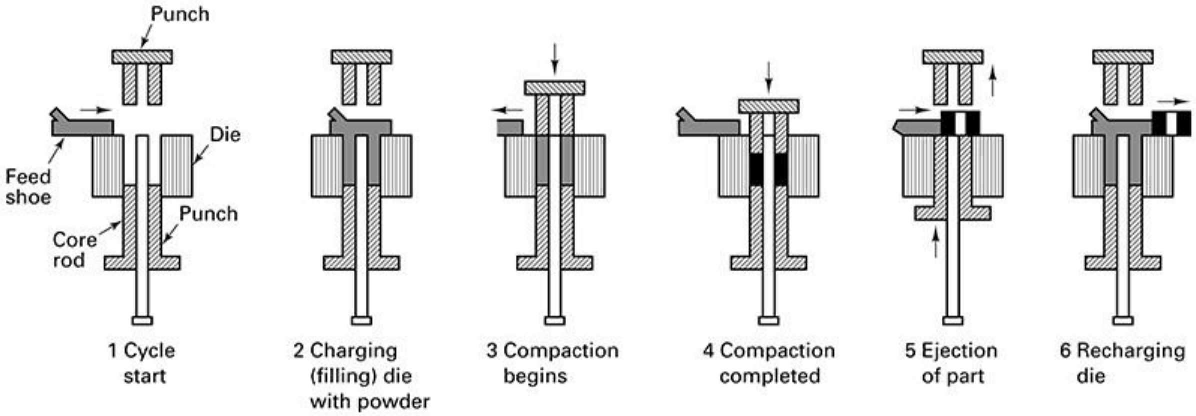


Figure 18-4 Typical compaction sequence for a single-level part, showing the functions of the feed shoe, die core rod, and upper and lower punches. Loose powder is shaded; compacted powder is solid black.

Additional Considerations During Compacting

- When the pressure is applied by only one punch, the maximum density occurs right below the punch surface and decreases away from the punch
- For complex shapes, multiple punches should be used

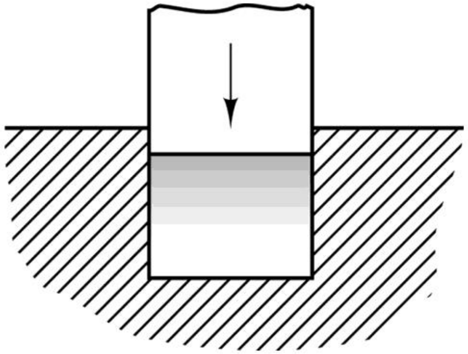


Figure 18-5 Compaction with a single moving punch, showing the resultant nonuniform density (shaded), highest where particle movement is the greatest.

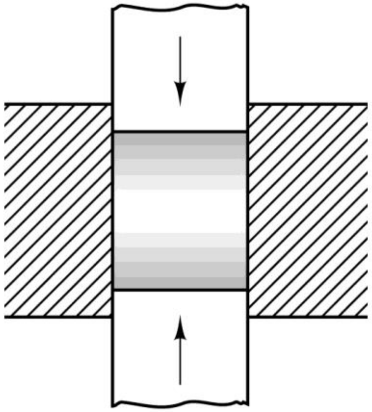


Figure 18-6 Density distribution obtained with a double-acting press and two moving punches. Note the increased uniformity compared to Figure 18-5. Thicker parts can be effectively compacted.

Effects of Compacting

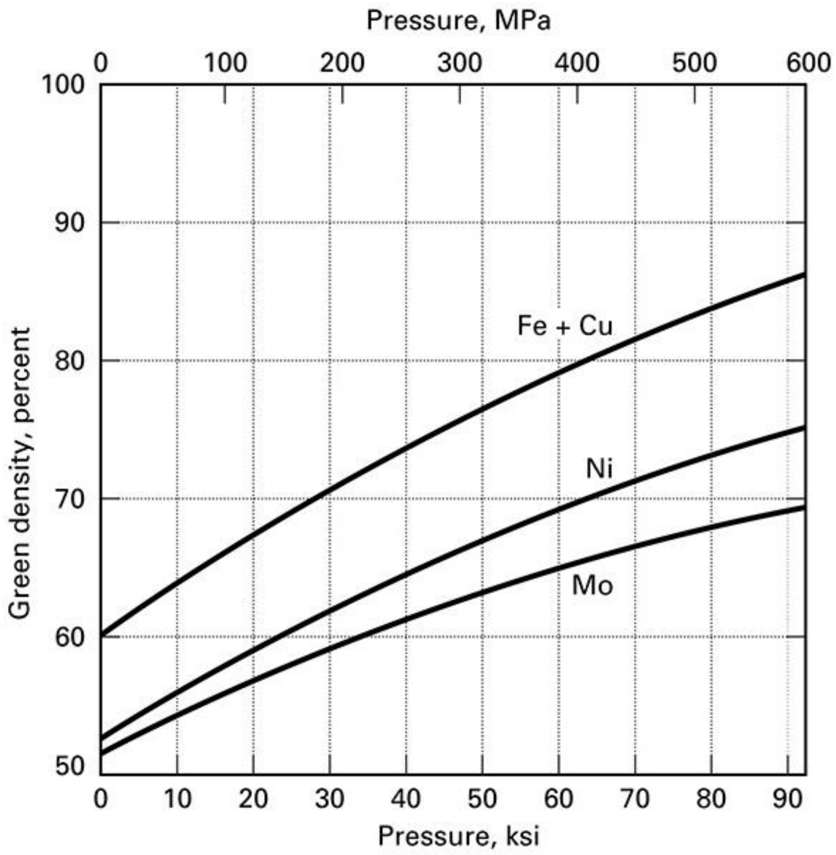


Figure 18-7 Effect of compacting pressure on green density (the density after compaction but before sintering). Separate curves are for several commercial powders.

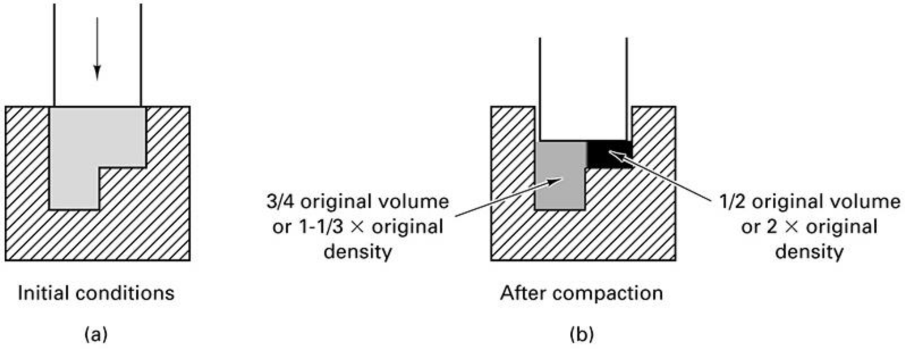
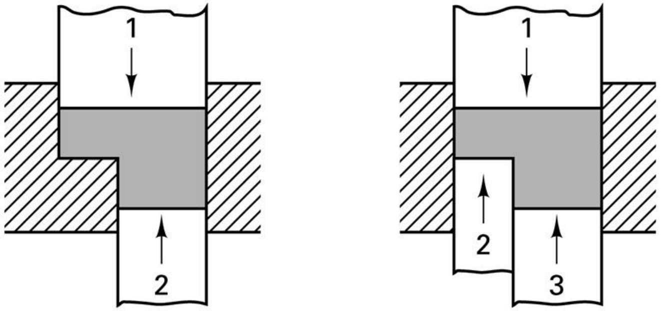


Figure 18-8 Compaction of a two-thickness part with only one moving punch. (a) Initial conditions; (b) after compaction by the upper punch. Note the drastic difference in compacted density.



Single lower punch

Double lower punch

Figure 18-9 Two methods of compacting a double-thickness part to near-uniform density. Both involve the controlled movement of two or more punches.

Classes of Powder Metallurgy Equipment

- The complexity of the part dictates the complexity of equipment
- Equipment has been grouped into classes

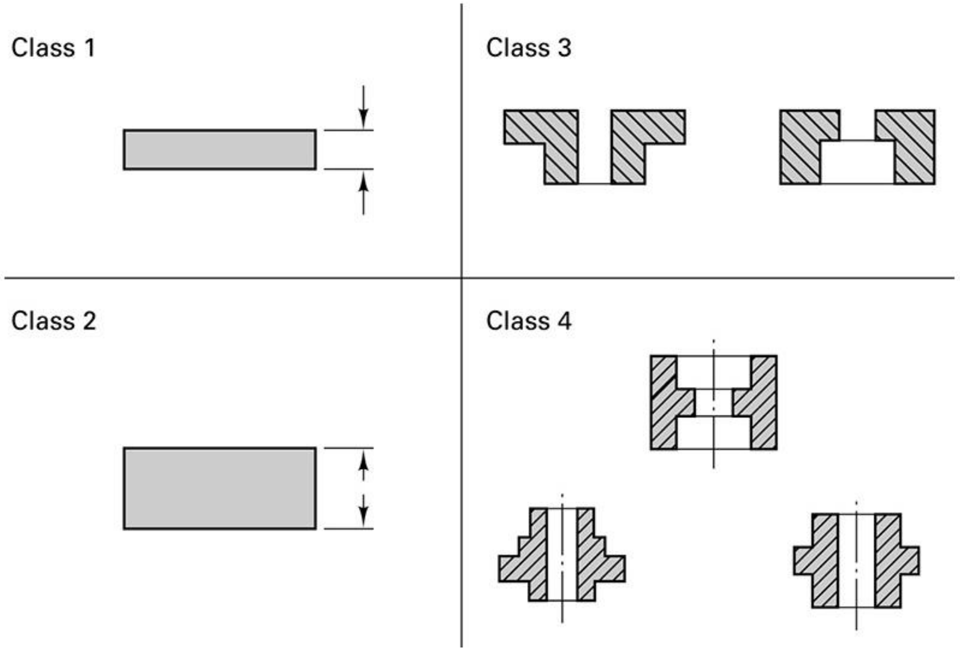


Figure 18-10 Sample geometries of the four basic classes of press-and-sinter powder metallurgy parts. Note the increased pressing complexity that would be required as class increases.

Complex Compacting

- If an extremely complex shape is desired, the powder may be encapsulated in a flexible mold, which is then immersed in a pressurized gas or liquid
    - Process is known as isostatic compaction
- In warm compaction, the powder is heated prior to pressing
- The amount of lubricant can be increased in the powder to reduce friction
- Because particles tend to be abrasive, tool wear is a concern in powder forming

18.8 Sintering

- In the sintering operation, the pressed-powder compacts are heated in a controlled atmosphere to right below the melting point
- Three stages of sintering
  - Burn-off (purge)- combusts any air and removes lubricants or binders that would interfere with good bonding
  - High-temperature- desired solid-state diffusion and bonding occurs
  - Cooling period- lowers the temperature of the products in a controlled atmosphere
- All three stages must be conducted in oxygen-free conditions

18.9 Hot-Isostatic Pressing

- Hot-isostatic pressing (HIP) combines powder compaction and sintering into a single operation
  - Gas-pressure squeezing at high temperatures
- Heated powders may need to be protected from harmful environments
- Products emerge at full density with unifrom, isotropic properties
- Near-net shapes are possible

18.10 Other Techniques to Produce High-Density P/M Products

- High-temperature metal deformation processes can be used to produce high density P/M parts
- Ceracon process- a heated preform is surrounded by hot granular material, transmitting uniform pressure
- Spray forming- inert gases propel molten droplets onto a mold

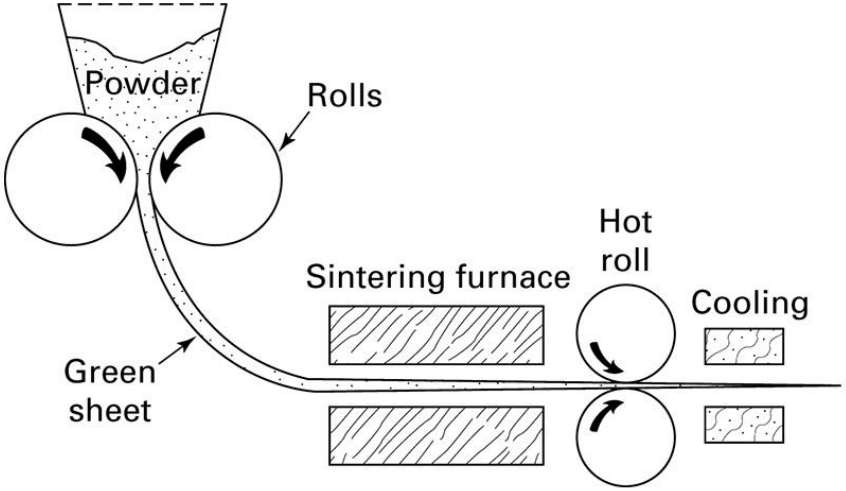


Figure 18-11 One method of producing continuous sheet products from powdered feedstock.

18.11 Metal Injection Molding (MIM) or Powder Injection Molding (PIM)

- Ultra-fine spherical-shaped metal, ceramic, or carbide powders are combined with a thermoplastic or wax
  - Becomes the feedstock for the injection process
- The material is heated to a pastelike consistency and injected into a heated mold cavity
- After cooling and ejection, the binder material is removed
  - Most expensive step in MIM and PIM

MIM

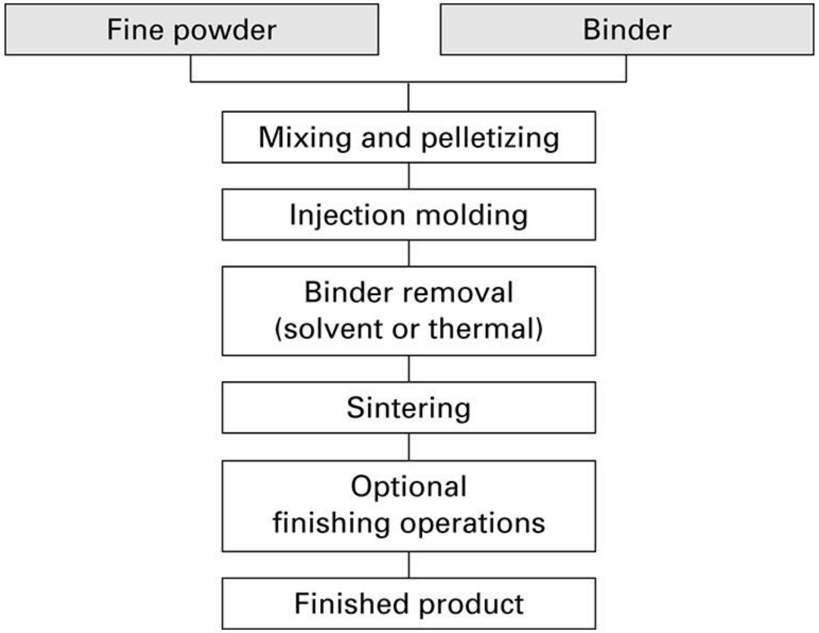


Figure 18-12 Flow chart of the metal injection molding process (MIM) used to produce small, intricate-shaped parts from metal powder.

Figure 18-13 Metal injection molding (MIM) is ideal for producing small, complex parts. (Courtesy of Megamet Solid Metals, Inc., St. Louis, MO.)

18.12 Secondary Operations

- Most powder metallurgy products are ready to use after the sintering process
- Some products may use secondary operation to provide enhanced precision, improved properties, or special characteristics
- Distortion may occur during nonuniform cool-down so the product may be repressed, coined, or sized to improve dimensional precision

Secondary Operations

- If massive metal deformation takes place in the second pressing, the operation is known as P/M forging
    - Increases density and adds precision
- Infiltration and impregnation- oil or other liquid is forced into the porous network to offer lubrication over an extended product lifetime
- Metal infiltration fills in pores with other alloying elements that can improve properties
- P/M products can also be subjected to the conventional finishing operations: heat treatment, machining, and surface treatments

Figure 18-14 (Right) Comparison of conventional forging and the forging of a powder metallurgy preform to produce a gear blank (or gear). Moving left to right, the top sequence shows the sheared stock, upset section, forged blank, and exterior and interior scrap associated with conventional forging. The finished gear is generally machined from the blank with additional generation of scrap. The bottom pieces are the powder metallurgy preform and forged gear produced entirely without scrap by P/M forging. (*Courtesy of GKN Sinter Metals, Auburn Hills, MI.)*

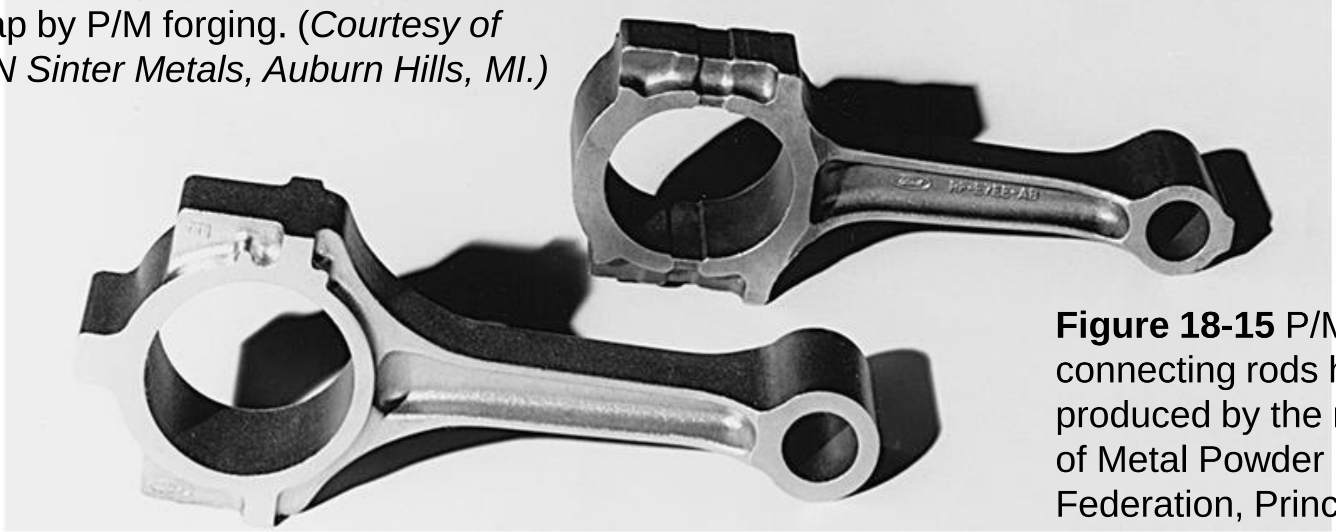


Figure 18-15 P/M forged connecting rods have been produced by the millions. (Courtesy of Metal Powder Industries Federation, Princeton, NJ.)

18.13 Properties of P/M Products

- The properties of P/M products depend on multiple variables
  - Type and size of powder
  - Amount and type of lubricant
  - Pressing pressure
  - Sintering temperature and time
  - Finishing treatments
- Mechanical properties are dependent on density
- Products should be designed (and materials selected) so that the final properties will be achieved with the anticipated final porosity

P/M Materials

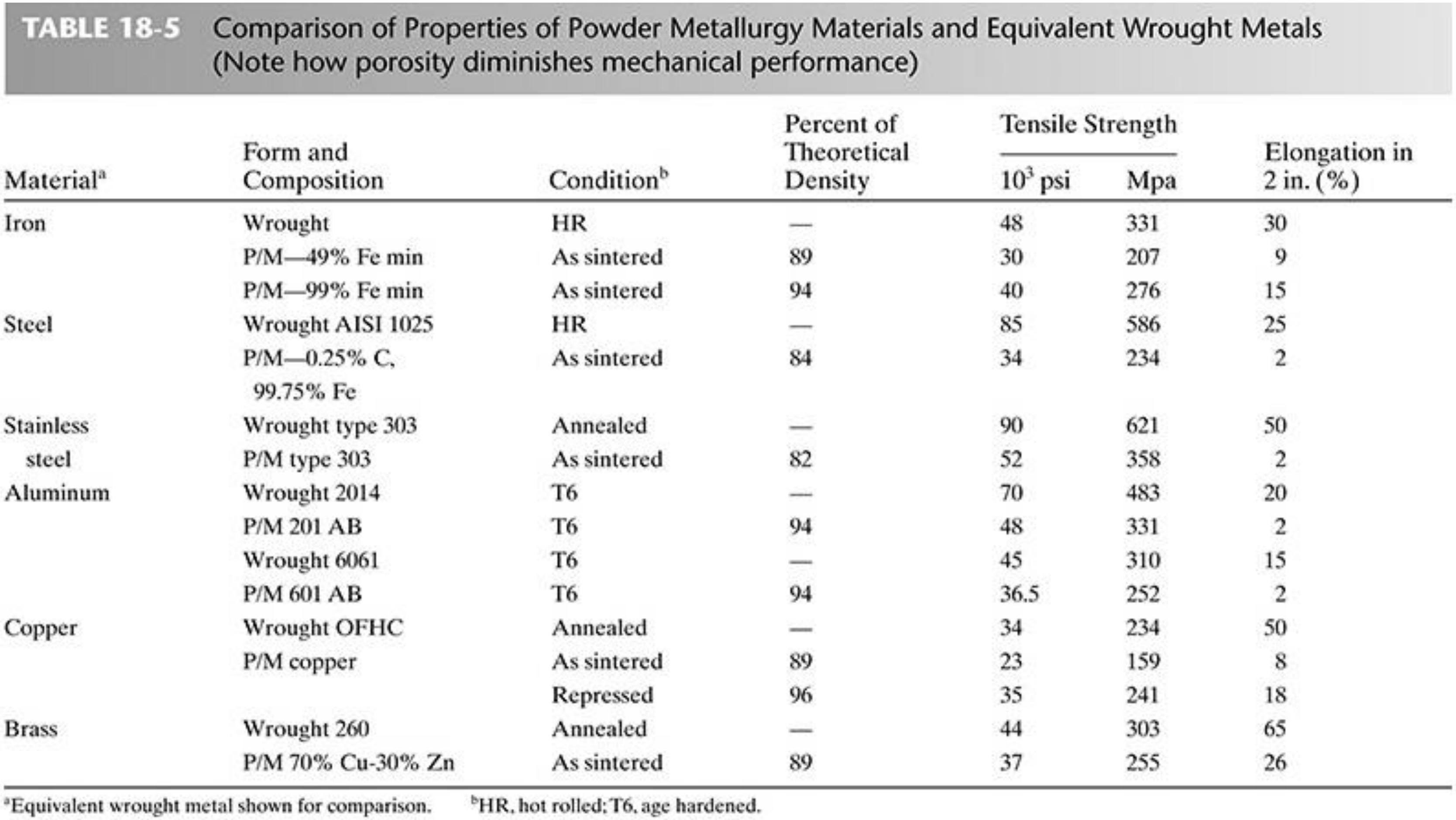


TABLE 18-5 Comparison of Properties of Powder Metallurgy Materials and Equivalent Wrought Metals (Note how porosity diminishes mechanical performance)

Material[a]	Form and Composition	Condition[b]	Percent of Theoretical Density	Tensile Strength		Elongation in 2 in. (%)
				10^3 psi	Mpa	
Iron	Wrought	HR	—	48	331	30
	P/M—49% Fe min	As sintered	89	30	207	9
	P/M—99% Fe min	As sintered	94	40	276	15
Steel	Wrought AISI 1025	HR	—	85	586	25
	P/M—0.25% C, 99.75% Fe	As sintered	84	34	234	2
Stainless steel	Wrought type 303	Annealed	—	90	621	50
	P/M type 303	As sintered	82	52	358	2
Aluminum	Wrought 2014	T6	—	70	483	20
	P/M 201 AB	T6	94	48	331	2
	Wrought 6061	T6	—	45	310	15
	P/M 601 AB	T6	94	36.5	252	2
Copper	Wrought OFHC	Annealed	—	34	234	50
	P/M copper	As sintered	89	23	159	8
		Repressed	96	35	241	18
Brass	Wrought 260	Annealed	—	44	303	65
	P/M 70% Cu-30% Zn	As sintered	89	37	255	26

[a] Equivalent wrought metal shown for comparison. [b] HR, hot rolled; T6, age hardened.

18.14 Design of Powder Metallurgy Parts

- Basic rules for the design of P/M parts
  - Shape of the part must permit ejection from die
  - Powder should not be required to flow into small cavities
  - The shape of the part should permit the construction of strong tooling
  - The thickness of the part should be within the range for which P/M parts can be adequately compacted
  - The part should be designed with as few changes in section thickness as possible

Basic Rules for P/M Parts

- Parts can be designed to take advantage of the fact that certain forms and properties can be produced by P/M that are impossible, impractical, or uneconomical by any other method
- The design should be consistent with available equipment
- Consideration should be made for product tolerances
- Design should consider and compensate for dimensional changes that will occur after pressing

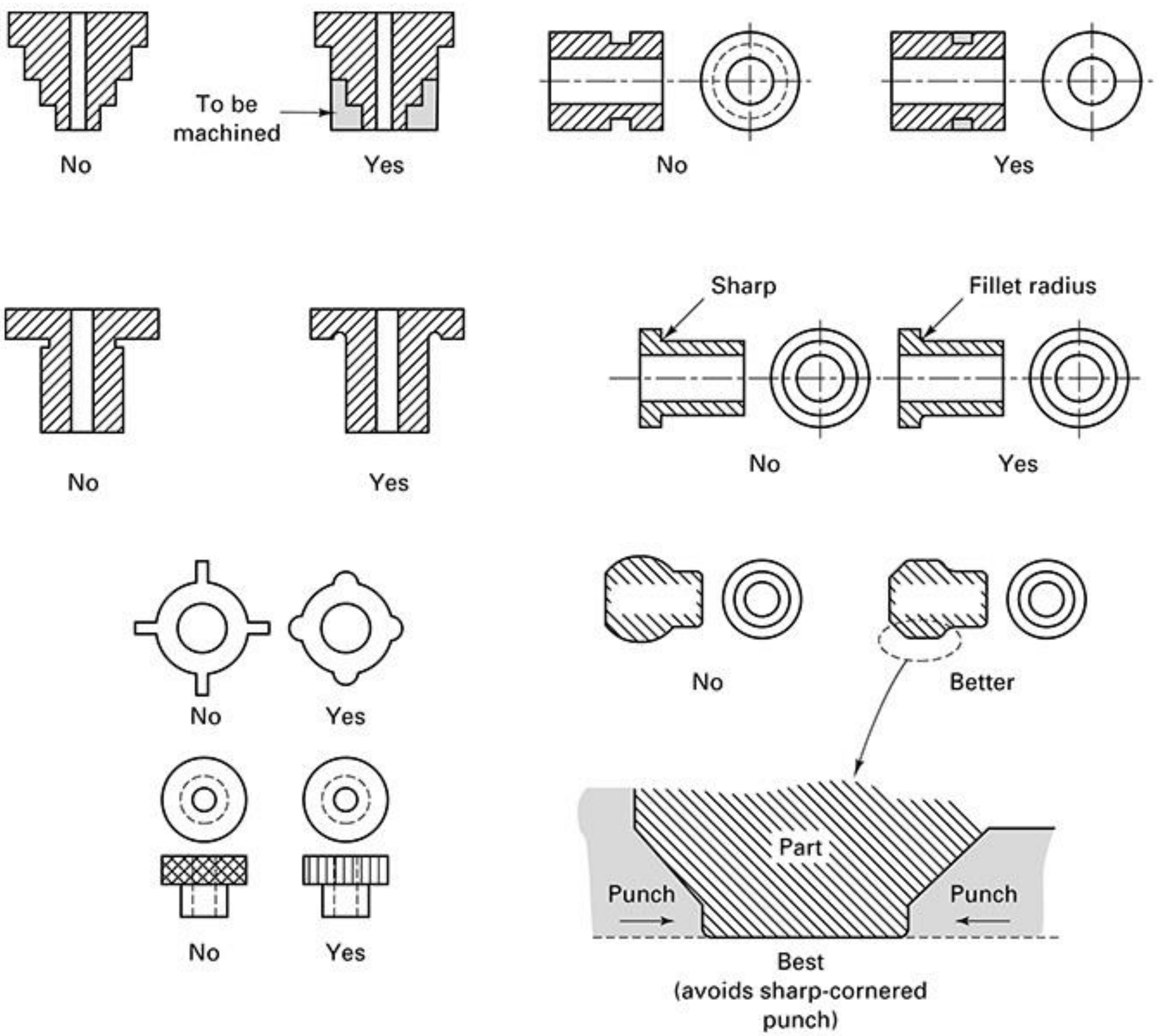


Figure 18-17 Examples of poor and good design features for powder metallurgy products. Recommendations are based on ease of pressing, design of tooling, uniformity of properties, and ultimate performance.

18.15 Powder Metallurgy Products

- Porous or permeable products such as bearings, filters, and pressure or flow regulators
- Products of complex shapes that would require considerable machining when made by other processes
- Products made from materials that are difficult to machine or materials with high melting points
- Products where the combined properties of two or more metals are desired
- Products where the P/M process produces clearly superior properties
- Products where the P/M process offers and economic advantage

18.16 Advantages and Disadvantages of Powder Metallurgy

- Advantages
  - Elimination or reduction of machining
  - High production rates
  - Complex shapes
  - Wide variations in compositions
  - Wide property variations
  - Scrap is eliminated or reduced

- Disadvantages
  - Inferior strength properties
  - High tooling costs
  - High material cost
  - Size and shape limitations
  - Dimensional changes during sintering
  - Density variations
  - Health and safety hazards

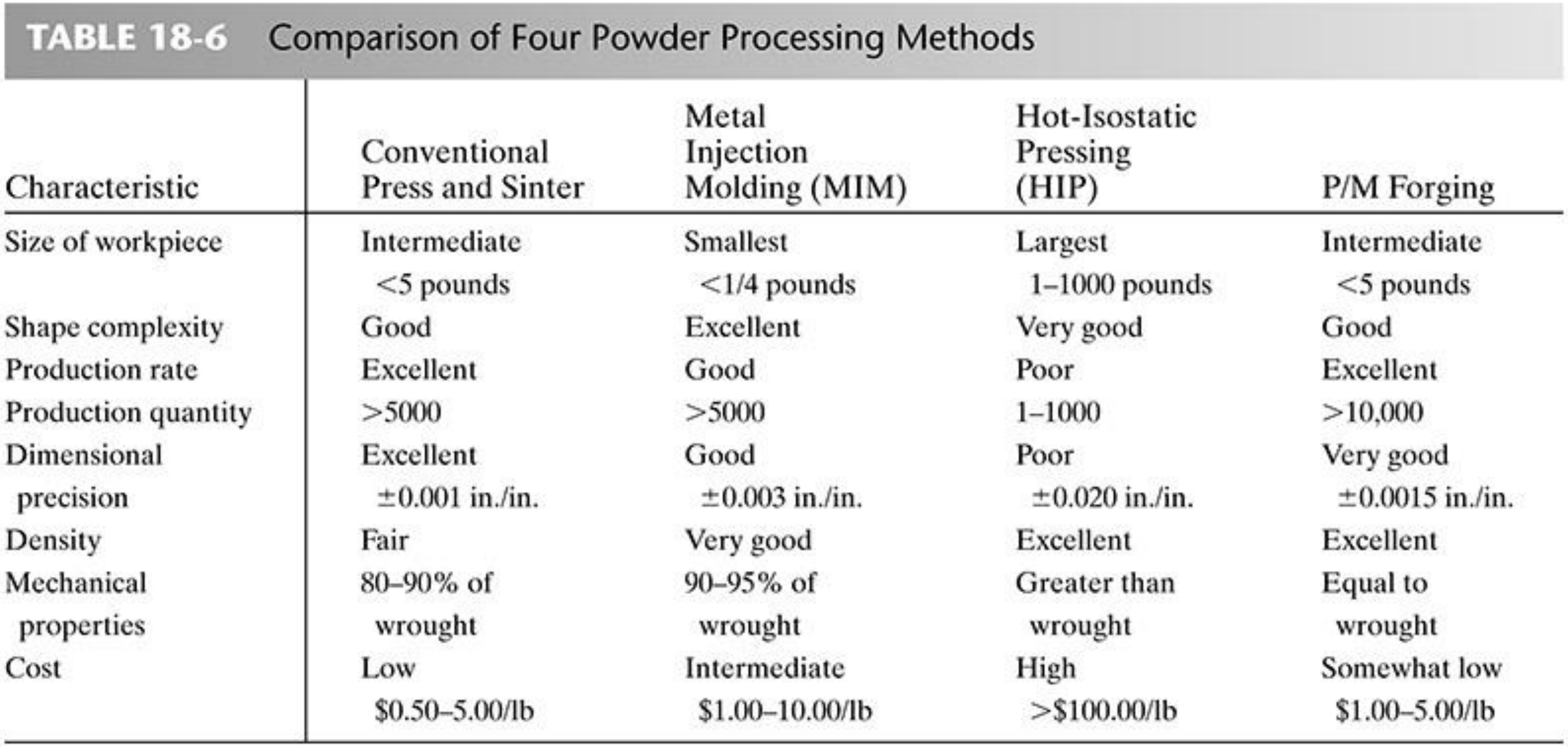


TABLE 18-6 Comparison of Four Powder Processing Methods

Characteristic	Conventional Press and Sinter	Metal Injection Molding (MIM)	Hot-Isostatic Pressing (HIP)	P/M Forging
Size of workpiece	Intermediate <5 pounds	Smallest <1/4 pounds	Largest 1–1000 pounds	Intermediate <5 pounds
Shape complexity	Good	Excellent	Very good	Good
Production rate	Excellent	Good	Poor	Excellent
Production quantity	>5000	>5000	1–1000	>10,000
Dimensional precision	Excellent ±0.001 in./in.	Good ±0.003 in./in.	Poor ±0.020 in./in.	Very good ±0.0015 in./in.
Density	Fair	Very good	Excellent	Excellent
Mechanical properties	80–90% of wrought	90–95% of wrought	Greater than wrought	Equal to wrought
Cost	Low $0.50–5.00/lb	Intermediate $1.00–10.00/lb	High >$100.00/lb	Somewhat low $1.00–5.00/lb

18.17 Summary

- Powder metallurgy can produce products out of materials that are otherwise very difficult to manufacture
- P/M products can be designed to provide the targeted properties
- Variations in product size, production rate, quantity, mechanical properties, and cost

Chapter 17: Fundamentals of Metal Forming

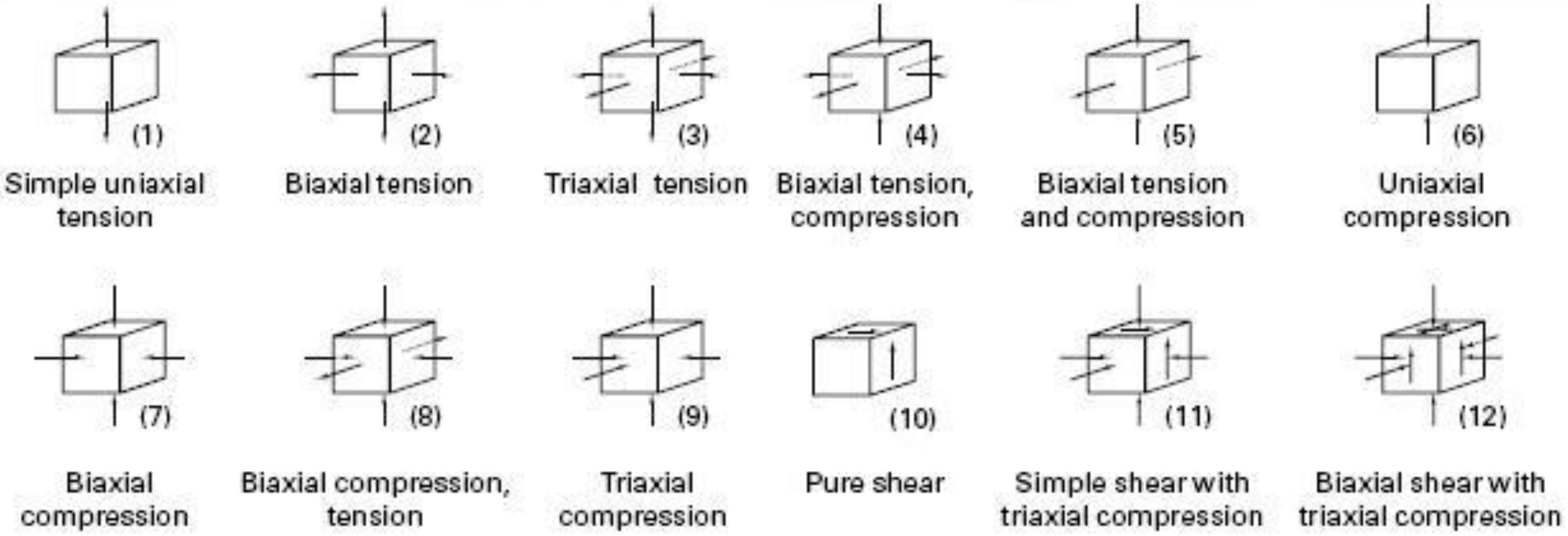
DeGarmo’s Materials and Processes in Manufacturing

15.1 Introduction

- Deformation processes have been designed to exploit the plasticity of engineering materials
- Plasticity is the ability of a material to flow as a solid without deterioration of properties
- Deformation processes require a large amount of force
- Processes include bulk flow, simple shearing, or compound bending

States of Stress

TABLE 15-1 Classification of States of Stress



(1) Simple uniaxial tension

(2) Biaxial tension

(3) Triaxial tension

(4) Biaxial tension, compression

(5) Biaxial tension and compression

(6) Uniaxial compression

(7) Biaxial compression

(8) Biaxial compression, tension

(9) Triaxial compression

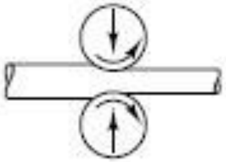
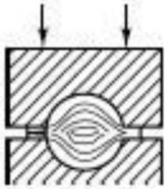
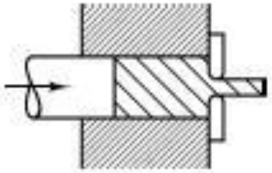
(10) Pure shear

(11) Simple shear with triaxial compression

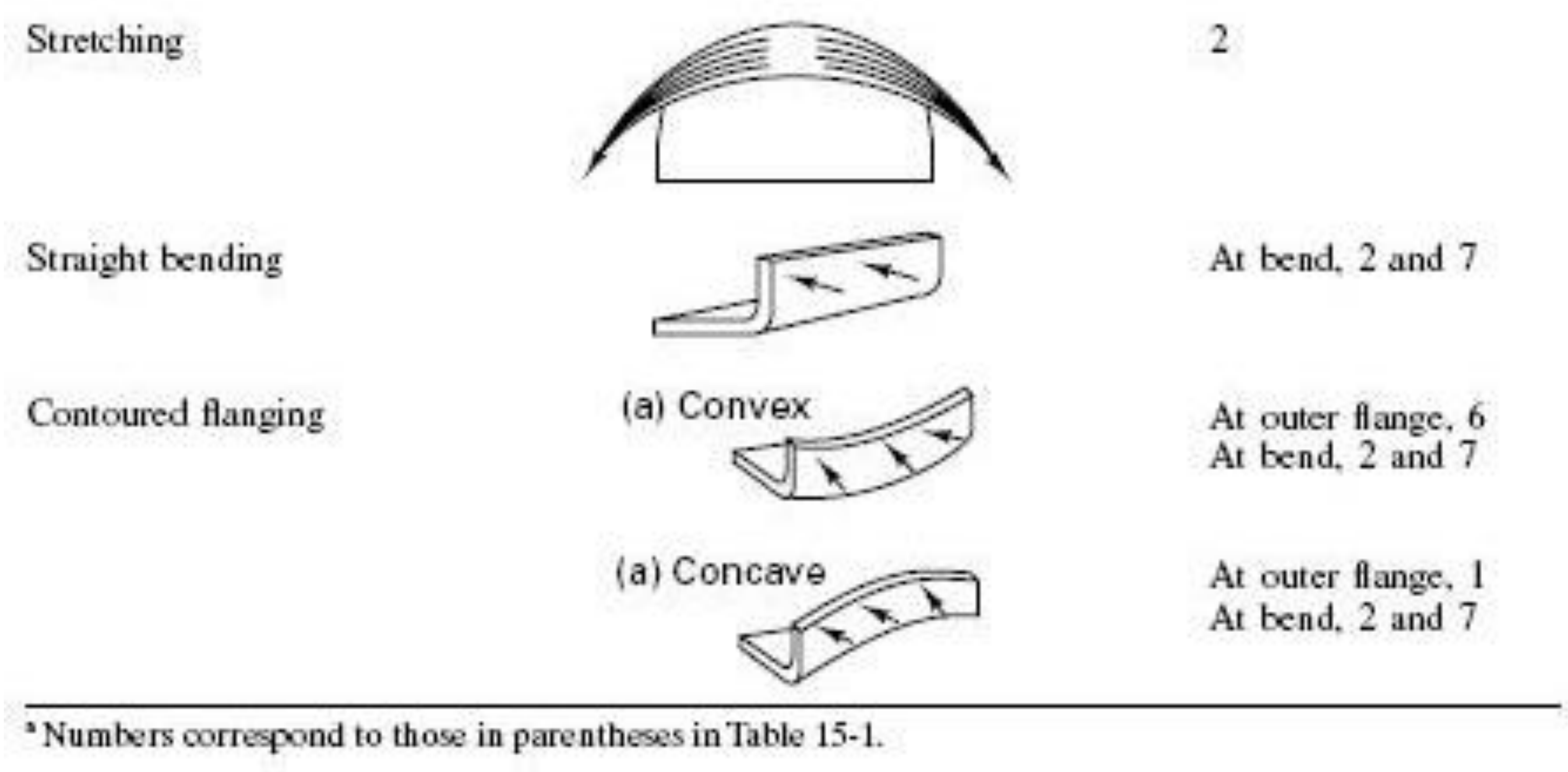
(12) Biaxial shear with triaxial compression

Forming Operations

TABLE 15-2 Classification of Some Forming Operations

Process	Schematic Diagram	State of Stress in Main Part During Forming[a]
Rolling		7
Forging		9
Extrusion		9
Shear spinning		12

Forming Operations



Stretching		2
Straight bending		At bend, 2 and 7
Contoured flanging	(a) Convex	At outer flange, 6 At bend, 2 and 7
	(a) Concave	At outer flange, 1 At bend, 2 and 7

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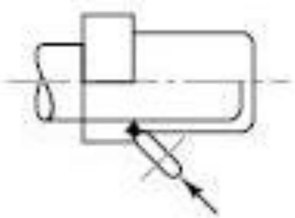
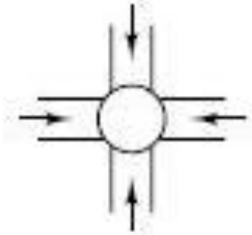
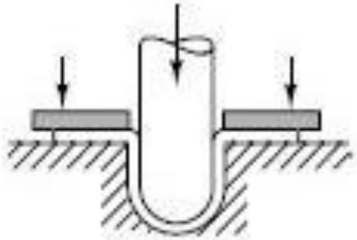
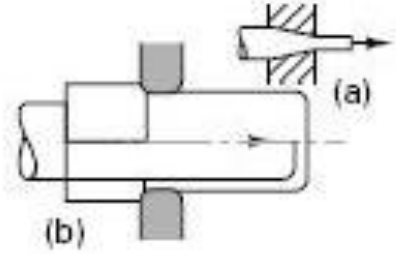
[a] Numbers correspond to those in parentheses in Table 15-1.

Forming Operations

Tube spinning		9
Swaging or kneading		7
Deep drawing		In flange of blank, 5 In wall of cup, 1
Wire and tube drawing		8

15.2 Forming Processes: Independent Variables

- Forming processes consist of independent and dependent variables
- Independent variables are the aspects of the processes that the engineer or operator has direct control
  - Starting material
  - Starting geometry of the workpiece
  - Tool or die geometry
  - Lubrication
  - Starting temperature
  - Speed of operation
  - Amount of deformation

15.3 Dependent Variables

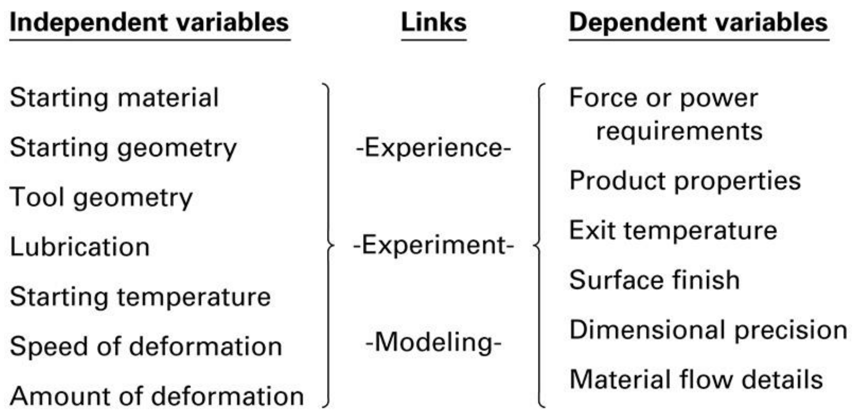
- Dependent variables are those that are determined by the independent variable selection
  - Force or power requirements
  - Material properties of the product
  - Exit or final temperature
  - Surface finish and precision
  - Nature of the material flow

15.4 Independent-Dependent Relationships

- Independent variables- control is direct and immediate
- Dependent variables- control is entirely indirect
  - Determined by the process
  - If a dependent variable needs to be controlled, the designer must select the proper independent variable that changes the dependent variable

Independent-Dependent Relationships

- Information on the interdependence of independent and dependent variables can be learned in three ways
  - Experience
  - Experiment
  - Process modeling



Independent variables

Starting material
Starting geometry
Tool geometry
Lubrication
Starting temperature
Speed of deformation
Amount of deformation

Links

-Experience-
-Experiment-
-Modeling-

Dependent variables

Force or power requirements
Product properties
Exit temperature
Surface finish
Dimensional precision
Material flow details

Figure 15-1 Schematic representation of a metalforming system showing independent variables, dependent variables, and the various means of linking the two.

15.5 Process Modeling

- Simulations are created using finite element modeling
- Models can predict how a material will respond to a rolling process, fill a forging die, flow through an extrusion die, or solidify in a casting
- Heat treatments can be simulation
- Costly trial and error development cycles can be eliminated

15.6 General Parameters

- Material being deformed must be characterized
  - Strength or resistance for deformation
  - Conditions at different temperatures
  - Formability limits
  - Reaction to lubricants
- Speed of deformation and its effects
- Speed-sensitive materials- more energy is required to produce the same results

15.7 Friction and Lubrication Under Metalworking Conditions

- High forces and pressures are required to deform a material
- For some processes, 50% of the energy is spent in overcoming friction
- Changes in lubrication can alter material flow, create or eliminate defects, alter surface finish and dimensional precision, and modify product properties
- Production rates, tool design, tool wear, and process optimization depend on the ability to determine and control friction

Friction Conditions

- Metalforming friction differs from the friction encountered in mechanical devices
- For light, elastic loads, friction is proportional to the applied pressure
  - μ is the coefficient of friction
- At high pressures, friction is related to the strength of the weaker material

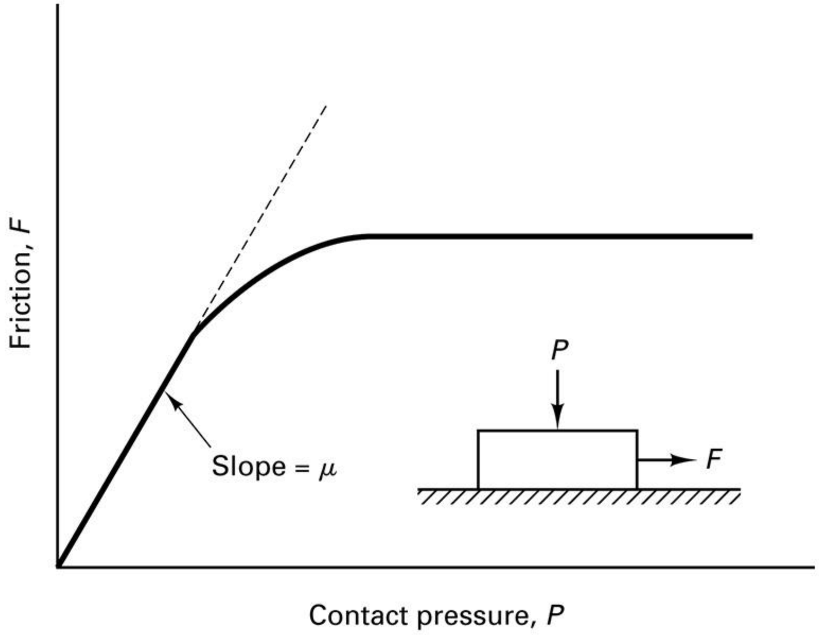


Figure 15-2 The effect of contact pressure on the frictional resistance between two surfaces.

Friction

- Friction is resistance to sliding along an interface
- Resistance can be attributed to:
  - Abrasion
  - Adhesion
- Resistance is proportional to the strength of the weaker material and the contact area

Surface Deterioration

- Surface wear is related to friction
- Wear on the workpiece is not objectionable, but wear on the tooling is
- Tooling wear is economically costly and can impact dimensional precision
- Tolerance control can be lost
- Tool wear can impact the surface finish

Lubrication

- Key to success in many metalforming operations
- Primarily selected to reduce friction and tool wear, but may be used as a thermal barrier, coolant, or corrosion retardant
- Other factors
  - Ease of removal, lack of toxicity, odor, flammability, reactivity, temperature, velocity, wetting characteristics

15.8 Temperature Concerns

- Workpiece temperature can be one of the most important process variables
- In general, an increase in temperature is related to a decrease in strength, increase in ductility, and decrease in the rate of strain hardening
- Hot working
- Cold working
- Warm working

Hot Working

- Plastic deformation of metals at a temperature above the recrystallization temperature
- Temperature varies greatly with material
- Recrystallization removes the effects of strain hardening
- Hot working may produce undesirable reactions from the metal and its surroundings

Structure and Property Modification by Hot Working

- The size of grains upon cooling is not typically uniform
- Undesirable grain shapes can be common (such as columnar grains)
- Recrystallization is followed by:
  - grain growth
  - additional deformation and recrystallization
  - drop in temperature that will terminate diffusion and freeze the recrystallized structure

Hot Working

- Engineering properties can be improved through reorienting inclusion or impurities
- During plastic deformation, impurities tend to flow along with the base metal or fraction into rows of fragments

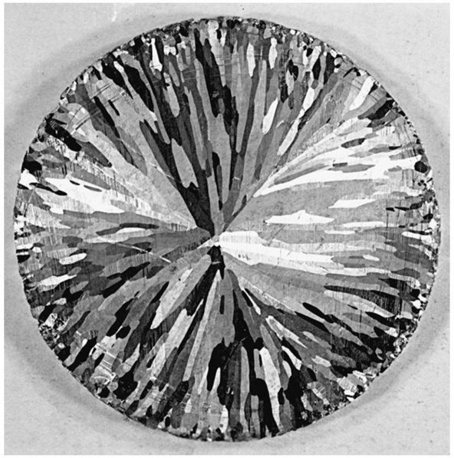


Figure 15-3 Cross section of a 4-in.-diameter case copper bar polished and etched to show the as-cast grain structure.

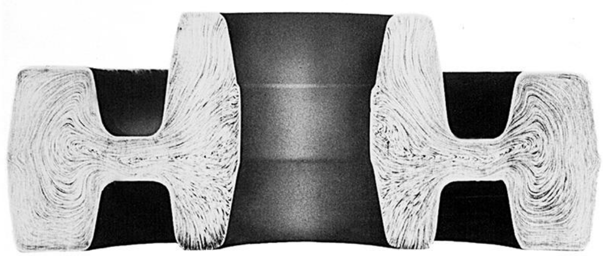


Figure 15-4 Flow structure of a hot-forged gear blank. Note how flow is parallel to all critical surfaces. (*Courtesy of Bethlehem Steel Corporation, Bethlehem, PA.)*

Temperature Variations in Hot Working

- Success or failure of a hot deformation process often depends on the ability to control temperatures
- Over 90% of the energy imparted to a deforming workpiece is converted to heat
- Nonuniform temperatures may be produced and may result in cracking
- Thin sections cool faster than thick sections

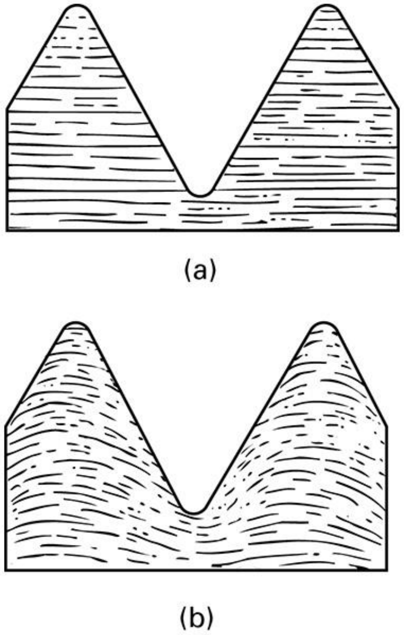


Figure 15-5 Schematic comparison of the grain flow in a machined thread (a) and a rolled thread (b). The rolling operation further deforms the axial structure produced by the previous wire- or rod-forming operations, while machining simply cuts through it.

Cold Working

- Plastic deformation below the recrystallization temperature
- Advantages as compared to hot working
    - No heating required
    - Better surface finish
    - Superior dimensional control
    - Better reproducibility
    - Strength, fatigue, and wear are improved
    - Directional properties can be imparted
    - Contamination is minimized

Disadvantages of Cold Working

- Higher forces are required to initiate and complete the deformation
- Heavier and more powerful equipment and stronger tooling are required
- Less ductility is available
- Metal surfaces must be clean and scale-free
- Intermediate anneals may be required
- Imparted directional properties can be detrimental
- Undesirable residual stresses may be produced

Metal Properties and Cold Working

- Two features that are significant in selecting a material for cold working are
  - Magnitude of the yield-point stress
  - Extent of the strain region from yield stress to fracture
- Springback should also be considered when selecting a material

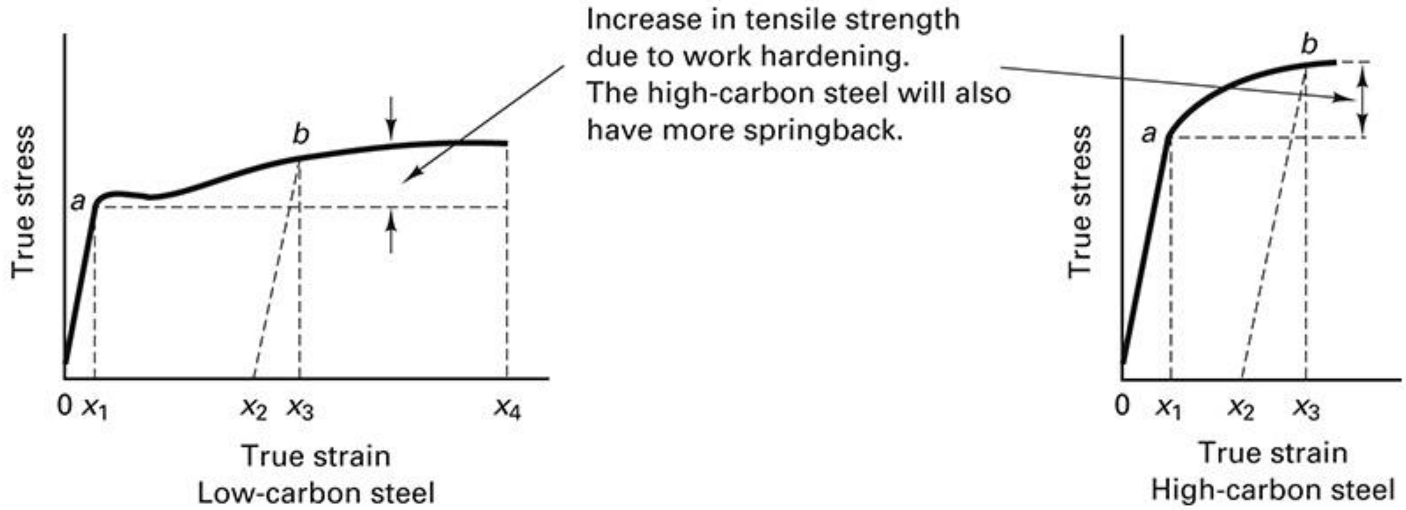
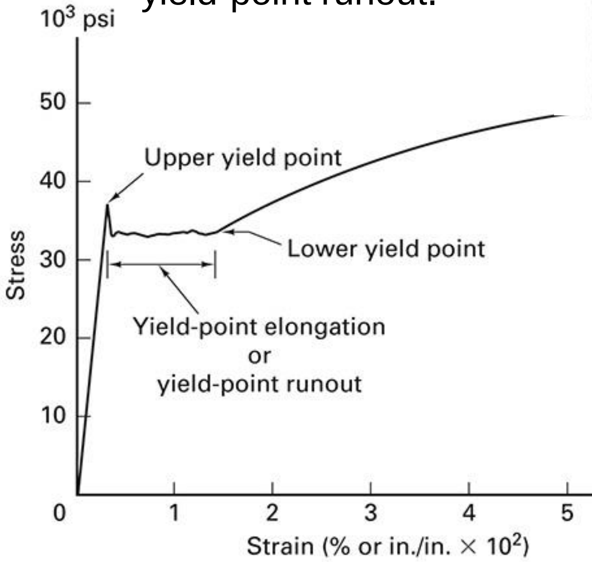


Figure 15-6 Use of true stress-true strain diagram to assess the suitability of two metals for cold working.

Initial and Final Properties in a Cold-Working Process

- Quality of the starting material is important to the success or failure of the cold-working process
- The starting material should be clean and free of oxide or scale that might cause abrasion to the dies or rolls

Figure 15-7 (Below) Stress-strain curve for a low-carbon steel showing the commonly observed yield-point runout; (Right) Luders bands or stretcher strains that form when this material is stretched to an amount less than the yield-point runout.



Additional Effects of Cold Working

- Annealing heat treatments may be performed prior or at intermediate intervals to cold working
- Heat treatments allows additional cold working and deformation processes
- Cold working produces a structure where properties vary with direction, anisotropy

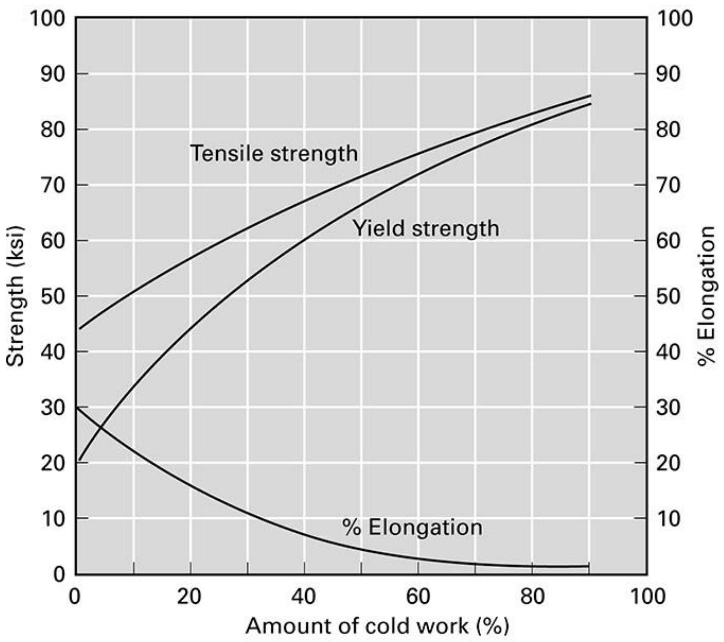


Figure 15-8 Mechanical properties of pure copper as a function of the amount of cold work (expressed in percent).

Warm Forming

- Deformations produced at temperatures intermediate to cold and hot working
- Advantages
  - Reduced loads on the tooling and equipment
  - Increased material ductility
  - Possible reduction in the number of anneals
  - Less scaling and decarburization
  - Better dimensional precision and smoother surfaces than hot working
  - Used for processes such as forging and extrusion

Isothermal Forming

- Deformation that occurs under constant temperature
- Dies and tooling are heated to the same temperature as the workpiece
- Eliminates cracking from nonuniform surface temperatures
- Inert atmospheres may be used

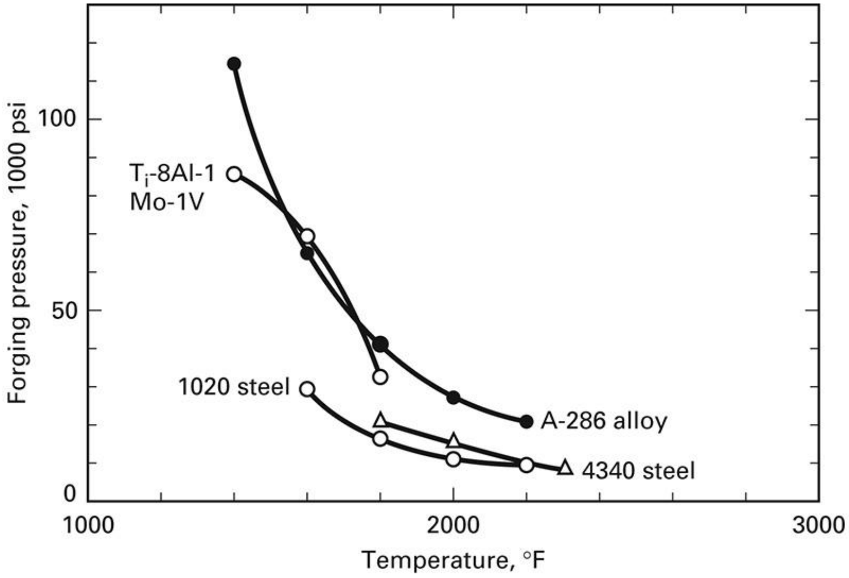


Figure 15-9 Yield strength of various materials (as indicated by pressure required to forge a standard specimen) as a function of temperature. Materials with steep curves may require isothermal forming. (*From "A Study of Forging Variables," ML-TDR-64-95, March 1964; courtesy of Battelle Columbus Laboratories, Columbus, OH.)*

Chapter 18:
Bulk Forming Processes

DeGarmo's Materials and Processes in Manufacturing

16.1 Introduction

- Metal has been shaped by deformation processes for several thousand years
- Forging, rolling, and wire drawing were performed in the Middle Ages
- The Industrial Revolution allowed these processes to be done at a higher level
- Recently, many processes have begun to be automated

16.2 Classification of Deformation Processes

- Bulk deforming processes can be classified as primary or secondary processes
  - Primary processes reduce a cast material into slabs, plates, and billets
  - Secondary processes reduce shapes into finished or semifinished products
- Bulk deformation processes are those processes where the thickness or cross sections are reduced
- Sheet-forming operations involve the deformation of materials whose thickness and cross section remain relatively constant

16.3 Bulk Deformation Processes

- Rolling
- Forging
- Extrusion
- Wire, rod, and tube drawing
- Cold forming, cold forging, and impact extrusion
- Piercing
- Squeezing processes

Bulk Deformation Processes

16.4 Rolling

- Rolling operations reduce the thickness or change the cross section of a material through compressive forces
- Often the first process that is used to convert material into a finished wrought product
- Thick stock can be rolled into blooms, billets, or slabs

Starting Stock

- Blooms have a square or rectangular cross section
- Billets are usually smaller than a bloom and can have a square or circular cross section
  - Can be further rolled into structural shapes
- Slabs are a rectangular solid with a width greater than twice the thickness
  - Can be used to produce plates, sheets, or strips

Flowchart of Rolling Operations

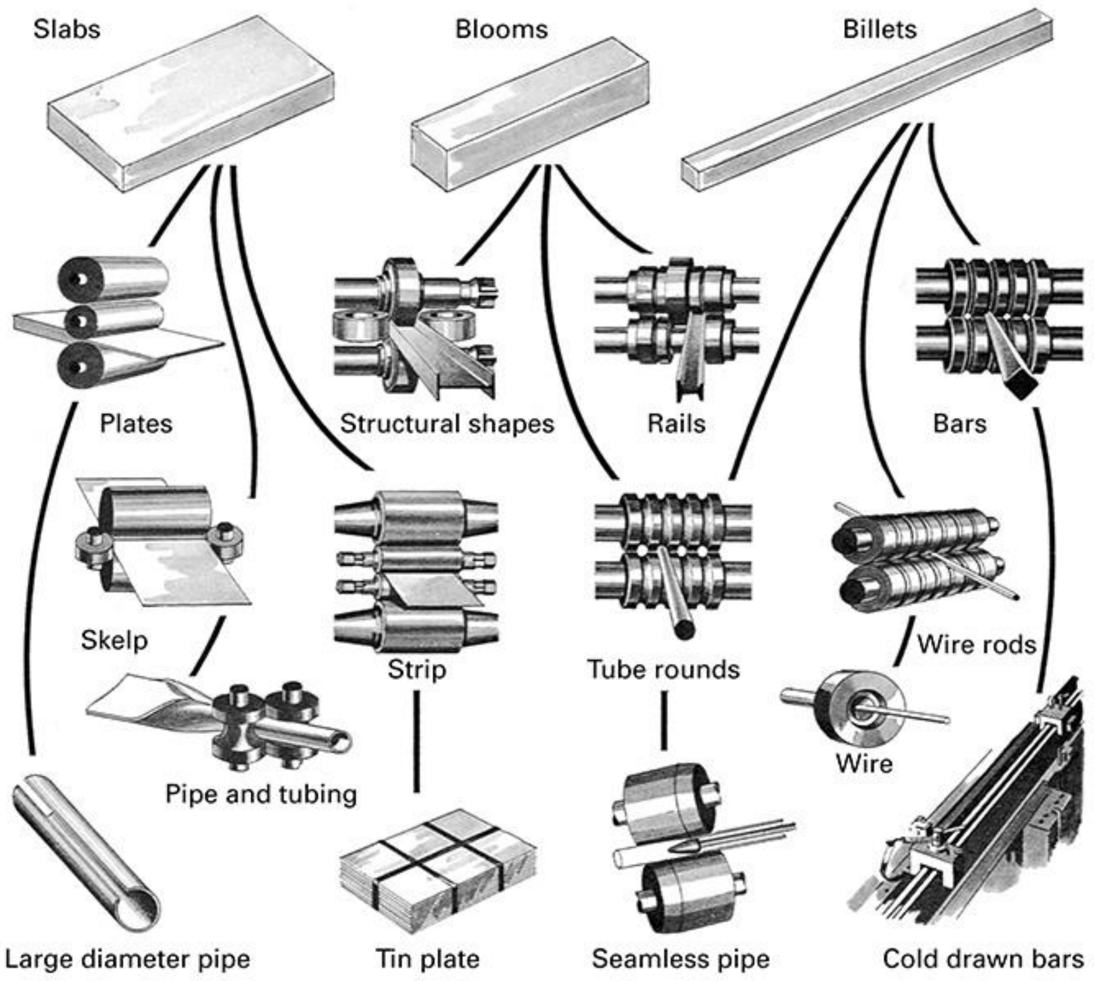


Figure 16-1 Flow chart for the production of various finished and semifinished steel shapes. Note the abundance of rolling operations. *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

Basic Rolling Process

- Metal is passed between two rolls that rotate in opposite directions
- Friction acts to propel the material forward
- Metal is squeezed and elongates to compensate for the decrease in cross-sectional area

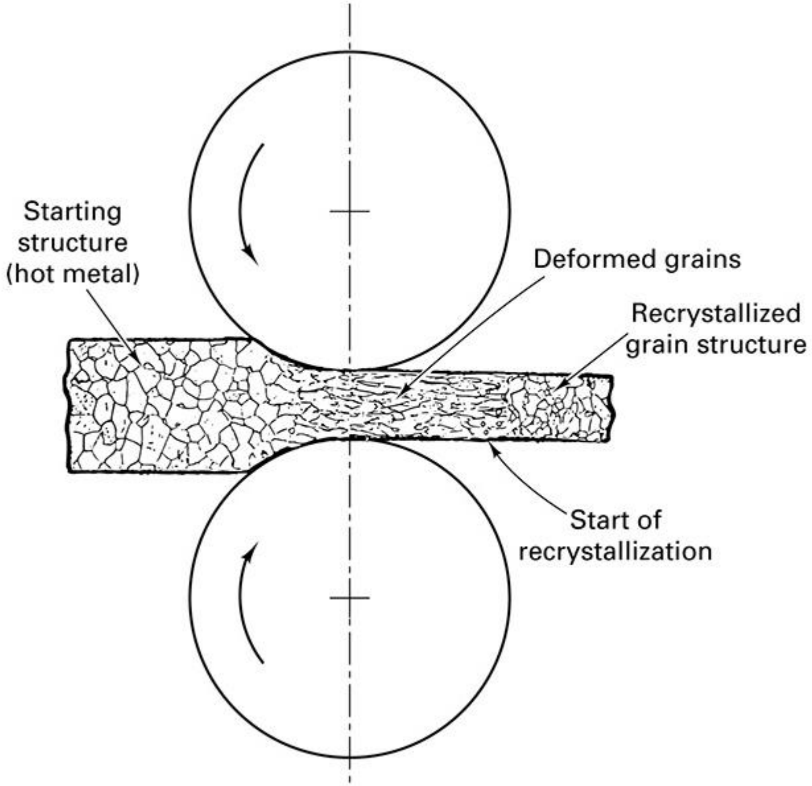


Figure 16-2 Schematic representation of the hot-rolling process, showing the deformation and recrystallization of the metal being rolled.

Hot Rolling and Cold Rolling

- In hot rolling, temperature control is required for successful forming
  - Temperature of the material should be uniform
  - Rolling is terminated when the temperature falls to about 50 to 100 degrees above the recrystallization temperature
  - Ensures the production of a uniform grain size
- Cold rolling products sheet, strip, bar and rod products with smooth surfaces and accurate dimensions

Rolling Mill Configurations

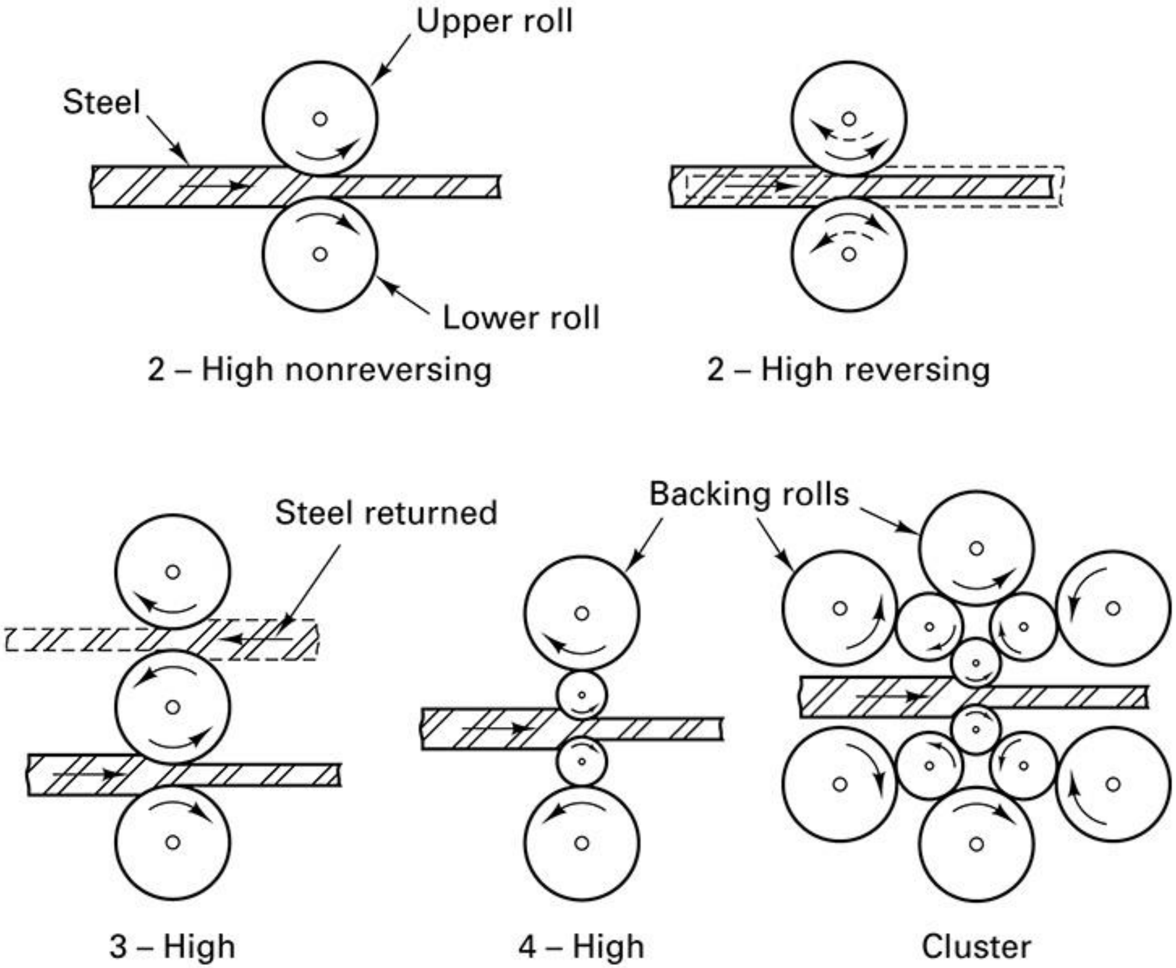
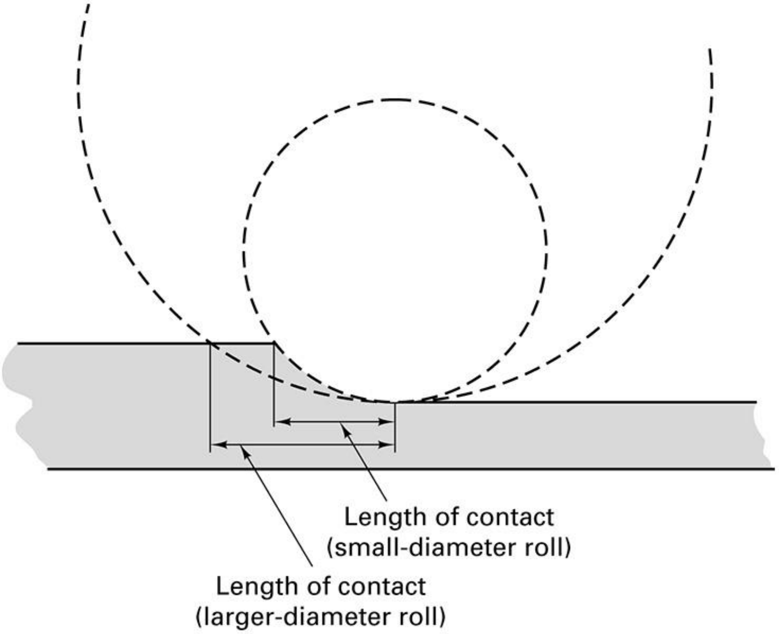


Figure 16-3 Various roll configurations used in rolling operations.

Rolling Mill Configurations

- Smaller diameter rolls produce less length of contact for a given reduction and require less force to produce a given change in shape
- Smaller cross section provides a reduced stiffness
  - Rolls may be prone to flex elastically because they are only supported on the ends

Figure 16-4 The effect of roll diameter on length of contact for a given reduction.



Continuous (Tandem) Rolling Mills

- Billets, blooms, and slabs are heated and fed through an integrated series of nonreversing rolling mills
- Synchronization of rollers may pose issues

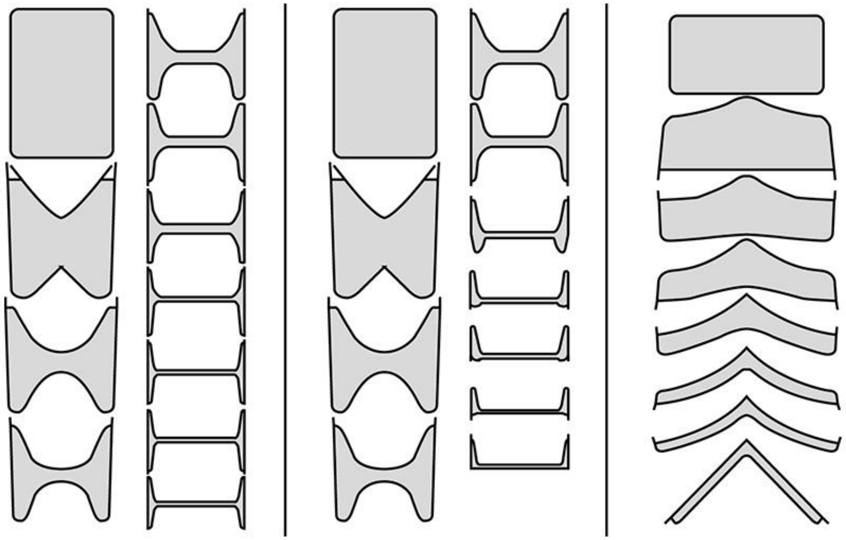


Figure 16-5 Typical roll-pass sequences used in producing structural shapes.

Ring Rolling

- One roll is placed through the hole of a thick-walled ring and a second roll presses on the outside
- Produces seamless rings
- Circumferential grain orientation and is used in rockets, turbines, airplanes, pressure vessels, and pipelines

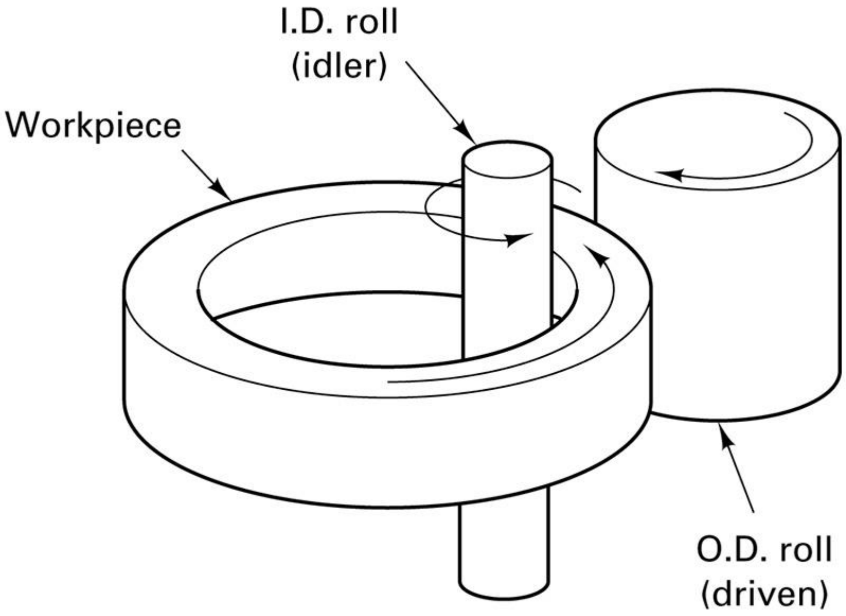
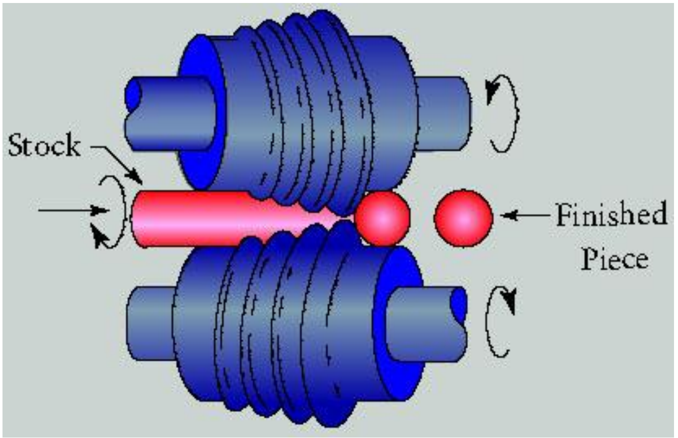


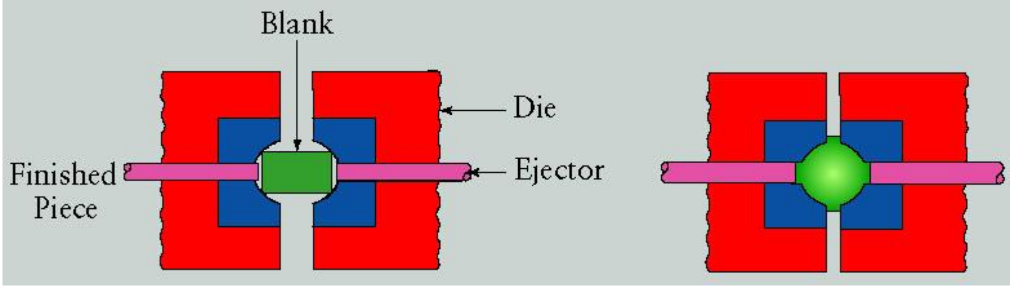
Figure 16-6 Schematic of horizontal ring rolling operation. As the thickness of the ring is reduced, its diameter will increase.

Manufacture of Spherical Blanks



- Production of steel balls for bearings by the skew-rolling process. This is a high throughput operation.

Production of steel balls by upsetting of a cylindrical blank. Note the formation of flash. The balls are subsequently ground and polished for use as ball bearings and in other mechanical components.



Characteristics, Quality, and Precision of Rolled Products

- Hot-rolled products have little directionality in their properties
- Hot-rolled products are therefore uniform and have dependable quality
  - Surfaces may be rough or may have a surface oxide known as mill scale
- Dimensional tolerances vary with the kind of metal and the size of the product
- Cold-rolled products exhibit superior surface finish and dimensional precision

Flatness Control and Rolling Defects

- Rollers must be evenly spaced throughout for perfectly flat pieces to be produced
- Sometimes this variation in roller “flatness” may be desired

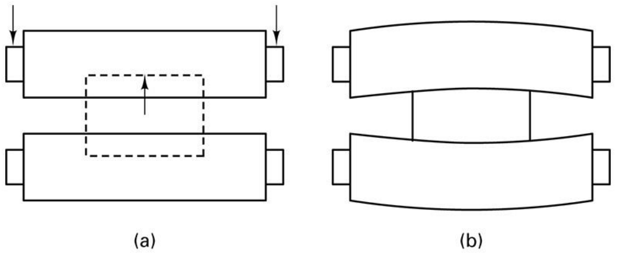


Figure 16-7 (above) (a) Loading on a rolling mill roll. The top roll is pressed upward in the center while being supported on the ends. (b) The elastic response to the three-point bending.

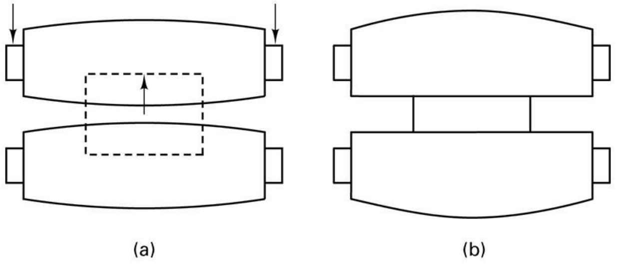


Figure 16-8 Use of a “crowned” roll to compensate for roll flexure. When the roll flexes in three-point bending, the crowned roll flexes into flatness.

Thermomechanical Processing and Controlled Rolling

- Heat may be used to reduce forces and promote plasticity, but heat treatments are typically subsequent operations
- Thermomechanical processing combines the deformation and thermal processing into a single shape with the desired properties
- Requires computer-controlled facilities
- Substantial energy savings

16.5 Forging

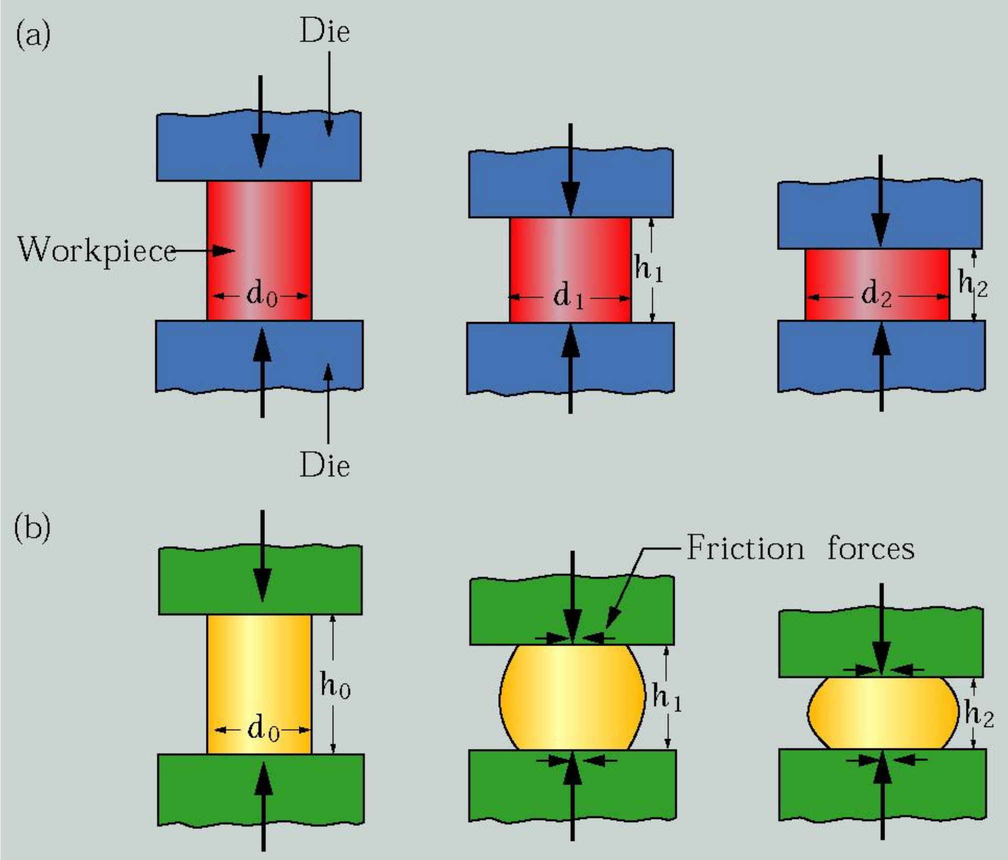
- Processes that induce plastic deformation through localized compressive forces applied through dies
- Oldest known metalworking process
- Parts can range in size
- Methods
  - Drawing
  - Upset
  - Squeezed in closed impression dies

Traditional Forging

Open-die Hammer Forging

- Same type of forging done by a blacksmith but mechanical equipment performs the operation
- An impact is delivered by some type of mechanical hammer
- Simplest industrial hammer is a gravity drop machine
- Computer controlled-hammers can provide varying blows

Open Die Forging: Upsetting-ideal



- (a) **Ideal deformation** of a solid cylindrical specimen compressed between flat frictionless dies.
- (b) Deformation in upsetting with friction at the die-workpiece interfaces.

Open-die Hammer Forging

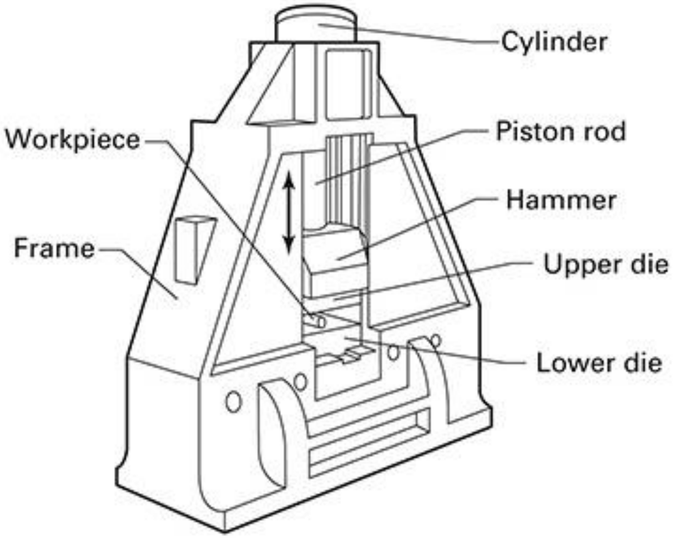
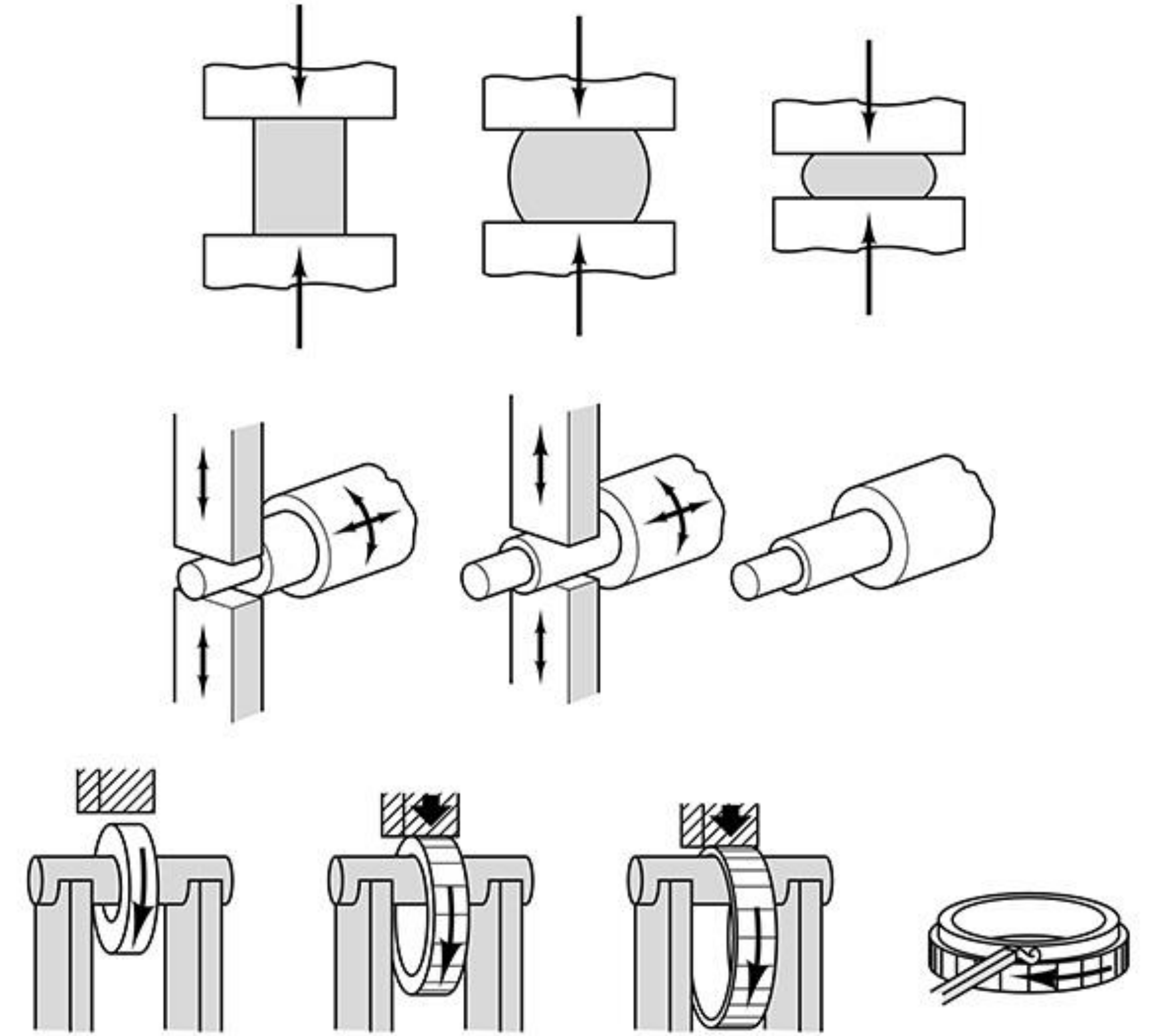


Figure 16-9 (Left) Double-frame drop hammer. (*Courtesy of Erie Press Systems, Erie, PA*.) (Right) Schematic diagram of a forging hammer.



1 Preform mounted on saddle/mandrel.

2 Metal displacement–reduce preform wall thickness to increase diameter.

3 Progressive reduction of wall thickness to produce ring dimensions.

4 Machining to near net shape.

Figure 16-10 (Top) Illustration of the unrestrained flow of material in open-die forging. Note the barrel shape that forms due to friction between the die and material. (Middle) Open-die forging of a multidiameter shaft. (Bottom) Forging of a seamless ring by the open-die method. (Courtesy of Forging Industry Association, Cleveland, OH.)

Impression-Die Hammer Forging

- The dies are shaped to control the flow of metal
- Upper piece attaches to the hammer and the lower piece to the anvil
- Metal flows and completely fills the die

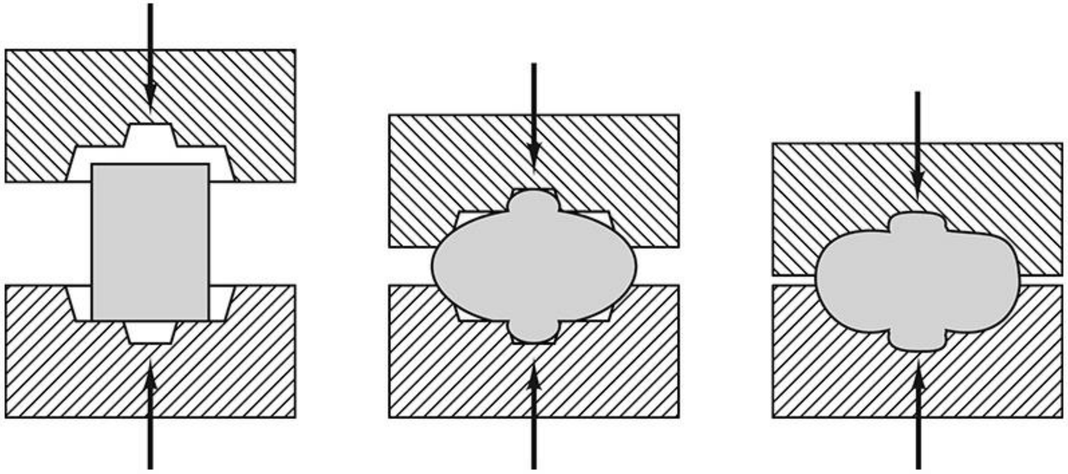
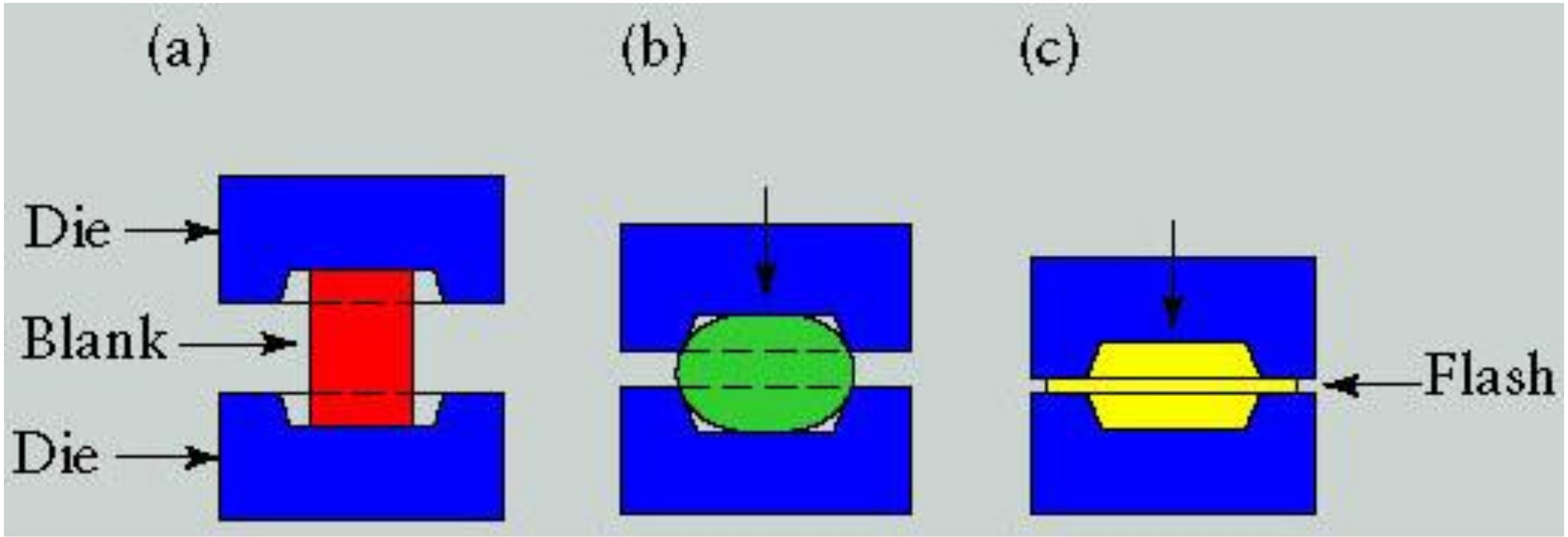


Figure 16-11 Schematic of the impression-die forging process, showing partial die filling and the beginning of flash formation in the center sketch and the final shape with flash in the right-hand sketch.

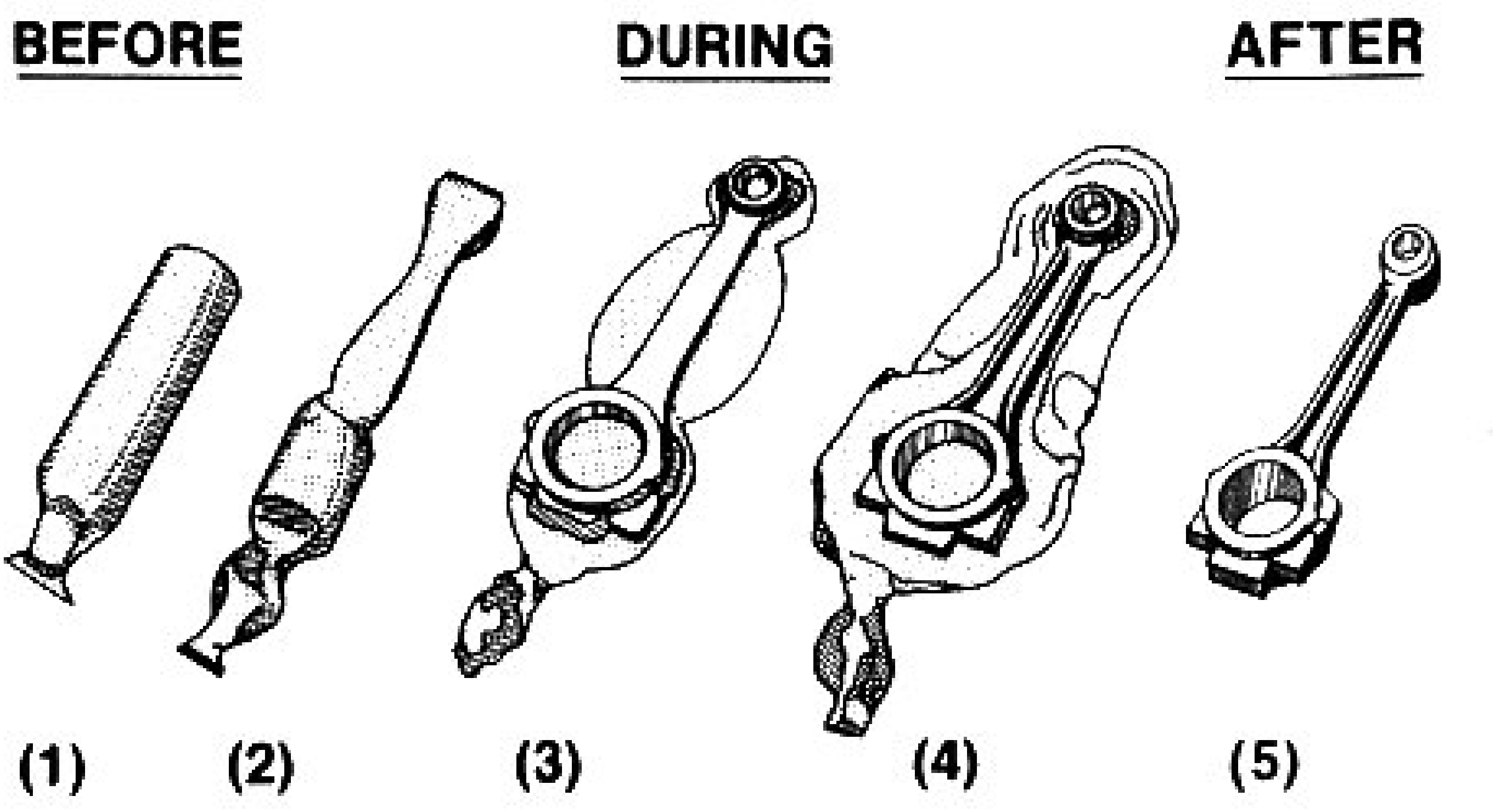
Impression Die Forging



Impression-Die Hammer Forging

- Excess metal may squeeze out of the die
    - This metal is called flash
- Flashless forging can be performed if the metal is deformed in a cavity that provides total confinement
- Many forged products are produced with a series of cavities
    - First impression is called edging, fullering, or bending
    - Intermediate impressions are for blocking the metal to approximately its final shape
    - Final shape is given in its final forging operation

Impression Die Forging



(1) & (2) by upsetting

(3) & (4) by impression die

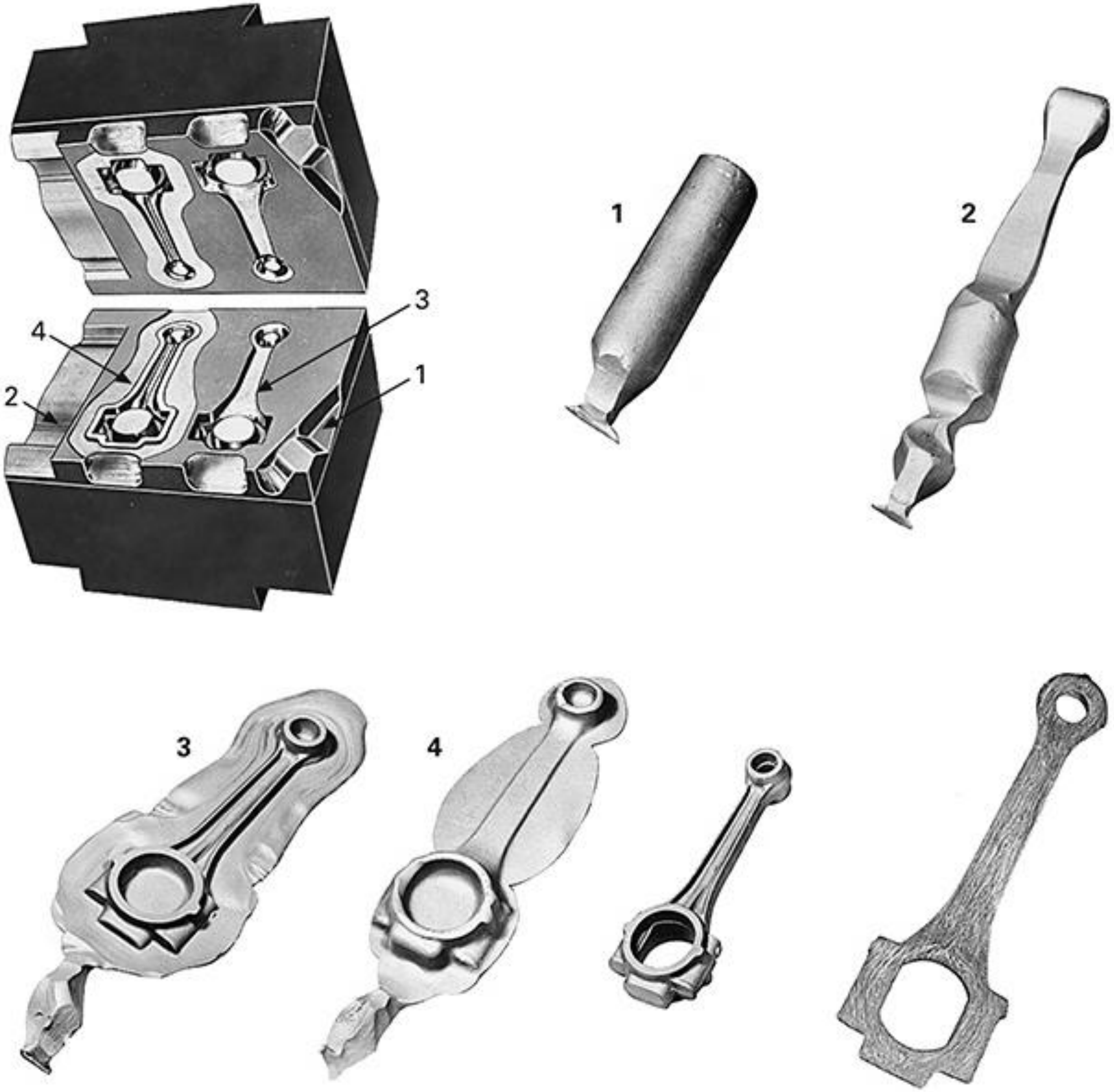


Figure 16-12
Impression drop-forging dies and the product resulting from each impression. The flash is trimmed from the finished connecting rod in a separate trimming die. The sectional view shows the grain flow resulting from the forging process. (*Courtesy of Forging Industry Association, Cleveland, OH.)*

Alternatives to Hammer and Anvil Arrangement

- Two hammers may form a workpiece
- Impactors operate with less noise and less vibration

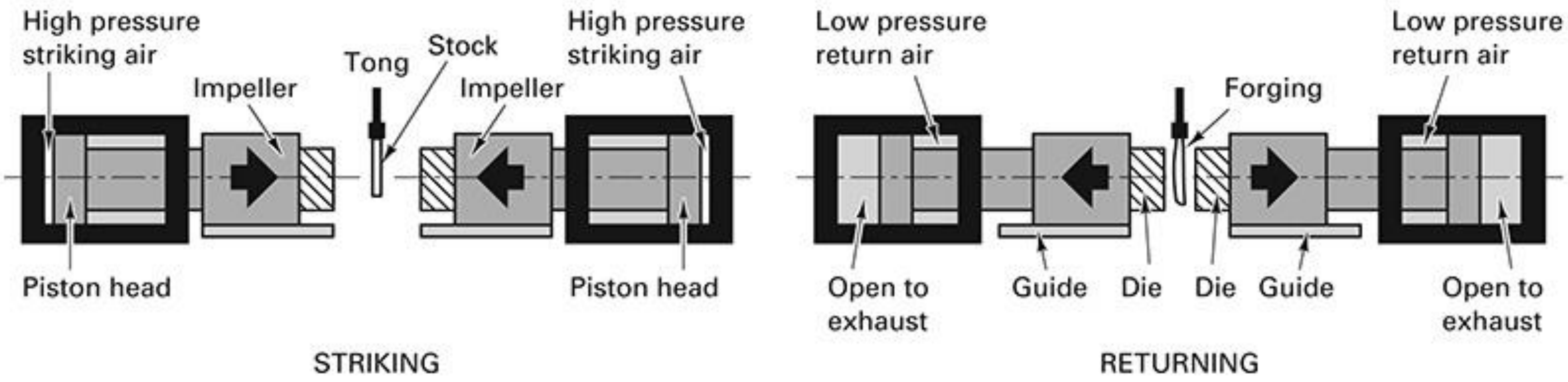


Figure 16-13 Schematic diagram of an impactor in the striking and returning modes. (*Courtesy of Chambersburg Engineering Company, Chambersburg, PA*)

Press Forging

- Press forging is used for large or thick products
- Slow squeezing action penetrates completely through the metal
    - Produces a more uniform deformation and flow
    - Longer time of contact between the die and workpiece
- Dies may be heated (isothermal forging)
- Presses are either mechanical or hydraulic

Design of Impression-Die Forgings and Associated Tooling

- Forging dies are typically made of high-alloy or tool steel
- Rules for better and more economical parts:
    - Dies should part along a single, flat plane or follow the contour of the part
    - Parting surface should be a plane through the center of the forging
    - Adequate draft
    - Generous fillets and radii
    - Ribs should be low and wide
    - Various cross sections should be balanced
    - Full advantage should be taken of fiber flow lines
    - Dimensional tolerances should not be closer than necessary

Impression-Die Forgings

- Important design details
  - Number of intermediate steps
  - Shape of each step
  - Amount of excess metal to fill the die
  - Dimensions of flash at each step
  - Good dimensional accuracy

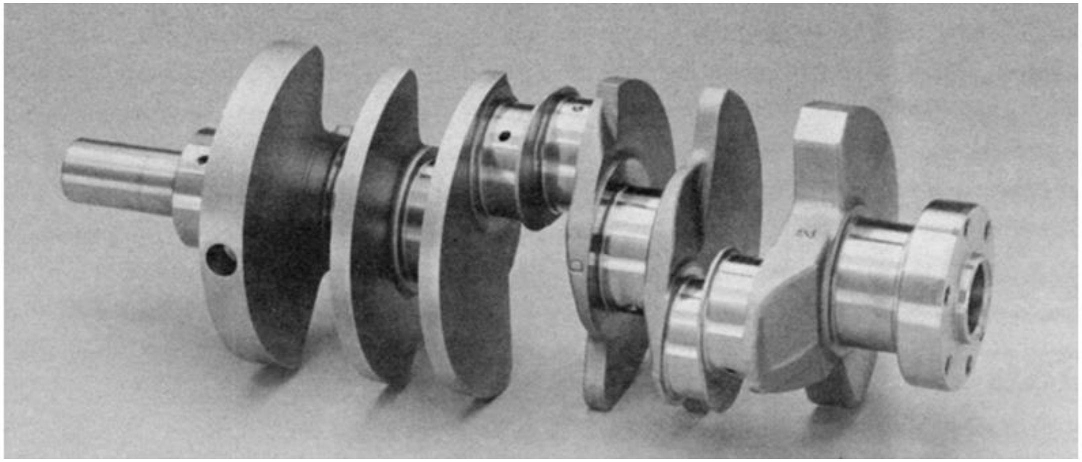


Figure 16-15 A forged-and-machined automobile engine crankshaft that has been formed from microalloyed steel. Performance is superior to cranks of cast ductile iron.

Upset Forging

- Increases the diameter of a material by compressing its length
- Both cold and hot upsetting
- Three rules of upset forging
  - 1. The length of the unsupported material that can be gathered or upset in one blow without injurious buckling should be limited to three times the diameter of the bar.
  - 2. Lengths of stock greater than three times the diameter may be upset successfully provided that the diameter of the upset is not more than 1 times the diameter of the bar.
  - 3. In an upset requiring stock length greater than three times the diameter of the bar, and where the diameter of the cavity is not more than 1 times the diameter of the bar (the conditions of rule 2), the length of the unsupported metal beyond the face of the die must not exceed the diameter of the bar.

Upset Forging

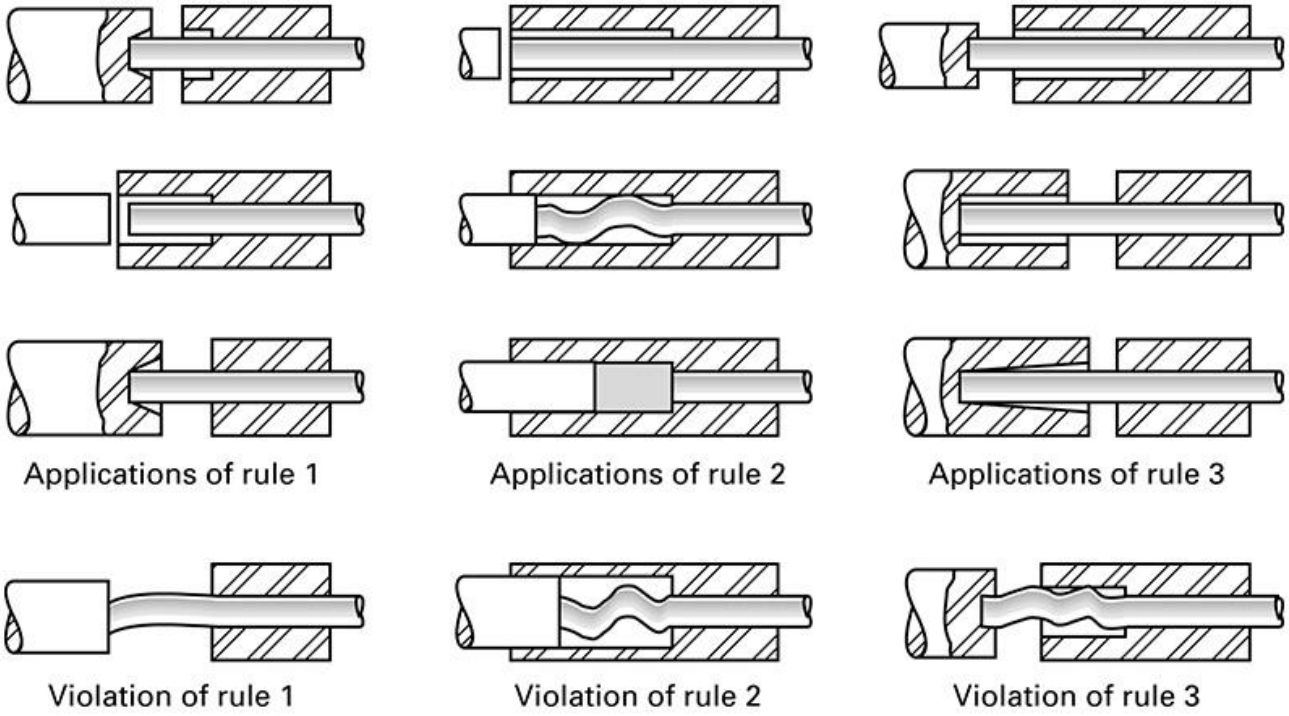
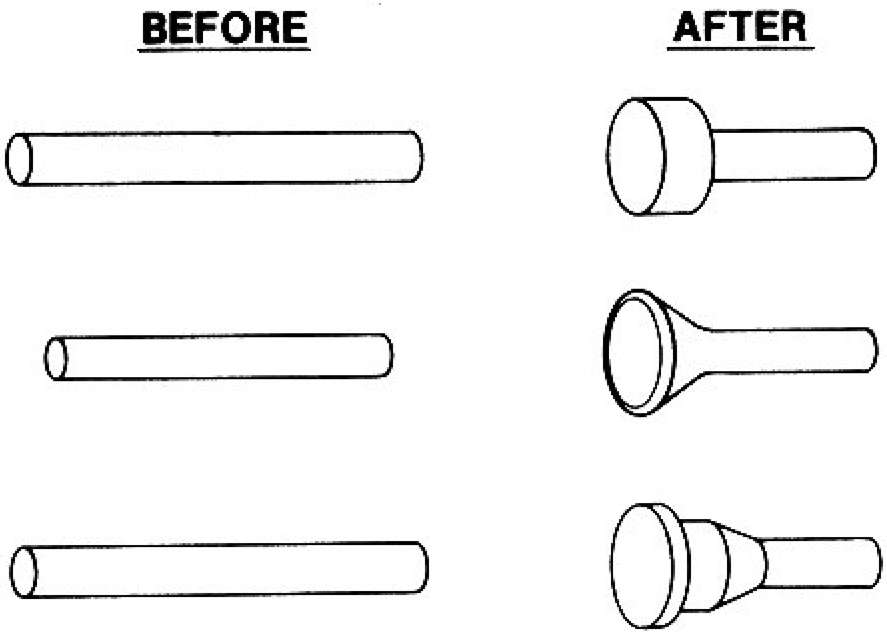
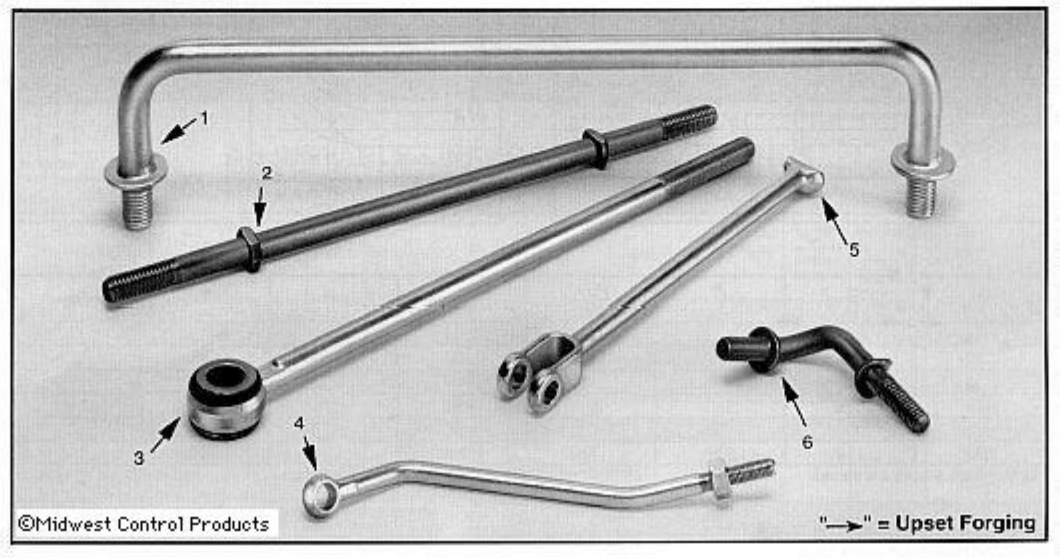


Figure 16-17 Schematics illustrating the rules governing upset forging. (*Courtesy of National Machinery Company, Tiffin, OH.)*

Upsetting



Upsetting Examples



FORGING--EXAMPLE

Automatic Hot Forging

- Slabs, billets, and blooms can be slid into one end of a room and hot-forged products can emerge at the other end, with every process automated

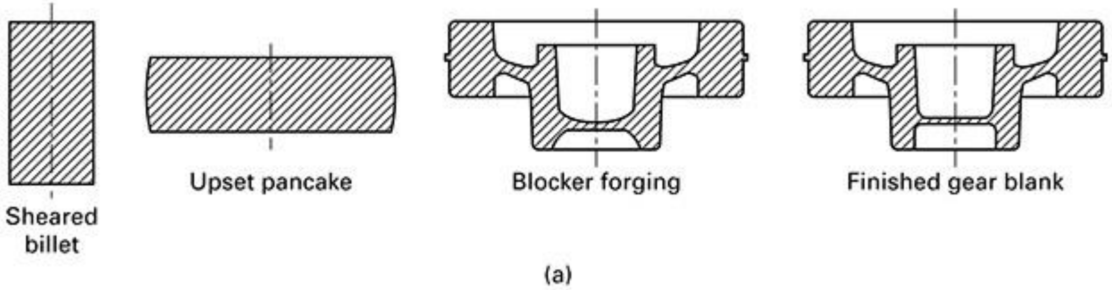


Figure 16-18 (a) Typical four-step sequence to produce a spur-gear forging by automatic hot forging. The sheared billet is progressively shaped into an upset pancake, blocker forging, and finished gear blank. (b) Samples of ferrous parts produced by automatic hot forging at rates between 90 and 180 parts per minute. (*Courtesy of National Machinery Company, Tiffin, OH.)*

Roll Forging

- Round or flat bar stock is reduced in thickness and increased in length
- Produces products such as axles, tapered levers, and leaf springs
- Little or no flash is produced

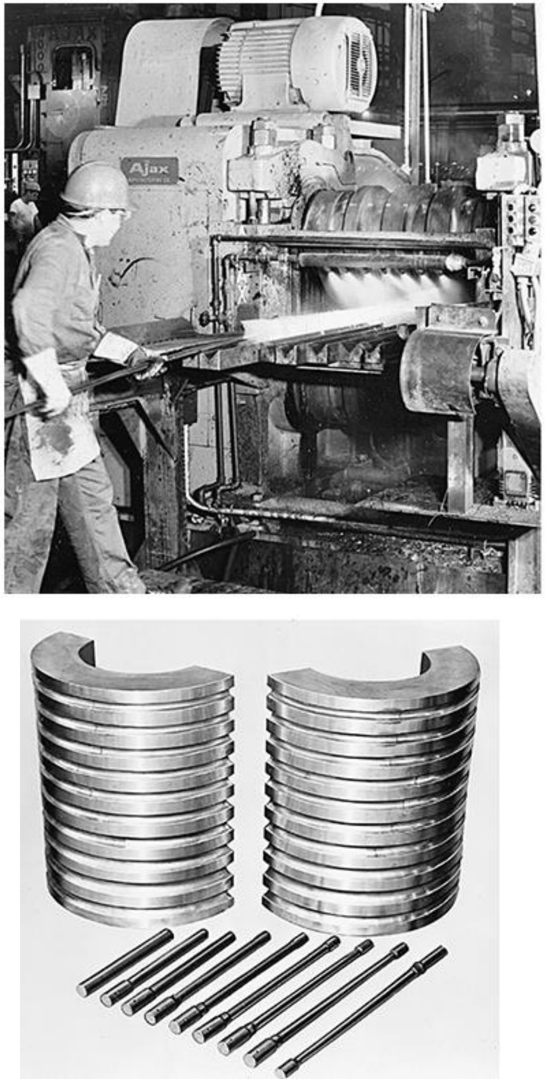
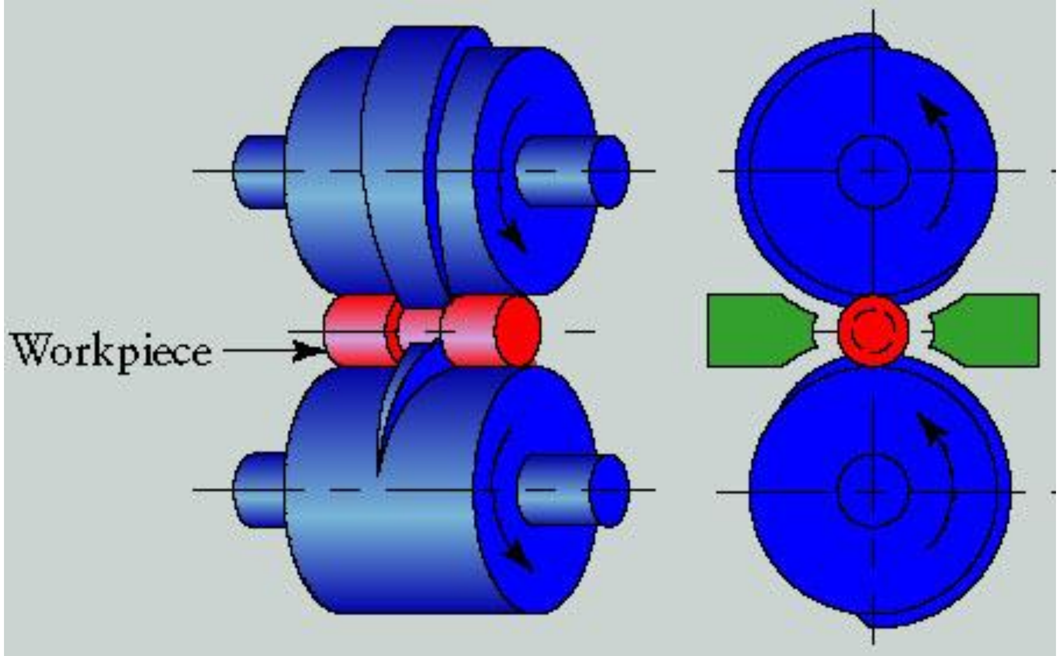


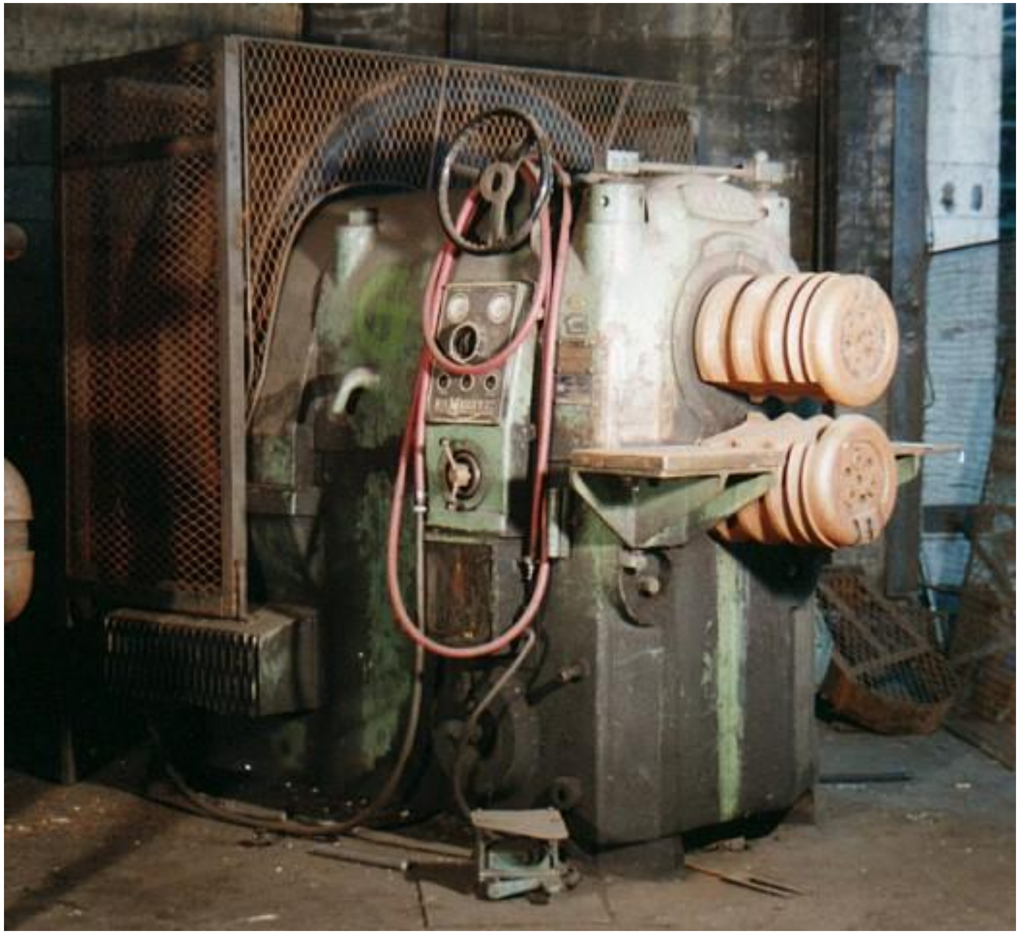
Figure 16-19 (Top) Roll-forging machine in operation. (Right) Rolls from a roll-forging machine and the various stages in roll forging a part. (Courtesy of Ajax Manufacturing Company, Euclid, OH)

Roll Forging Operation



- Roll forging (cross-rolling) operation forging that is done by using a pair of rollers with shaped grooves
- Tapered leaf springs and knives can be made by this process with specially designed rolls.

Roll Forging Machine



Swaging

- Also known as rotary swaging and radial forging
- Uses external hammering to reduce the diameter or produce tapers or points on round bars of tubes

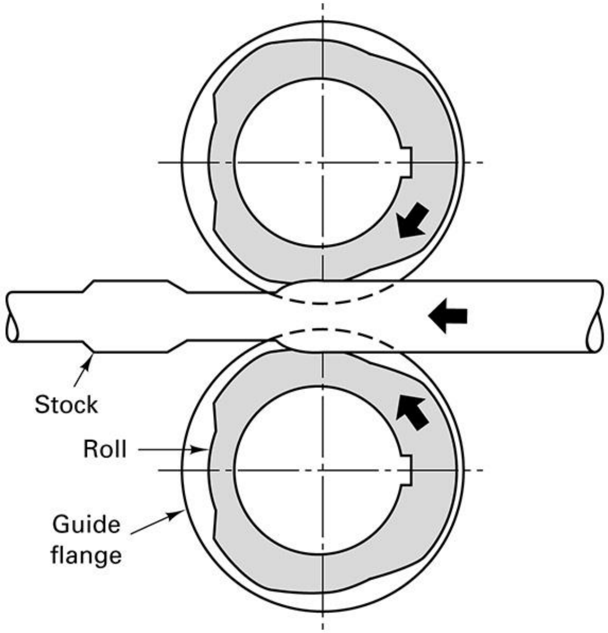


Figure 16-20 Schematic of the roll-forging process showing the two shaped rolls and the stock being formed. (*Courtesy of Forging Industry Association, Cleveland, OH.)*

Swaging

Figure 16-21 (Below) Tube being reduced in a rotary swaging machine. (*Courtesy of the Timkin Company, Canton, OH.)*

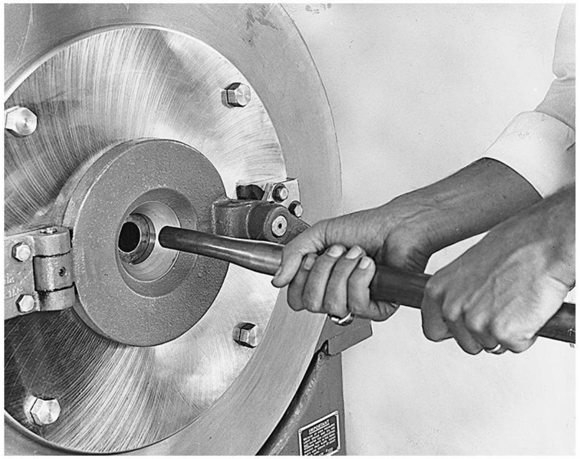


Figure 16-23 (Below) A variety of swaged parts, some with internal details. (*Courtesy of Cincinnati Milacron, Inc. Cincinnati, OH.)*

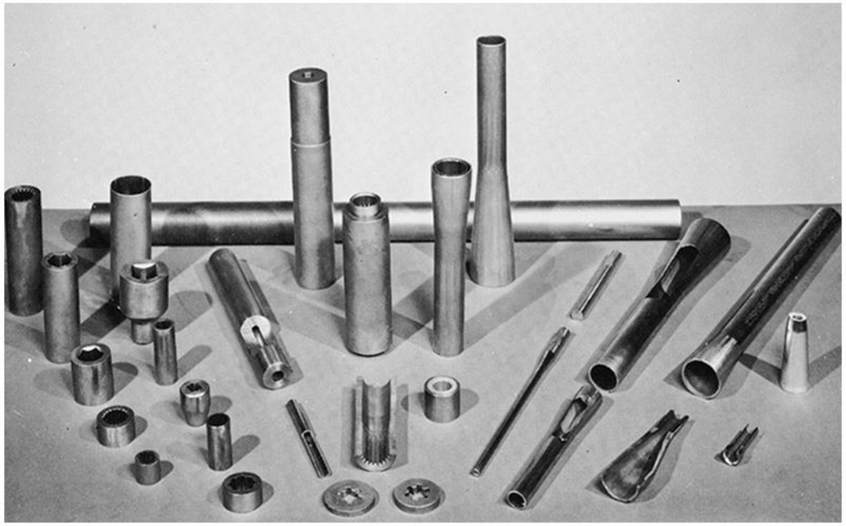
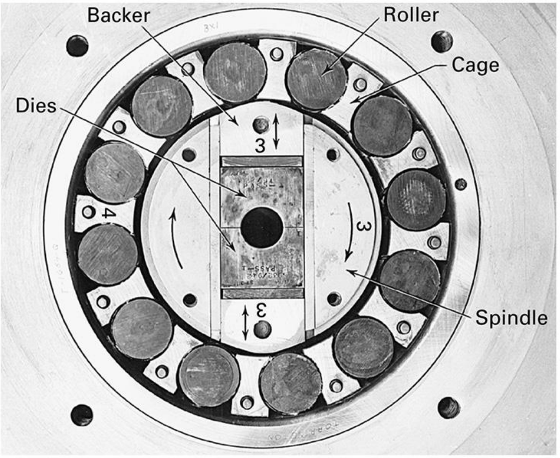
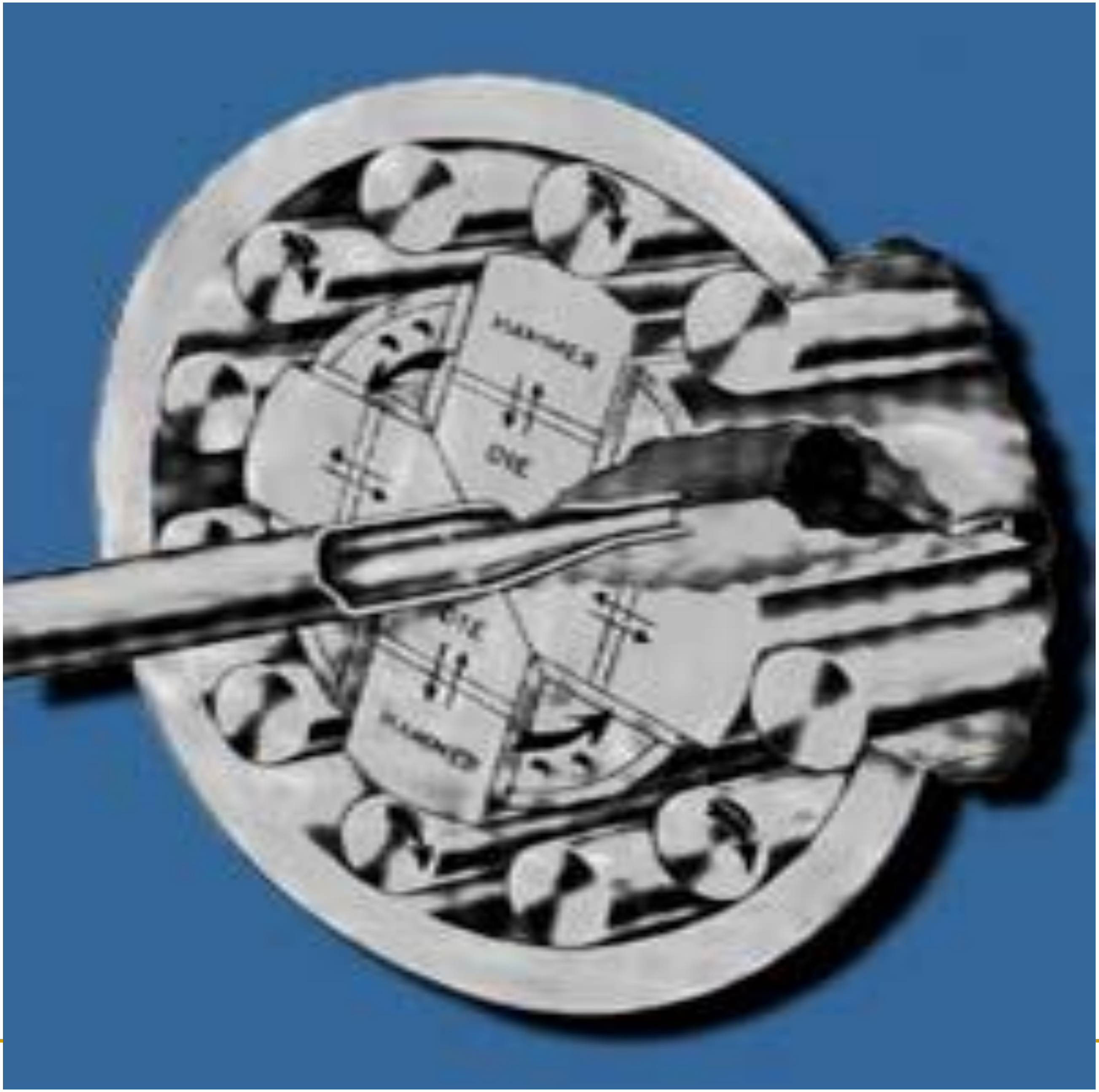


Figure 16-22 (Right) Basic components and motions of a rotary swaging machine. (Note: The cover plate has been removed to reveal the interior workings.) (*Courtesy of the Timkin Company, Canton, OH.)*




HAMMER
DIE
DIE
HAMMER

Net-Shape and Near-Net-Shape Forging

- 80% of the cost of a forged-part can be due to post-forging operations
- To minimize expense and waste, parts should be forged as close the final shape as possible
- These processes are known as net-shape or precision forging

16.6 Extrusion

- Metal is compressed and forced to flow through a shaped die to form a product with a constant cross section
- May be performed hot or cold
- A ram advances from one end of the die and causes the metal to flow plastically through the die
- Commonly extruded metals: aluminum, magnesium, copper, and lead

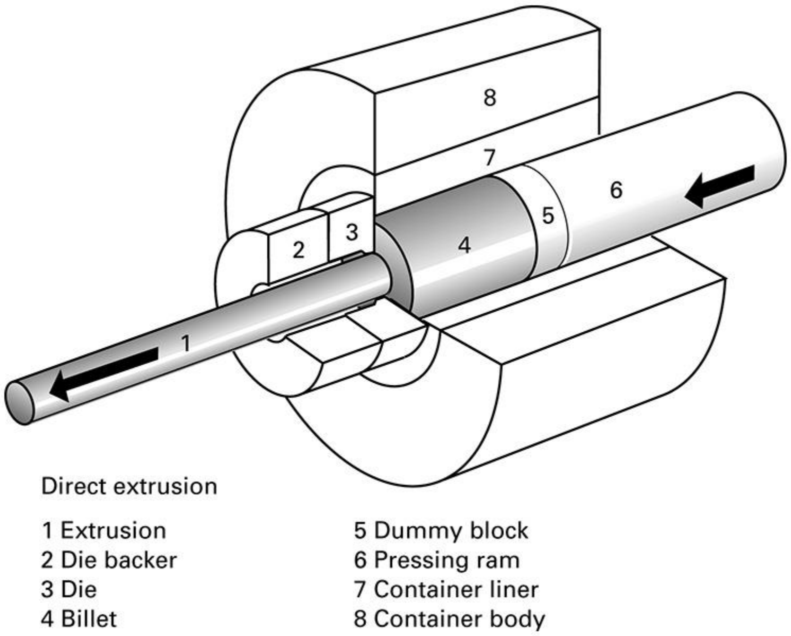


Figure 16-25 Direct extrusion schematic showing the various equipment components. (*Courtesy of Danieli Wean United, Cranberry Township, PA*.)

Typical Extruded Products

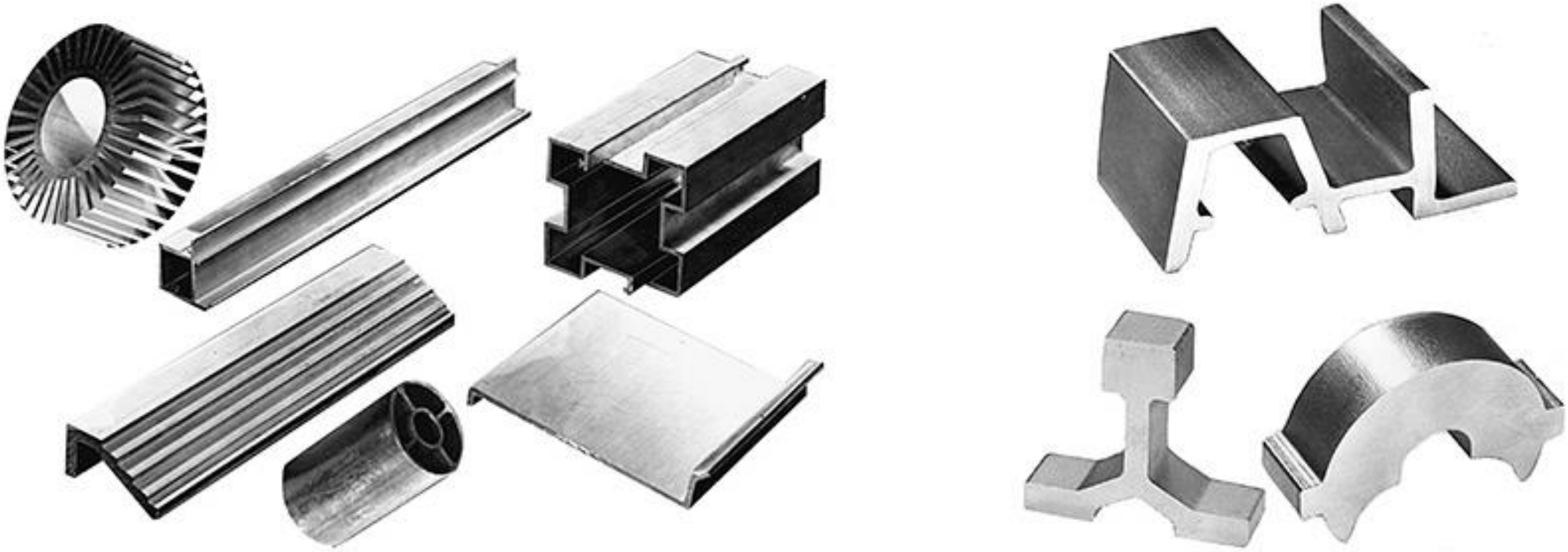


Figure 16-26 Typical shapes produced by extrusion. (Left) Aluminum products. (*Courtesy of Aluminum Company of America, Pittsburgh, PA*.) (Right) Steel products. (*Courtesy of Allegheny Ludlum Steel Corporation, Pittsburgh, PA*.)

Advantages of Extrusion

- Many shapes can be produced that are not possible with rolling
- No draft is required
- Amount of reduction in a single step is only limited by the equipment, not the material or the design
- Dies are relatively inexpensive
- Small quantities of a desired shape can be produced economically

Extrusion Methods

- Direct extrusion
  - Solid ram drives the entire billet to and through a stationary die
  - Must provide power to overcome friction
- Indirect extrusion
  - A hollow ram pushes the die back through a stationary, confined billet

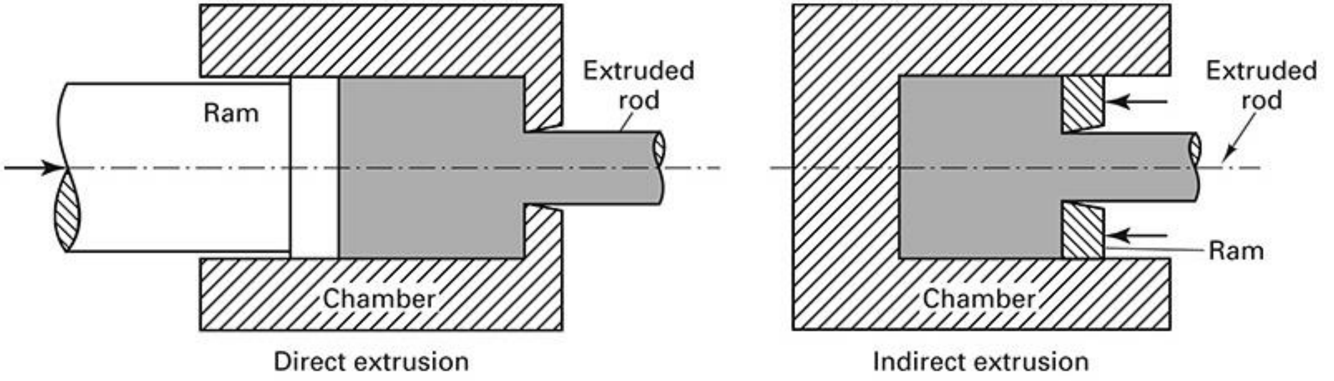


Figure 16-27 Direct and indirect extrusion. In direct extrusion, the ram and billet both move and friction between the billet and the chamber opposes forward motion. For indirect extrusion, the billet is stationary. There is no billet-chamber friction, since there is no relative motion.

Forces in Extrusion

- Lubrication is important to reduce friction and act as a heat barrier
- Metal flow in extrusion
  - Flow can be complex
  - Surface cracks, interior cracks and flow-related cracks need to be monitored
  - Process control is important

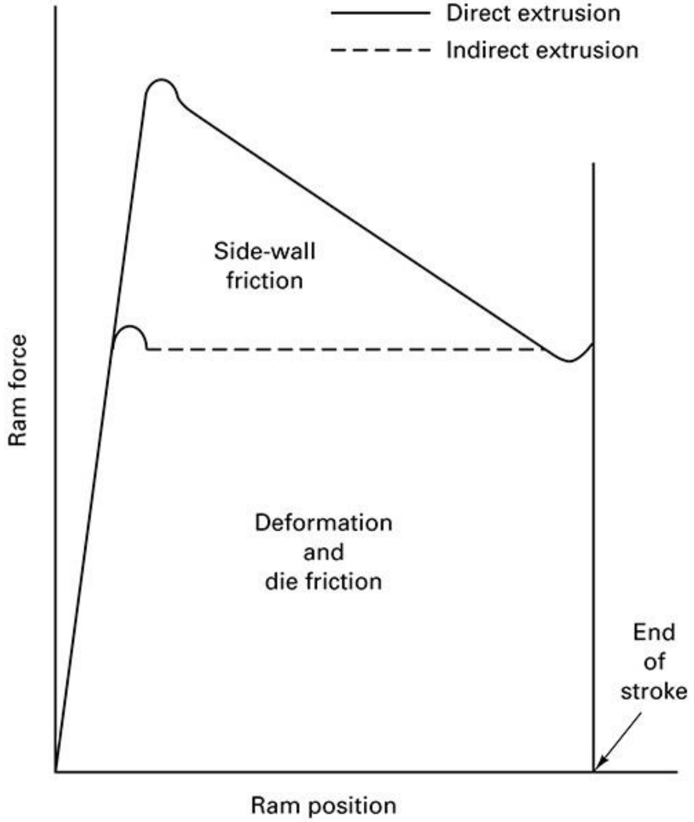


Figure 16-28 Diagram of the ram force versus ram position for both direct and indirect extrusion of the same product. The area under the curve corresponds to the amount of work (force x distance) performed. The difference between the two curves is attributed to billet-chamber friction.

Extrusion of Hollow Shapes

- Mandrels may be used to produce hollow shapes or shapes with multiple longitudinal cavities

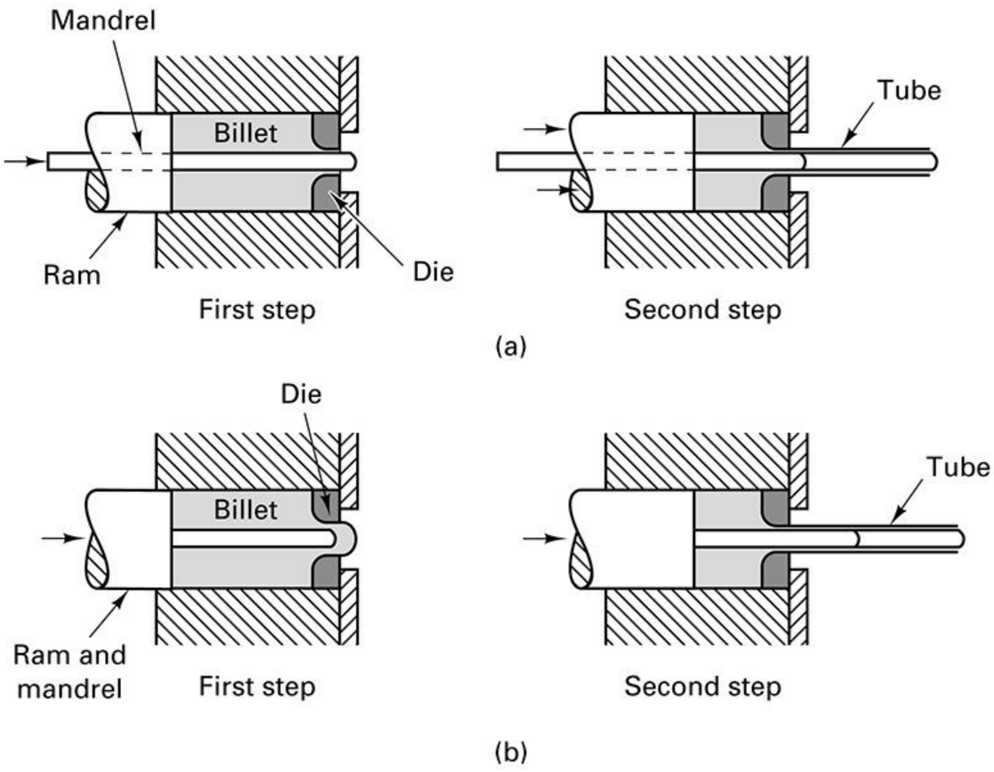


Figure 16-30 Two methods of extruding hollow shapes using internal mandrels. In part (a) the mandrel and ram have independent motions; in part (b) they move as a single unit.

Hydrostatic Extrusion

- High-pressure fluid surrounds the workpiece and applies the force to execute extrusion
    - Billet-chamber friction is eliminated
- High efficiency process
- Temperatures are limited because the fluid acts as a heat sink
- Seals must be designed to keep the fluid from leaking

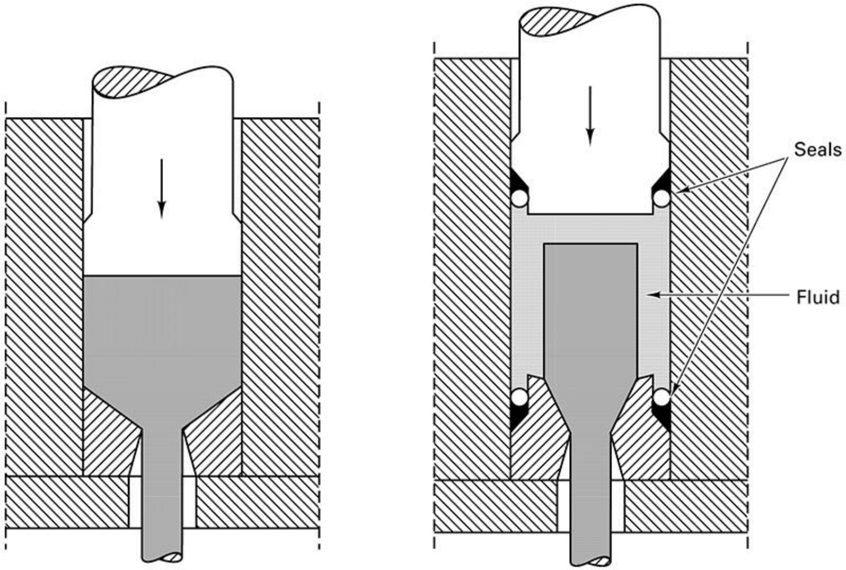


Figure 16-32 Comparison of conventional (left) and hydrostatic (right) extrusion. Note the addition of the pressurizing fluid and the O-ring and miter-ring seals on both the die and ram.

Continuous Extrusion

- Conform process
  - Continuous feedstock is fed into a grooved wheel and is drive by surface friction into a chamber created by a mating die segment
  - The material upsets to conform to the chamber
  - Feedstock can be solid, metal powder, punchouts, or chips
  - Metallic and nonmetallic powders can be intimately mixed

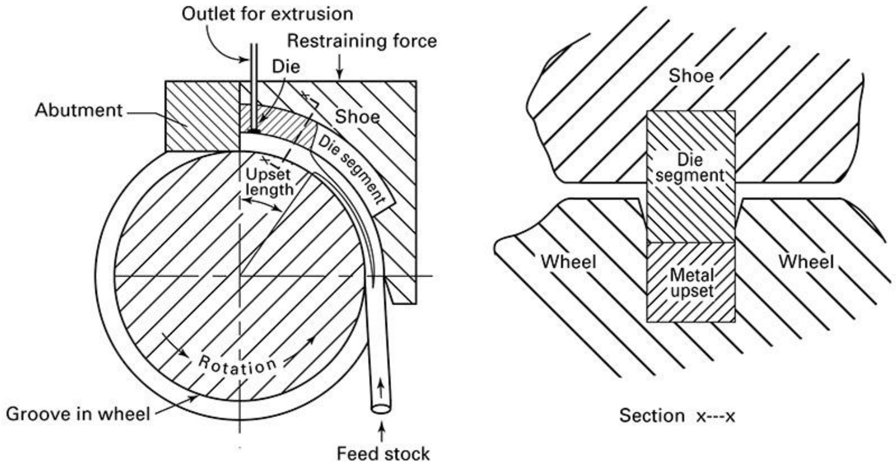
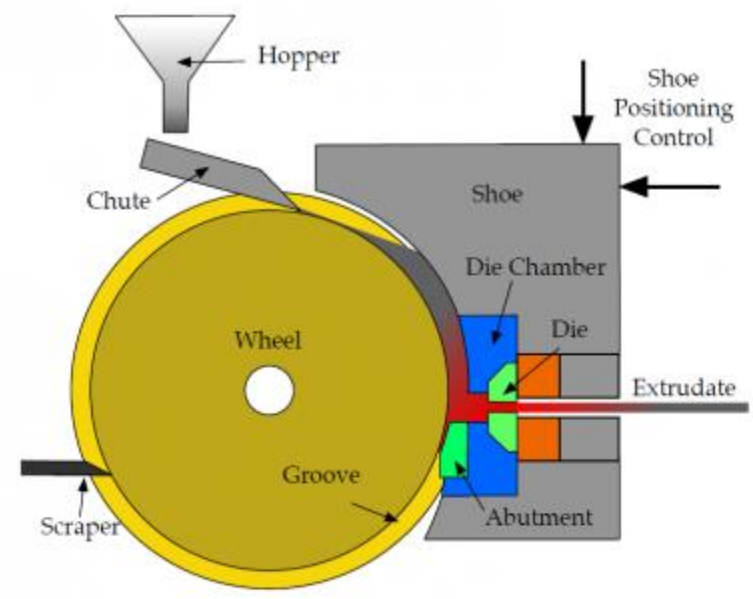
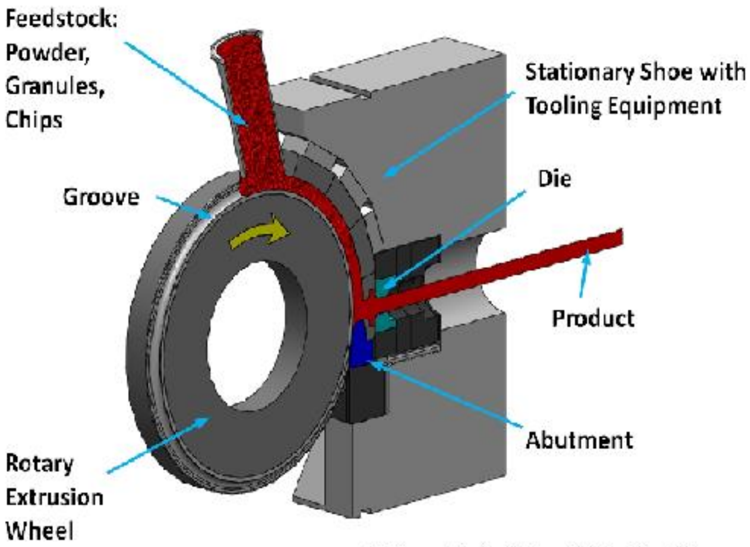


Figure 16-33 Cross-sectional schematic of the Conform continuous extrusion process. The material upsets at the abutment and extrudes. Section x-x shows the material in the shoe.





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16.7 Wire, Rod, and Tube Drawing

- Reduce the cross section of a material by pulling it through a die
- Similar to extrusion, but the force is tensile

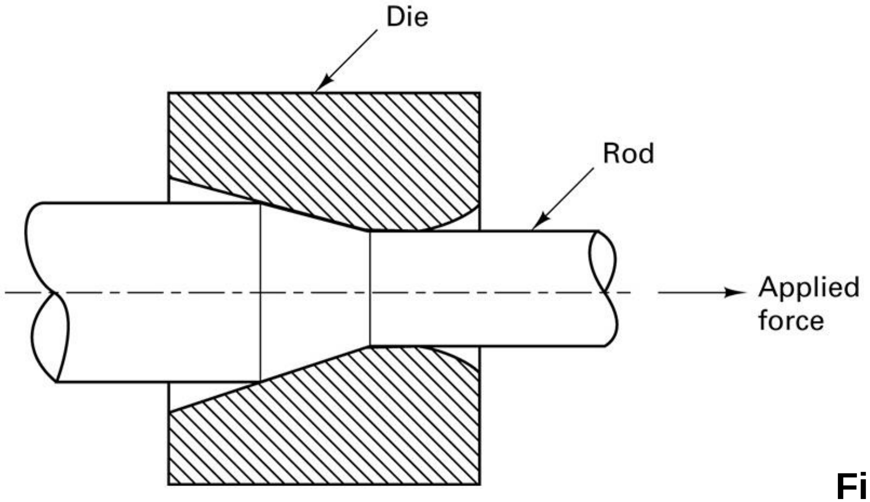


Figure 16-34 Schematic drawing of the rod-or bar-drawing process.

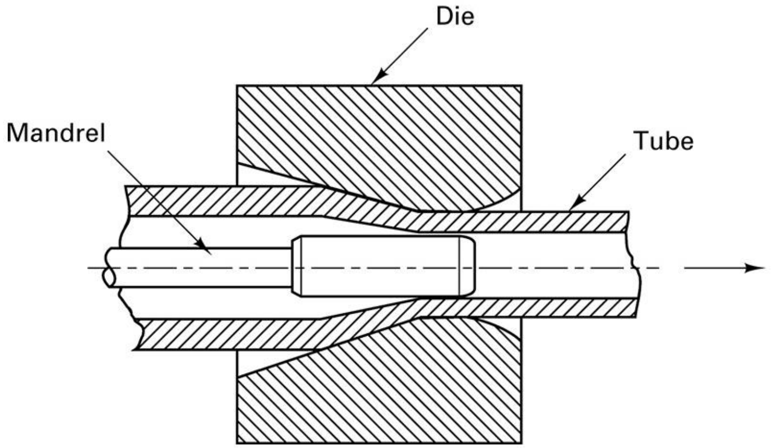


Figure 16-36 Cold-drawing smaller tubing from larger tubing. The die sets the outer dimension while the stationary mandrel sizes the inner diameter.

Tube and Wire Drawing

- Tube sinking does not use a mandrel
  - Internal diameter precision is sacrificed for cost and a floating plug is used

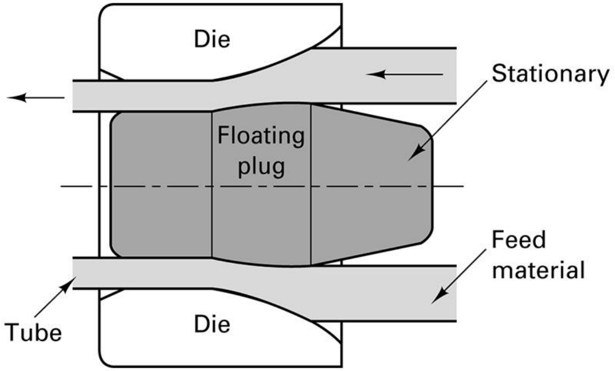
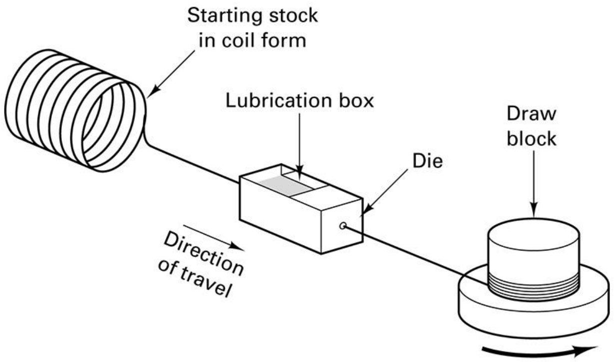


Figure 16-37 (Above) Tube drawing with a floating plug.

Figure 16-38 Schematic of wire drawing with a rotating draw block. The rotating motor on the draw block provides a continuous pull on the incoming wire.



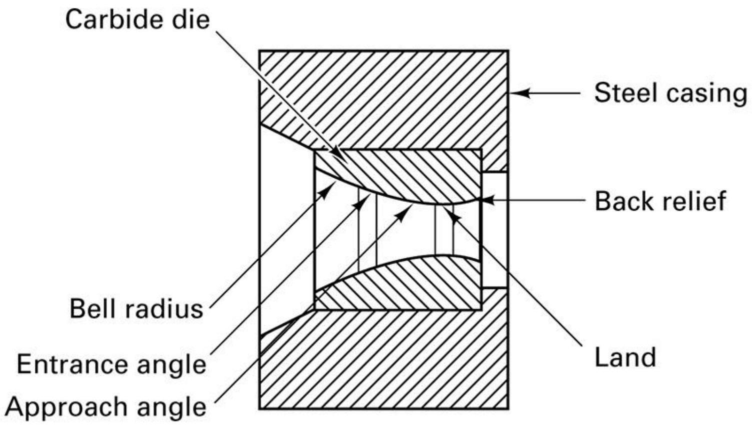


Figure 16-39 Cross section through a typical carbide wire-drawing die showing the characteristic regions of the contour.

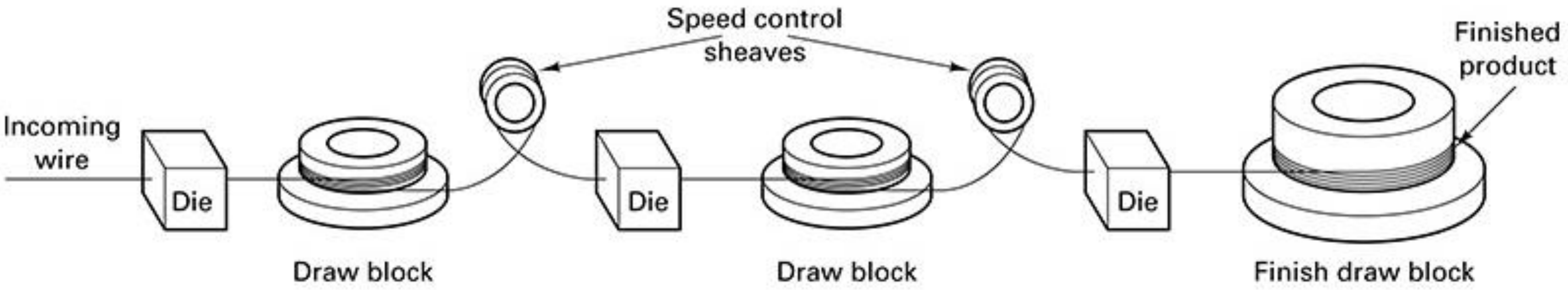


Figure 16-40 Schematic of a multistation synchronized wire-drawing machine. To prevent accumulation or breakage, it is necessary to ensure that the same volume of material passes through each station in a given time. The loops around the sheaves between the stations use wire tensions and feedback electronics to provide the necessary speed control.

16.8 Cold Forming, Cold Forging, and Impact Extrusion

- Slugs of material are squeezed into or extruded from shaped die cavities to produce finished parts of precise shape and size
- Cold heading is a form of upset forging
  - Used to make the enlarged sections on the ends of rod or wire (i.e. heads of nails, bolts, etc.)

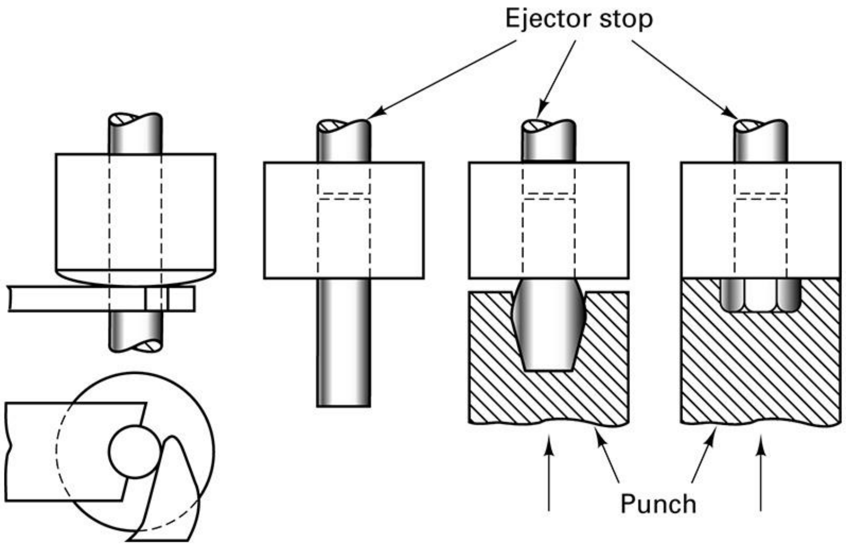
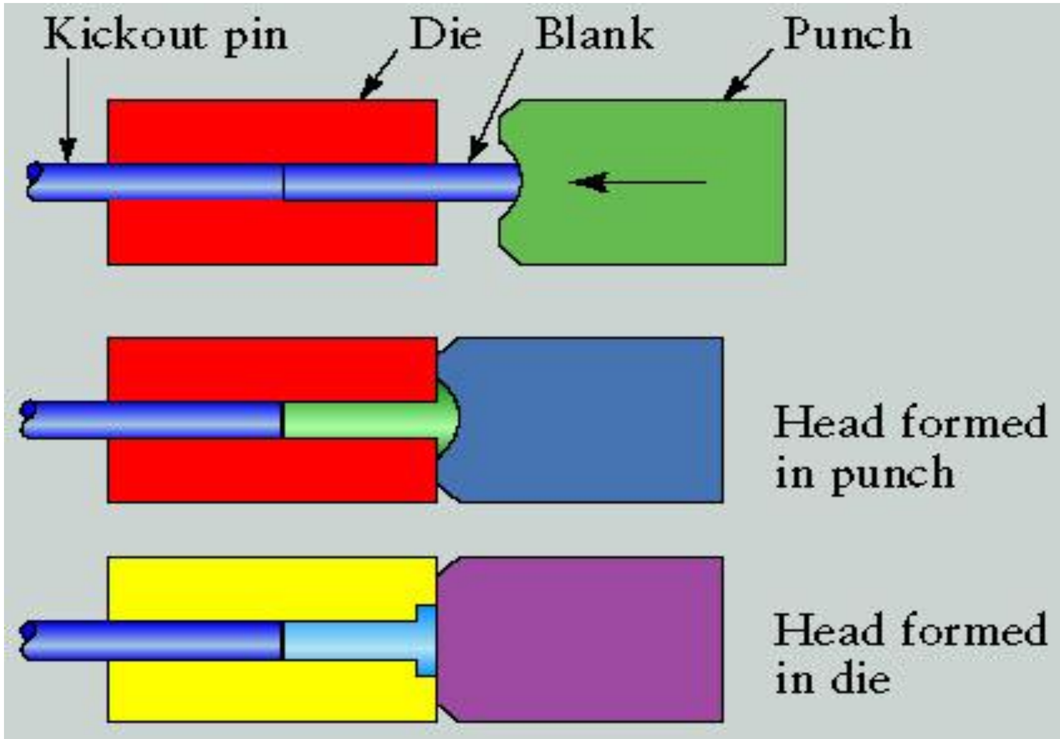


Figure 16-41 Typical steps in a shearing and cold-heading operation.

Heading

- an upsetting process used to create head bolts, screws or other fasteners.
- 

Impact Extrusion

- A metal slug is positioned in a die cavity where it is struck by a single blow
- Metal may flow forward, backward or some combination
- The punch controls the inside shape while the die controls the exterior shape

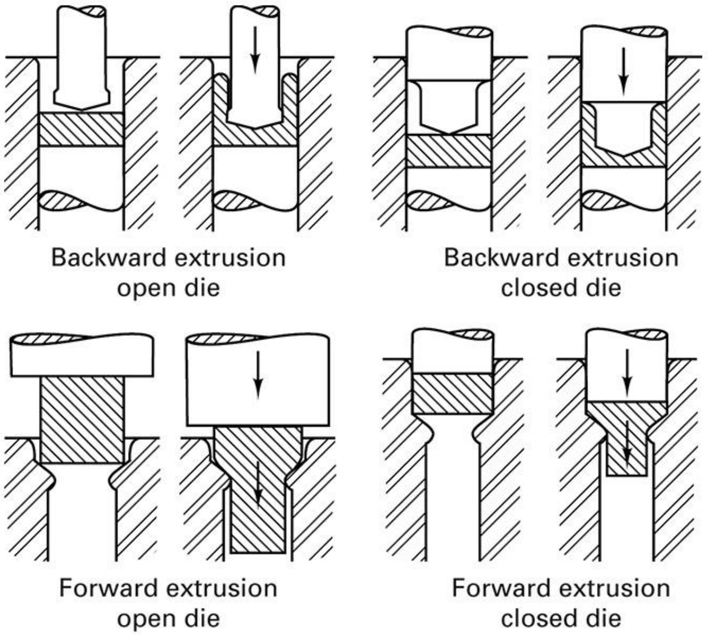


Figure 16-43 Backward and forward extrusion with open and closed dies.

Cold Extrusion

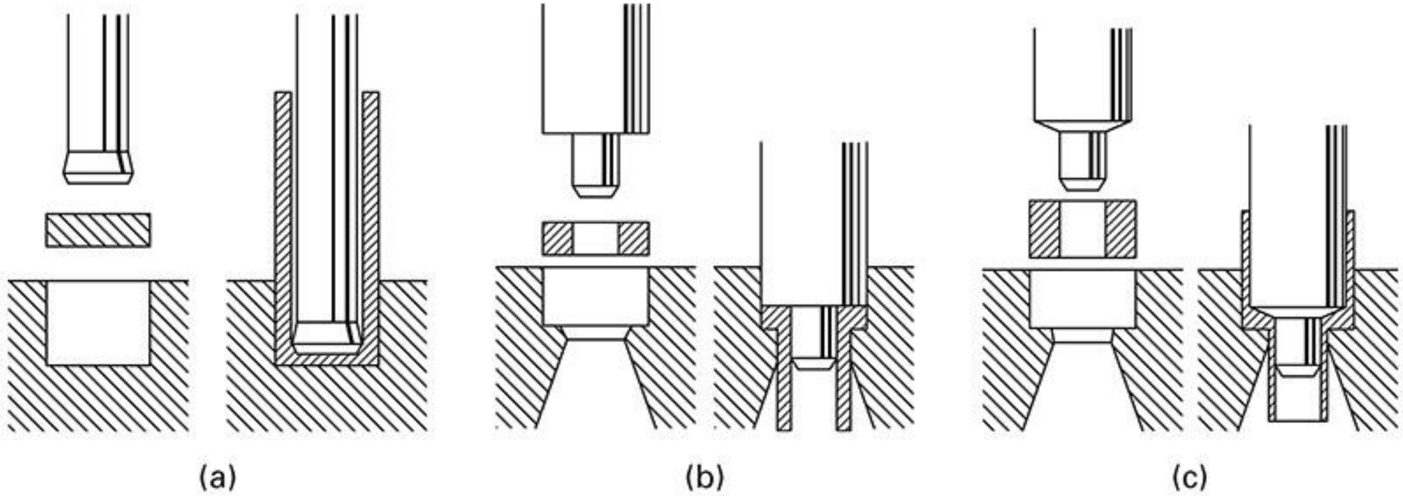


Figure 16-44
(a) Reverse
(b) forward
(c) combined forms of cold extrusion. (Courtesy the Aluminum Association, Arlington, VA.)

Figure 16-45 (Right) Steps in the forming of a bolt by cold extrusion, cold heading, and thread rolling. (Courtesy of National Machinery Co. Tiffin, OH.)

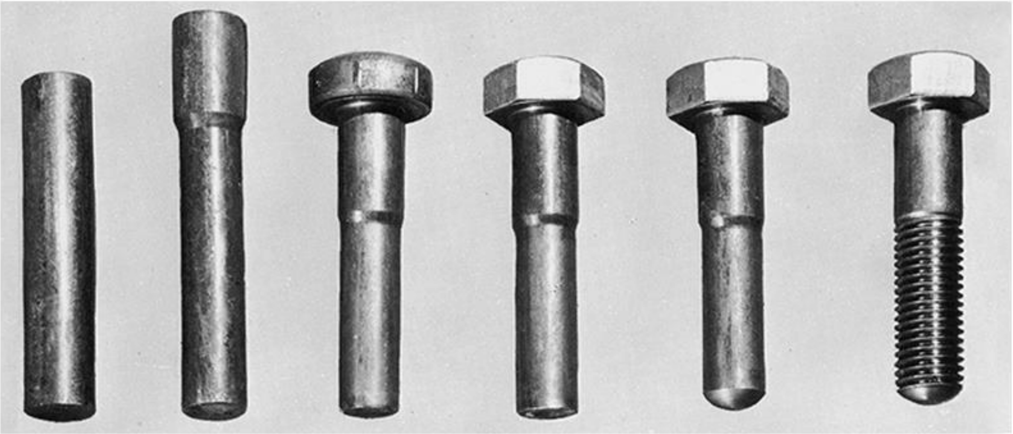


Figure 16-46 Cold-forming sequence involving cutoff, squaring, two extrusions, an upset, and a trimming operation. Also shown are the finished part and the trimmed scrap. (*Courtesy of National Machinery Co., Tiffin, OH*.)

Figure 16-47 Typical parts made by upsetting and related operations. (*Courtesy of National Machinery Co., Tiffin, OH*.)

16.9 Piercing

- Thick-walled seamless tubing can be made by rotary piercing
- Heated billet is fed into the gap between two large, convex-tapered rolls
- Forces the billet to deform into a rotating ellipse

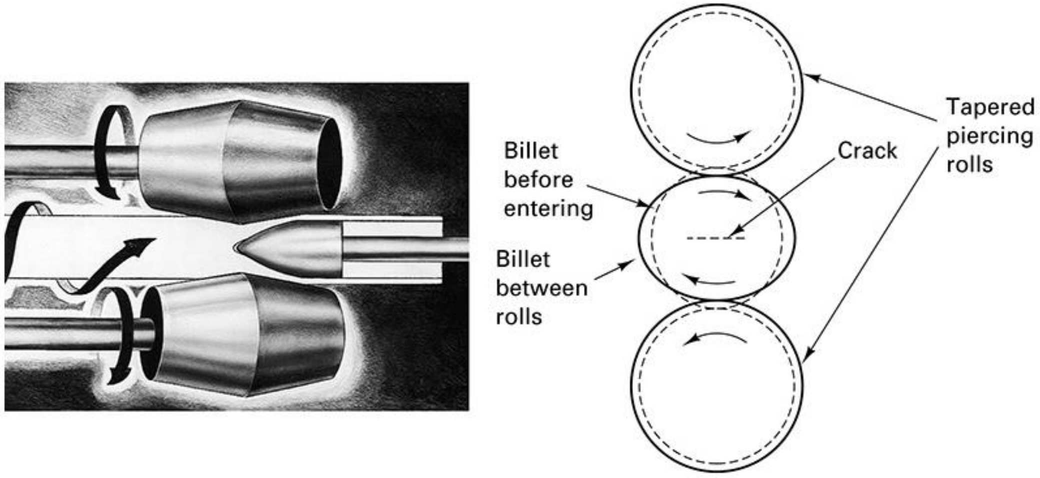


Figure 16-50 (Left) Principle of the Mannesmann process of producing seamless tubing. (*Courtesy of American Brass Company, Cleveland, OH.)* (Right) Mechanism of crack formation in the Mannesmann process.

16.10 Other Squeezing Processes

- Roll extrusion- thin walled cylinders are produced from thicker-wall cylinders
- Sizing-involves squeezing all or select regions of products to achieve a thickness or enhance dimensional precision
- Riveting- permanently joins sheets or plates of material by forming an expanded head on the shank end of a fastener
- Staking-permanently joins parts together when a segment of one part protrudes through a hole in the other

Other Squeezing Processes

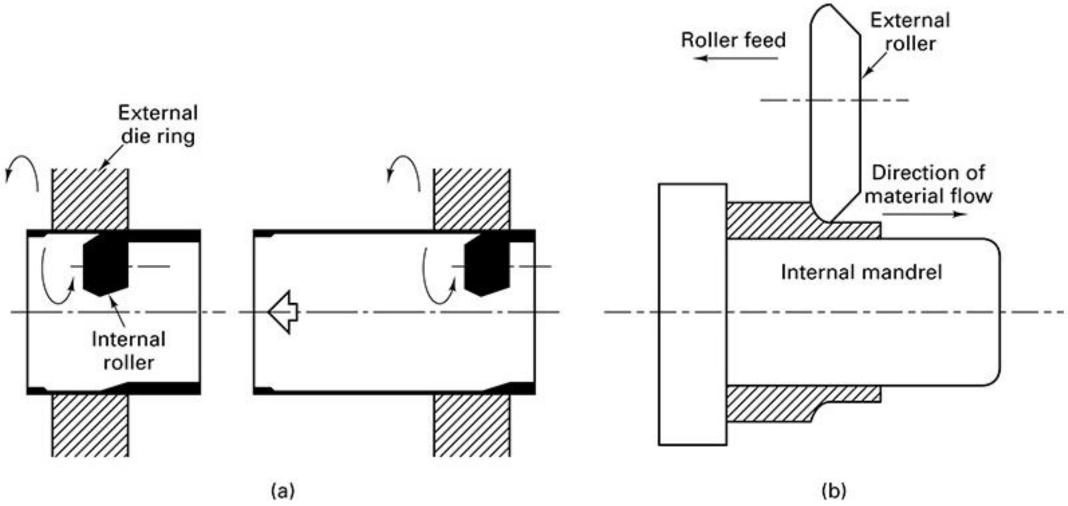


Figure 16-51 The roll-extrusion process: (a) with internal rollers expanding the inner diameter; (b) with external rollers reducing the outer diameter.

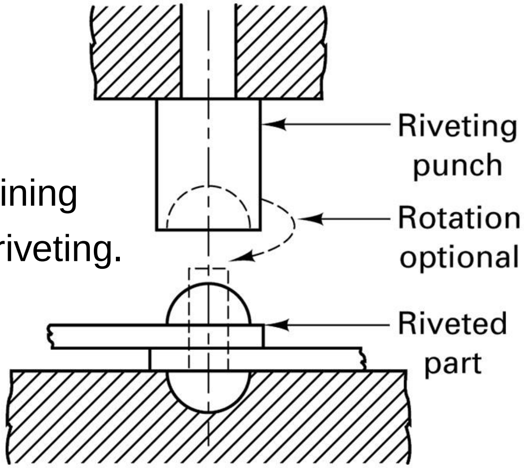


Figure 16-52 Joining components by riveting.

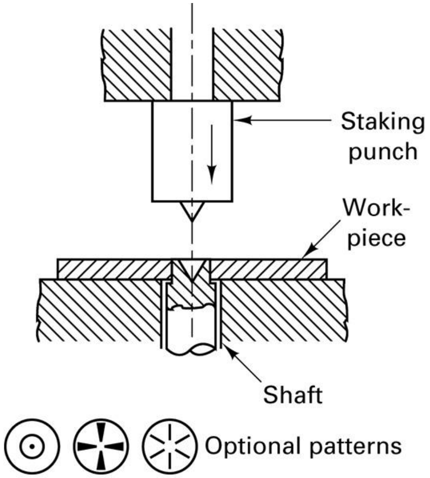
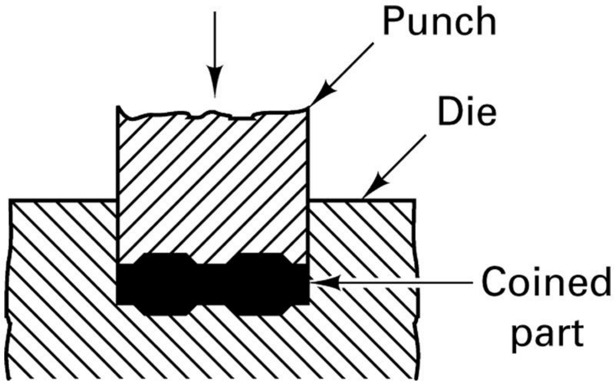


Figure 16-54 Permanently attaching a shaft to a plate by staking.

Other Squeezing Operations

- Coining- cold squeezing of metal while all of the surfaces are confined within a set of dies
- Hubbing- plastically forms recessed cavities in a workpiece

Figure 16-55 The coining process.



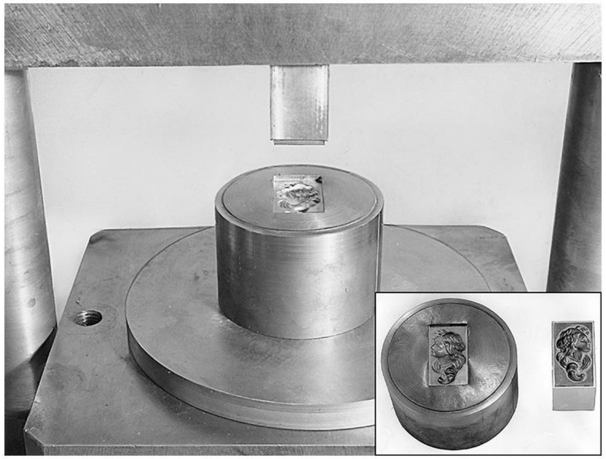


Figure 16-56 Hubbing a die block in a hydraulic press. Inset shows close-up of the hardened hub and the impression in the die block. The die block is contained in a reinforcing ring. The upper surface of the die block is then machined flat to remove the bulged metal.

16.11 Surface Improvement by Deformation Processing

- Deformation processes can be used to improve or alter the surfaces of the metal
- Peening- mechanical working of surfaces by repeated blows of impelled shot or a round-nose tool
- Burnishing- rubbing a smooth, hard object under pressure over the minute surface irregularities
- Roller burnishing- used to improve the size and finish of internal and external cylindrical and conical surfaces

Summary

- There are a variety of bulk deformation processes
- The main processes are rolling, forging, extrusion, and drawing
- Each has limits and advantages as to its capabilities
- The correct process depends on the desired shape, surface finish, quantity, etc.

Chapter 19:
Sheet-Forming Processes

DeGarmo’s Materials and Processes in Manufacturing

17.1 Introduction

- Sheet metal processes involve plane stress loadings and lower forces than bulk forming
- Almost all sheet metal forming is considered to be secondary processing
- The main categories of sheet metal forming are:
  - Shearing
  - Bending
  - Drawing

17.2 Shearing Operations

- Shearing- mechanical cutting of material without the formation of chips or the use of burning or melting
  - Both cutting blades are straight
- Curved blades may be used to produce different shapes
  - Blanking
  - Piercing
  - Notching
  - Trimming

Metalforming

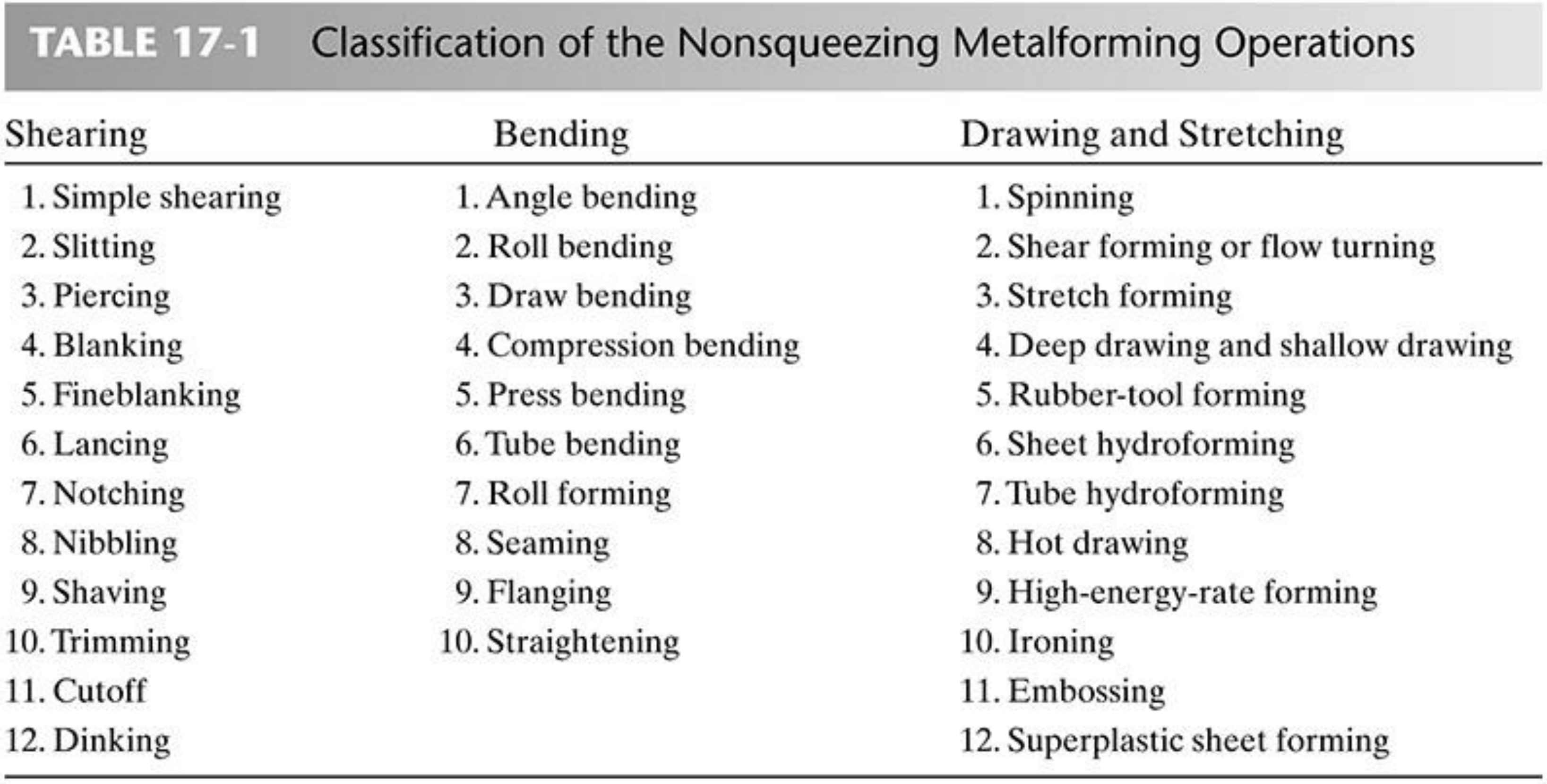


TABLE 17-1 Classification of the Nonsqueezing Metalforming Operations

Shearing	Bending	Drawing and Stretching
1. Simple shearing	1. Angle bending	1. Spinning
2. Slitting	2. Roll bending	2. Shear forming or flow turning
3. Piercing	3. Draw bending	3. Stretch forming
4. Blanking	4. Compression bending	4. Deep drawing and shallow drawing
5. Fineblanking	5. Press bending	5. Rubber-tool forming
6. Lancing	6. Tube bending	6. Sheet hydroforming
7. Notching	7. Roll forming	7. Tube hydroforming
8. Nibbling	8. Seaming	8. Hot drawing
9. Shaving	9. Flanging	9. High-energy-rate forming
10. Trimming	10. Straightening	10. Ironing
11. Cutoff		11. Embossing
12. Dinking		12. Superplastic sheet forming

Shearing Operations

- Fracture and tearing begin at the weakest point and proceed progressively or intermittently to the next-weakest location
  - Results in a rough and ragged edge
- Punch and die must have proper alignment and clearance
- Sheared edges can be produced that require no further finishing

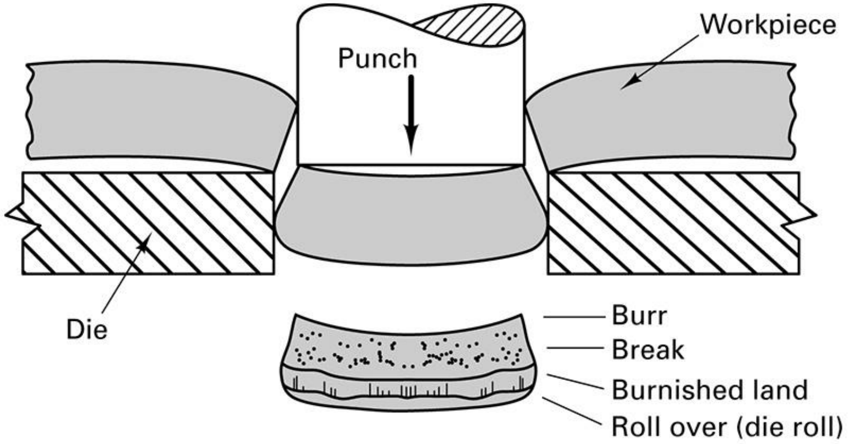


Figure 17-1 (Left) Simple blanking with a punch and die.

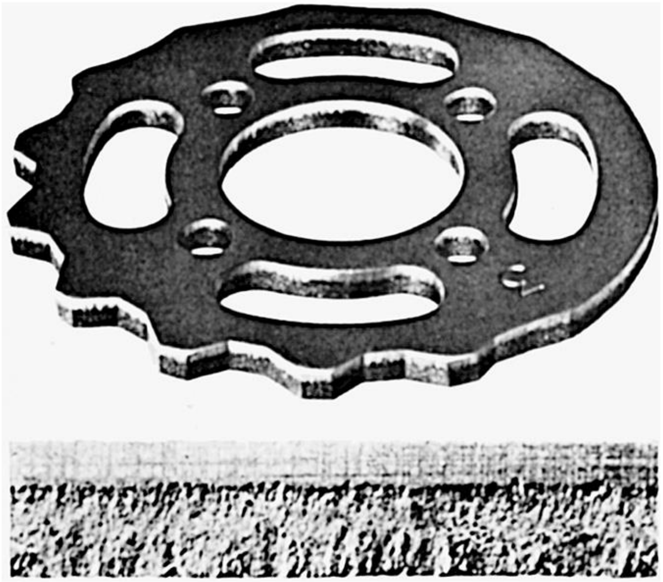
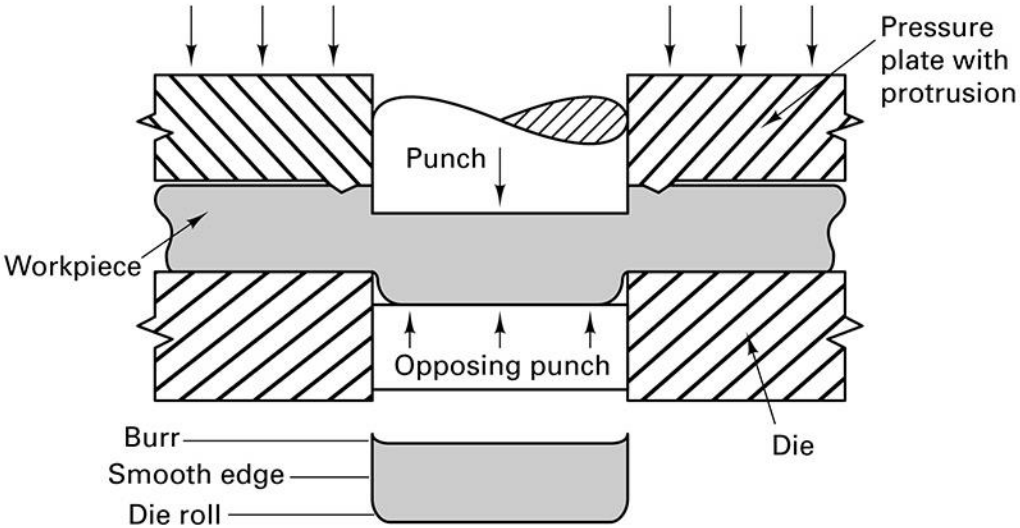


Figure 17-2 (Right) (Top) Conventionally sheared surface showing the distinct regions of deformation and fracture and (bottom) magnified view of the sheared edge. (*Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*

Figure 17-3 (Right) Method of obtaining a smooth edge in shearing by using a shaped pressure plate to put the metal into localized compression and a punch and opposing punch descending in unison.



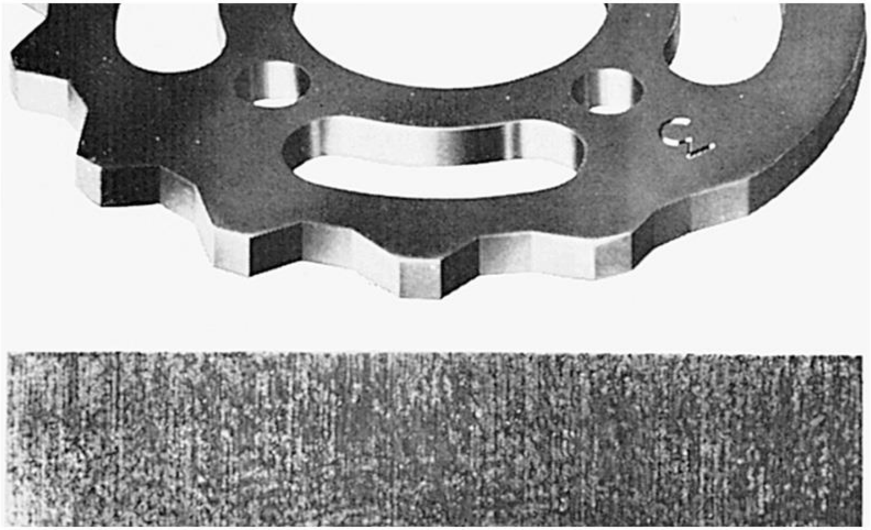


Figure 17-4 Fineblanked surface of the same component as shown in Figure 17-2. (*Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*

Types of Shearing

- Simple shearing- sheets of metal are sheared along a straight line
- Slitting- lengthwise shearing process that is used to cut coils of sheet metal into several rolls of narrower width

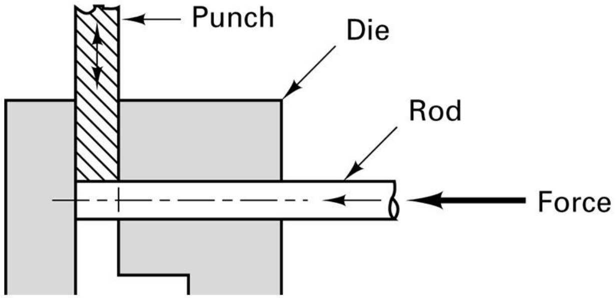


Figure 17-5 Method of smooth shearing a rod by putting it into compression during shearing.

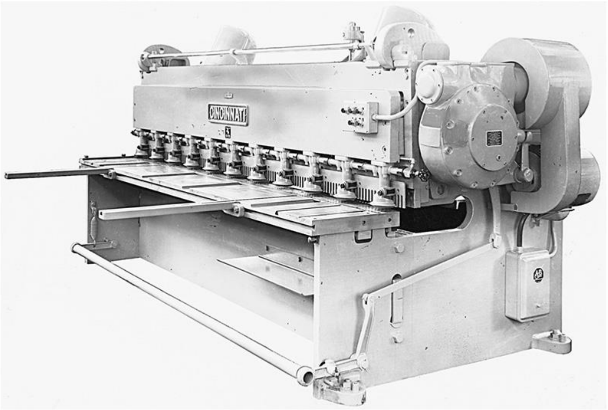


Figure 17-6 A 3-m (10ft) power shear for 6.5 mm (1/4-in.) steel. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

Piercing and Blanking

- Piercing and blanking are shearing operations where a part is removed from sheet material by forcing a shaped punch through the sheet and into a shaped die
- Blanking- the piece being punched out becomes the workpiece
- Piercing- the punchout is the scrap and the remaining strip is the workpiece

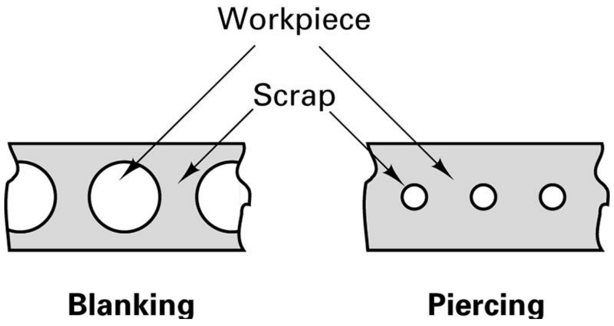


Figure 17-7 Schematic showing the difference between piercing and blanking.

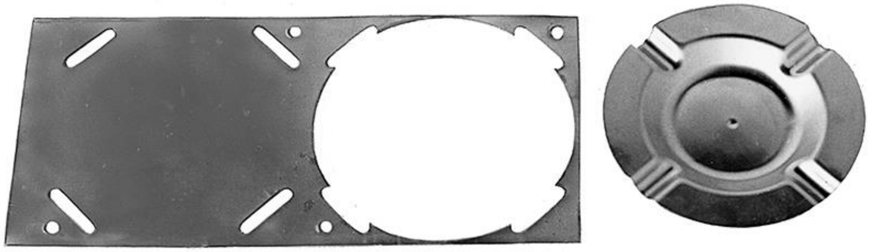


Figure 17-8 (Above) (Left to Right) Piercing, lancing, and blanking precede the forming of the final ashtray. The small round holes assist positioning and alignment.

Types of Piercing and Blanking

- Lancing- piercing operation that forms either a line cut or hole
- Perforating- piercing a large number of closely spaced holes
- Notching- removes segments from along the edge of an existing product
- Nibbling- a contour is progressively cut by producing a series of overlapping slits or notches

Types of Piercing and Blanking

- Shaving- finishing operation in which a small amount of metal is sheared away from the edge of an already blanked part
- Cutoff- a punch and a die are used to separate a stamping or other product from a strip of stock
- Dinking- used to blank shapes from low-strength materials such as rubber, fiber, or cloth

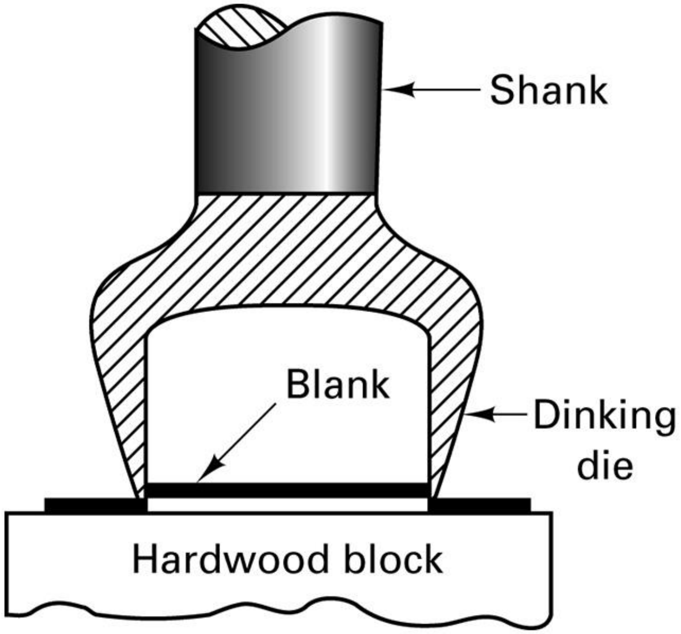


Figure 17-10 The dinking process.

Tools and Dies for Piercing and Blanking

- Basic components of a piercing and blanking die set are: punch, die, and stripper plate
- Punches and dies should be properly aligned so that a uniform clearance is maintained around the entire border
- Punches are normally made from low-distortion or air-hardenable tool steel

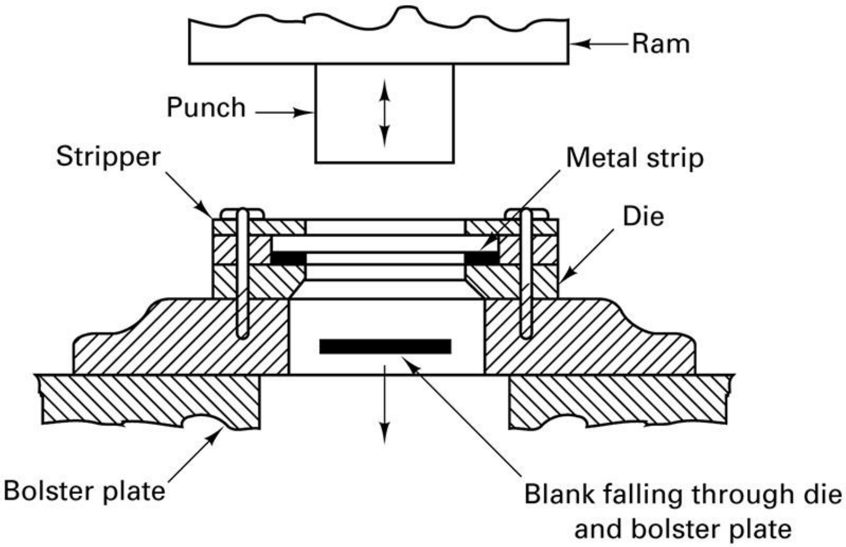


Figure 17-11 The basic components of piercing and blanking dies.

Blanking Operations

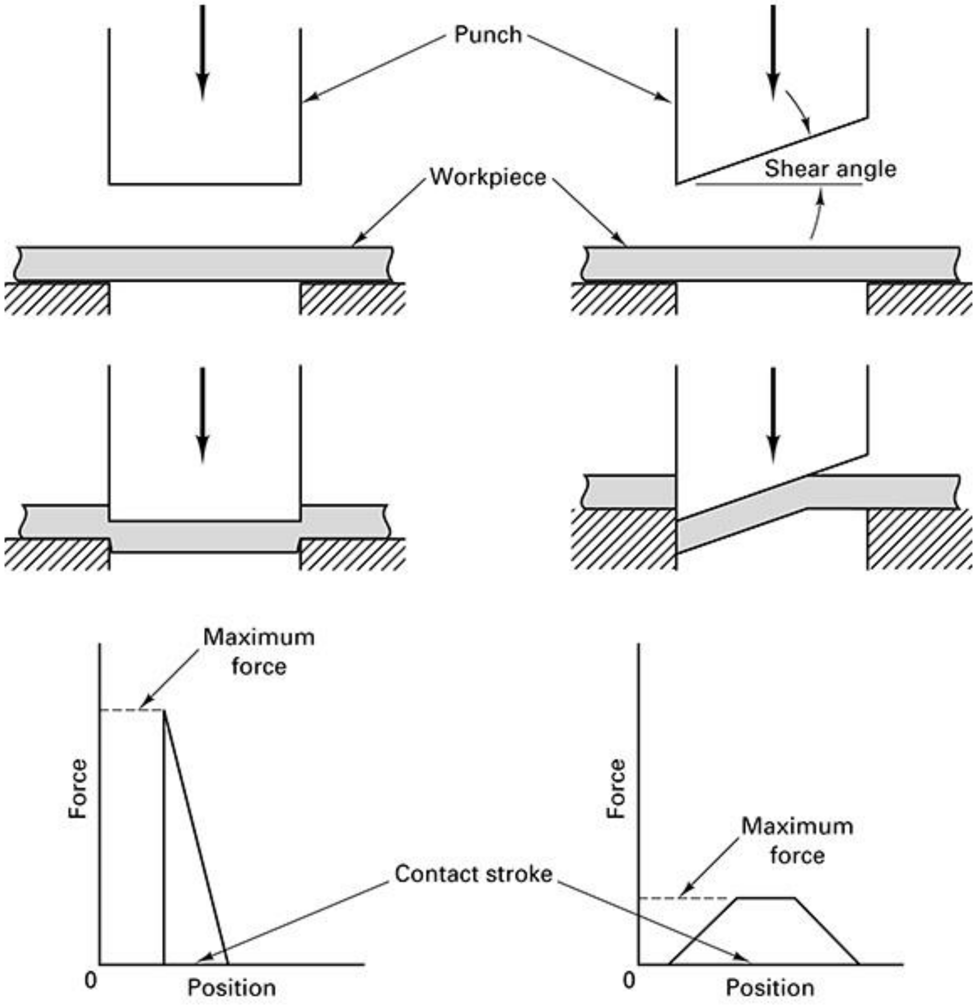


Figure 17-12 Blanking with a square-faced punch (left) and one containing angular shear (right). Note the difference in maximum force and contact stroke. The total work (the are under the curve) is the same for both processes.

Blanking Operations

Figure 17-13 (Below) Typical die set having two alignment guideposts. (*Courtesy of Danly IEM, Cleveland, OH.)*

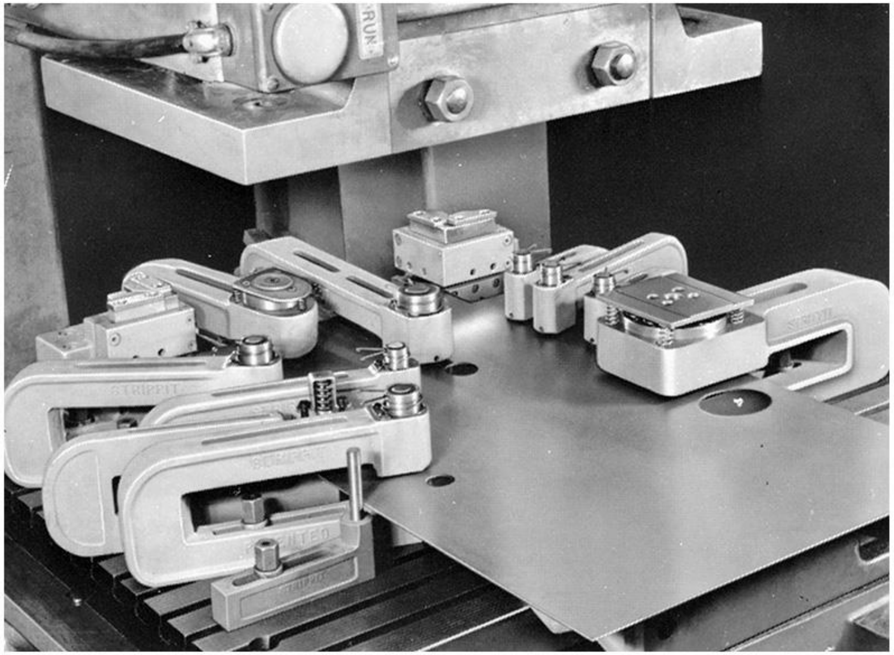


Figure 17-14 (Above) A piercing and blanking setup using self-contained subpress tool units. (*Courtesy of Strippit Division, Houdaille Industries, Inc., Akron, NY.)*

Progressive Die Sets

- Progressive die sets- two or more sets of punches and dies mounted in tandem
- Transfer dies move individual parts from operation to operation within a single press
- Compound dies combine processes sequentially during a single stroke of the ram

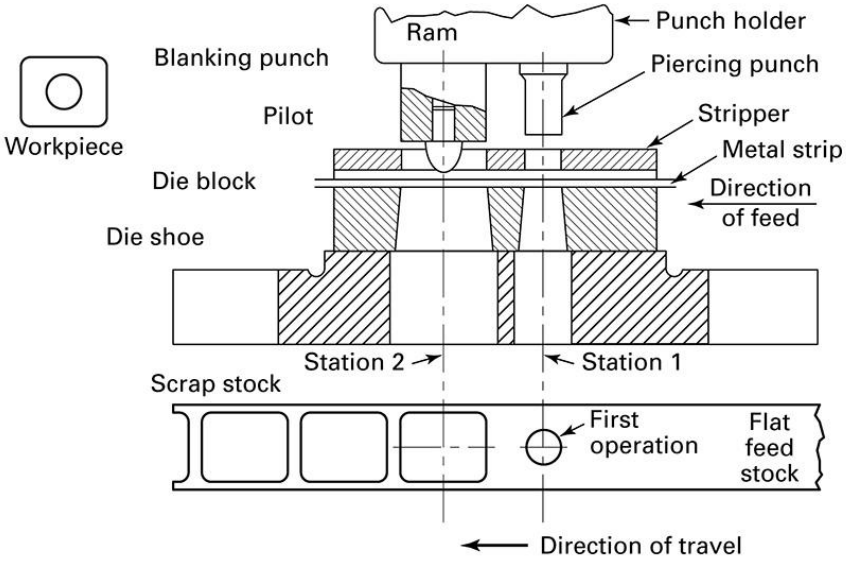


Figure 17-16 Progressive piercing and blanking die for making a square washer. Note that the punches are of different length.

Design Example

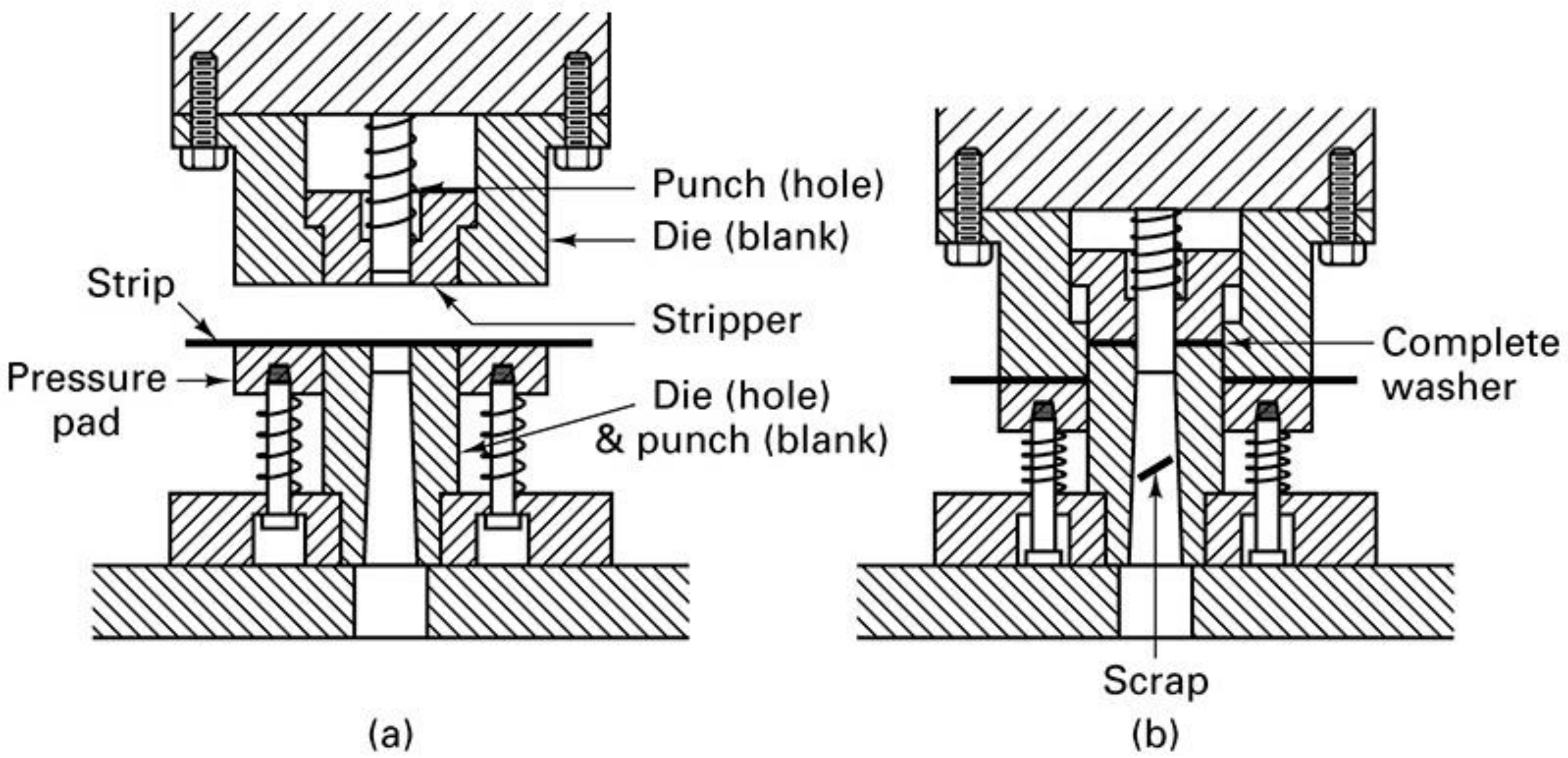


Figure 17-18 Method for making a simple washer in a compound piercing and blanking die. Part is blanked (a) and subsequently pierced (b) in the same stroke. The blanking punch contains the die for piercing.

Design for Piercing and Blanking

- Design rules
  - Diameters of pierced holes should not be less than the thickness of the metal
  - Minimum distance between holes or the edge of the stock should be at least equal to the metal thickness
  - The width of any projection or slot should be at least 1times the metal thickness
  - Keep tolerances as large as possible
  - Arrange the pattern of parts on the strip to minimize scrap

17.3 Bending

- Bending is the plastic deformation of metals about a linear axis with little or no change in the surface area
- Forming- multiple bends are made with a single die
- Drawing and stretching- axes of deformation are not linear or are not independent
- Springback is the “unbending” that occurs after a metal has been deformed

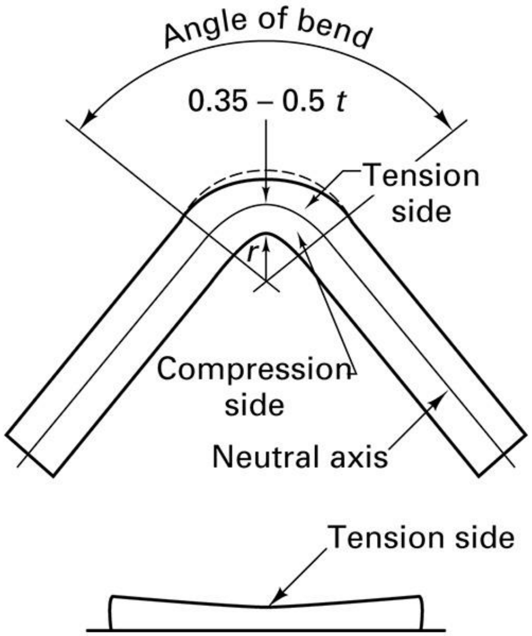


Figure 17-19 (Top) Nature of a bend in sheet metal showing tension on the outside and compression on the inside. (Bottom) The upper portion of the bend region, viewed from the side, shows how the center portion will thin more than the edges.

Angle Bending (Bar Folder and Press Brake)

- Bar folders make angle bends up to 150 degrees in sheet metal
- Press brakes make bends in heavier sheets or more complex bends in thin material

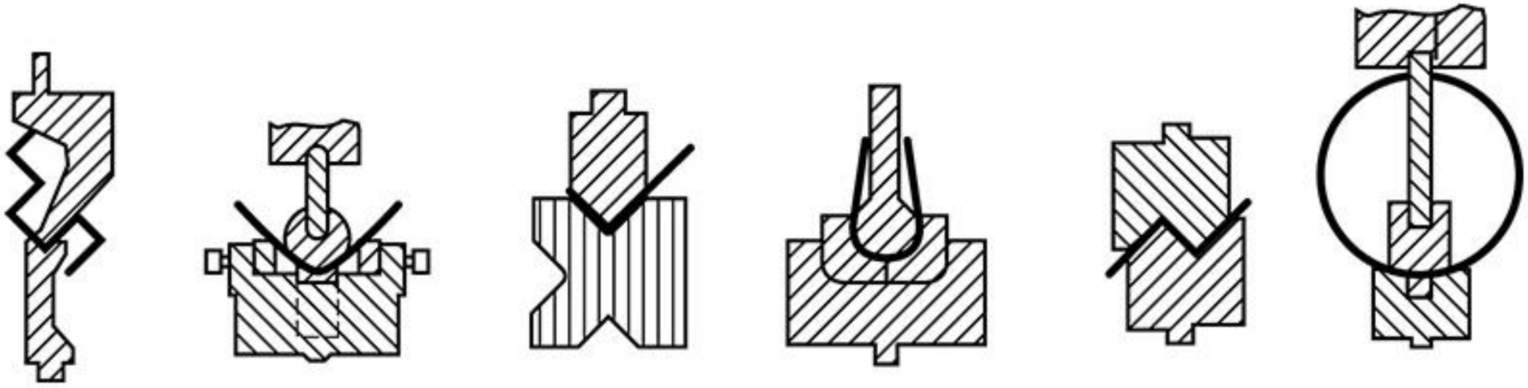


Figure 17-22 Press brake dies can form a variety of angles and contours. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

Bar Folder

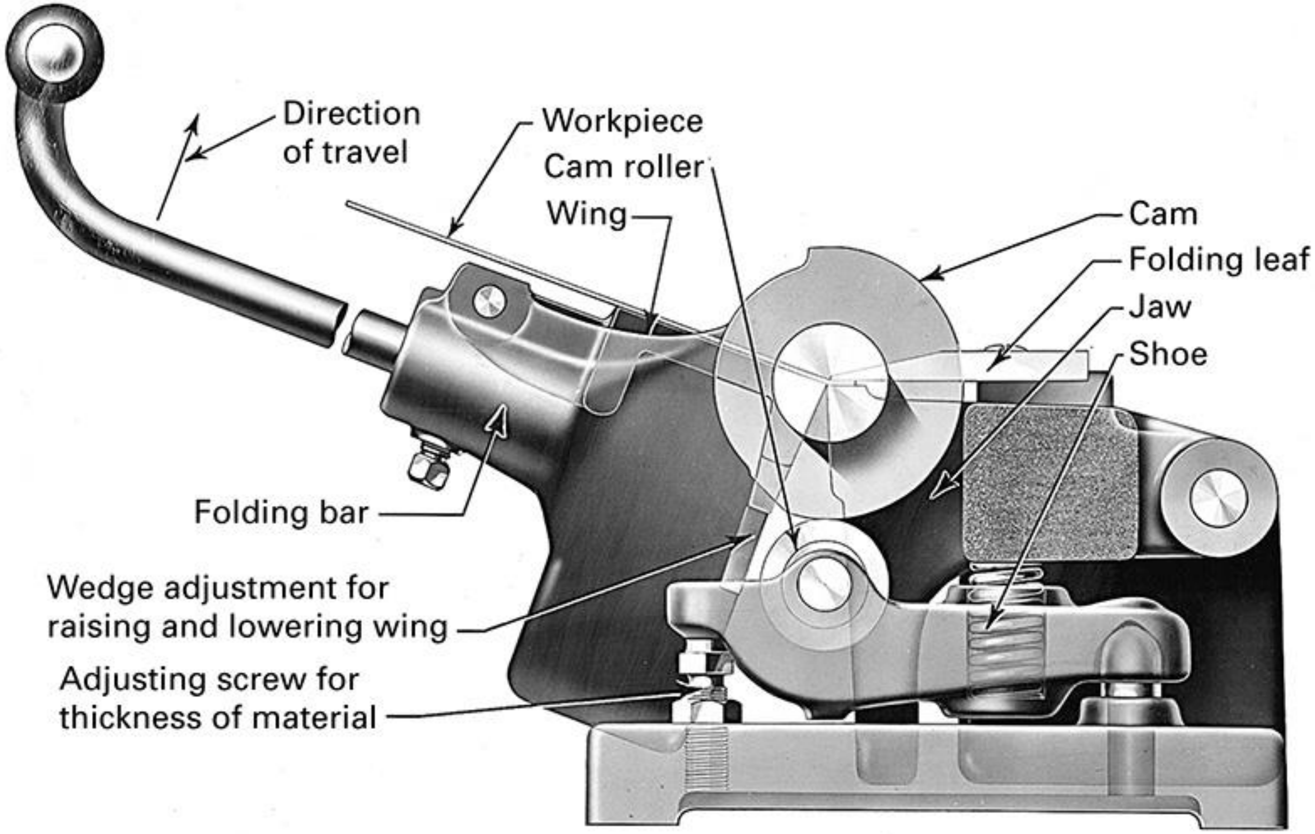


Figure 17-20 Phantom section of a bar folder, showing position and operation of internal components. (*Courtesy of Niagara Machine and Tool Works, Buffalo, N.Y.)*

Press Brake

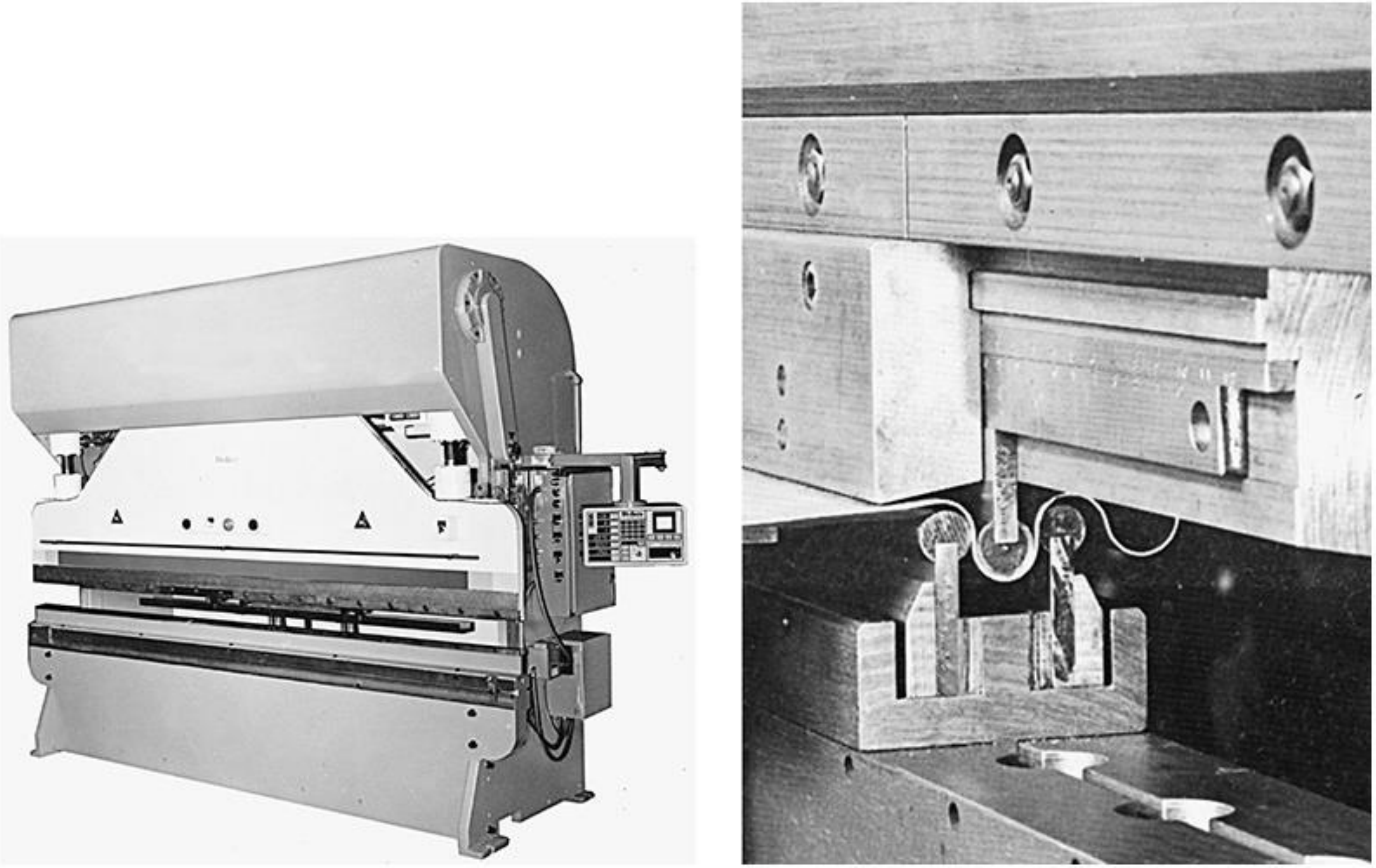


Figure 17-21 (Left) Press brake with CNC gauging system. (*Courtesy of DiAcro Division, Acrotech Inc., Lake City, MN.)* (Right) Close-up view of press brake dies forming corrugations. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

Design for Bending

- Several factors are important in specifying a bending operation
    - Determine the smallest bend radius that can be formed without cracking the metal
    - Metal ductility
    - Thickness of material

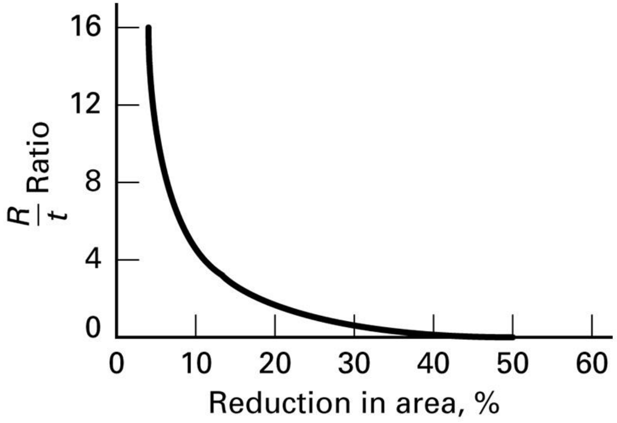


Figure 17-24 Relationship between the minimum bend radius (relative to thickness) and the ductility of the metal being bent (as measured by the reduction in area in a uniaxial tensile test).

Considerations for Bending

- If the punch radius is large and the bend angle is shallow, large amounts of springback are often encountered
- The sharper the bend, the more likely the surfaces will be stressed beyond the yield point

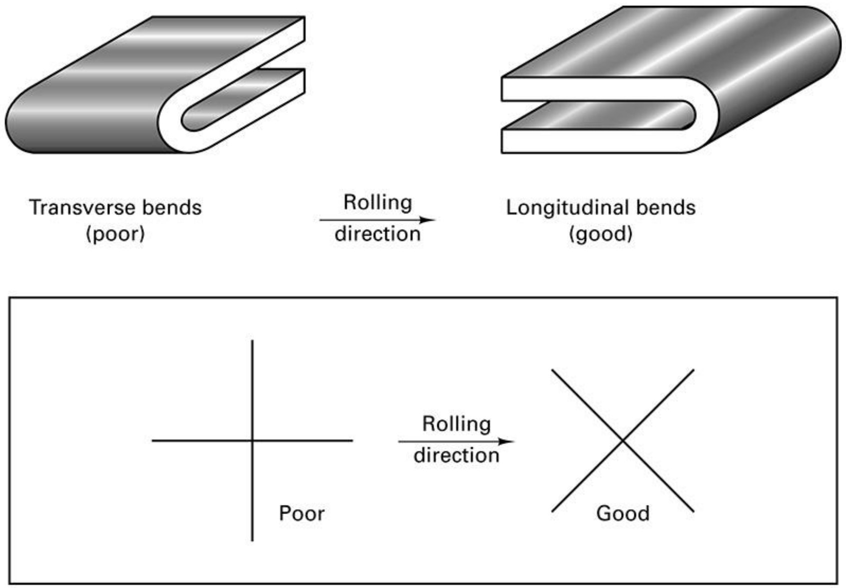
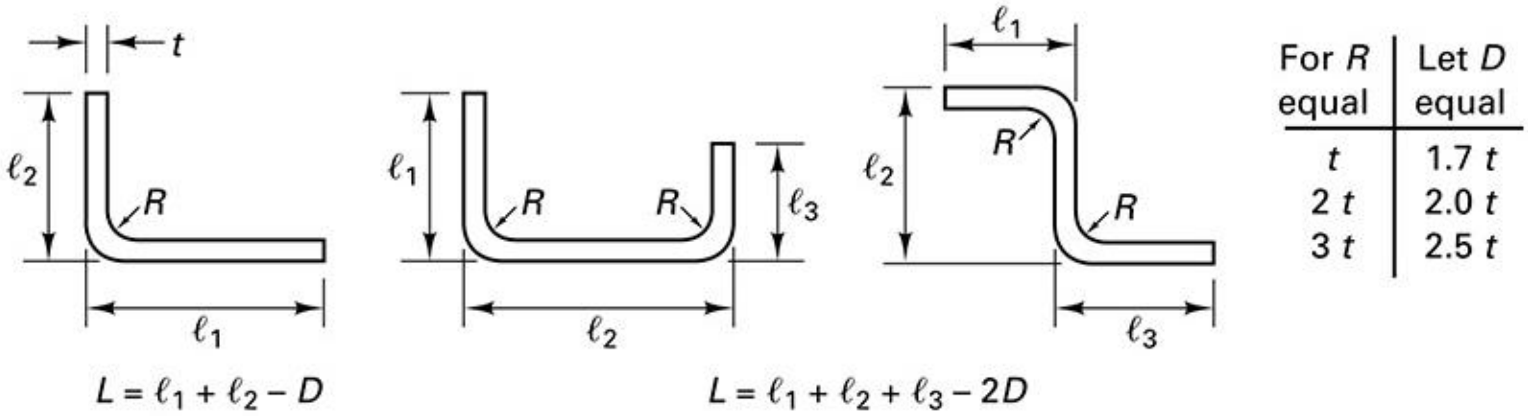


Figure 17-25 Bends should be made with the bend axis perpendicular to the rolling direction. When intersecting bends are made, both should be at an angle to the rolling direction, as shown.

Design Considerations

- Determine the dimensions of a flat blank that will produce a bent part of the desired precision
- Metal tends to thin when it is bent



$L = \ell_1 + \ell_2 - D$

$L = \ell_1 + \ell_2 + \ell_3 - 2D$

For *R* equal	Let *D* equal
t	1.7 *t*
2 *t*	2.0 *t*
3 *t*	2.5 *t*

Figure 17-26 One method of determining the starting blank size (*L*) for several bending operations. Due to thinning, the product will lengthen during forming. l_1, l_2, and l_3 are the desired product dimensions. See table to determine *D* based on size of radius *R* where t is the stock thickness.

Air-Bend, Bottoming, and Coining Dies

- Bottoming dies contact and compress the full area within the tooling
  - Angle of the bend is set by the geometry of the tooling
- Air bend dies produce the desired geometry by simple three-point bending
- If bottoming dies go beyond the full-contact position, the operation is similar to coining

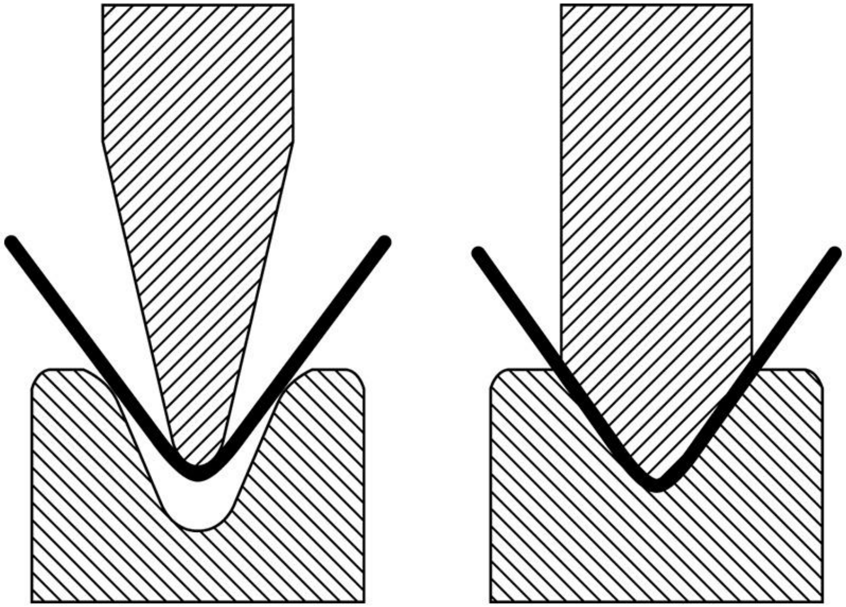


Figure 17-27 Comparison of air-bend (left) and bottoming (right) press brake dies. With the air-bend die, the amount of bend is controlled by the bottoming position of the upper die.

Roll Bending

- Roll bending is a continuous form of three-point bending
  - Plates, sheets, beams, pipes

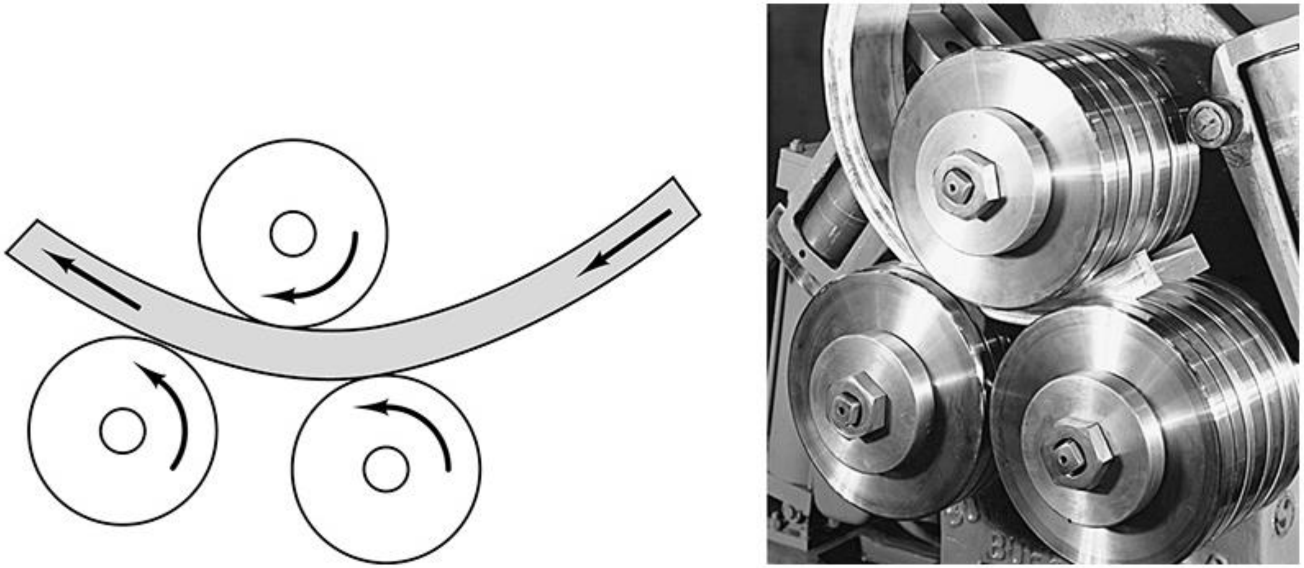


Figure 17-28 (Left) Schematic of the roll-bending process; (right) the roll bending of an I-beam section. Note how the material is continuously subjected to three-point bending. *(Courtesy of Buffalo Forge Company, Buffalo, NY.)*

Draw Bending, Compression Bending, and Press Bending

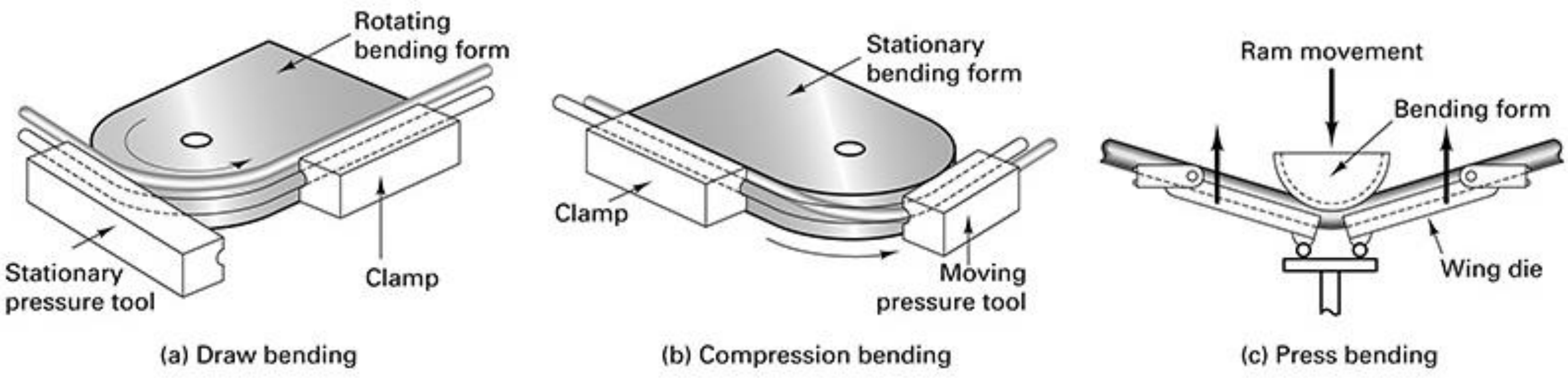


Figure 17-29 (a) Draw bending, in which the form block rotates; (b) compression bending, in which a moving tool compresses the workpiece against a stationary form; (c) press bending, where the press ram moves the bending form.

Tube Bending

- Key parameters: outer diameter of the tube, wall thickness, and radius of the bend

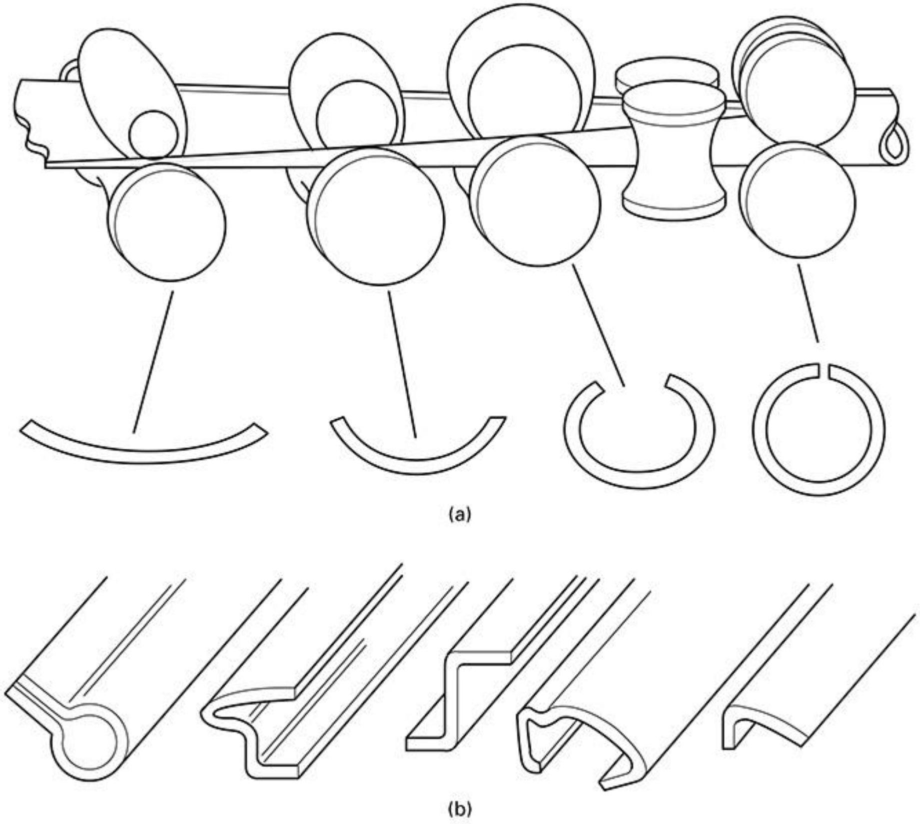


Figure 17-30 (a) Schematic representation of the cold roll-forming process being used to convert sheet or plate into tube. (b) Some typical shapes produced by roll forming.

Roll Forming

- Roll forming is a process by which a metal strip is progressively bent as it passes through a series of forming rolls
- Only bending takes place during this process, and all bends are parallel to one another
- A wide variety of shapes can be produced, but changeover, setup, and adjustment may take several hours

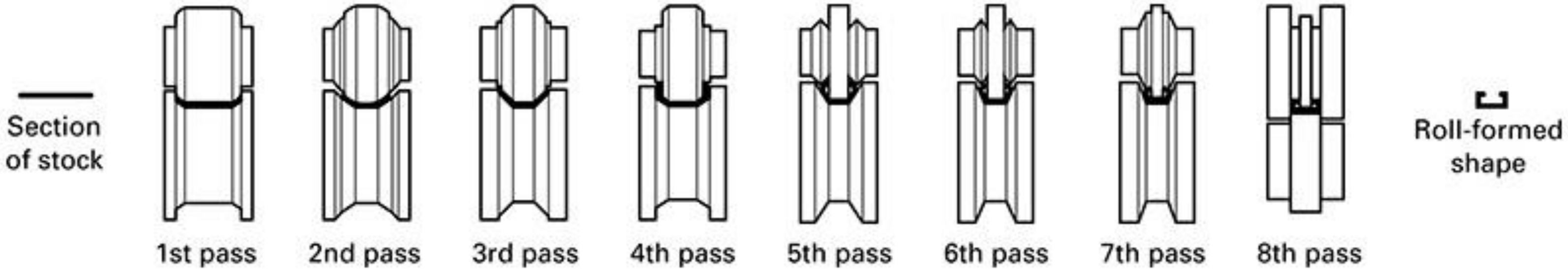


Figure 17-31 Eight-roll sequence for the roll forming of a box channel. (*Courtesy of the Aluminum Association, Washington, DC.)*

Seaming and Flanging

- Seaming is a bending operation that can be used to join the ends of sheet metal in some form of mechanical interlock
- Common products include cans, pails, drums, and containers
- Flanges can be rolled on sheet metal in a similar manner as seams

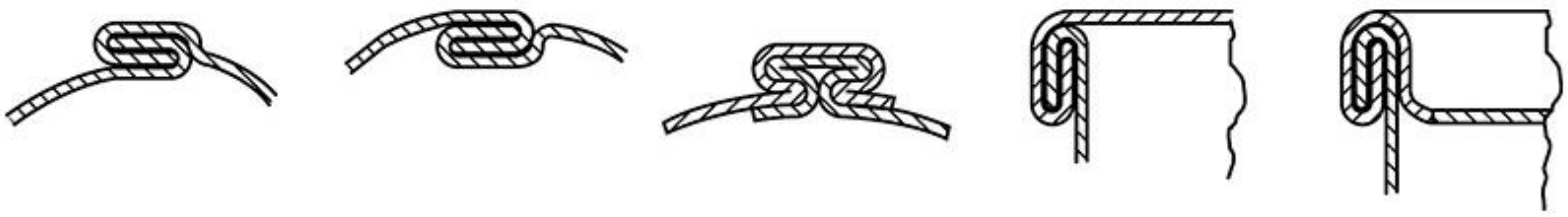


Figure 17-31 Various types of seams used on sheet metal.

Straightening

- Straightening or flattening is the opposite of bending
- Done before subsequent forming to ensure the use of flat or straight material
- Various methods to straighten material
  - Roll straightening (Roller levering)
  - Stretcher leveling- material is mechanically gripped and stretch until it reaches the desired flatness

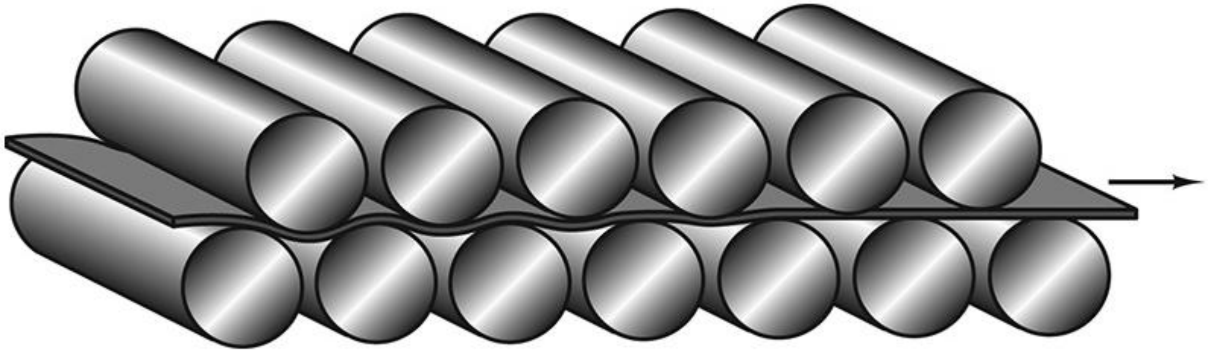


Figure 17-33 Method of straightening rod or sheet by passing it through a set of straightening rolls. For rods, another set of rolls is used to provide straightening in the transverse direction.

17.4 Drawing and Stretching Processes

- Drawing refers to the family of operations where plastic flow occurs over a curved axis and the flat sheet is formed into a three-dimensional part
- Spinning is a cold forming operation
  - Sheet metal is rotated and shaped over a male form, or mandrel
  - Produces rotationally symmetrical shapes
    - Spheres, hemispheres, cylinders, bells, and parabolas

Spinning

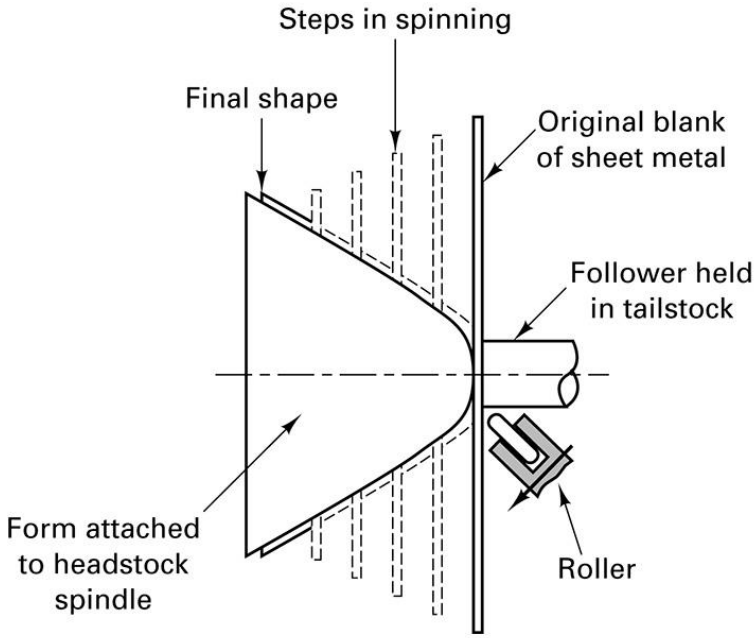


Figure 17-35 (Below) Two stages in the spinning of a metal reflector. (*Courtesy of Spincraft, Inc. New Berlin, WI.)*

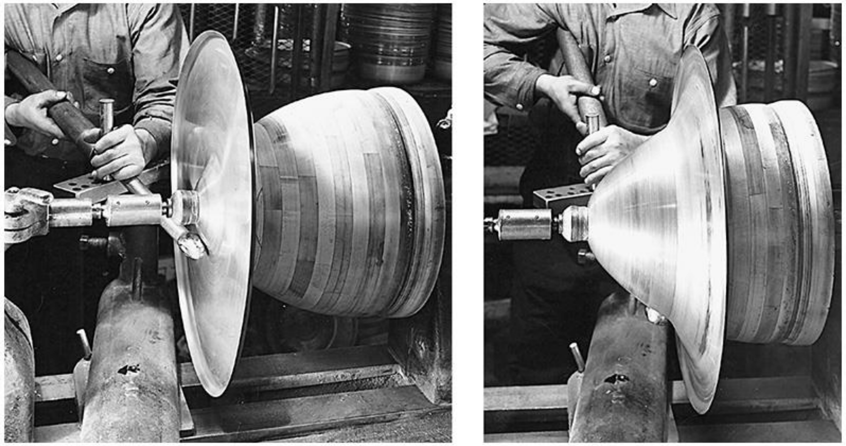


Figure 17-34 (Above) Progressive stages in the spinning of a sheet metal product.

Shear Forming and Stretch Forming

- Shear forming is a version of spinning
- In sheet forming a sheet of is gripped and a form block shapes the parts

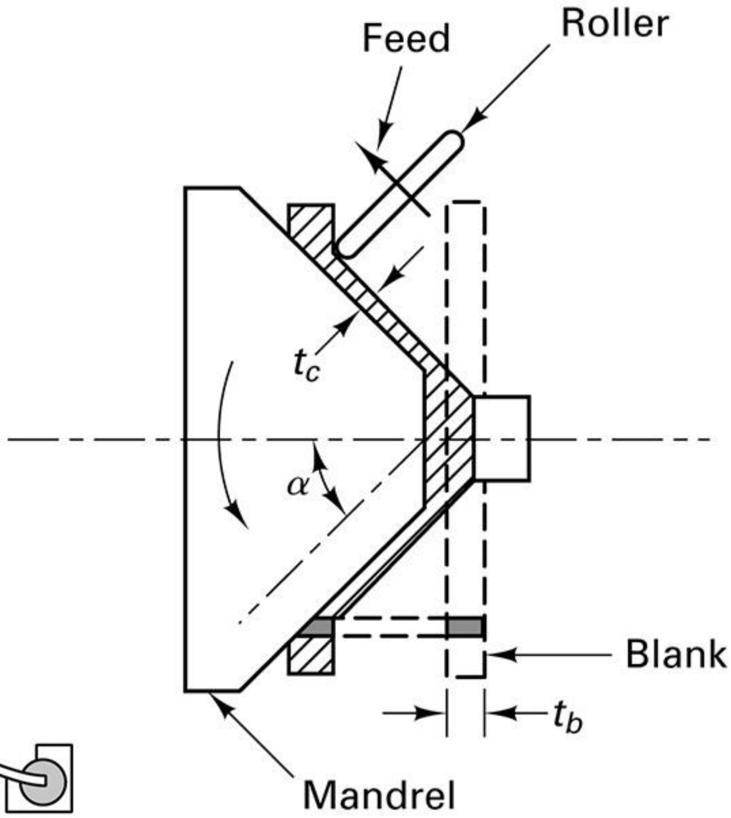


Figure 17-36 Schematic representation of the basic shear-forming process.

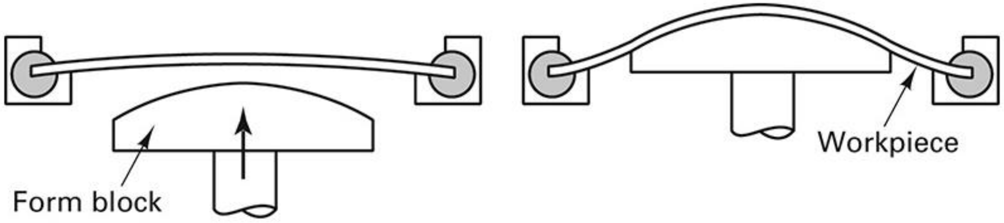


Figure 17-39 Schematic of a stretch-forming operation.

Deep Drawing and Shallow Drawing

- Deep drawing is typically used to form solid-bottom cylindrical or rectangular containers from sheet metal
- Key variables:
  - Blank and punch diameter
  - Punch and die radius
  - Clearance
  - Thickness of the blank
  - Lubrication
  - Hold-down pressure

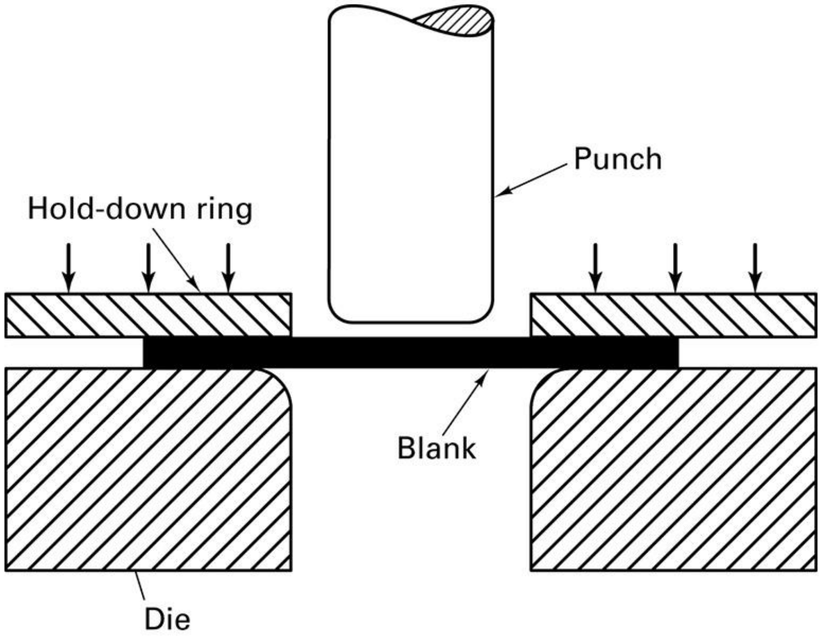


Figure 17-40 Schematic of the deep-drawing process.

Limitations of Deep Drawing

- Wrinkling and tearing are typical limits to drawing operations
- Different techniques can be used to overcome these limitations
  - Draw beads
  - Vertical projections and matching grooves in the die and blankholder
- Trimming may be used to reach final dimensions

Forming with Rubber Tooling or Fluid Pressure

- Blanking and drawing operations usually require mating male and female die sets
- Processes have been developed that seek to
  - Reduce tooling cost
  - Decrease setup time and expense
  - Extend the amount of deformation for a single set of tools

Alternative Forming Operations

- Several forming operations replace one of the dies with rubber or fluid pressure
  - Guerin process
- Other forming operations use fluid or rubber to transmit the pressure required to expand a metal blank
  - Bulging

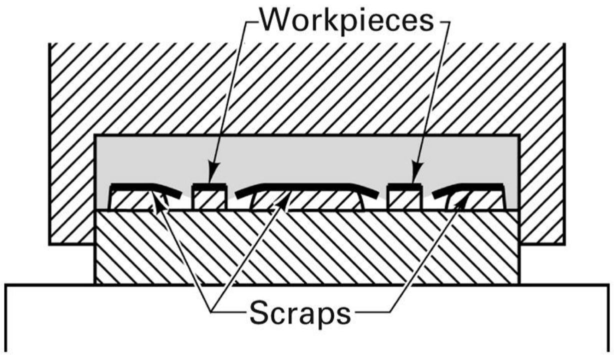


Figure 17-47 Method of blanking sheet metal using the Guerin process.

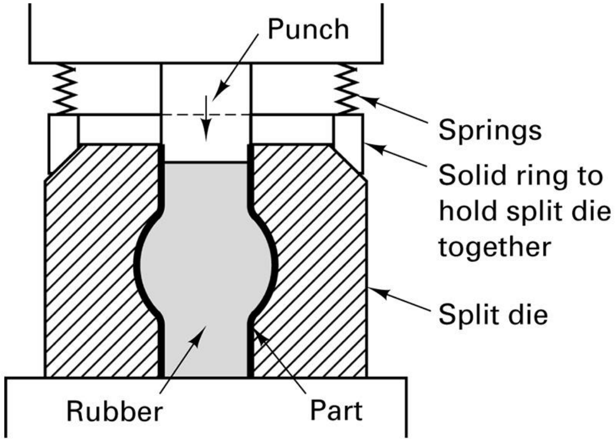


Figure 17-48 Method of bulging tubes with rubber tooling.

Sheet Hydroforming

- Sheet hydroforming is a family of processes in which a rubber bladder backed by fluid pressure replaces either the solid punch or female die set
- Advantages
  - Reduced cost of tooling
  - Deeper parts can be formed without fracture
  - Excellent surface finish
  - Accurate part dimensions

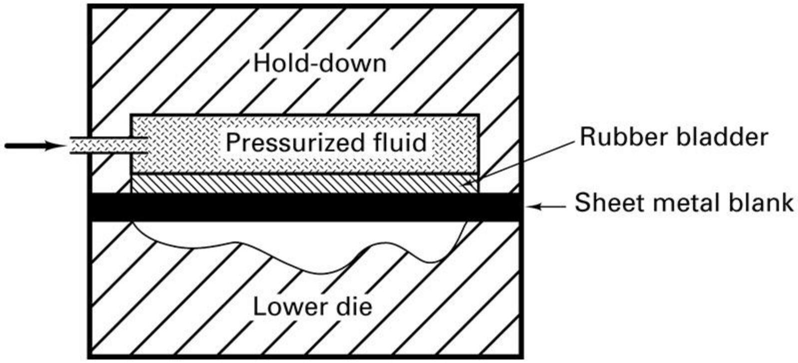


Figure 17-50 (Above) One form of sheet hydroforming.

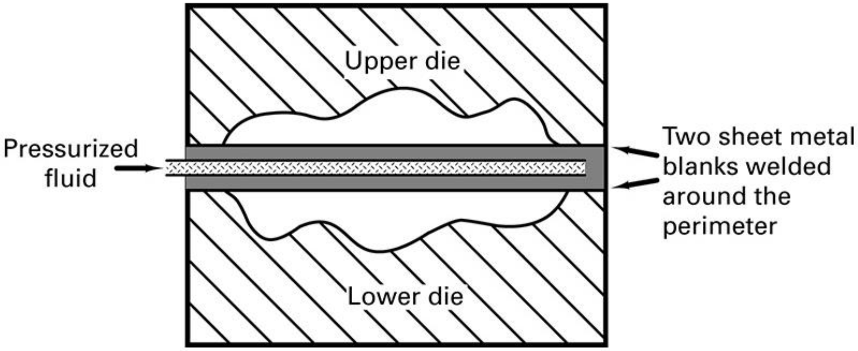


Figure 17-51 Two-sheet hydroforming, or pillow forming.

Tube Hydroforming

- Process for manufacturing strong, lightweight, tubular components
- Frequently used process for automotive industry
- Advantages
  - Lightweight, high-strength materials
  - Designs with varying thickness or varying cross section can be made
  - Welded assemblies can be replaced by one-piece components
- Disadvantages
  - Long cycle time
  - Relatively high tooling cost and process setup

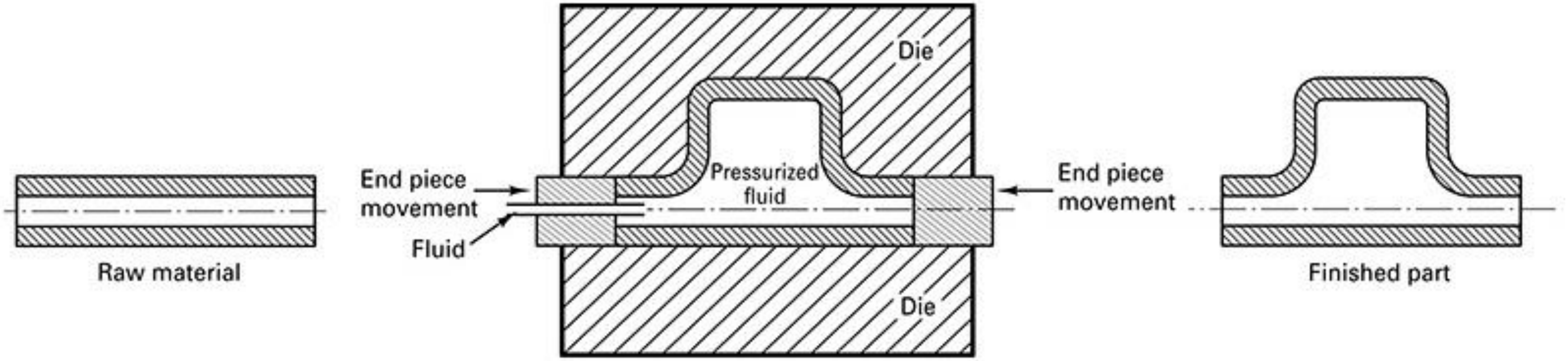


Figure 17-52 Tube hydroforming. (a) Process schematic.

Additional Drawing Operations

- Hot-drawing
  - Sheet metal has a large surface area and small thickness, so it cools rapidly
  - Most sheet forming is done at mildly elevated temperatures
- High-Energy Rate Forming
  - Large amounts of energy in a very short time
  - Underwater explosions, underwater spark discharge, pneumatic-mechanical means, internal combustion of gaseous mixtures, rapidly formed magnetic fields
- Ironing
  - Process that thins the walls of a drawn cylinder by passing it between a punch and a die

Additional Drawing Operations

- Embossing
  - Pressworking process in which raised lettering or other designs are impressed in sheet material
- Superplastic sheet forming
  - Materials that can elongate in the range of 2000 to 3000% can be used to form large, complex-shaped parts
  - Superplastic forming techniques are similar to that of thermoplastics

Properties of Sheet Material

- Tensile strength of the material is important in determining which forming operations are appropriate
- Sheet metal is often anisotropic- properties vary with direction or orientation
- Majority of failures during forming occur due to thinning or fracture
- Strain analysis can be used to determine the best orientation for forming

17.5 Alternative Methods of Producing Sheet-Type Products

- Electroforming
  - Directly deposits metal onto preshaped forms or mandrels
  - Nickel, iron, copper, or silver can used
  - A wide variety of sizes and shapes can be made by electroforming
- Spray forming
  - Spray deposition
  - Uses powdered material in a plasma torch
  - Molten metal may also be sprayed

17.6 Pipe Welding

- Skelp is long strips of steel used in welding
- Butt-welded pipe
  - Steel skelp is heated to a specified hot-working temperature
  - The skelp rolls back on each other through rollers and produces a welded seam
- Lap-welded pipe
  - Skelp has beveled edges and the rolls form the weld by forcing the lapped edges down

17.7 Presses

TABLE 17-2 Classification of the Drive Mechanisms of Commercial Presses

Manual	Mechanical	Hydraulic
Kick presses	Crank	Single slide
	Single	Multiple slide
	Double	
	Eccentric	
	Cam	
	Knuckle joint	
	Toggle	
	Screw	
	Rack and pinion	

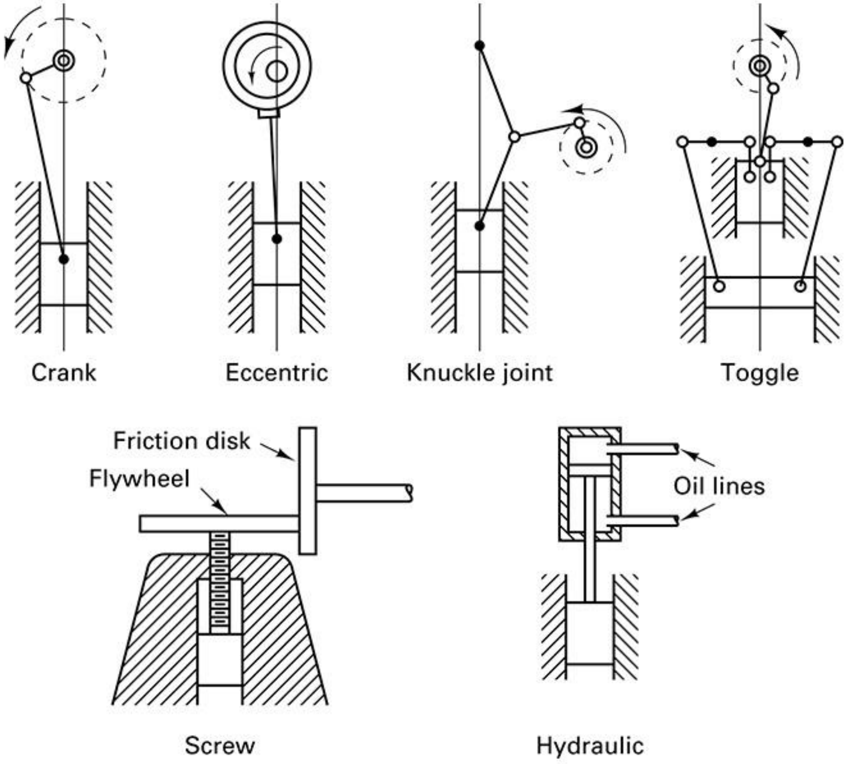


Figure 17-58 Schematic representation of the various types of press drive mechanisms.

Types of Press Frame

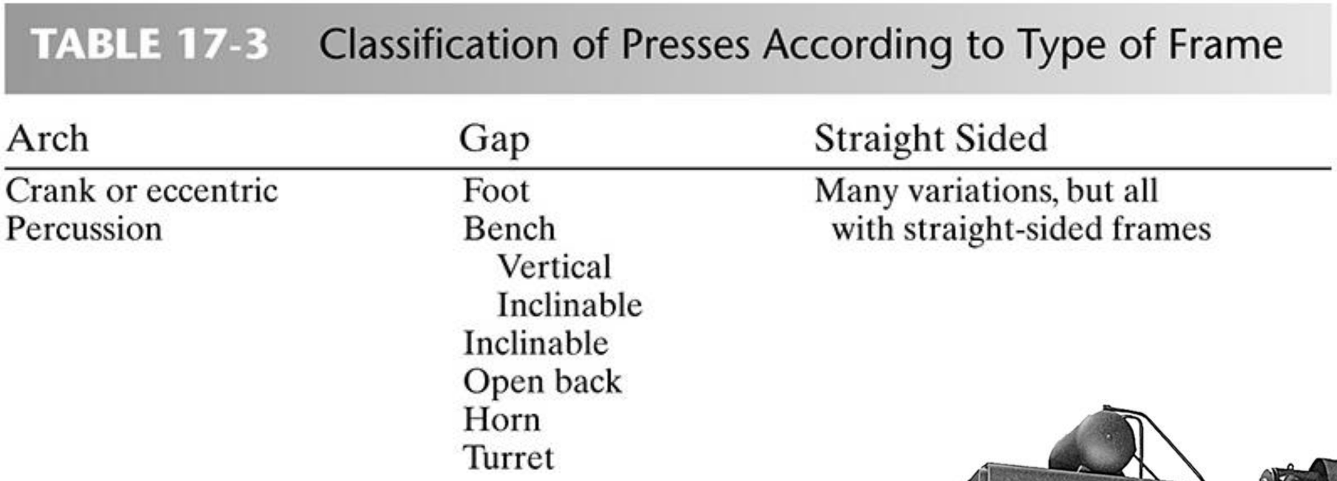


TABLE 17-3 Classification of Presses According to Type of Frame

Arch	Gap	Straight Sided
Crank or eccentric	Foot	Many variations, but all with straight-sided frames
Percussion	Bench	
	Vertical	
	Inclinable	
	Inclinable	
	Open back	
	Horn	
	Turret	

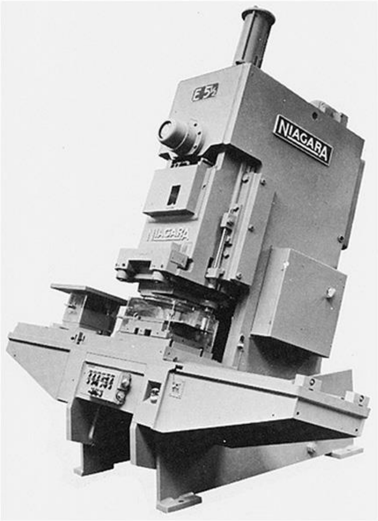


Figure 17-60 (Left) Inclinable gap-frame press with sliding bolster to accommodate two die sets for rapid change of tooling. (*Courtesy of Niagara Machine & Tool Works, Buffalo, NY.)*

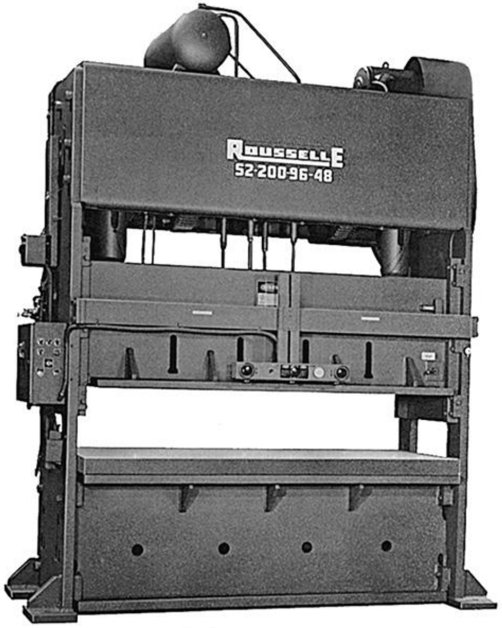


Figure 17-61 (Right) A 200-ton (1800-kN) straight-sided press. (*Courtesy of Rousselle Corporation, West Chicago, IL.)*

Special Types of Presses

- Presses have been designed to perform specific types of operations
- Transfer presses have a long moving slide that enables multiple operations to be performed simultaneously in a single machine
- Four-slide or multislide machines are used to produce small, intricately shaped parts from continuously fed wire or coil strip

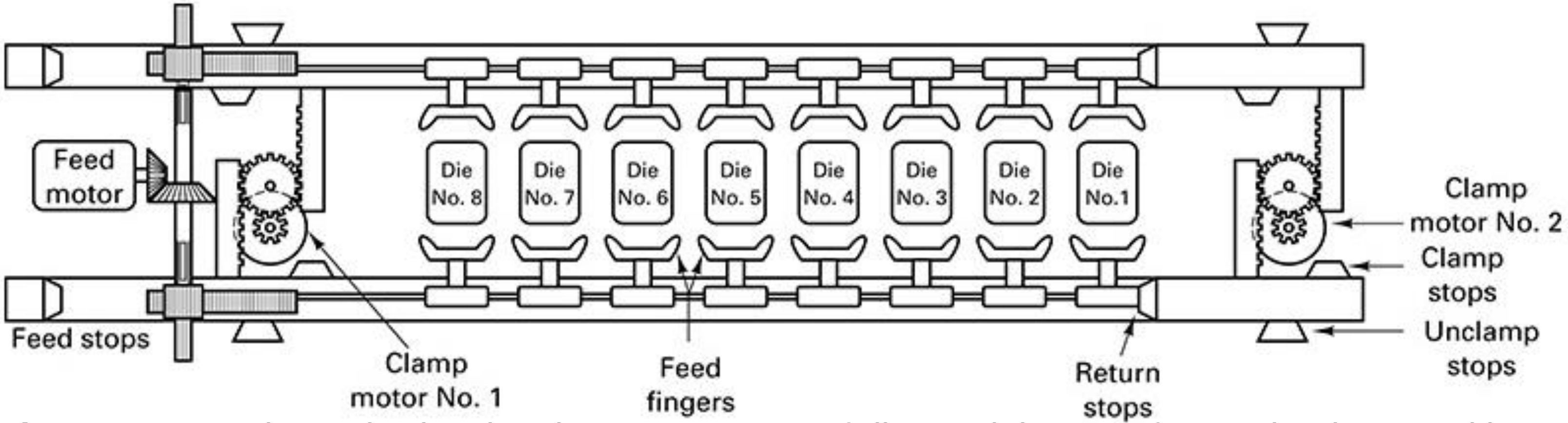


Figure 17-62 Schematic showing the arrangement of dies and the transfer mechanism used in transfer presses. (*Courtesy of Verson Allsteel Press Company, Chicago, IL.)*

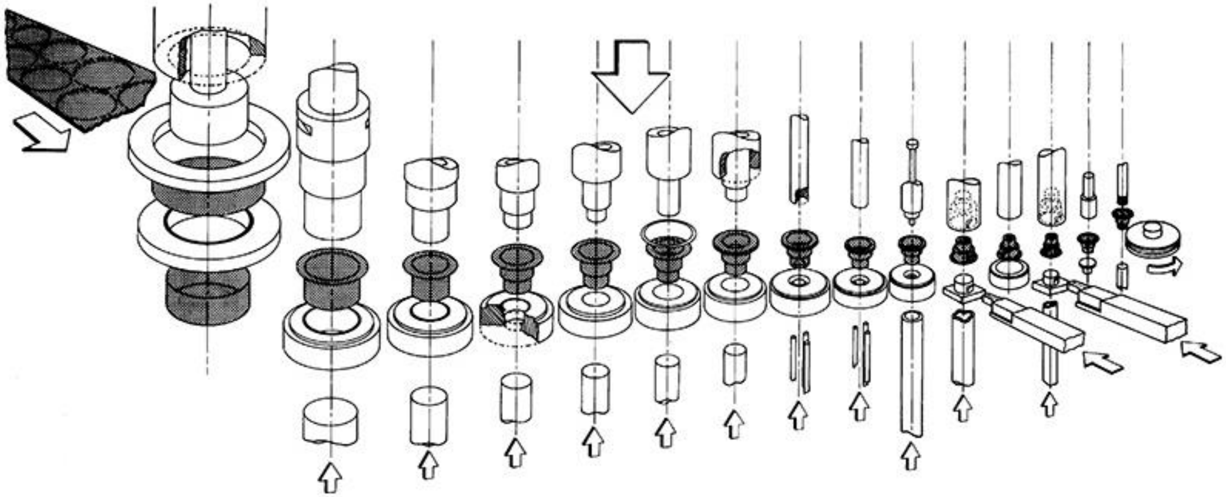


Figure 17-63 Various operations can be performed during the production of stamped and drawn parts on a transfer press. (Courtesy of U.S. Baird Corporation, Stratford, CT.)

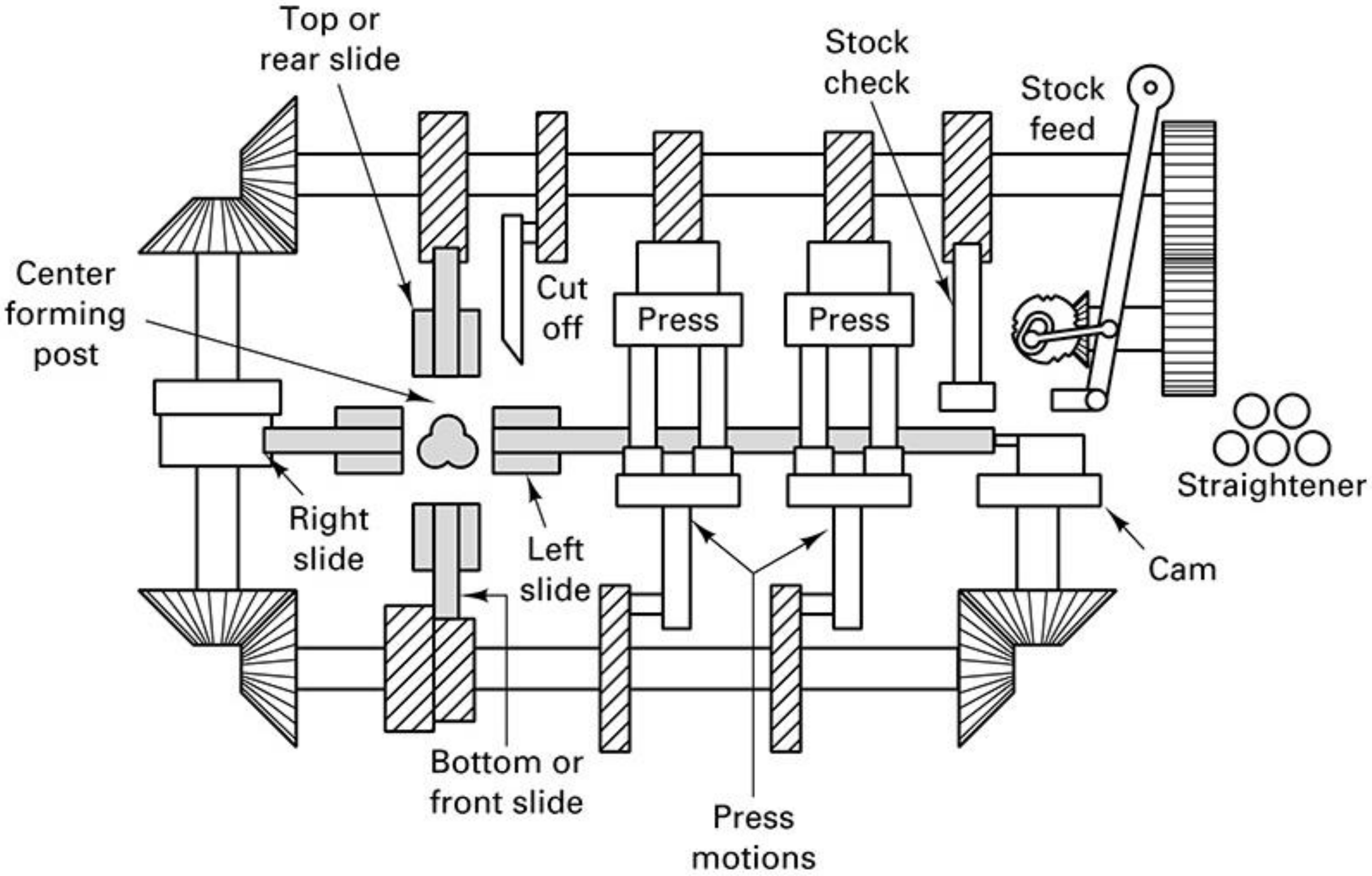


Figure 17-65 Schematic of the operating mechanism of a multislide machine. The material enters on the right and progresses toward the left as operations are performed. (*Courtesy of U.S. Baird Corporation, Stratford, CT.)*

Summary

- Sheet forming processes can be grouped in several broad categories
    - Shearing
    - Bending
    - Drawing
    - Forming
- Basic sheet forming operations involve a press, punch, or ram and a set of dies
- Material properties, geometry of the starting material, and the geometry of the desired final product play important roles in determining the best process

Chapter 20:
Fabrication of Plastics, Ceramics, and Composites

DeGarmo’s Materials and Processes in Manufacturing

8.2 Plastics

- Plastics are engineered materials
  - Large molecules that are composed of smaller molecules
  - Made from natural or synthetic resins and compounds
  - Can be molded, extruded, cast, or used for coatings
  - Low density, low tooling costs, good corrosion resistance, low cost
  - Plastics are very versatile materials and are used more than steel, aluminum, and copper combined in the United States
  - Used in applications such as cars, artificial organs, shower curtains, contact lenses, computers, etc.

Polymer Structure

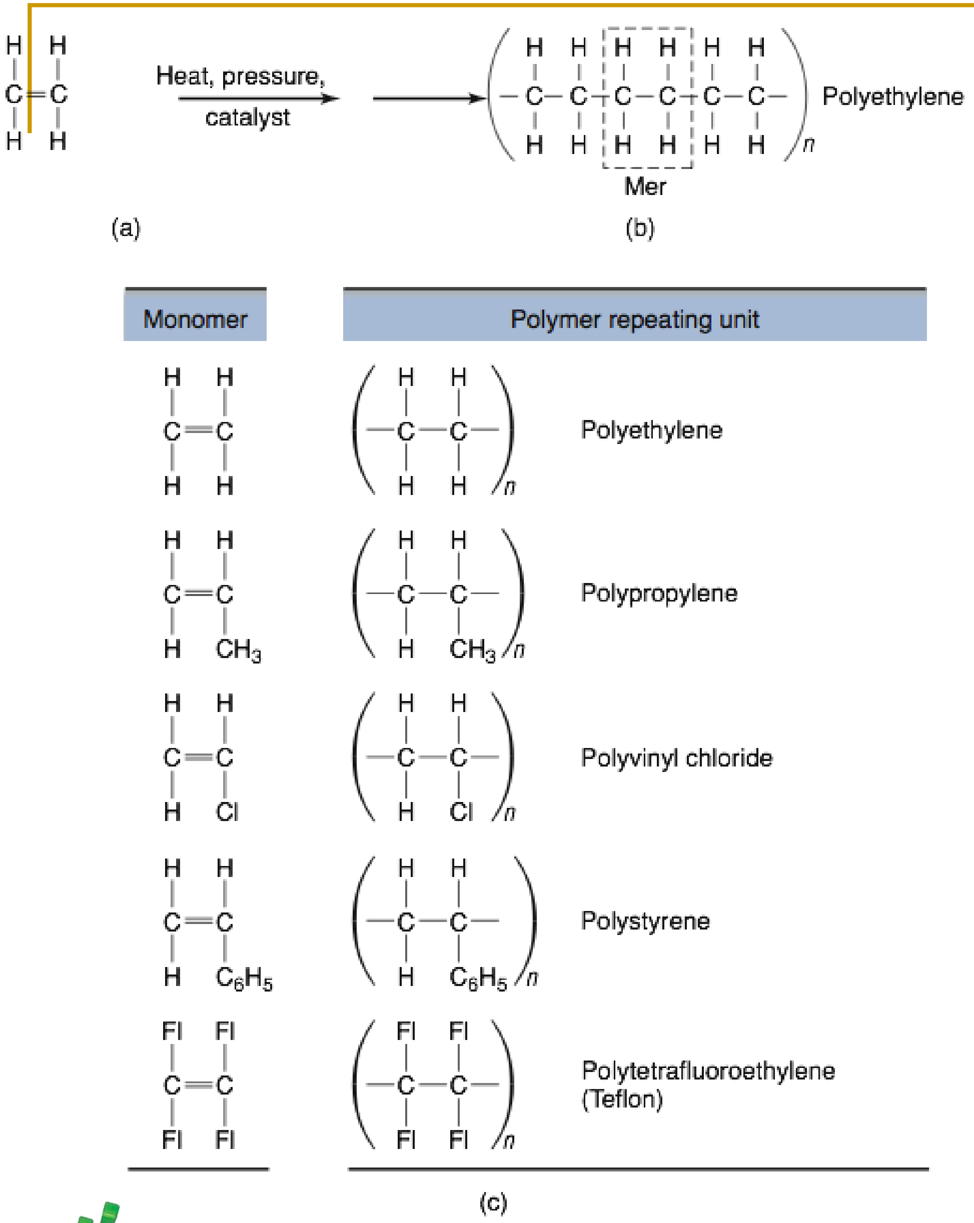
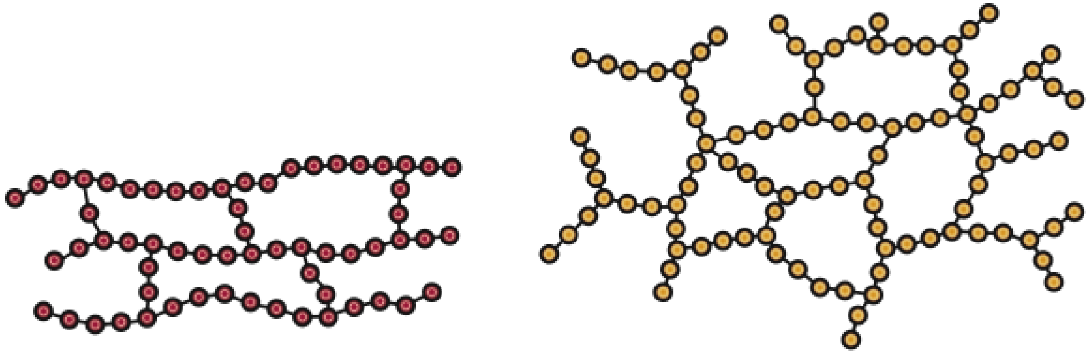


FIGURE 10.1 Basic structure of some polymer molecules: (a) ethylene molecule; (b) polyethylene, a linear chain of many ethylene molecules; (c) molecular structure of various polymers. These molecules are examples of the basic building blocks for plastics.

Polymer Chains

(a) Linear

(b) Branched



(c) Cross-linked

(d) Network

FIGURE 10.3 Schematic illustration of polymer chains. (a) Linear structure; thermoplastics such as acrylics, nylons, polyethylene, and polyvinyl chloride have linear structures. (b) Branched structure, such as polyethylene. (c) Cross-linked structure; many rubbers and elastomers have this structure. Vulcanization of rubber produces this structure. (d) Network structure, which is basically highly cross-linked; examples include thermosetting plastics such as epoxies and phenolics.

14.1 Introduction

- Plastics, ceramics, and composites have different structure and properties than metals
- Principles of material selection and manufacturing are different
- Large, complex shapes can be formed as a single unit
- Processes can produce a near perfect shape and surface product

14.2 Fabrication of Plastics

- A successful plastic product is manufactured so that it satisfies the various mechanical and physical property requirements
- The preferred manufacturing method is determined by the desired size, shape, and quantity
- There are three main different types of polymers: thermoplastics, thermosets, and elastomers

Thermoplastics

- Contain molecules of different lengths
- Do not have a definite melting temperature
- Above the melting temperature, the material can be poured and cast
    - Additionally, injection molding
- Application of a force deforms the material both elastically and plastically
    - Plastic deformation occurs by adjacent fibers and chains slipping past one another

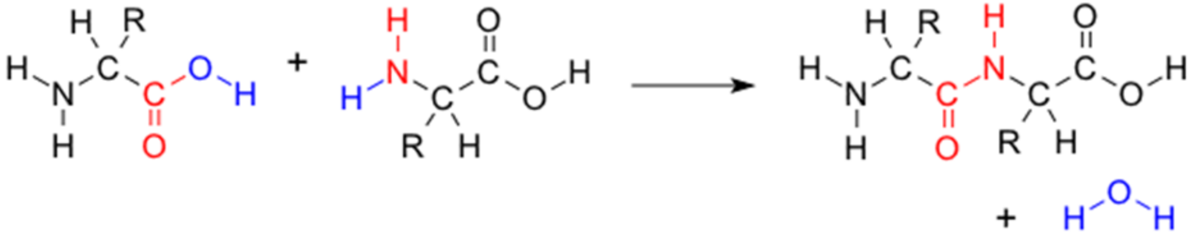
Thermoplastics

- If cooled below the melting temperature, thermoplastics crystallize
  - Polymer becomes stiffer, harder, less ductile, and more resistant to solvents and heat
- Common thermoplastics
  - Polyethylene (PE)
  - Polypropylene (PP)
  - Polystyrene (PS)
  - Polyvinyl Chloride (PVC)

Thermosets

- Highly cross-linked
- Three-dimensional framework connected by covalent bonds
- Typically produced by condensation polymerization
  - Elevated temperatures produce an irreversible reaction(Once polymerized cannot be formed again)
  - Once set, subsequent heating will not soften the material
  - Polymerization and forming occurs simultaneously

- **Condensation Mechanism:** Two molecules combine to form larger molecule with loss of smaller molecule



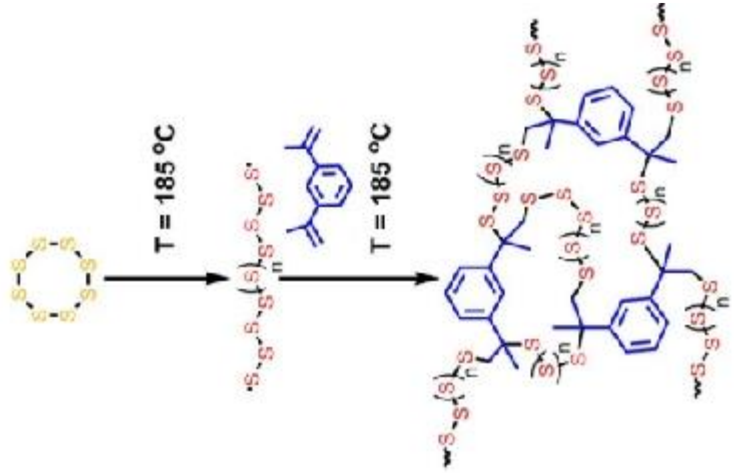
Thermosets

- Significantly stronger and more rigid than thermoplastics
- Able to resist higher temperatures
- Greater dimensional stability
- Lower ductility
- Poorer impact properties
- Heating changes their structure permanently
- The setting time is very important because it can not be repeated

8.3 Elastomers

- Linear polymers that have large amounts of plastic deformation
  - Return to their original shape when the load is removed
- Cross-linking restricts the viscous deformation; retains the elastic response
- Rubber
  - Natural and synthetic
  - Charles Goodyear discovered vulcanization
  - Natural rubbers have good flexibility, good electrical insulation, low internal friction, and resistance to most inorganic acids, salts, and alkalis
  - Poor resistance to oil, gasoline, and other petroleum products

Vulcanization (or vulcanisation) is a chemical process for converting natural rubber or related polymers into more durable materials via the addition of sulfur or other equivalent curatives or accelerators. These additives modify the polymer by forming cross-links (bridges) between individual polymer chains.



Artificial Elastomers

- Natural rubbers are expensive, so many artificial or synthetic rubbers have been developed
- Can be classified as thermoplastics or thermosets
- Thermosets are formed using vulcanization
- Thermoplastics are formed using injection molding, extrusion, blow molding, etc.

Casting

- Simplest of the shape-forming processes
- No fillers and no pressure is required
- Not all plastic can be cast
- Thermoplastics are the main type of polymer that can be casted
  - Acrylics, nylons, urethanes, and PVC plastisols
- Some thermosets can also be cast

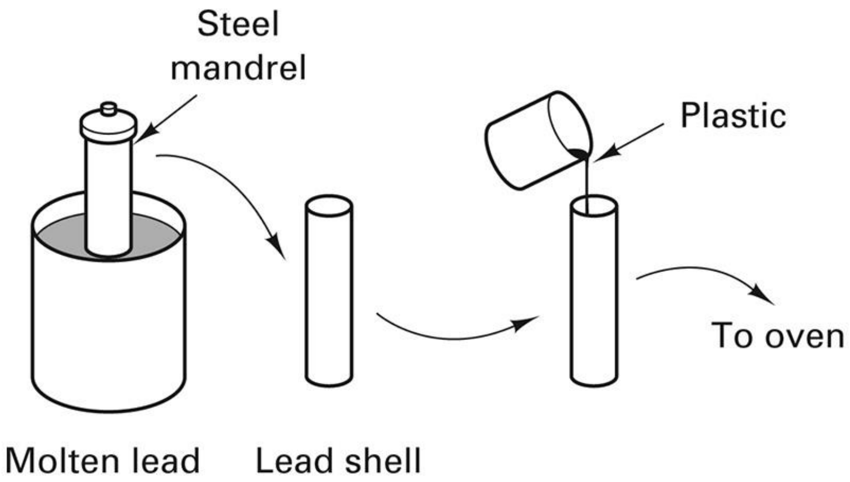
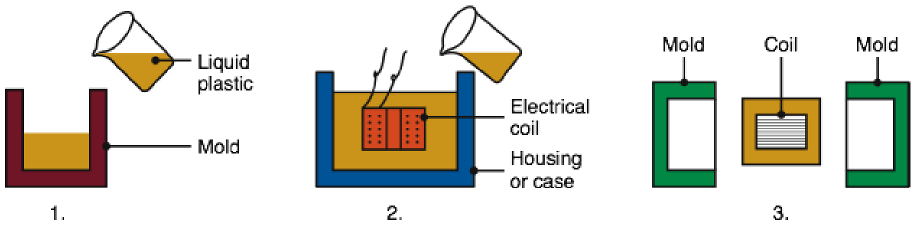


Figure 14-1 Steps in the casting of plastic parts using a lead shell mold.



Casting

- Liquid polymer is poured into container having the shape of the desired part.
- Sheets and tubing can be cast by the following methods:
  - between plates of glass
  - continuous products can be made by introducing the liquid polymer between moving belts of stainless steel, or into the gap of a rolling mill setup
  - tubular products can be made by spinning the liquid against the walls of a rotating mold

Blow Molding

- Thermoplastics can be converted to hollow-shape containers such as bottles
- The preform is heated and placed between the two mold halves
- The mold closes and the preform is expanded from air or gas pressure
- The mold is then cooled, halves separated, and the product is removed
- Flash, extra material, is trimmed from the part and recycled

Blow Molding

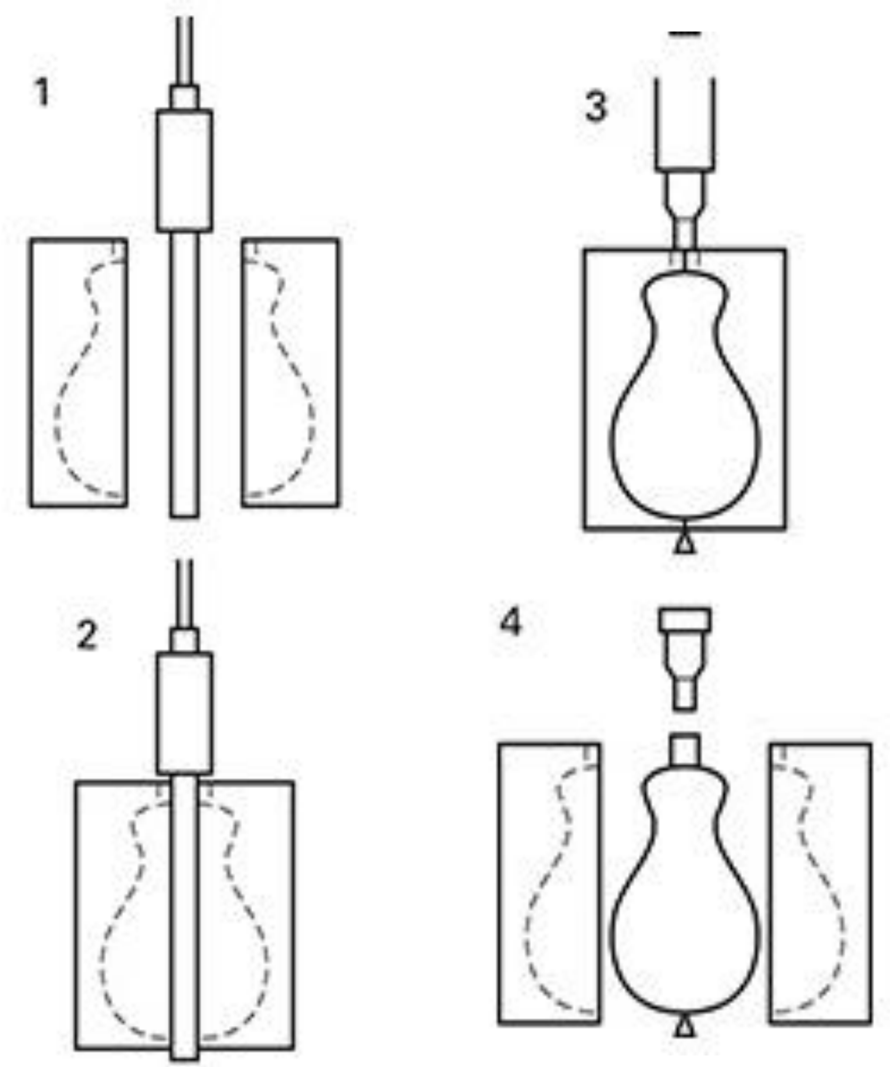


Figure 14-2 Steps in blow molding plastic parts: (1) a tube of heated plastic is placed in the open mold; (2) the mold closes over the tube, simultaneously sealing the bottom; (3) air expands the tube against the sides of the mold; and (4) after sufficient cooling, the mold opens to release the product.

Blow Molding

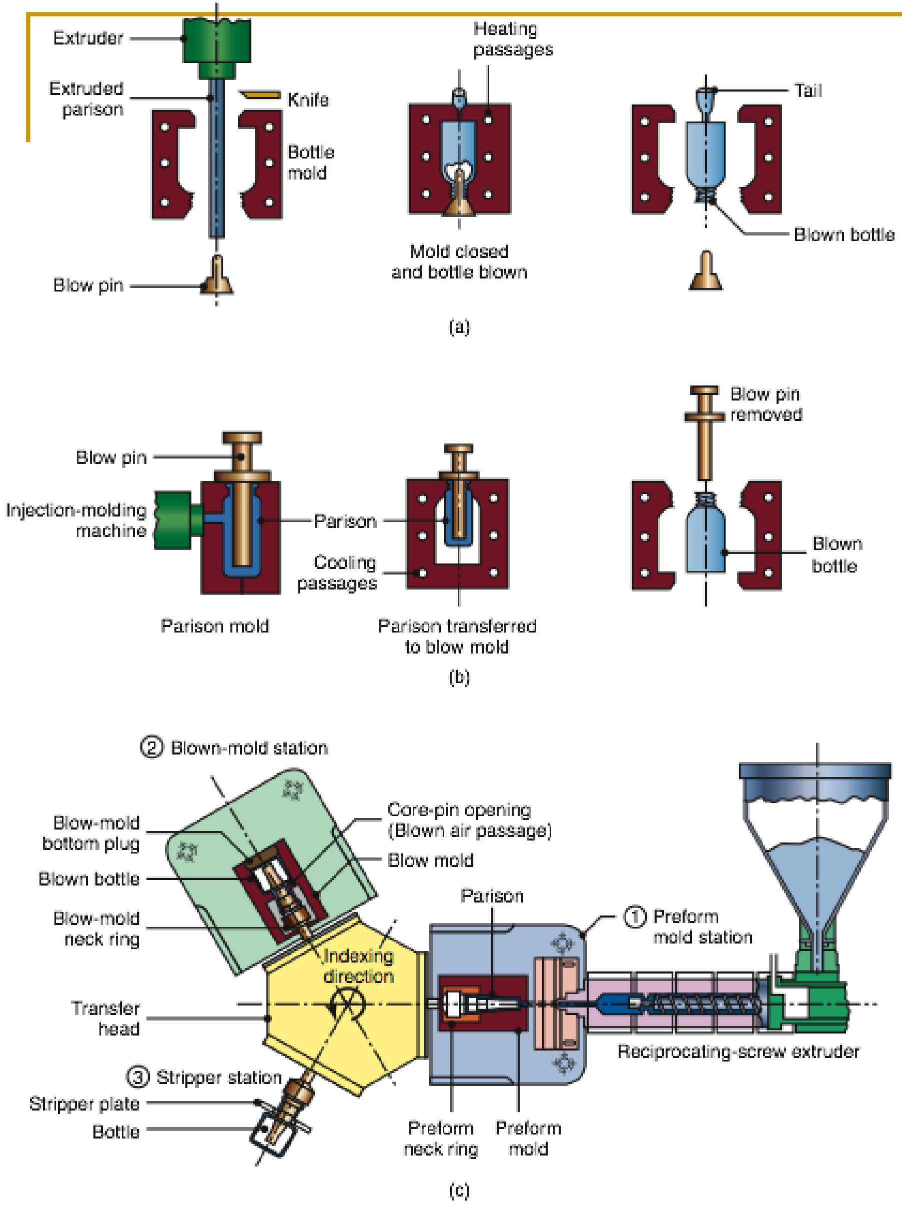


FIGURE 10.32 Schematic illustrations of (a) the blow-molding process for making plastic beverage bottles and (b) a three-station injection-blow-molding machine.

Blown-Film Manufacture

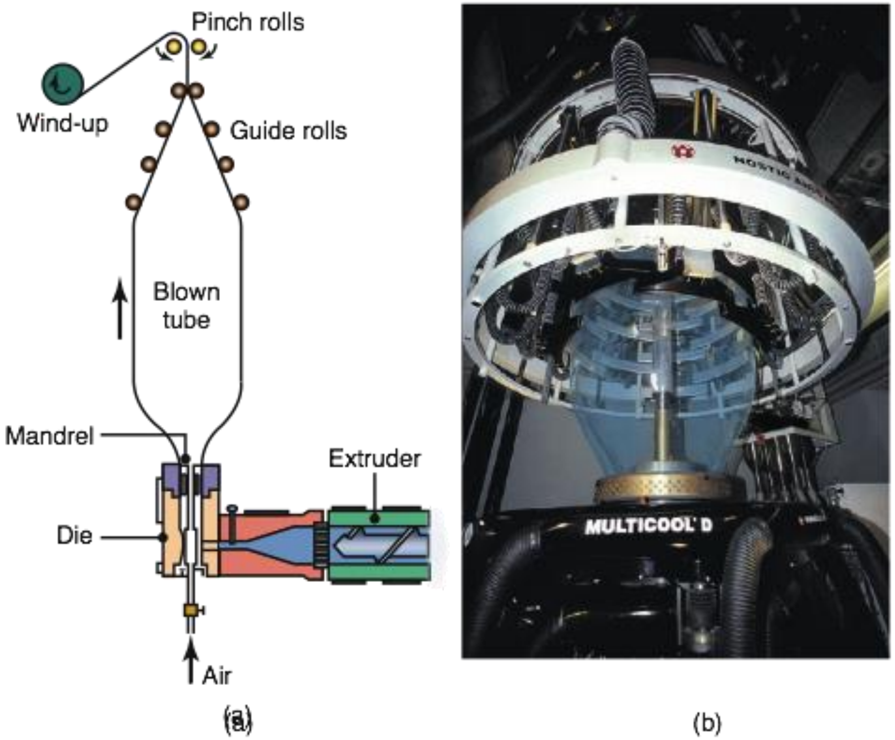


FIGURE 10.25 (a) Schematic illustration of production of thin film and plastic bags from a tube produced by an extruder, and then blown by air. (b) A blown-film operation. *Source:* Courtesy of Windmoeller & Hoelscher Corp.

Compression Molding or Hot-Compression Molding

- Solid granules or preformed tablets of unpolymerized plastic are placed into an open, heated cavity
- A heated plunger applies pressure to the plastics, melting it and making it turn into a fluid
- The pressure in the cavity is maintained until the material is set(curd or polymerized)

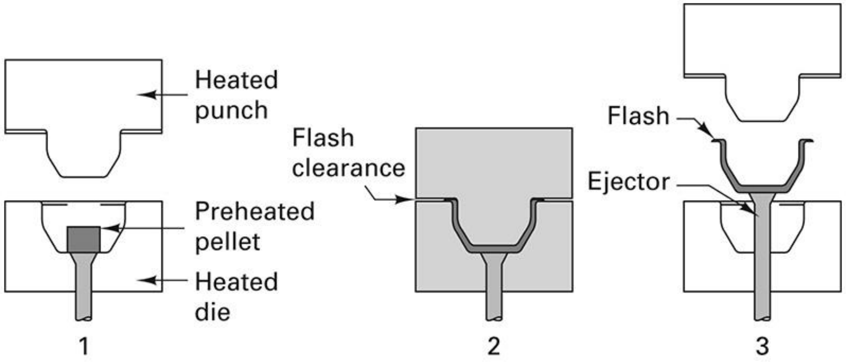


Figure 14-3 The hot-compression molding process: (1) solid granules or a preform pellet is placed in a heated die; (2) a heated punch descends and applies pressure; and (3) after curing (thermosets) or cooling (thermoplastics), the mold is opened and the part is removed.

Compression Molding

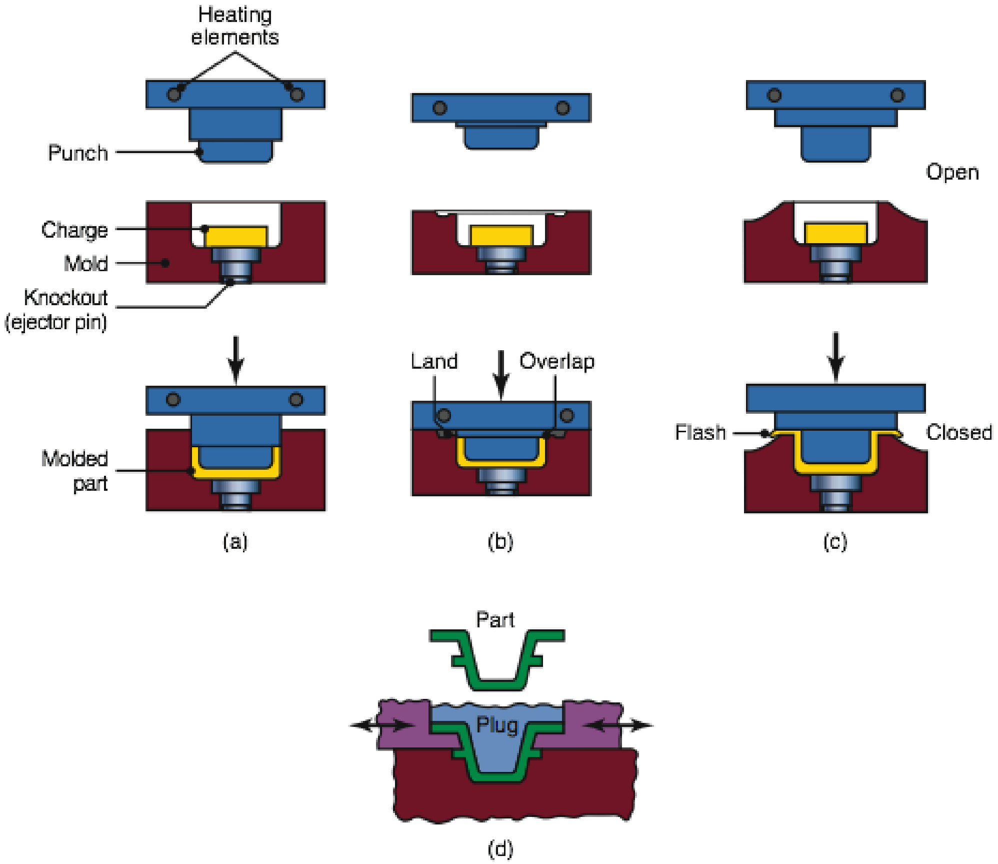


FIGURE 10.35 Types of compression molding, a process similar to forging: (a) positive, (b) semipositive, and (c) flash. The flash in part (c) is trimmed off. (d) Die design for making a compression-molded part with undercuts. Such designs also are used in other molding and shaping operations.

Compression Molding or Hot-Compression Molding

- Costs for compression molding are much lower than complete processing
- High dimensional precision and high surface finishing
- Typical parts are gaskets, seals, exterior automotive panels, and aircraft fairings
- Manufacturing equipment typically consists of a hydraulic or pneumatic press

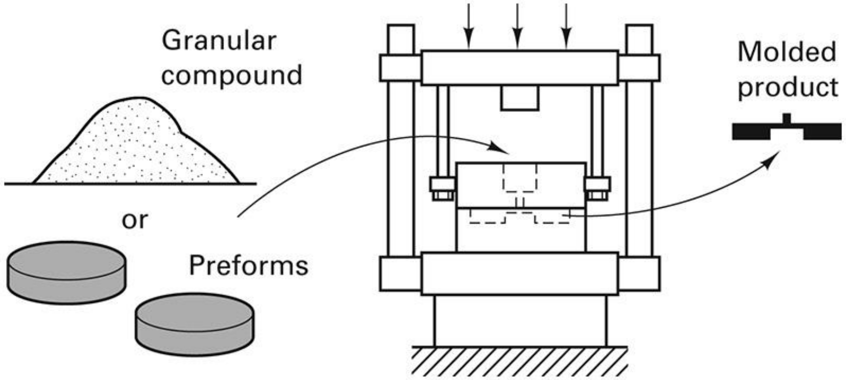
Compression Molding or Hot-Compression Molding

- Used mainly for thermosetting polymers
- Can be used for thermoplastic polymers
- Low cost of machines
- Good for small products with simple shapes
- Thicker sections are not preferred because they take much time
- Can use fiber-reinforced plastics

Transfer Molding

- Variation of compression molding
- Reduces turbulence and uneven flow that occurs often in high pressure, hot-compression molding
- The material is first heated until molten and then is forced into the cavity by a plunger
- The temperature and pressure are maintained until the thermosetting resin has cured

Figure 14-4 Diagram of the transfer molding process. Molten or softened material is first formed in the upper heated cavity. A plunger then drives the material into an adjacent die.



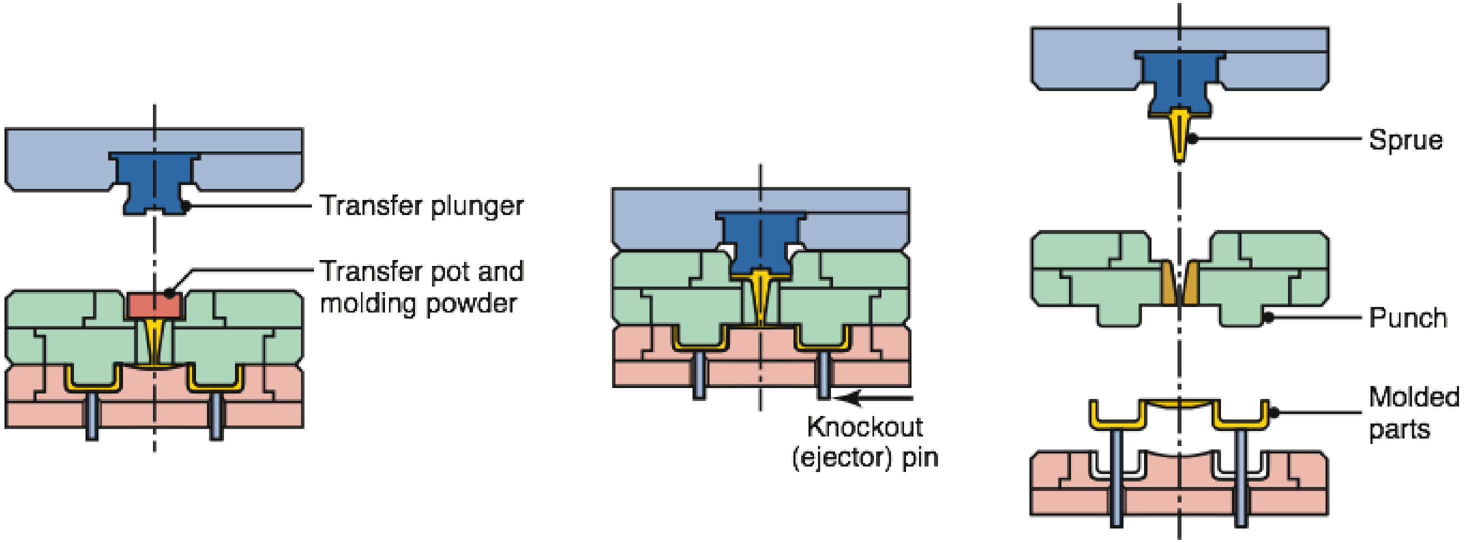
Transfer Molding

- Mainly for thermosetting materials
- Can be used where inserts are to be incorporated into the products
- Can use reinforced fillers (cellulose, glass, silica, alumina)
- Characterized by: excellent detail, and good tolerances

Cold Molding

- Thermosetting is pressed while cold and moved to oven for curing.

Transfer Molding



1. Insert polymer in mold

2. Mold closed and cavities filled

3. Mold open and molded parts ejected

FIGURE 10.36 Sequence of operations in transfer molding of thermosetting plastics. This process is particularly suitable for making intricate parts with varying wall thicknesses.

Injection Molding

- Used for high-volume production of complex thermoplastic parts
- Most widely used process
- Many types of machines as:
  - Plunger type
  - Reciprocating screw type
  - Two stage type (separation of melting and compression to save time)

Injection Molding (Plunger type)

- Granules of a raw material are fed through a hopper into a cavity that is ahead of a plunger
- The plunger moves forward and the material is heated
- In the torpedo section, the material is mixed, melted, and superheated
- The fluid then flows through a nozzle that is against the mold
- Sprues and runners are used in the same way as in metal casting

Injection Molding (Plunger type)

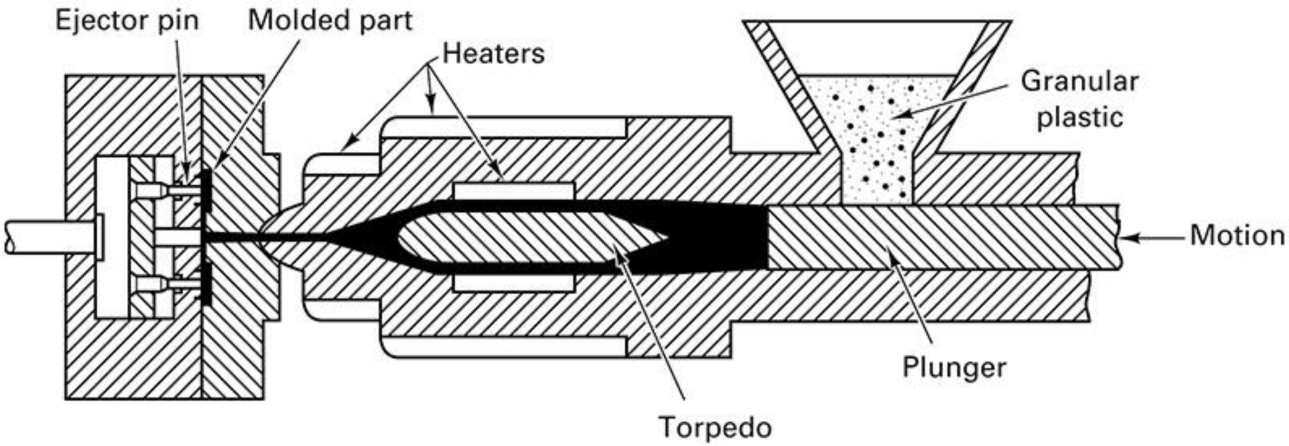


Figure 14-5 Schematic diagram of the injection molding process. A moving plunger advances material through a heating region (in this case, through a heated manifold and over a heated torpedo) and further through runners into a mold where the molten thermoplastic cools and solidifies.

Injection Molding

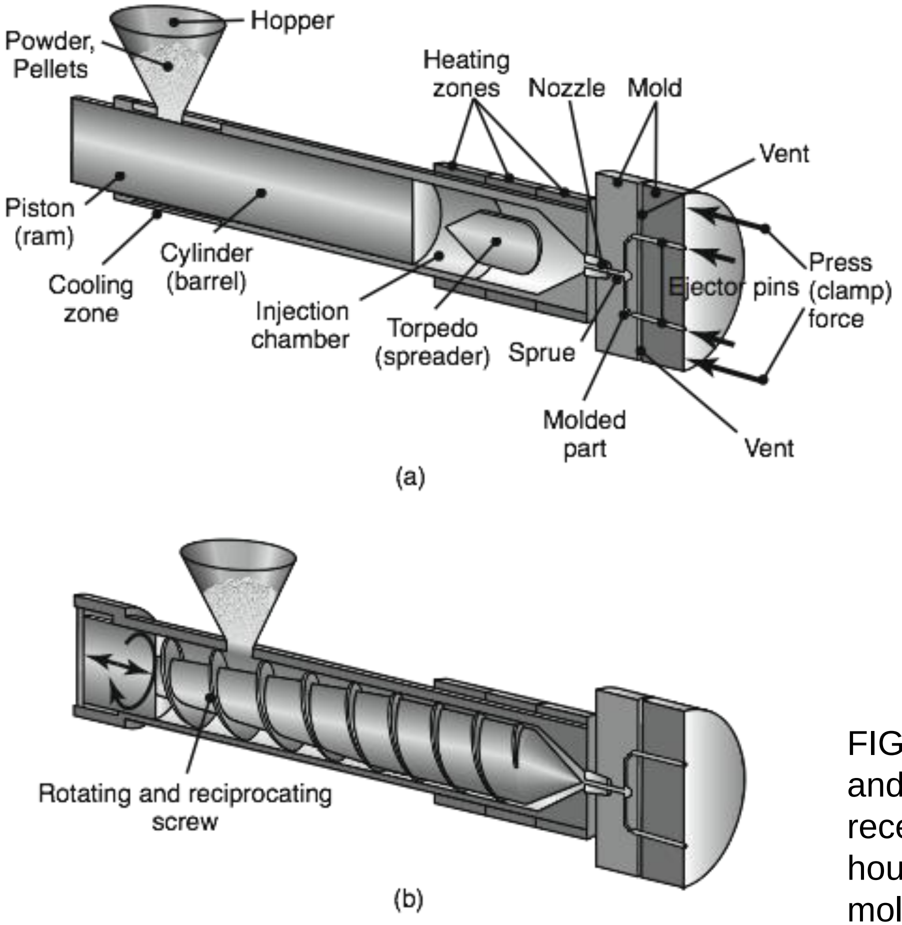
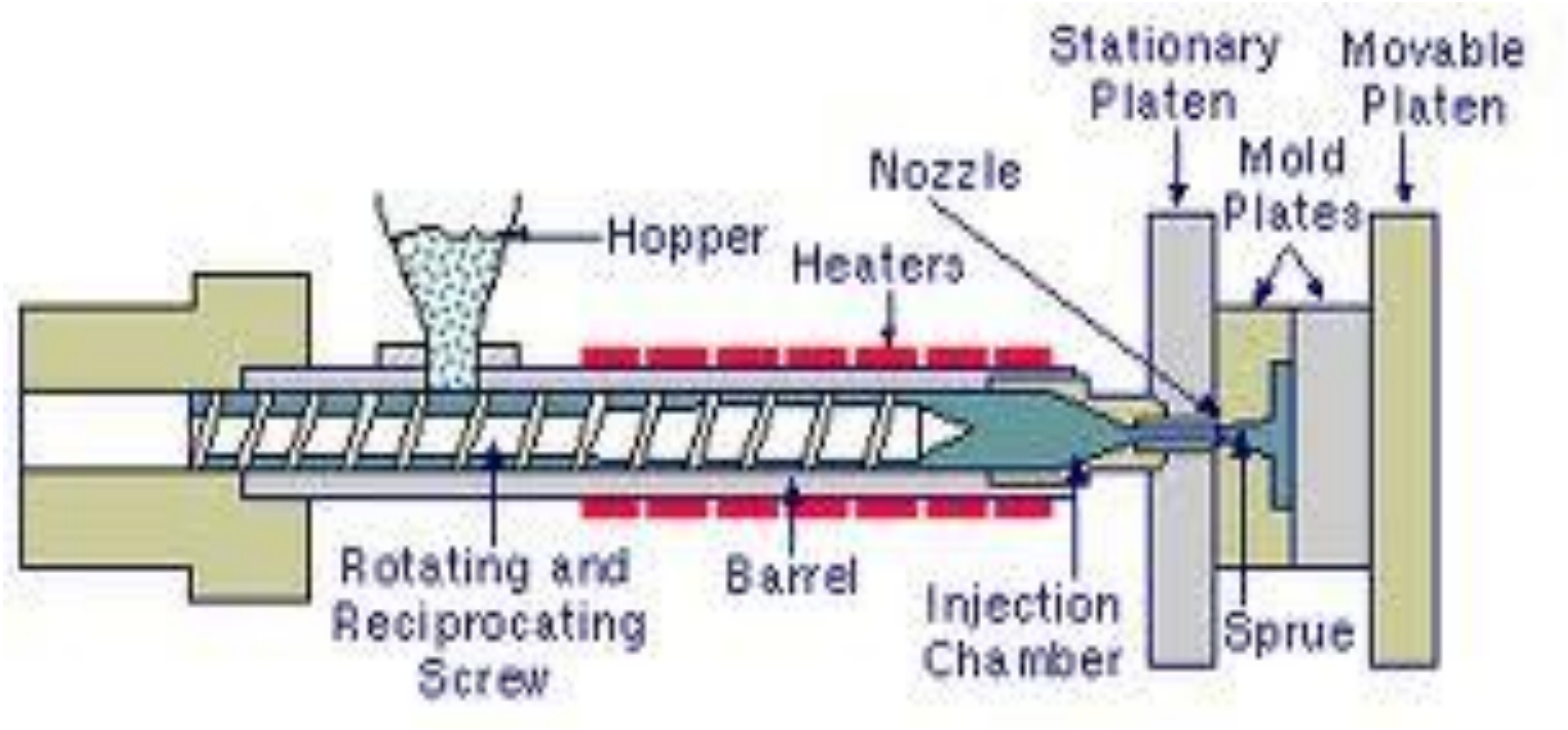


FIGURE 10.27 Injection molding with (a) a plunger and (b) a reciprocating rotating screw. Telephone receivers, plumbing fittings, tool handles, and housings are examples of parts made by injection molding.

Injection Molding(Reciprocating screw type)



Mold Features

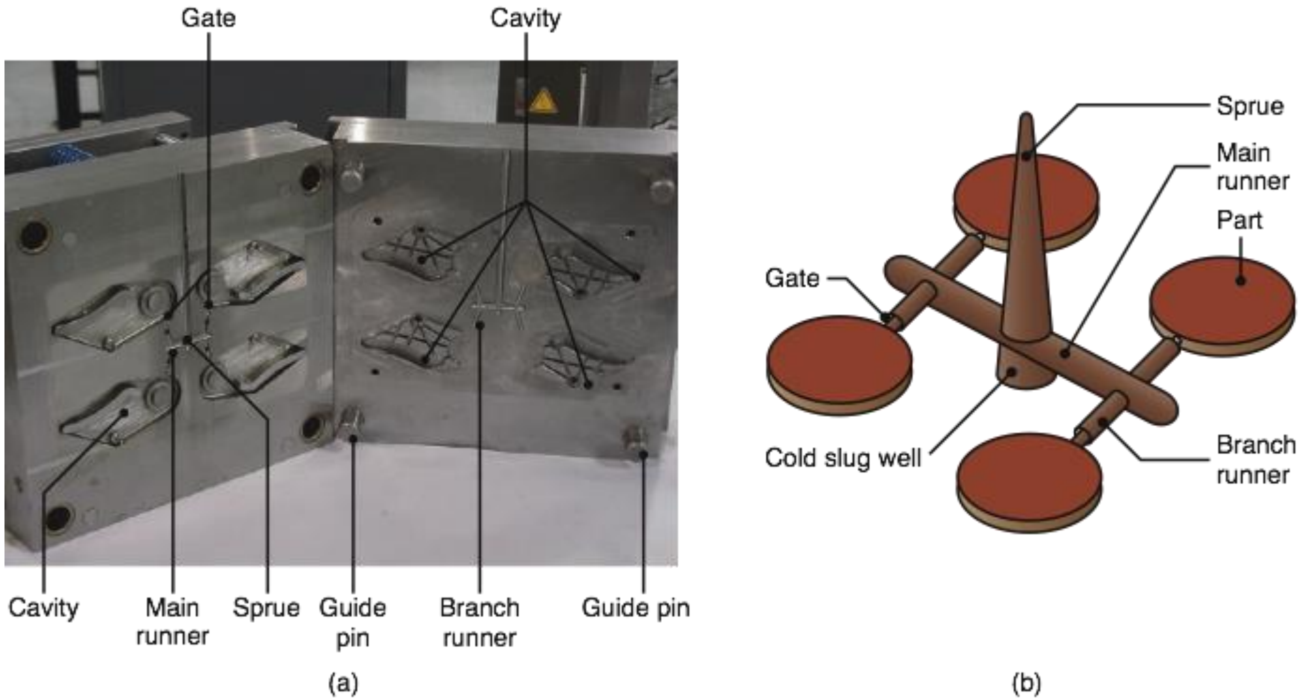


FIGURE 10.28 Illustration of mold features for injection molding. (a) Two-plate mold, with important features identified; (b) injection molding of four parts, showing details and the volume of material involved. *Source:* Courtesy of Tooling Molds West, Inc.

Injection Molding

- Thermoplastic molding:
  - material is preheated at chamber
  - material is melted and superheated from 200 to 300ºC before exiting the nozzle
- Thermosetting molding:
  - material is preheated in chamber
  - it is heated through the nozzle
  - heated in the mold to complete curing (during curing the nozzle is cooled so that the material inside it will not set
  - longer cycle time

Reaction Injection Molding

- Two or more liquid reactants are mixed under pressure
- The mixture then flows through a pressure-reducing chamber and into a mold
- Exothermic reaction causes the thermosets to polymerize
- Curing times are typically less than a minute
- Low processing temperatures and low injection pressures
  - Typical for casting large parts
  - Products: automotive applications (steering wheels, airbag covers, instrument panels, bumpers), refrigerators, picnic coolers

Reaction Injection Molding

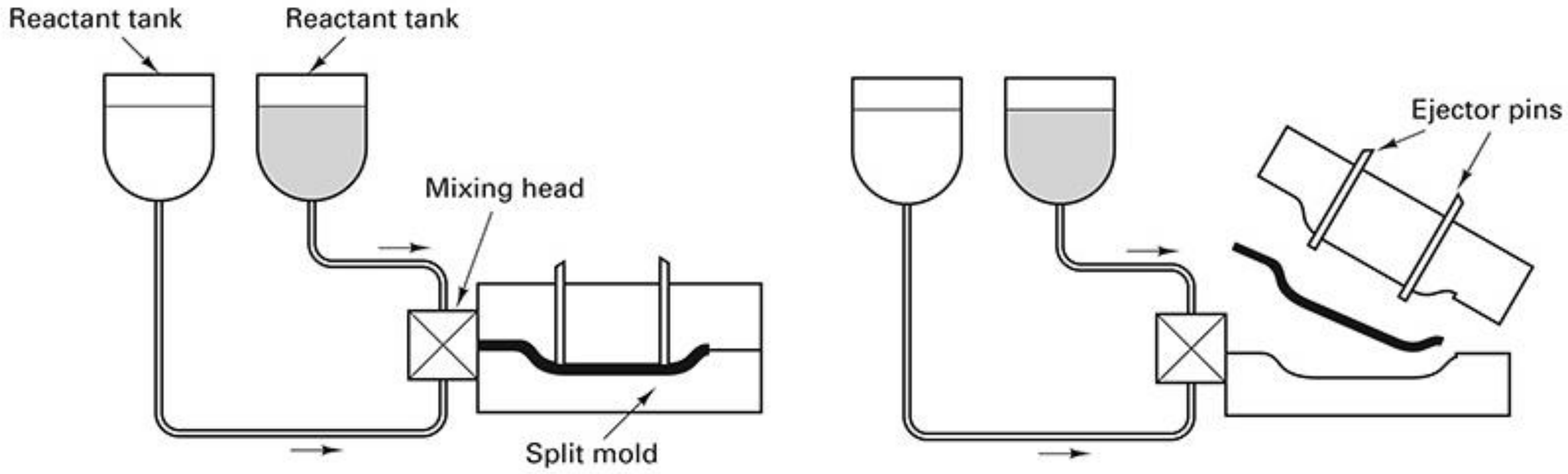


Figure 14-6 The reaction injection molding process. (Left) Measured amounts of reactants are combined in the mixing head and injected into the split mold. (Right) After sufficient curing, the mold is opened and the component is ejected.

Reaction-Injection Molding

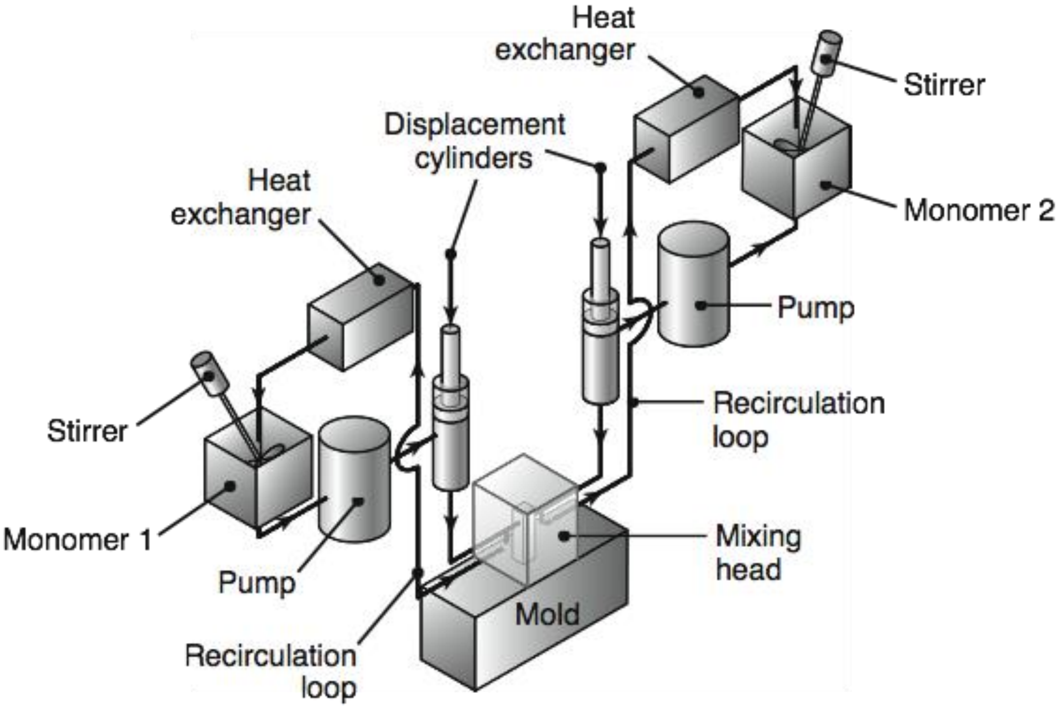


FIGURE 10.31 Schematic illustration of the reaction-injection-molding process.

Extrusion

- Used for long plastic products with a uniform cross-section
- Pellets or powders are fed through a hopper and then into a chamber with a large screw
- The screw rotates and propels the material through a preheating section where it is heated, homogenized, and compressed
- To preserve its shape, the material is cooled by jets of air or water spraying

Extrusion

- Products: tubes, pipes, coated wires and cables

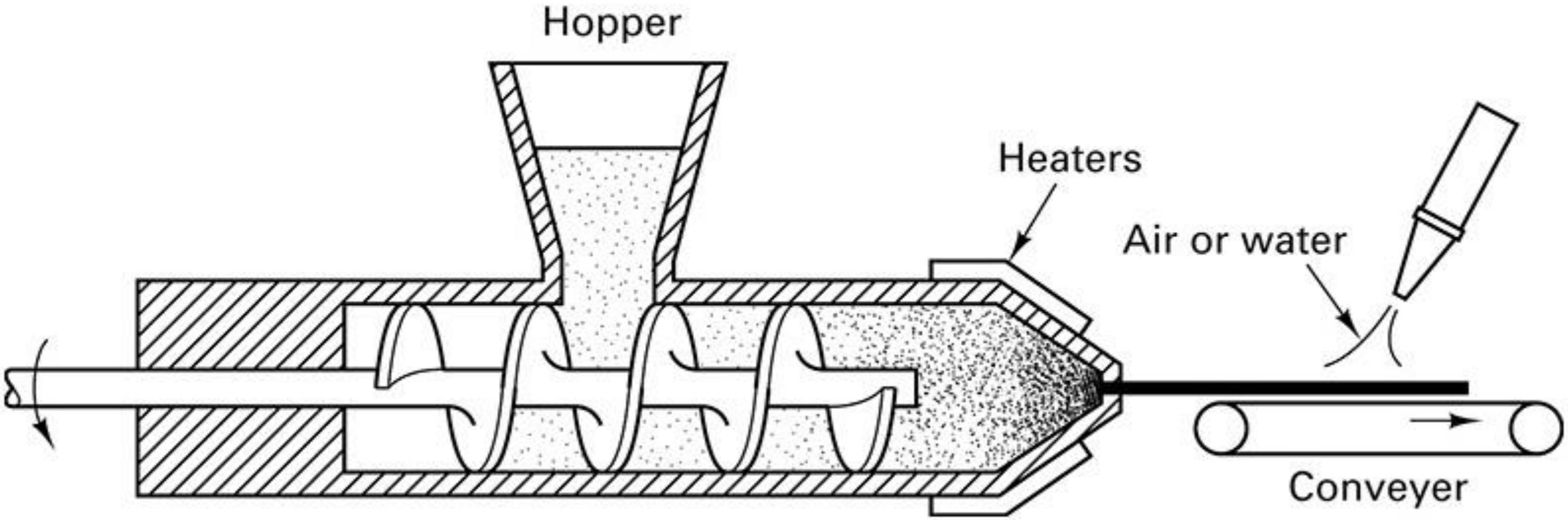


Figure 14-7 A screw extruder producing thermoplastic product. Some units may have a changeable die at the exit to permit production of different-shaped parts.

Extrusion

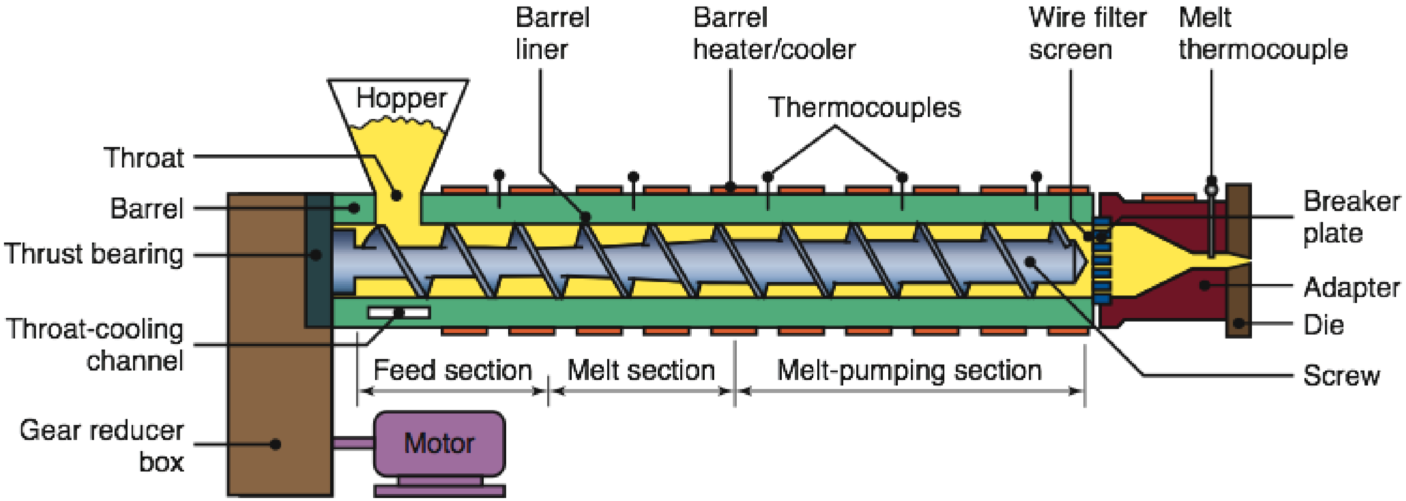


FIGURE 10.22 Schematic illustration of a typical extruder.

Thermoforming

- Thermoplastic sheet material is heated and then placed over a mold
- A vacuum, pressure, or mechanical tool is applied to draw the material into the mold
- The die can impart the dimensions and finish or texture on the final product
- Typical products are thin-walled parts, plastic luggage, plastic trays, and panels for light fixtures

Thermoforming

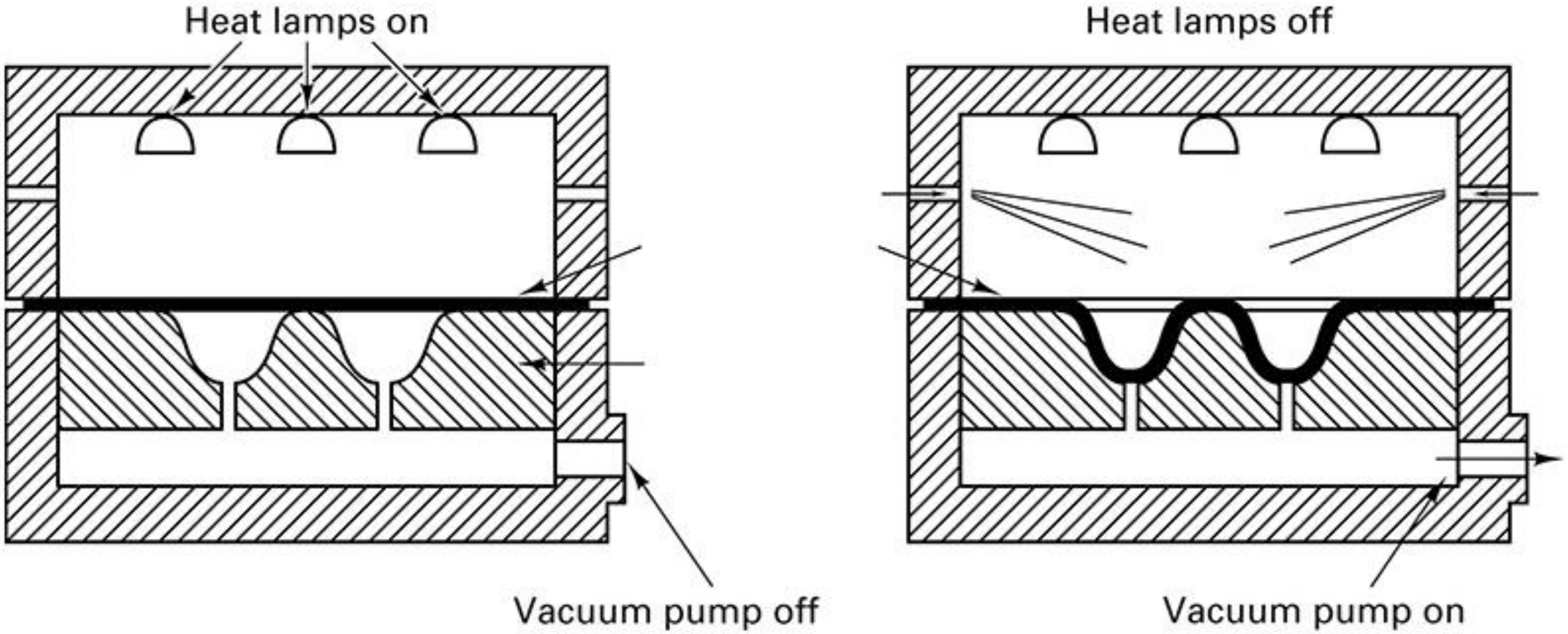


Figure 14-8 A type of thermoforming where thermoplastic sheets are shaped using a combination of heat and vacuum.

Thermoforming

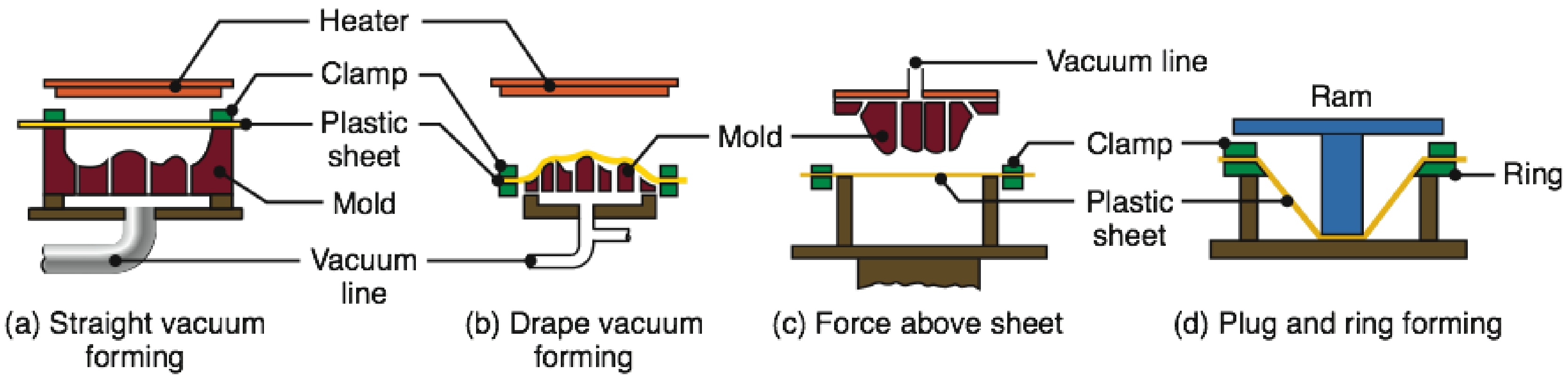


FIGURE 10.35 Various thermoforming processes for thermoplastic sheet. These processes are commonly used in making advertising signs, cookie and candy trays, panels for shower stalls, and packaging.

Rotational Molding

- Produces hollow, seamless products
- Typical products are tanks, bins, refuse containers, doll parts, footballs, helmets, and boat hulls
- A mold or cavity is filled with a specific amount of thermoplastic powder or liquid
- The molds are then placed in an oven and rotated simultaneously about two axes
- The resin is evenly distributed across the mold walls
- Mold is then cooled and opened

Rotational Molding

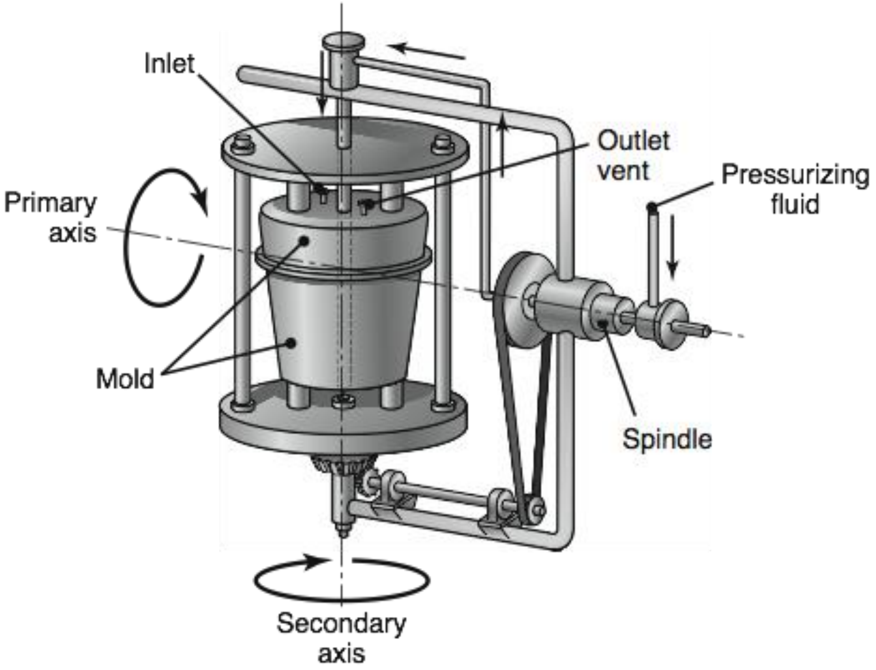


FIGURE 10.33 The rotational molding (rotomolding or rotocasting) process. Trash cans, buckets, carousel horses and plastic footballs can be made by this process.

Foam Molding

- A foaming agent is mixed with a plastic resin and releases gas when the material is heated during molding
- The materials expand to 2 to 50 times their original size
- Produces low density products
- Both rigid and flexible foams can be produced
  - Rigid type is used for structural applications such as computer housings, packaging, and shipping containers
  - Flexible foams are used for cushioning

Other Plastic-Forming Processes

- Calendaring process
- Drawing
- Rolling
- Spinning
- Blow molding
  - Plastic bags
- Many of these processes can be combined with other processes to produce a final part

Machining of Plastics

- Plastics can undergo many of the same processes of metals
  - Milling, sawing, drilling, and threading
- General characteristics of plastics that affect machining
  - Poor thermal conductors
  - Soft and may clog tooling
  - Softening may reduce the precision of the final dimensions of thermoplastics
  - Thermosets can have more precise dimensions because of its rigidity

Tooling Considerations for Machining Plastics

- High temperatures may develop at the cutting point and cause the tools to be hot
- Carbide tools may be preferred over high-speed tool steels if high-speed cutting is performed
- Coolants can be used to keep temperatures down
  - Water, soluble oil and water, weak solutions of sodium silicate
- Lasers may be used for cutting operations

Finishing and Assembly Operations

- Printing, hot stamping, vacuum metallizing, electroplating, and painting can be used on plastics
- Thermoplastic polymers can be joined by heating relevant surfaces
    - The heat can be applied by a stream of hot gases, applied through a soldering iron, or generated by ultrasonic vibrations
- Snap-fits may be used to assemble plastic components
- Self-tapping screws can also be used

Designing for Fabrication

- Materials should be selected with the manufacturing processes in mind
- The designer should be aware that polymers can soften or burn at elevated temperatures, have poor dimensional stability, and properties deteriorate with age
- Many property evaluation tests are conducted under specific test conditions
  - Materials should be selected that take these conditions into account

Designing for Fabrication

- Each process has limitations and design considerations
    - Shrinkage in casting
    - Solidification issues
    - Part removal and ejection
    - Surface finish
    - Section thickness
    - Thick corners

Inserts

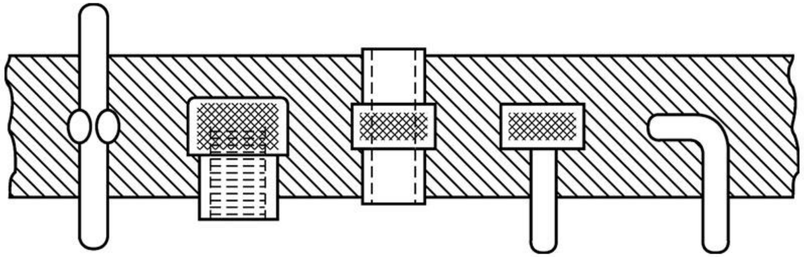
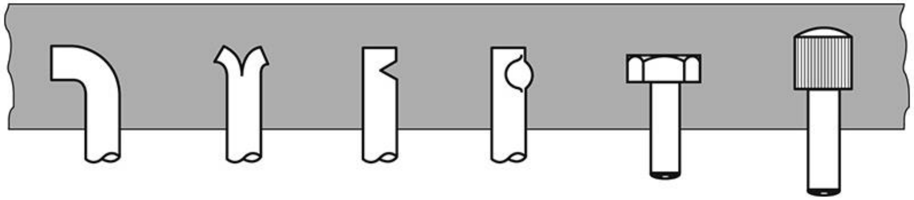


Figure 14-11 Typical metal inserts used to provide threaded cavities, holes, and alignment pins in plastic parts.

Figure 14-12 Various ways of anchoring metal inserts in plastic parts (left to right): bending, splitting, notching, swaging, noncircular head, and grooves and shoulders. Knurling is depicted in Figure 14-11.



- Metal (brass or steel) may be incorporated into plastic products to enhance performance
    - Threaded inserts
- May serve as mounting surfaces
- Often used for electrical terminals

Insert Molding

(a) (b)

FIGURE 10.30 Products made by insert injection molding. Metallic components are embedded in these parts during molding. *Source:* (a) Courtesy of Plainfield Molding, Inc., and (b) Courtesy of Rayco Mold and Mfg. LLC.

Design Factors Related to Finishing

- Finish and appearance of plastics is important to consumers
- Decorations or letters can be produced on the surface of the plastic, but may increase cost
- Processes should be chosen so that secondary machining is minimized
- If parting lines will result in flash, the parting lines should be placed in geometrically easy locations (i.e. corners and edges) if possible

Design Factors Related to Finishing

- Plastics have a low modulus of elasticity, so flat areas should be avoided
- Flow marks may be apparent, so dimples or textured surfaces can be used
- Holes should be countersunk

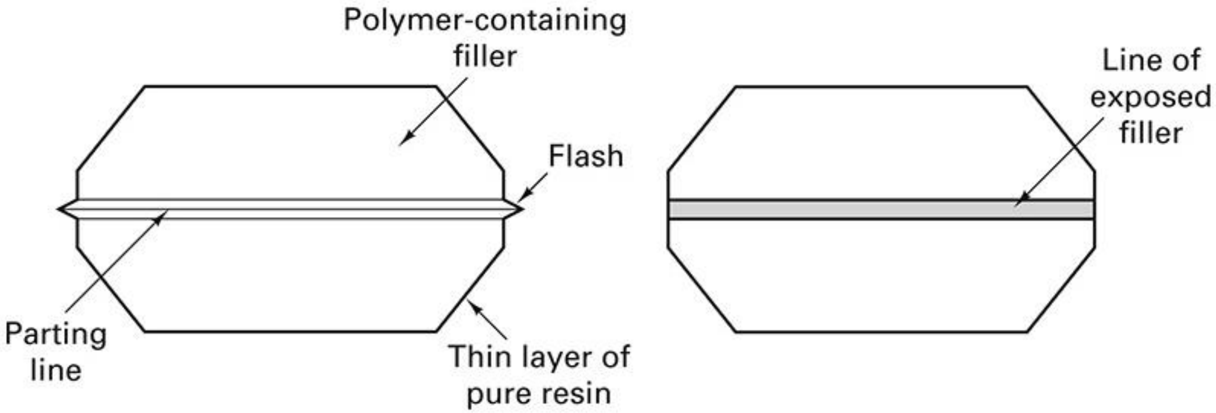


Figure 14-13 Trimming the flash from a plastic part ruptures the thin layer of pure resin along the parting line and creates a line of exposed filler.

14.3 Processing of Rubber and Elastomers

- Dipping
  - For uniform and thin parts as boots, gloves
  - A master form is produced from some type of metal
  - This master form is then dipped into a liquid or compound, then removed and allowed to dry
  - Additional dips are done to achieve a desired thickness
  - Electrostatic charges may be used to accelerate the process
  - Other molding processes: injection, compression, and transfer molding, and extrusion

Rubber and Elastomer Compounds

- Elastomeric resin, vulcanizers, fillers, antioxidants, accelerators, and pigments may be added to the compounds
  - Typically done in a mixer
  - Injection, compression, and transfer molding may be used
  - Some compounds can be directly cast to shape
- Rubber compounds can be made into sheets using calenders
- Inner tubes, tubing, etc. can be produced by extrusion
- Rubber or artificial elastomers can be bonded to metals using adhesives

Processing of Elastomers and Rubbers

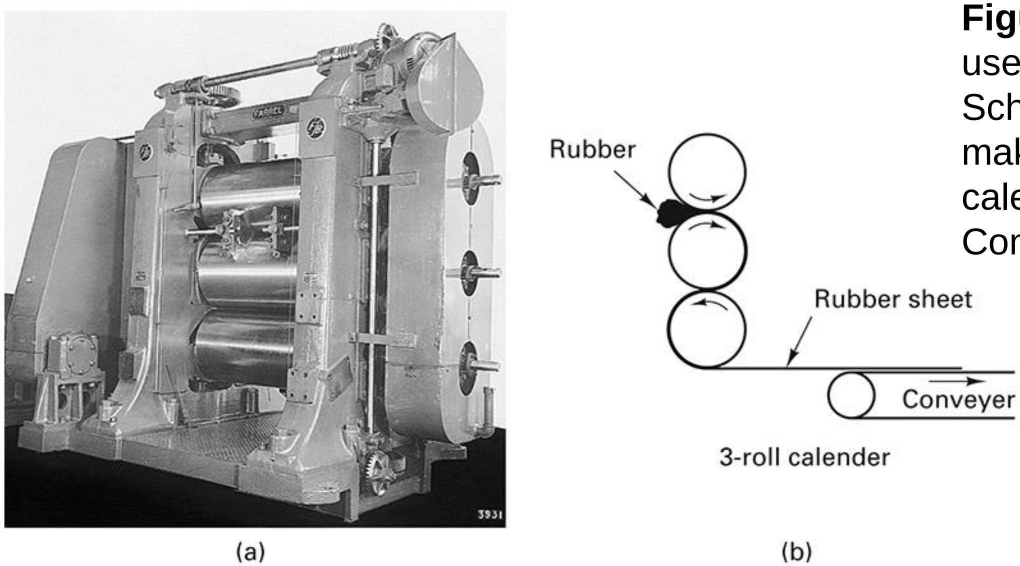


Figure 14-15 (Left) (a) Three-roll calender used for producing rubber or plastic sheet. (b) Schematic diagram showing the method of making sheets of rubber with a three-roll calender. [(a) (Courtesy of Farrel-Birmingham Company, Inc. Ansonia, CT.)]

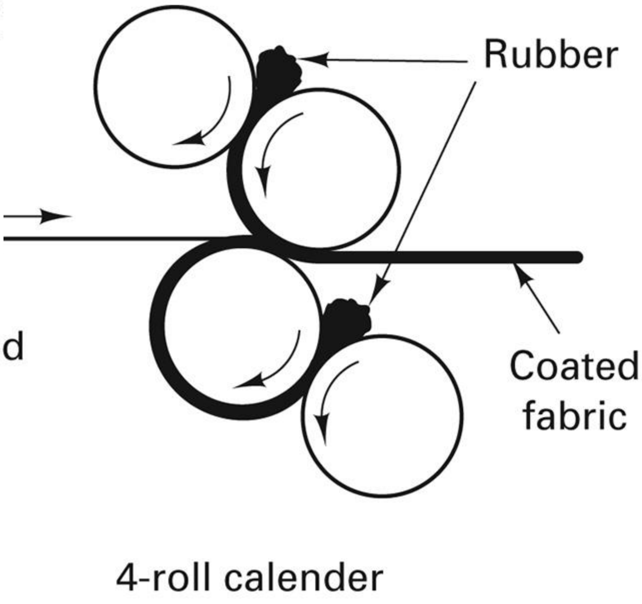
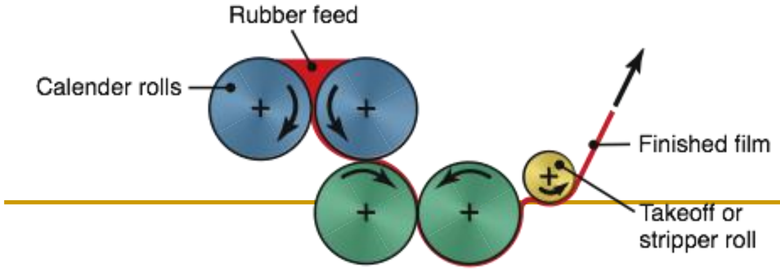


Figure 14-16 (Right) Arrangement of the rolls, fabric, and coating material for coating both sides of a fabric in a four-roll calender.



14.4 Processing of Ceramics

- Two distinct classes of processing ceramics
  - Glasses are manufactured by means of molten material via viscous flow
  - Crystalline ceramics are manufactured by pressing moist aggregates or powder into shape
  - The material is then bonded together using one of several mechanisms
    - Chemical reaction
    - Vitrification (cementing with liquified material)
    - Sintering

Fabrication Techniques for Glasses

- Shaped at elevated temperatures
- Sheet and plate glass is formed by extrusion through a narrow slit and rolling it through water-cooled rolls
- Glass shapes can be made by pouring molten material into a mold
  - Cooling rates may be controlled
- Constant cross section products can be made through extrusion
  - Glass fibers are made through an extrusion process

Fabrication Techniques for Glasses

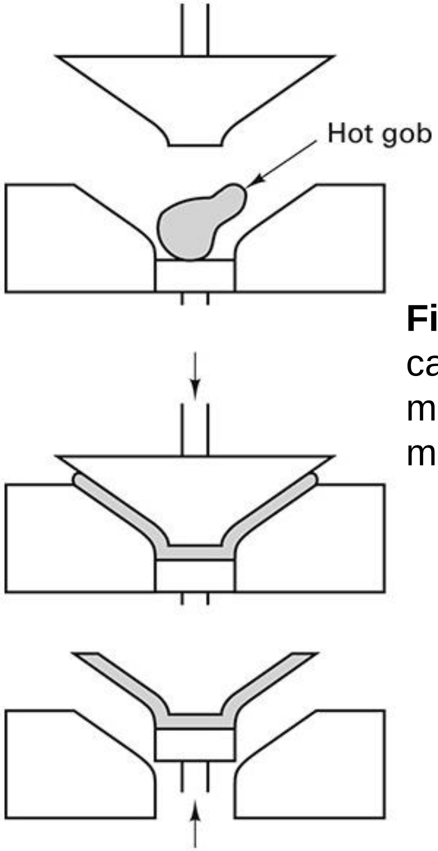


Figure 14-17 Viscous glass can be easily shaped by mating male and female die members.

- Viscous masses may be used instead of molten glass
    - Female and male die members are typically used
    - Processes similar to blow molding are used to make bottles and containers

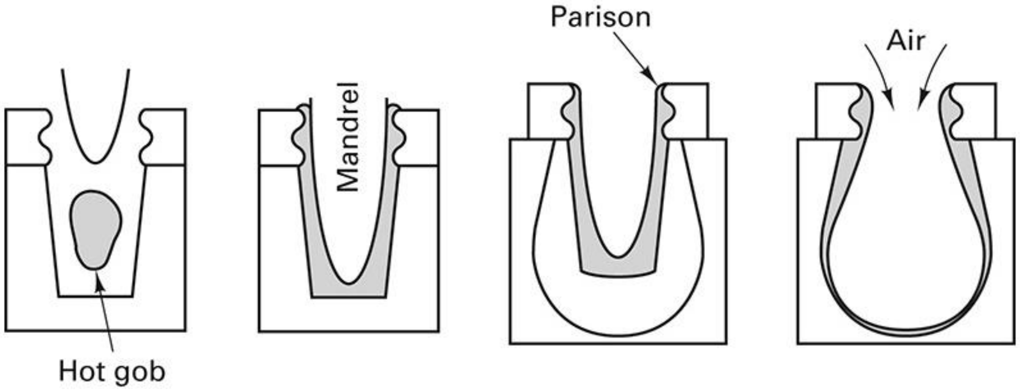


Figure 14-18 Thin-walled glass shapes can be produced by a combination of pressing and blow molding.

Fabrication Techniques for Glasses

- Heat treatments
  - Forced cooling produces surface compression and this glass is known as tempered glass
- Glass ceramics
  - Part crystalline and part glass
  - Glass material is subjected to devitrification
    - Controls nucleation and growth
    - Products such as cookware and ceramic stove tops

Fabrication of Crystalline Ceramics

- Crystalline ceramics are hard, brittle materials that have high melting points
- Cannot be formed by techniques that require plasticity or melting
- Processed in the solid state
  - Dry pressing
  - Isostatic pressing
- Clay products are ceramics blended with water and additives

Fabrication of Crystalline Ceramics

- Plastic forming can be done if additives are added that increase plasticity
  - Wet pressing
  - Extrusion
  - Injection molding
- Casting processes
  - Begin with a pourable slurry
  - Slip casting
  - Tape casting
- Sol-gel processing

Fabrication of Crystalline Ceramics

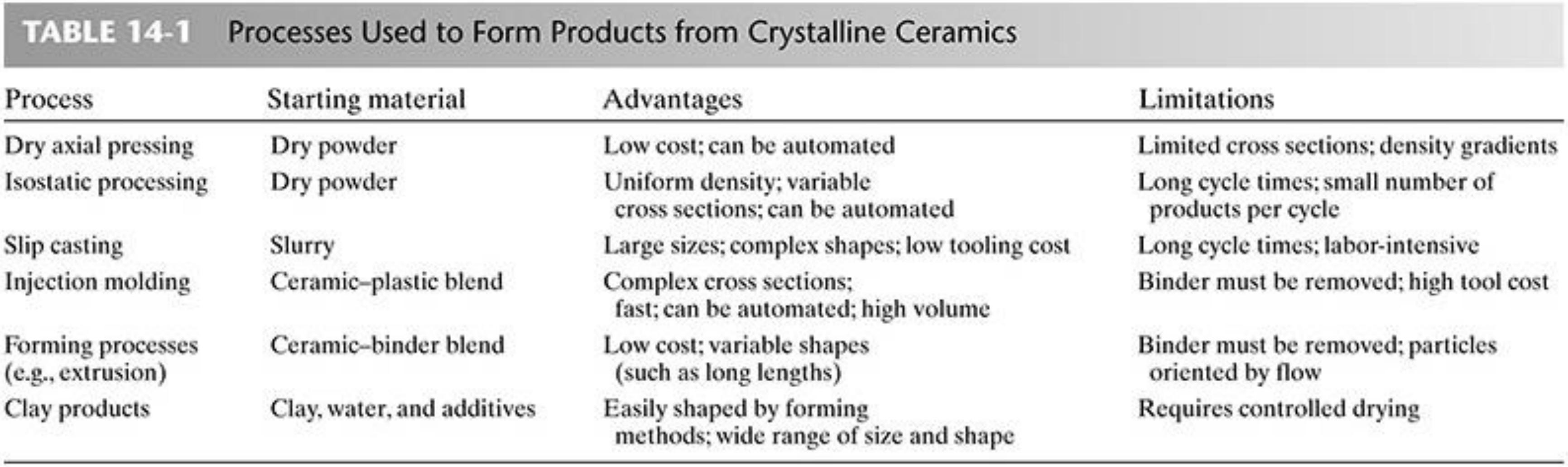


TABLE 14-1 Processes Used to Form Products from Crystalline Ceramics

Process	Starting material	Advantages	Limitations
Dry axial pressing	Dry powder	Low cost; can be automated	Limited cross sections; density gradients
Isostatic processing	Dry powder	Uniform density; variable cross sections; can be automated	Long cycle times; small number of products per cycle
Slip casting	Slurry	Large sizes; complex shapes; low tooling cost	Long cycle times; labor-intensive
Injection molding	Ceramic–plastic blend	Complex cross sections; fast; can be automated; high volume	Binder must be removed; high tool cost
Forming processes (e.g., extrusion)	Ceramic–binder blend	Low cost; variable shapes (such as long lengths)	Binder must be removed; particles oriented by flow
Clay products	Clay, water, and additives	Easily shaped by forming methods; wide range of size and shape	Requires controlled drying

Producing Strength in Particulate Ceramics

- Useful strength in ceramics is created from subsequent heat treating
- Firing or sintering
  - Liquid-phase sintering- surface melting
  - Reaction sintering- component reactions
  - Vitrification
- Cementation does not require subsequent heating
  - Liquid binders are used and a chemical reaction converts the liquid to a solid
- Laser sintering

Machining of Ceramics

- Most ceramics are hard and brittle, so machining is difficult
- Machining before firing is called green machining
- Machining after firing are typically nonconventional machining processes
  - Grinding, lapping, polishing, drilling, cutting, ultrasonic, laser, electron beam, water-jet, and chemical

Design Considerations

- Joining of Ceramics
  - Adhesive bonding
  - Brazing
  - Diffusion bonding
  - Threaded assemblies
- Most ceramics are designed to be one piece structures
- Bending and tensile loading should be minimized during manufacture
- Sharp corners and edges should be avoided
- It is costly to achieve precise dimensions and surface finishing

14.5 Fabrication of Composite Materials

- Most processes are slow and require considerable amounts of hand labor
- Fabrication of particulate composites
  - Consist of discrete particles dispersed in a ductile, fracture resistant polymer or metal matrix
  - Processed by introducing particles into a liquid melt or slurry
  - Powder metallurgy methods

Composite Material Microstructure

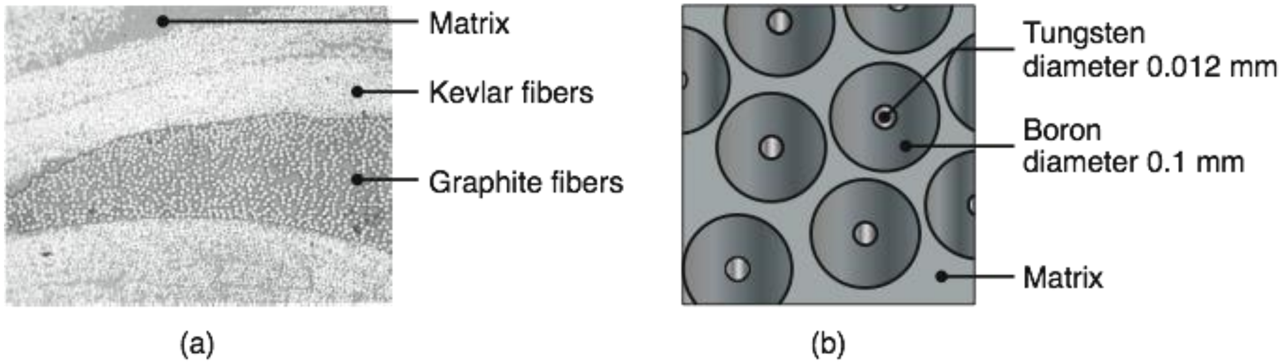


FIGURE 10.18 (a) Cross-section of a tennis racket, showing graphite and aramid (Kevlar) reinforcing fibers. *Source:* After J. Dvorak and F. Garrett. (b) Cross-section of boron-fiber-reinforced composite material.

Fabrication of Laminar Composites

- Include coatings, protective surfaces, claddings, bimetallics, and laminates
- Processes are designed to form a high-quality bond between distinct layers
- If metals are used, composites can be produced by hot or cold roll bonding
  - U.S. coins use this process
- Explosive bonding bonds layers of metal
  - Pressure wave induces bonding

Fabrication of Laminar Composites

- Adhesive bonding
  - Gluing
  - Pressing of unpolymerized resins
- Sandwich structures
  - Corrugated cardboard
  - Honeycomb structure

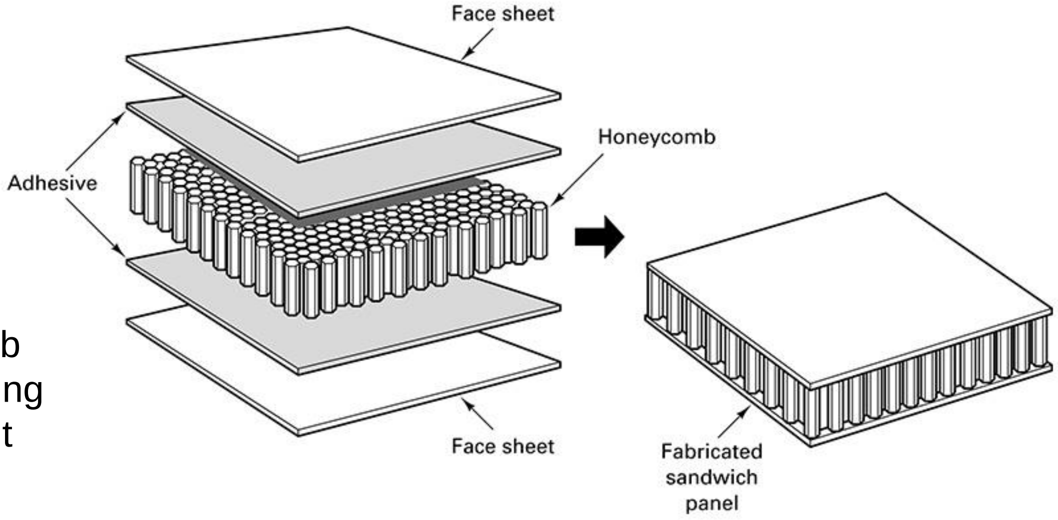


Figure 14-19 Fabrication of a honeycomb sandwich structure using adhesive bonding to join the facing sheets to the lightweight honeycomb filler. (*Courtesy of ASM International. Metals Park, OH.*)

Fabrication of Fiber-Reinforced Composites

- Matrix and fiber reinforcement provide a system that has a combination of properties
- Fibers can be oriented in a way that optimizes properties
    - The fibers can be continuous or discontinuous
    - Discontinuous fibers can be combined in a matrix to provide a random or preferred orientation
    - Continuous fibers can be aligned in a unidirectional fashion in rods or tapes, woven into fabric layers, wound around a mandrel, or woven into three dimensional shapes

Production of Reinforcing Fibers

- Many are produce through conventional drawing and extrusion processes
- Materials that are too brittle, such as Boron, carbon, and silicon carbide, are produces by deformation processes
- Individual filaments are often bundled
  - Yarn- twisted assemblies of filaments
  - Tows- untwisted assemblies of fibers
  - Rovings- untwisted assemblies of filaments or fibers

Processes Designed to Combine Fibers and a Matrix

- Casting-type processes
  - Capillary action
  - Vacuum infiltration
  - Pressure casting
  - Centrifugal casting
- Prepegs- sheets of unidirectional fibers or woven fabric that have been infiltrated with matrix material
- Mats- sheets of nonwoven randomly oriented fibers in a matrix
  - Mats can be stacked later into a continuous solid matrix

Processes Designed to Combine Fibers and a Matrix

- Individual filaments can be coated and then assembled
  - Drawing through a molten bath
  - Plasma spraying
  - Vapor deposition
  - Electrodeposition
  - Can be wound around a mandrel with a specified spacing and then used to produce tapes
- Sheet-molding compounds are composed of chopped fibers and partially cured thermoset resins
- Bulk-molding compounds are fiber-reinforced, thermoset, molding materials with short fibers distributed randomly

Fabrication of Final Shapes from Fiber-Reinforced Fibers

- Pultrusion- continuous process that is used to produce long lengths of relatively simple shapes with uniform cross section
  - Fishing poles, golf club shafts, and ski poles

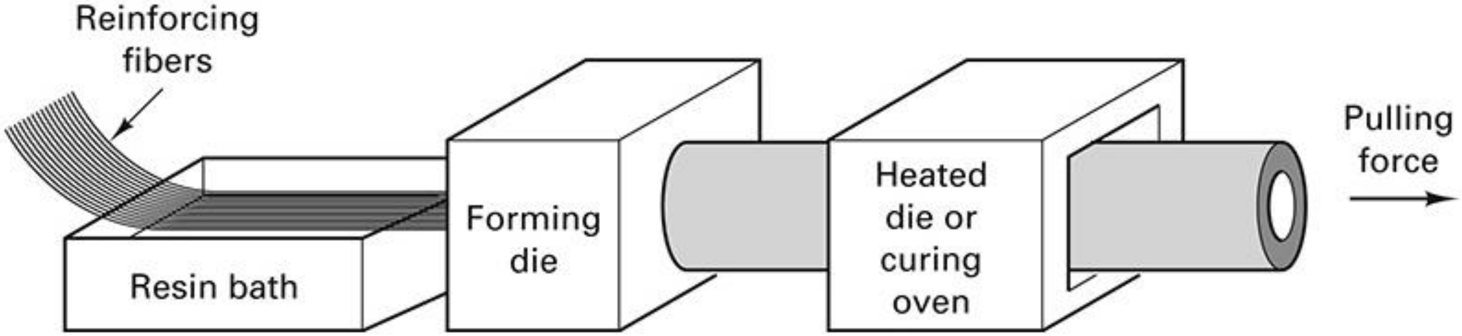
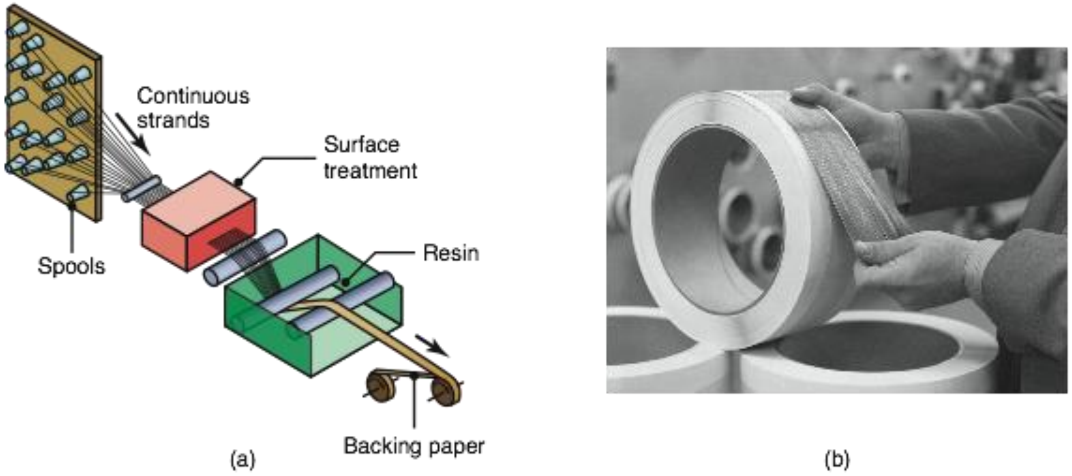


Figure 14-20 Schematic diagram of the pultrusion process. The heated dies cure the thermoset resin.

Manufacture of Prepregs

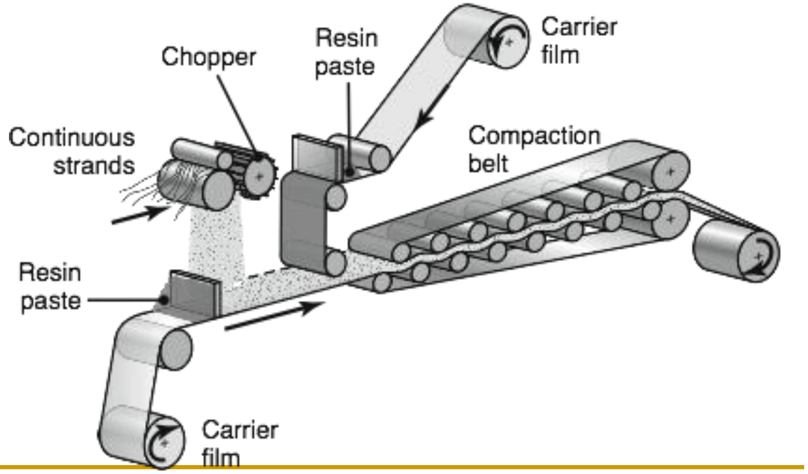


(a)

(b)

FIGURE 10.40 (a) Manufacturing process for polymer-matrix composite. *Source:* After T.-W. Chou, R.L. McCullough, and R.B. Pipes. (b) Boron-epoxy prepreg tape. *Source:* Textron Systems.

FIGURE 10.41 Manufacturing process for producing reinforced-plastic sheets. The sheet is still viscous at this stage and can later be shaped into various products. *Source:* After T.-W. Chou, R. L. McCullough, and R. B. Pipes.



Filament Winding

- Resin coated or resin-impregnated filaments, bundles, or tapes made from fibers of glass, graphite, and boron
  - Produces cylinders, spheres, cones and other containers

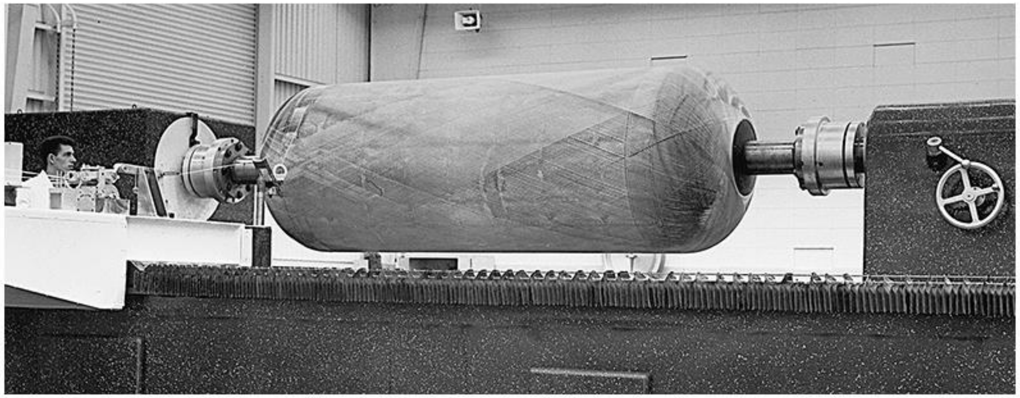


Figure 14-21 A large tank being made by filament winding. (*Courtesy of Rohr Inc., Chula Vista, CA.*)

Filament Winding

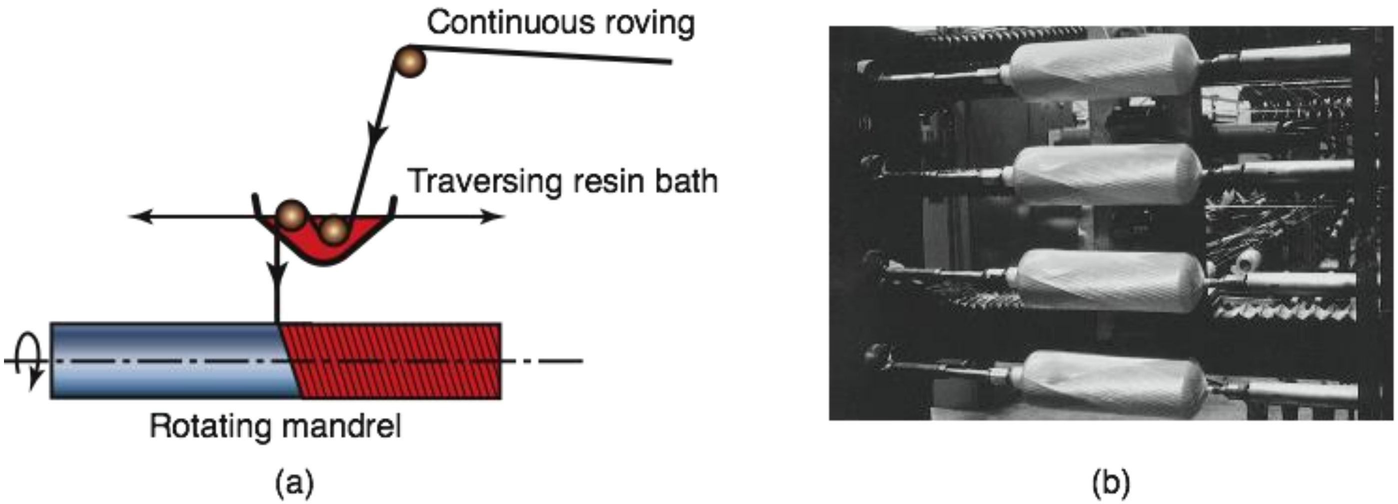


FIGURE 10.44 (a) Schematic illustration of the filament-winding process. (b) Fiberglass being wound over aluminum liners for slide-raft inflation vessels for the Boeing 767 aircraft. *Source:* Advanced Technical Products Group, Inc., Lincoln Composites.

Fiber Spinning

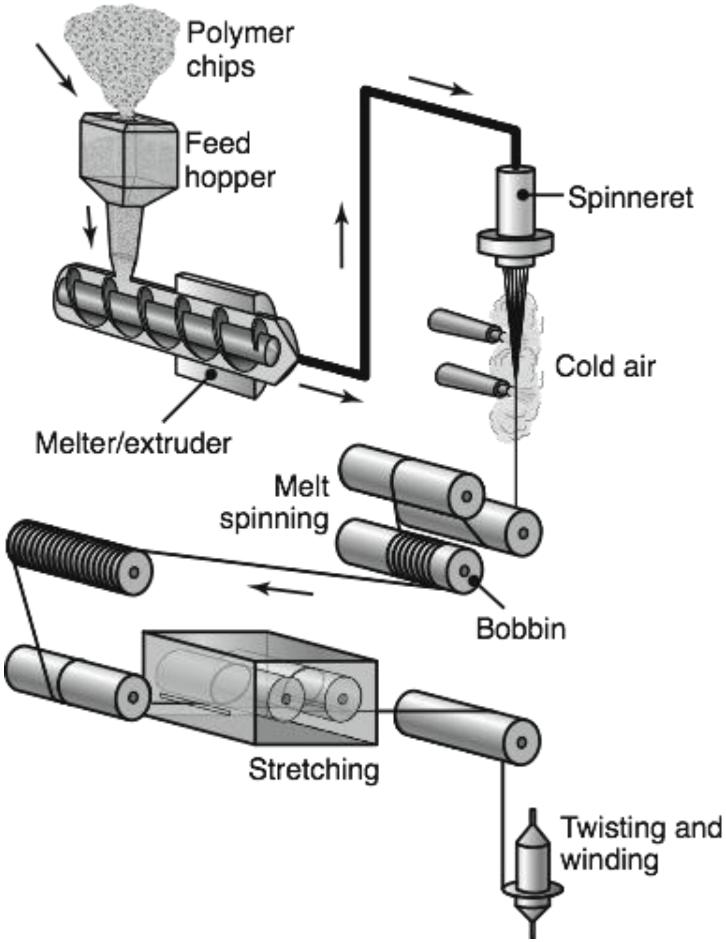


FIGURE 10.1 The melt spinning process for producing polymer fibers. The fibers are used in a variety of applications, including fabrics and as reinforcements for composite materials.

Lamination and Lamination-Type Processes

- Pre-pegs, mats, or tapes are stacked to produce a desired thickness
  - Cured under pressure and heat
- High strength laminate with a smooth, attractive appearance
- Laminated materials can be produced as sheets, tubes, or rods

Lamination

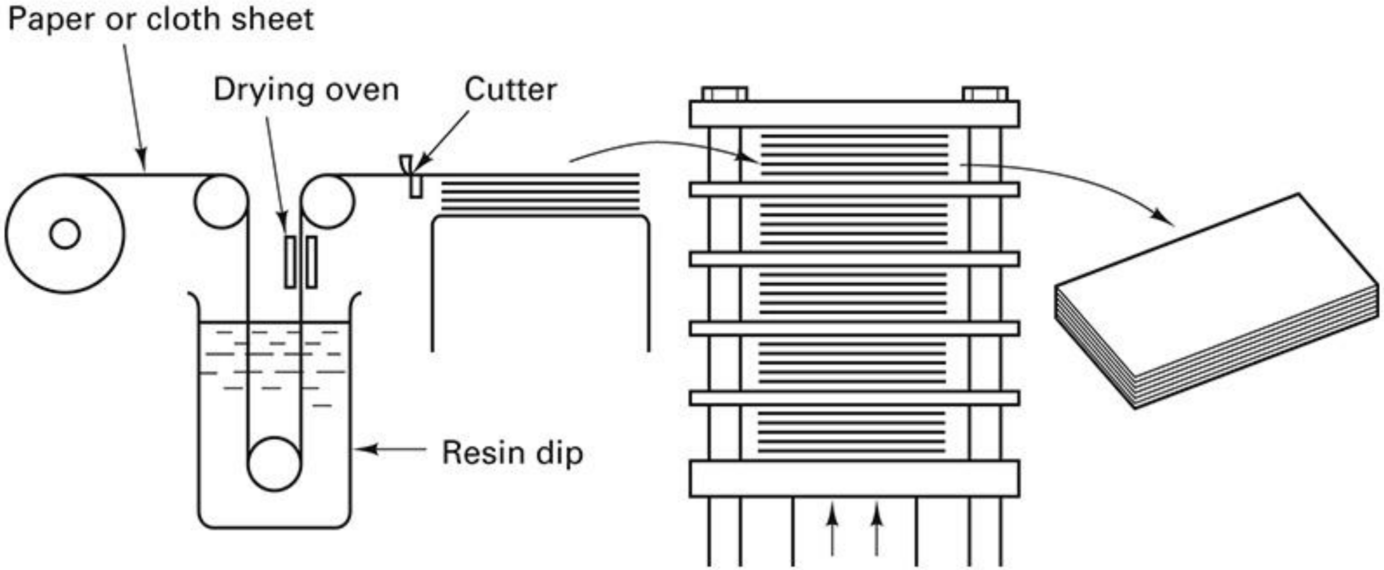


Figure 14-22 Method of producing multiple sheets of laminated plastic material.

Lamination

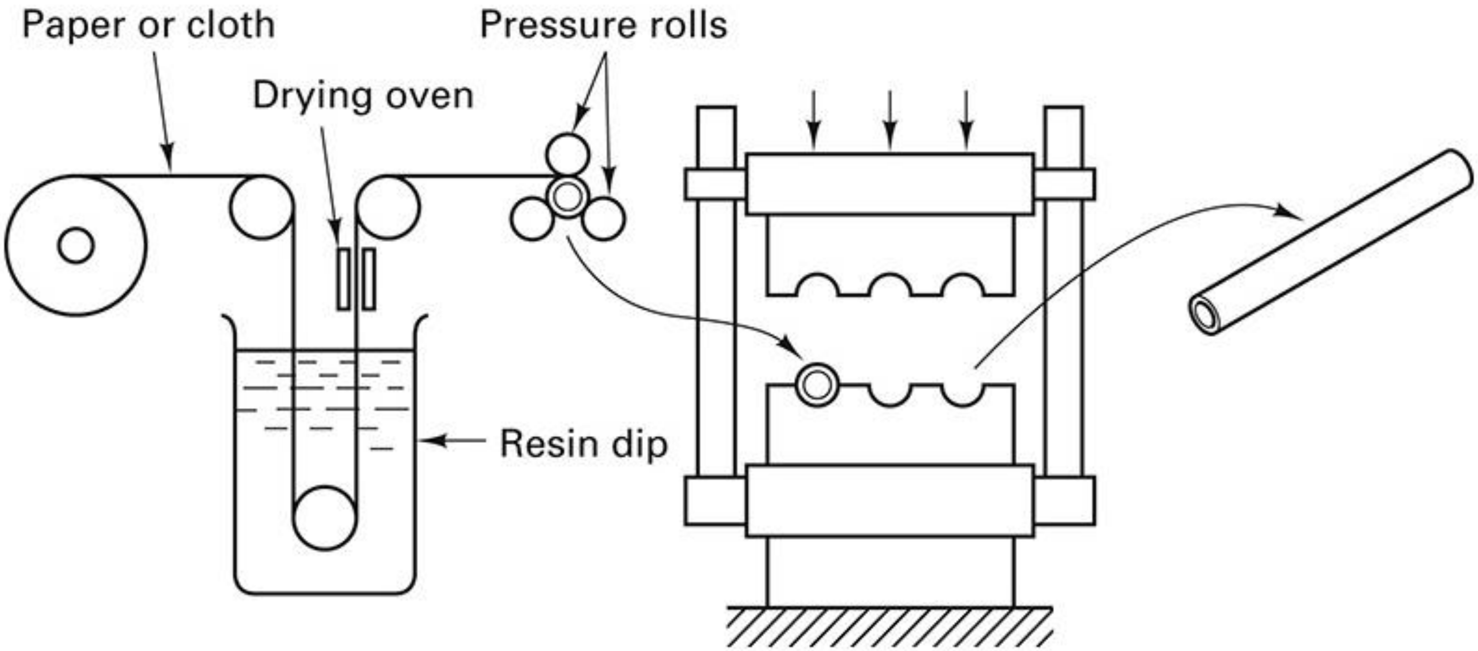


Figure 14-23 Method of producing laminated plastic tubing. In the final operation, the rolled tubes are cured by being held in heated tooling.

Lamination

- Final operation in lamination is curing
  - Typically involves elevated temperatures and/or applied pressure
- Manufacturing processes that require zero to moderate pressures and low curing temperatures can be used to produce simple curves and contours
  - Boat bodies, automobile panels, aerospace panels, safety helmets, etc.

Aerodynamic Styling

Figure 14-24 Aerodynamic styling and smooth surfaces characterize the hood and fender of Ford Motor Company’s AeroMax truck. This one-piece panel was produced as a resin-transfer molding by Rockwell International. (*Courtesy of ASM International, Metals Park, OH.)*

Lamination Processes

- Vacuum bag molding process
  - Entire assembly is placed in a nonadhering, flexible bag and the air is evacuated
- Pressure bag molding
  - A flexible membrane is positioned over the female mold cavity and is pressurized to force the individual plies together
- Parts may be cured in an autoclave
- Compression molding
- Resin-transfer molding

Lamination Processes

- Hand lay-up (open mold processing)
  - Successive layers of pliable resin-coated cloth are placed in an open mold and draped over a form
  - Slow and labor intensive process
  - Low tooling costs
  - Large parts can be made as a single unit

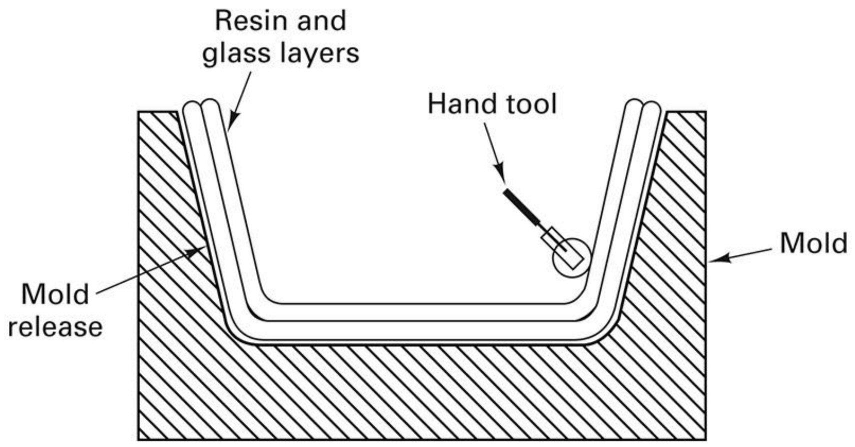
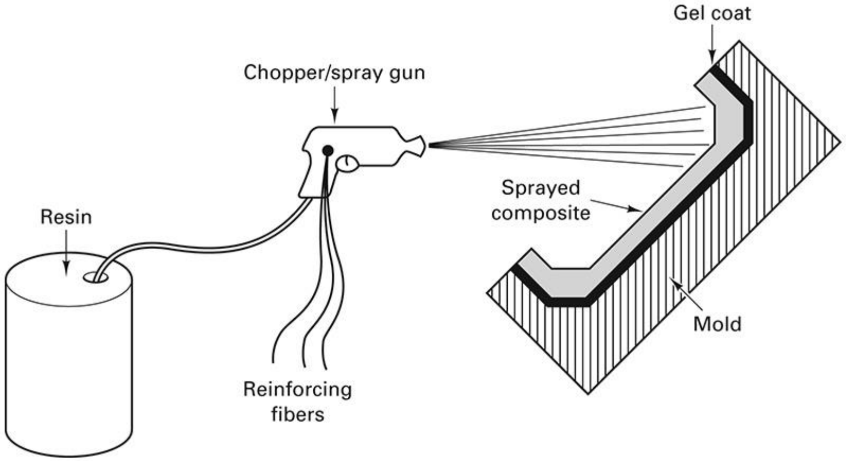


Figure 14-25 Schematic of the hand lay-up lamination process.

Additional Processes

- Spray molding
  - Chopped fibers, fillers, and catalyzed resins are mixed and sprayed onto a mold
- Sheet stamping
  - Thermoplastic sheets are reinforced with nonwoven fibers and press formed
- Injection molding
  - Chopped or continuous fibers are placed in a mold and then a resin is injected
- Braiding, three dimensional knitting, and three-dimensional weaving

Figure 14-26 Schematic diagram of the spray forming of chopped-fiber-reinforced polymeric composite.



Fabrication of Fiber-Reinforced Metal-Matrix Composites

- Continuous-fiber metal-matrix composites can be produced by filament winding, extrusion and pultrusion
- Fiber-reinforced sheets can be made by electroplating, plasma spray deposition coating, or vapor deposition of metal onto a fabric or mesh
- Casting processes
- Products that use discontinuous fibers can be produced by powder metallurgy or spray-forming

Fabrication of Fiber-Reinforced Metal-Matrix Composites

- Concerns with metal-matrix composites
  - Possibility of reactions between the reinforcements and the matrix during processing at the high melting temperatures
- Graphite-reinforced aluminum is twice as stiff as steel and 1/3rd to 1/4th the weight
- Aluminum reinforced with silicon carbide has increased strength as well as hardness, fatigue strength, and elastic modulus

Fabrication of Fiber-Reinforced Ceramic-Matrix Composites

- Often fail due to flaws in the matrix
- Fibers or mats may be passed through a slurry mixture that contains the matrix material and then dried, assembled and fired
- Chemical vapor deposition
- Chemical vapor infiltration
- Hot-pressing

Secondary Processing and Finishing of Fiber-Reinforced Composites

- Most composites can be processed further with conventional equipment
  - Sawed, drilled, routed, tapped, threaded, etc.
- Composites are not uniform materials, so care should be taken
- Sharp tools, high speeds, and low feeds are generally required
- Many of the reinforcing fibers are abrasive and quickly dull the cutting tools

Summary

- Plastics, ceramics, and composites use a variety of manufacturing techniques
- The final shape and desired properties of these materials dictate which processes should be used
- Temperature is often a concern when selecting the proper manufacturing process

Chapter 21: Fundamentals of Chip-Type Machining Processes

DeGarmo’s Materials and Processes in Manufacturing

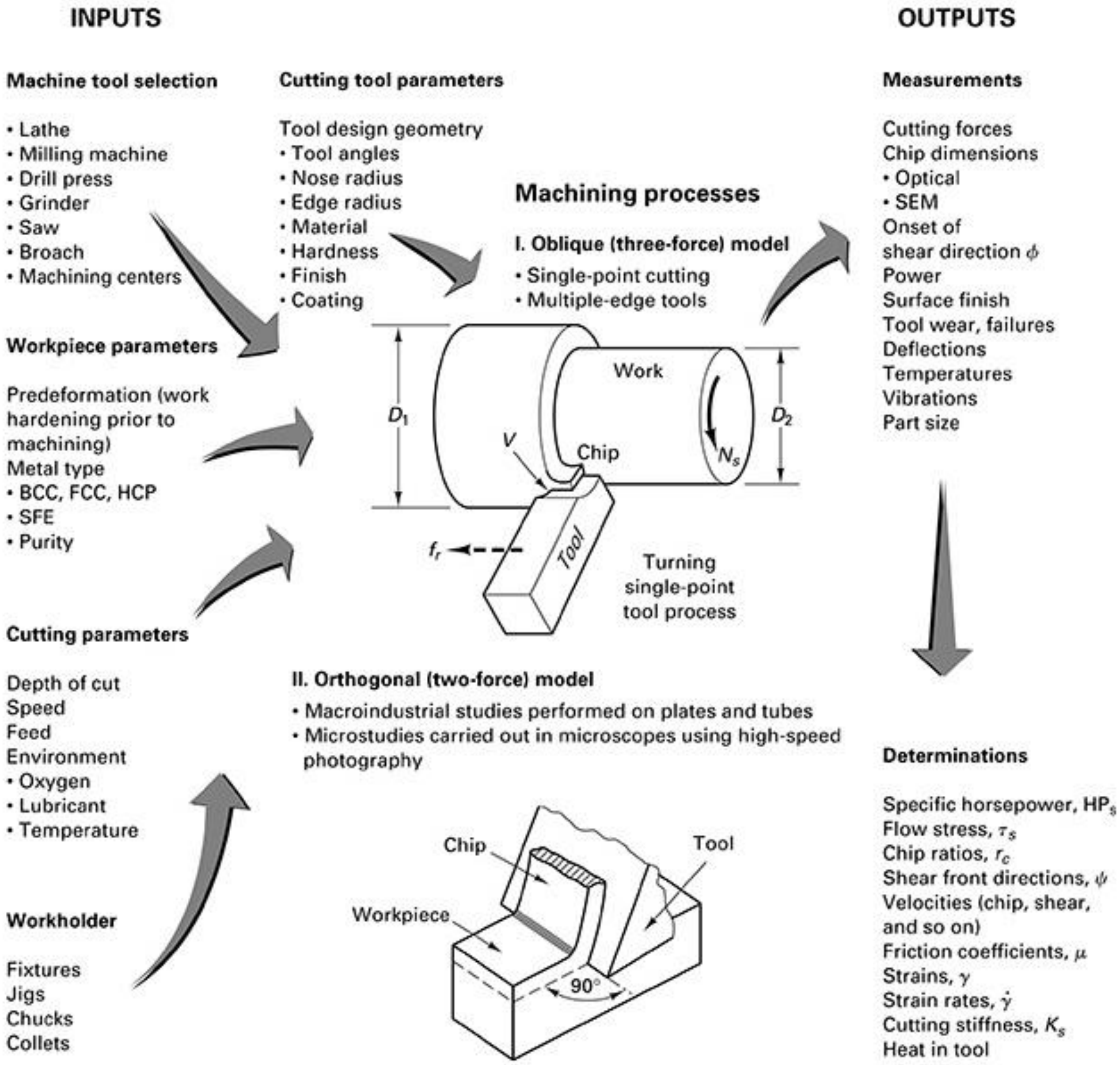
20.1 Introduction

Machining: The process of removing unwanted material in the form of chips.

The process is unique and difficult to analyze because:

- Different materials behave differently
- Unconstrained process
- The level of strain is very high
- The strain rate is very high
- The process is sensitive to variations in tool geometry, material, temperature, cutting fluid.

FIGURE 20-1 The fundamental inputs and outputs to machining processes.



20.2 Fundementals

- Basic chip formation processes: shaping, turning, milling, drilling, sawing, broaching, and grinding
- Important terms: Speed (V), feed (f), Depth of cut (DOF) or (d), metal removal rate (MRR), cutting time (CT).
- Each material to be cut has its input parameters (V, f, and d) as shown in Table 20.4

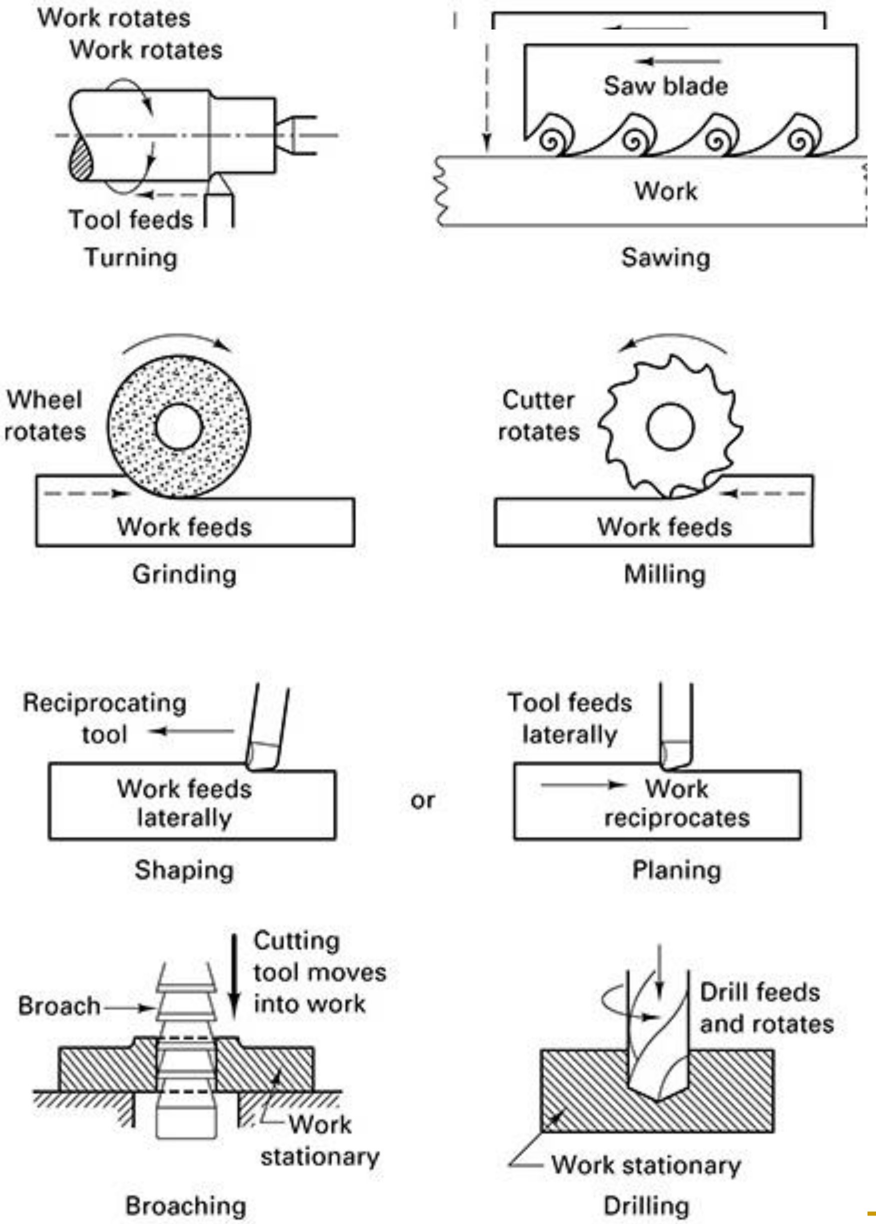
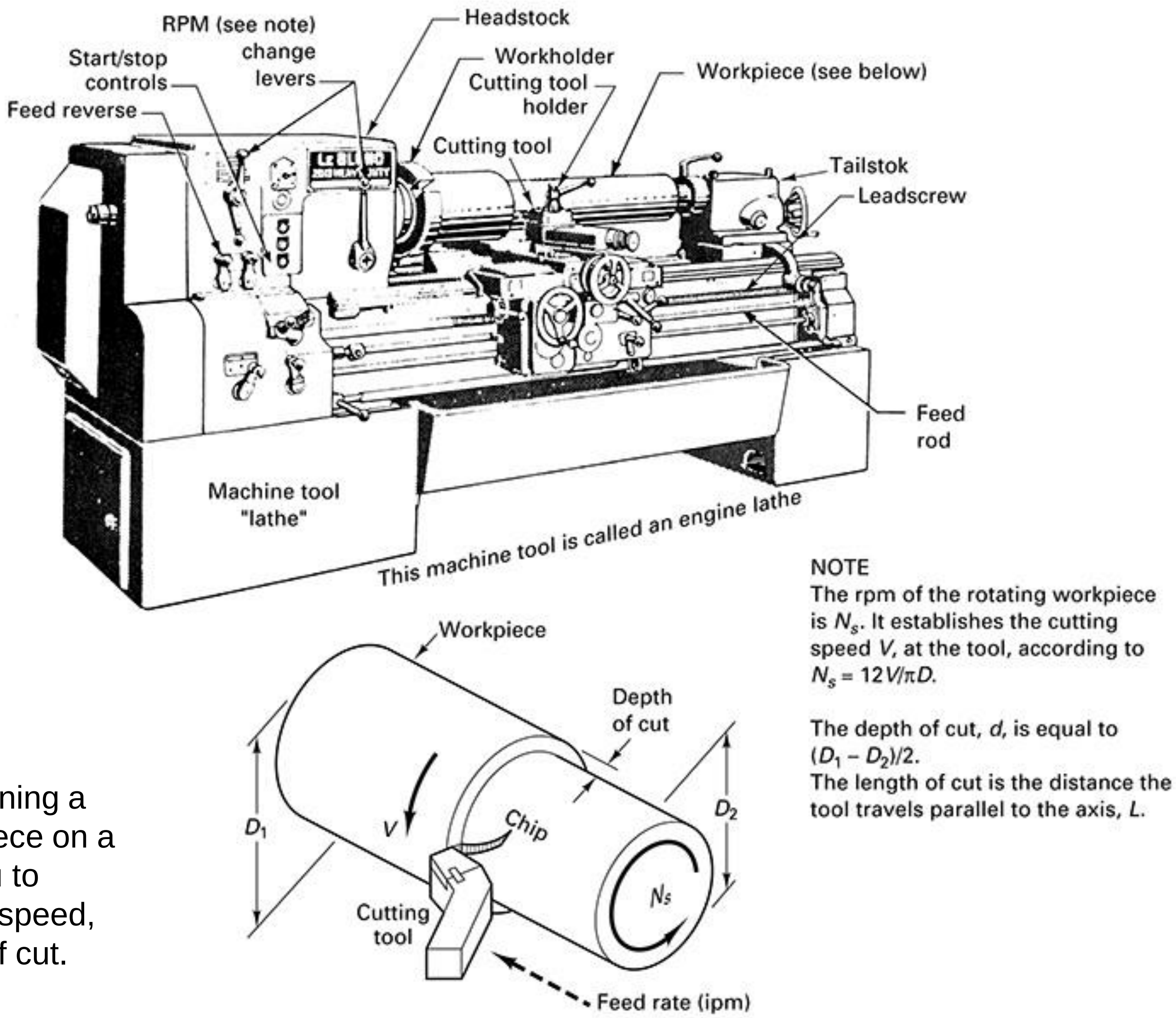


FIGURE 20-2 The seven basic machining processes used in chip formation.



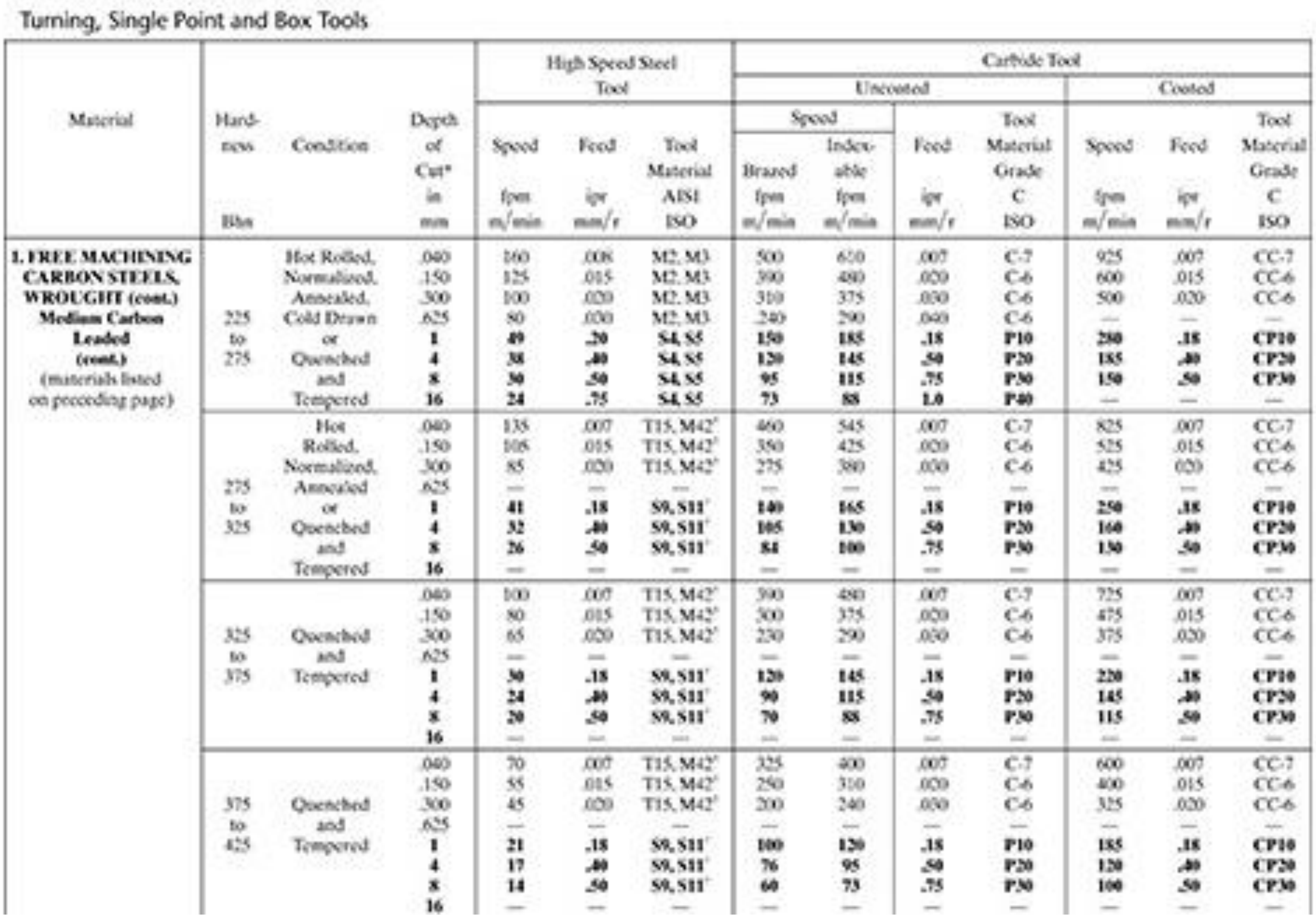
NOTE

The rpm of the rotating workpiece is N_s. It establishes the cutting speed V, at the tool, according to $N_s = 12V/\pi D$.

The depth of cut, d, is equal to $(D_1 - D_2)/2$.

The length of cut is the distance the tool travels parallel to the axis, L.

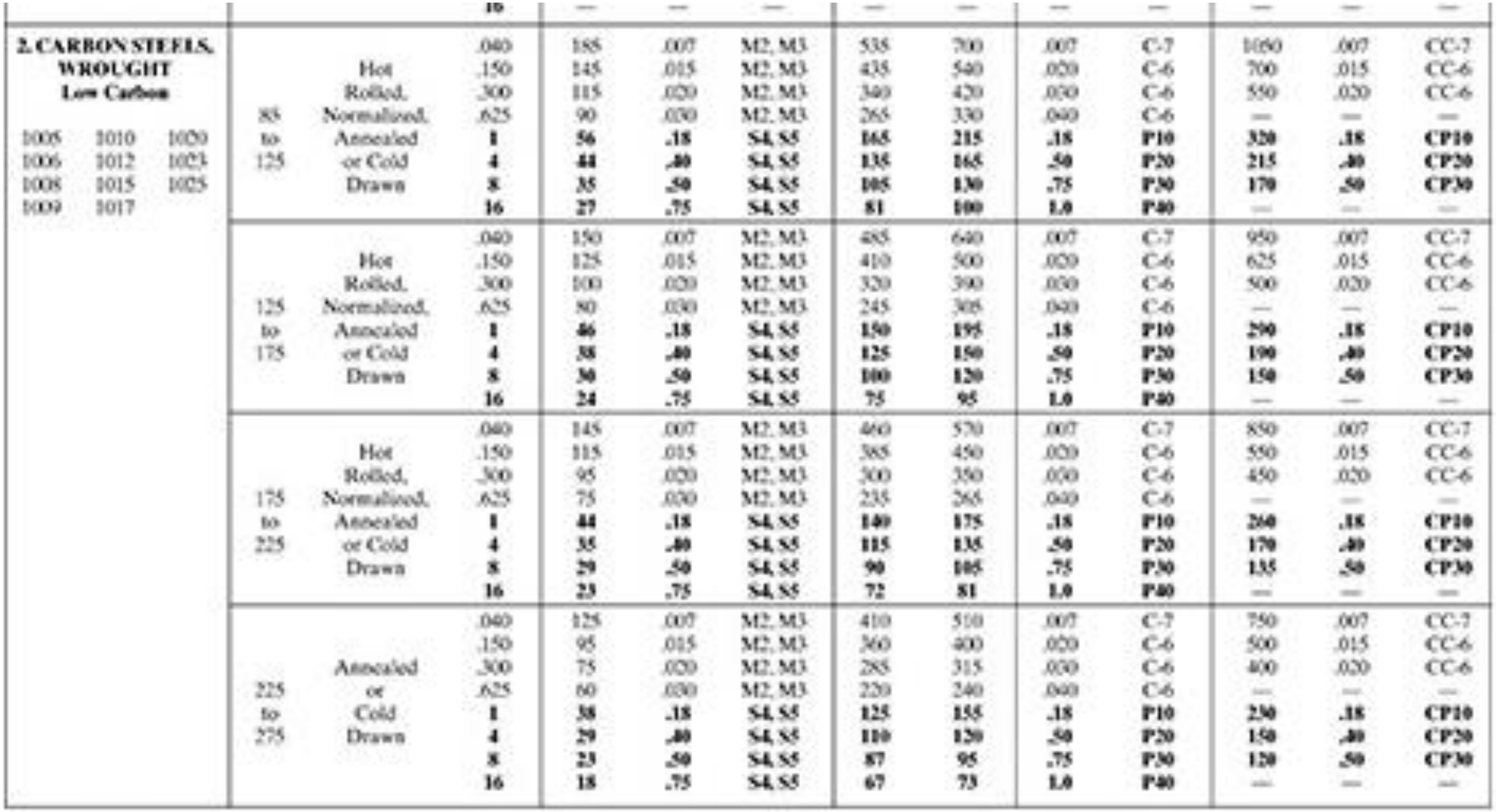
FIGURE 20-3 Turning a cylindrical workpiece on a lathe requires you to select the cutting speed, feed, and depth of cut.



Turning, Single Point and Box Tools

Material	Hardness Bhn	Condition	Depth of Cut* in mm	High Speed Steel Tool			Carbide Tool						
							Uncoated				Coated		
				Speed fpm m/min	Feed ipr mm/r	Tool Material AISI ISO	Speed Brazed fpm m/min	Speed Indexable fpm m/min	Feed ipr mm/r	Tool Material Grade C ISO	Speed fpm m/min	Feed ipr mm/r	Tool Material Grade C ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Leaded (cont.)** (materials listed on preceding page)	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	.040	160	.008	M2, M3	500	610	.007	C-7	925	.007	CC-7
			.150	125	.015	M2, M3	390	480	.020	C-6	600	.015	CC-6
			.300	100	.020	M2, M3	310	375	.030	C-6	500	.020	CC-6
			.625	80	.030	M2, M3	240	290	.040	C-6	—	—	—
			1	**49**	**.20**	**S4, S5**	**150**	**185**	**.18**	**P10**	**280**	**.18**	**CP10**
			4	**38**	**.40**	**S4, S5**	**120**	**145**	**.50**	**P20**	**185**	**.40**	**CP20**
			8	**30**	**.50**	**S4, S5**	**95**	**115**	**.75**	**P30**	**150**	**.50**	**CP30**
			16	**24**	**.75**	**S4, S5**	**73**	**88**	**1.0**	**P40**	—	—	—
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	.040	135	.007	T15, M42[*]	460	545	.007	C-7	825	.007	CC-7
			.150	105	.015	T15, M42[*]	350	425	.020	C-6	525	.015	CC-6
			.300	85	.020	T15, M42[*]	275	380	.030	C-6	425	.020	CC-6
			.625	—	—	—	—	—	—	—	—	—	—
			1	**41**	**.18**	**S9, S11**[†]	**140**	**165**	**.18**	**P10**	**250**	**.18**	**CP10**
			4	**32**	**.40**	**S9, S11**[†]	**105**	**130**	**.50**	**P20**	**160**	**.40**	**CP20**
			8	**26**	**.50**	**S9, S11**[†]	**84**	**100**	**.75**	**P30**	**130**	**.50**	**CP30**
			16	—	—	—	—	—	—	—	—	—	—
	325 to 375	Quenched and Tempered	.040	100	.007	T15, M42[*]	390	480	.007	C-7	725	.007	CC-7
			.150	80	.015	T15, M42[*]	300	375	.020	C-6	475	.015	CC-6
			.300	65	.020	T15, M42[*]	230	290	.030	C-6	375	.020	CC-6
			.625	—	—	—	—	—	—	—	—	—	—
			1	**30**	**.18**	**S9, S11**[†]	**120**	**145**	**.18**	**P10**	**220**	**.18**	**CP10**
			4	**24**	**.40**	**S9, S11**[†]	**90**	**115**	**.50**	**P20**	**145**	**.40**	**CP20**
			8	**20**	**.50**	**S9, S11**[†]	**70**	**88**	**.75**	**P30**	**115**	**.50**	**CP30**
			16	—	—	—	—	—	—	—	—	—	—
	375 to 425	Quenched and Tempered	.040	70	.007	T15, M42[*]	325	400	.007	C-7	600	.007	CC-7
			.150	55	.015	T15, M42[*]	250	310	.020	C-6	400	.015	CC-6
			.300	45	.020	T15, M42[*]	200	240	.030	C-6	325	.020	CC-6
			.625	—	—	—	—	—	—	—	—	—	—
			1	**21**	**.18**	**S9, S11**[†]	**100**	**120**	**.18**	**P10**	**185**	**.18**	**CP10**
			4	**17**	**.40**	**S9, S11**[†]	**76**	**95**	**.50**	**P20**	**120**	**.40**	**CP20**
			8	**14**	**.50**	**S9, S11**[†]	**60**	**73**	**.75**	**P30**	**100**	**.50**	**CP30**
			16	—	—	—	—	—	—	—	—	—	—

FIGURE 20-4 Examples of a table for selection of speed and feed for turning. *(Source:* Metcut's Machinability Data Handbook.*)*



			16	—	—	—	—	—	—	—	—	—	—
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1010 1020 1006 1012 1023 1008 1015 1025 1009 1017	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	185	.007	M2, M3	535	700	.007	C-7	1050	.007	CC-7
			.150	145	.015	M2, M3	435	540	.020	C-6	700	.015	CC-6
			.300	115	.020	M2, M3	340	420	.030	C-6	550	.020	CC-6
			.625	90	.030	M2, M3	265	330	.040	C-6	—	—	—
			1	56	.18	S4, S5	165	215	.18	P10	320	.18	CP10
			4	44	.40	S4, S5	135	165	.50	P20	215	.40	CP20
			8	35	.50	S4, S5	105	130	.75	P30	170	.50	CP30
			16	27	.75	S4, S5	81	100	1.0	P40	—	—	—
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	150	.007	M2, M3	485	640	.007	C-7	950	.007	CC-7
			.150	125	.015	M2, M3	410	500	.020	C-6	625	.015	CC-6
			.300	100	.020	M2, M3	320	390	.030	C-6	500	.020	CC-6
			.625	80	.030	M2, M3	245	305	.040	C-6	—	—	—
			1	46	.18	S4, S5	150	195	.18	P10	290	.18	CP10
			4	38	.40	S4, S5	125	150	.50	P20	190	.40	CP20
			8	30	.50	S4, S5	100	120	.75	P30	150	.50	CP30
			16	24	.75	S4, S5	75	95	1.0	P40	—	—	—
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	.040	145	.007	M2, M3	460	570	.007	C-7	850	.007	CC-7
			.150	115	.015	M2, M3	385	450	.020	C-6	550	.015	CC-6
			.300	95	.020	M2, M3	300	350	.030	C-6	450	.020	CC-6
			.625	75	.030	M2, M3	235	265	.040	C-6	—	—	—
			1	44	.18	S4, S5	140	175	.18	P10	260	.18	CP10
			4	35	.40	S4, S5	115	135	.50	P20	170	.40	CP20
			8	29	.50	S4, S5	90	105	.75	P30	135	.50	CP30
			16	23	.75	S4, S5	72	81	1.0	P40	—	—	—
	225 to 275	Annealed or Cold Drawn	.040	125	.007	M2, M3	410	510	.007	C-7	750	.007	CC-7
			.150	95	.015	M2, M3	360	400	.020	C-6	500	.015	CC-6
			.300	75	.020	M2, M3	285	315	.030	C-6	400	.020	CC-6
			.625	60	.030	M2, M3	220	240	.040	C-6	—	—	—
			1	38	.18	S4, S5	125	155	.18	P10	230	.18	CP10
			4	29	.40	S4, S5	110	120	.50	P20	150	.40	CP20
			8	23	.50	S4, S5	87	95	.75	P30	120	.50	CP30
			16	18	.75	S4, S5	67	73	1.0	P40	—	—	—

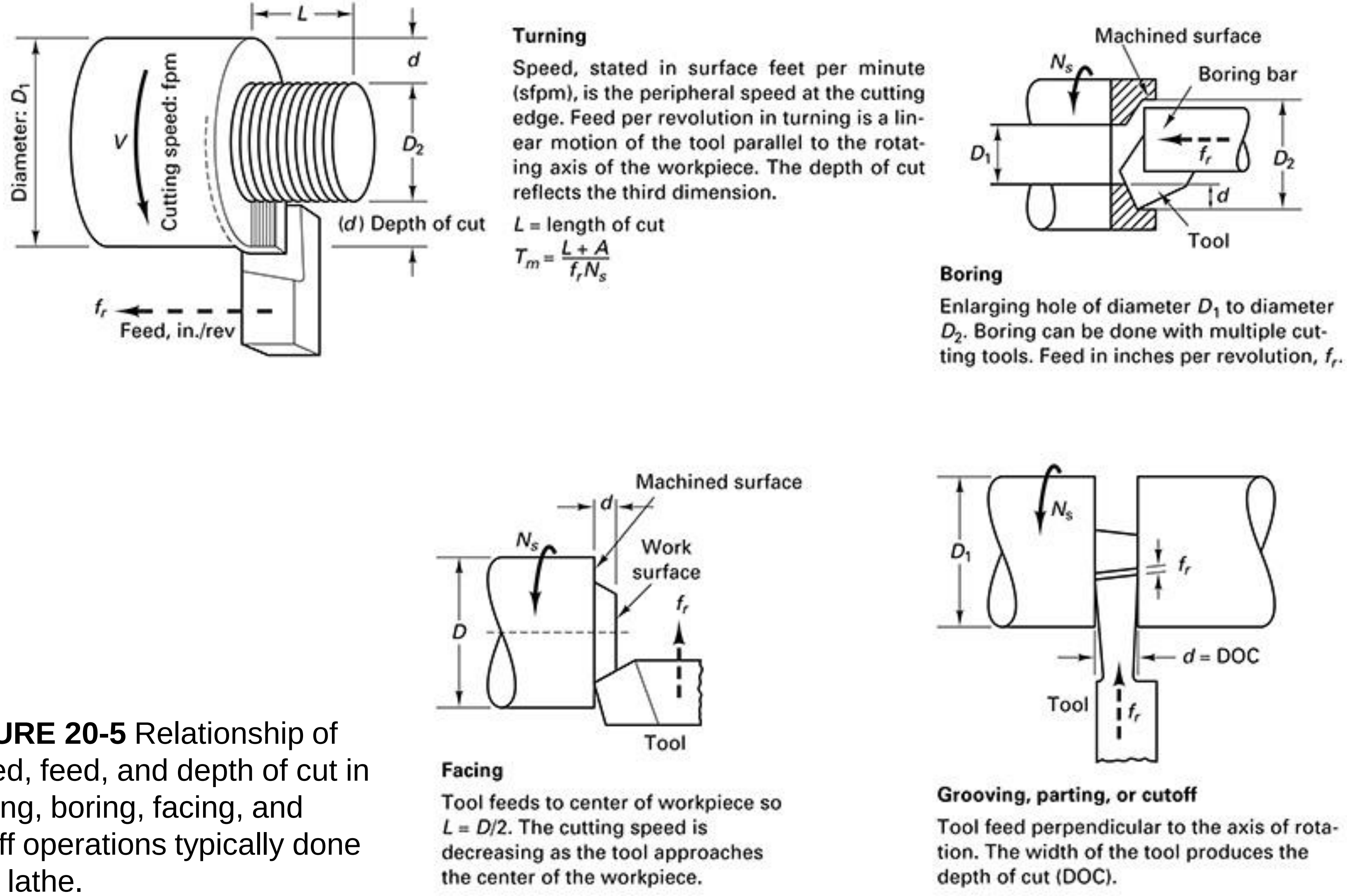
See section 15.1 for Tool Geometry.

*Caution: Check Horsepower requirements on heavier depths of cut.

See section 16 for Cutting Fluid Recommendations.

[†] Any premium HSS (T15, M33, M41–M47) or (S9, S10, S11, S12).

FIGURE 20-4 Examples of a table for selection of speed and feed for turning. *(Source:* Metcut's Machinability Data Handbook.*)*



Turning

Speed, stated in surface feet per minute (sfpm), is the peripheral speed at the cutting edge. Feed per revolution in turning is a linear motion of the tool parallel to the rotating axis of the workpiece. The depth of cut reflects the third dimension.

L = length of cut

$$T_m = \frac{L + A}{f_r N_s}$$

Boring

Enlarging hole of diameter D_1 to diameter D_2. Boring can be done with multiple cutting tools. Feed in inches per revolution, f_r.

Facing

Tool feeds to center of workpiece so $L = D/2$. The cutting speed is decreasing as the tool approaches the center of the workpiece.

Grooving, parting, or cutoff

Tool feed perpendicular to the axis of rotation. The width of the tool produces the depth of cut (DOC).

FIGURE 20-5 Relationship of speed, feed, and depth of cut in turning, boring, facing, and cutoff operations typically done on a lathe.

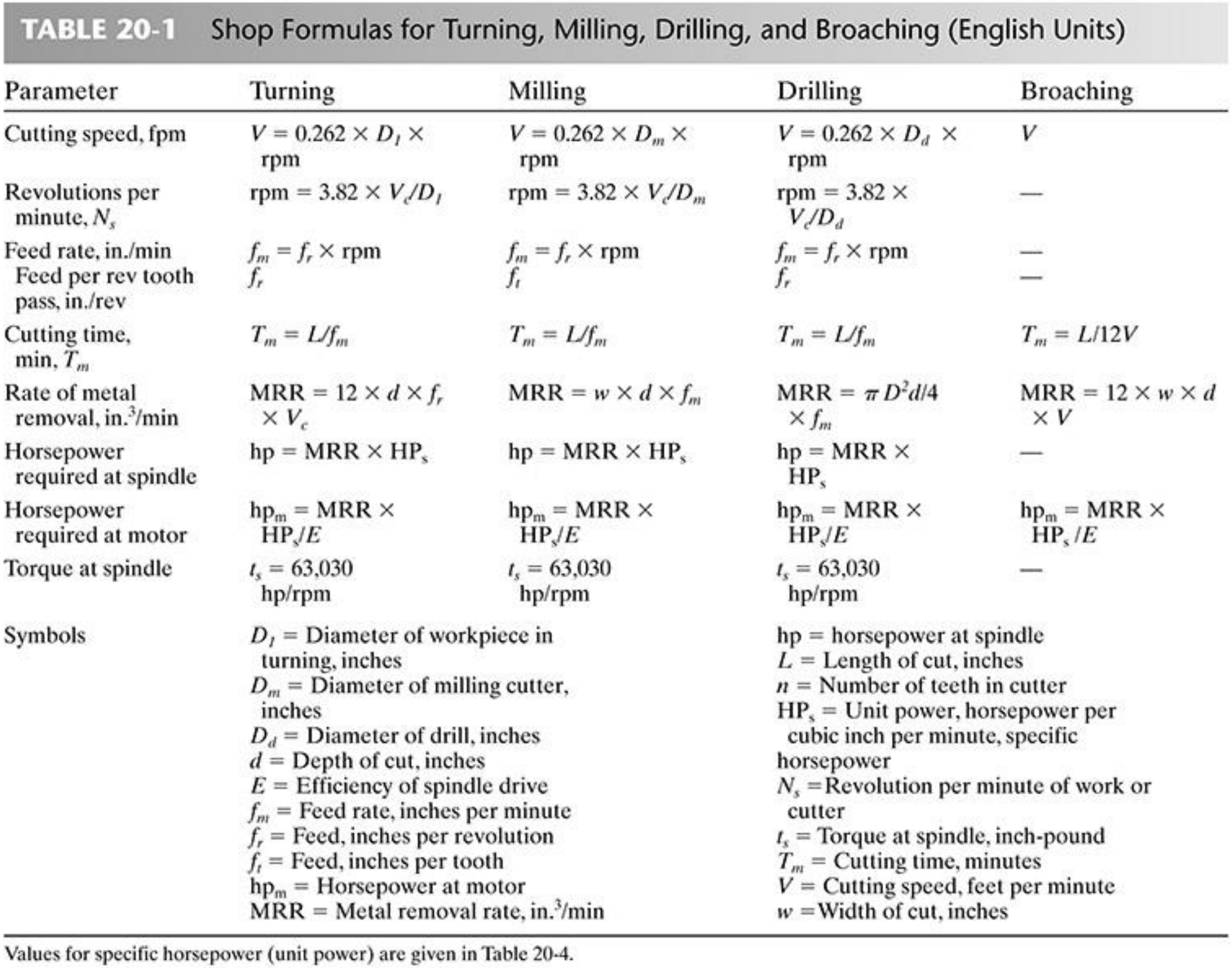
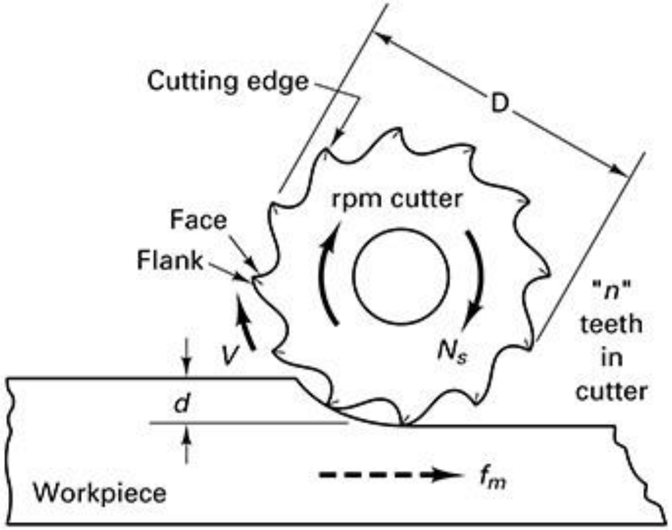


TABLE 20-1 Shop Formulas for Turning, Milling, Drilling, and Broaching (English Units)

Parameter	Turning	Milling	Drilling	Broaching
Cutting speed, fpm	$V = 0.262 \times D_t \times$ rpm	$V = 0.262 \times D_m \times$ rpm	$V = 0.262 \times D_d \times$ rpm	V
Revolutions per minute, N_s	rpm $= 3.82 \times V_c/D_t$	rpm $= 3.82 \times V_c/D_m$	rpm $= 3.82 \times V_c/D_d$	—
Feed rate, in./min	$f_m = f_r \times$ rpm	$f_m = f_r \times$ rpm	$f_m = f_r \times$ rpm	—
Feed per rev tooth pass, in./rev	f_r	f_t	f_r	—
Cutting time, min, T_m	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/12V$
Rate of metal removal, in.^{3}/min	MRR $= 12 \times d \times f_r \times V_c$	MRR $= w \times d \times f_m$	MRR $= \pi D^2 d/4 \times f_m$	MRR $= 12 \times w \times d \times V$
Horsepower required at spindle	hp $=$ MRR $\times$ HP$_s$	hp $=$ MRR $\times$ HP$_s$	hp $=$ MRR $\times$ HP$_s$	—
Horsepower required at motor	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$	hp$_m$ $=$ MRR $\times$ HP$_s/E$
Torque at spindle	$t_s = 63{,}030$ hp/rpm	$t_s = 63{,}030$ hp/rpm	$t_s = 63{,}030$ hp/rpm	—
Symbols	D_t = Diameter of workpiece in turning, inches D_m = Diameter of milling cutter, inches D_d = Diameter of drill, inches d = Depth of cut, inches E = Efficiency of spindle drive f_m = Feed rate, inches per minute f_r = Feed, inches per revolution f_t = Feed, inches per tooth hp$_m$ = Horsepower at motor MRR = Metal removal rate, in.^{3}/min		hp = horsepower at spindle L = Length of cut, inches n = Number of teeth in cutter HP$_s$ = Unit power, horsepower per cubic inch per minute, specific horsepower N_s = Revolution per minute of work or cutter t_s = Torque at spindle, inch-pound T_m = Cutting time, minutes V = Cutting speed, feet per minute w = Width of cut, inches	

Values for specific horsepower (unit power) are given in Table 20-4.



Slab milling – multiple tooth

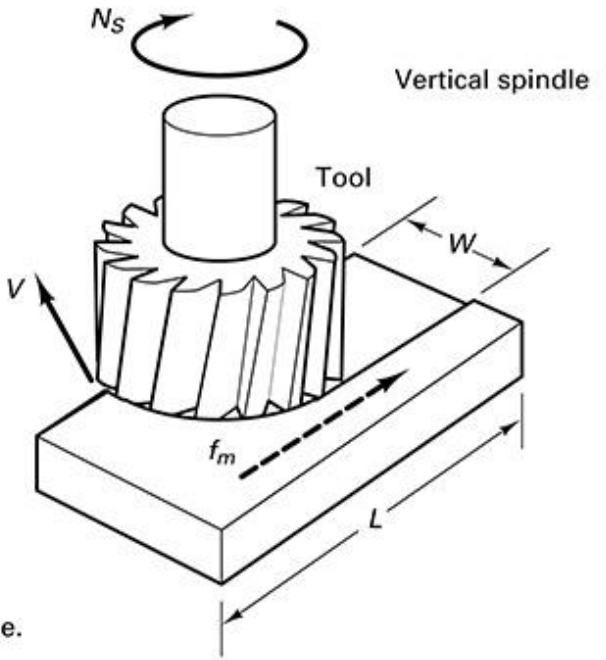
Slab milling is usually performed on a horizontal milling machine. Equations for T_m and MRR derived in Chapter 25.

The tool rotates at rpm N_s. The workpiece translates past the cutter at feed rate f_m, the table feed. The length of cut, L, is the length of workpiece plus allowance, L_A,

$$L_A = \sqrt{\frac{D^2}{4} - \left(\frac{D}{2} - d\right)^2} = \sqrt{d(D-d)} \text{ inches}$$

$$T_m = (L + L_A)/f_m$$

The MRR $= Wdf_m$ where $W =$ width of the cut and $d =$ depth of cut.



Face milling
Multiple-tooth cutting

Given a selected cutting speed V and a feed per tooth f_t, the rpm of the cutter is $N_s = 12V/\pi D$ for a cutting of diameter D. The table feed rate is $f_m = f_t n N_s$ for a cutter with n teeth.

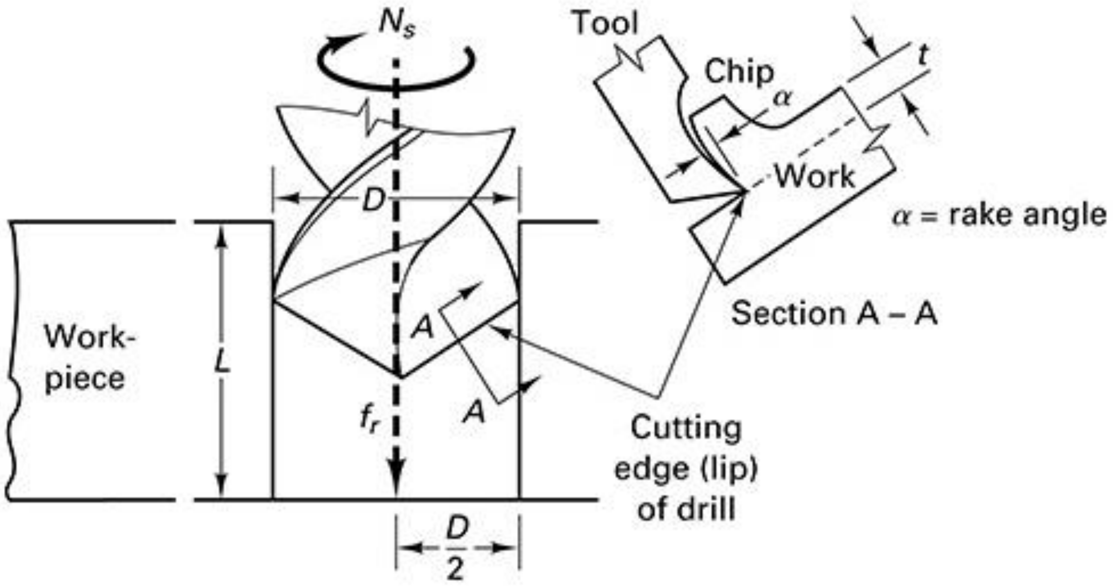
The cutting time, $T_m = (L + L_A + L_o)/f_m$

where $L_o = L_A = \sqrt{W(D-W)}$ for $W < D/2$

or $L_o = L_A = D/2$ for $W \geqslant D/2$.

The MRR $= Wdf_m$ where $d =$ depth of cut.

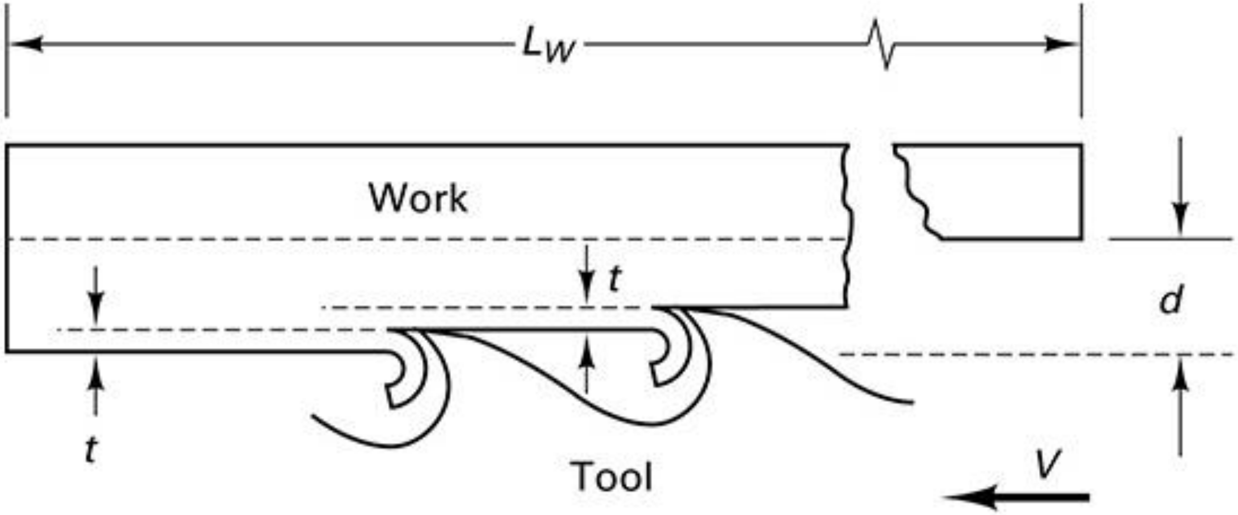
FIGURE 20-6 Basics of milling processes (slab, face, and end milling) including equations for cutting time and metal removal rate (MRR).



Drilling multiple-edge tool

Select cutting speed V, fpm and feed, f_r, in./rev. Select drill.
D = diameter of the drill which rotates 2 cutting edges at rpm N_s. V = velocity of outer edge of the lip of the drill.
$N_s = 12V/\pi D$. T_m = cutting time = $(L + A)/f_r N_s$ where f_r is the feed rate in in. per rev. The allowance $A = D/2$.
The MRR = $(\pi D^2/4) f_r N_s$ in.^{3} /min which is approximately $3DVf_r$.

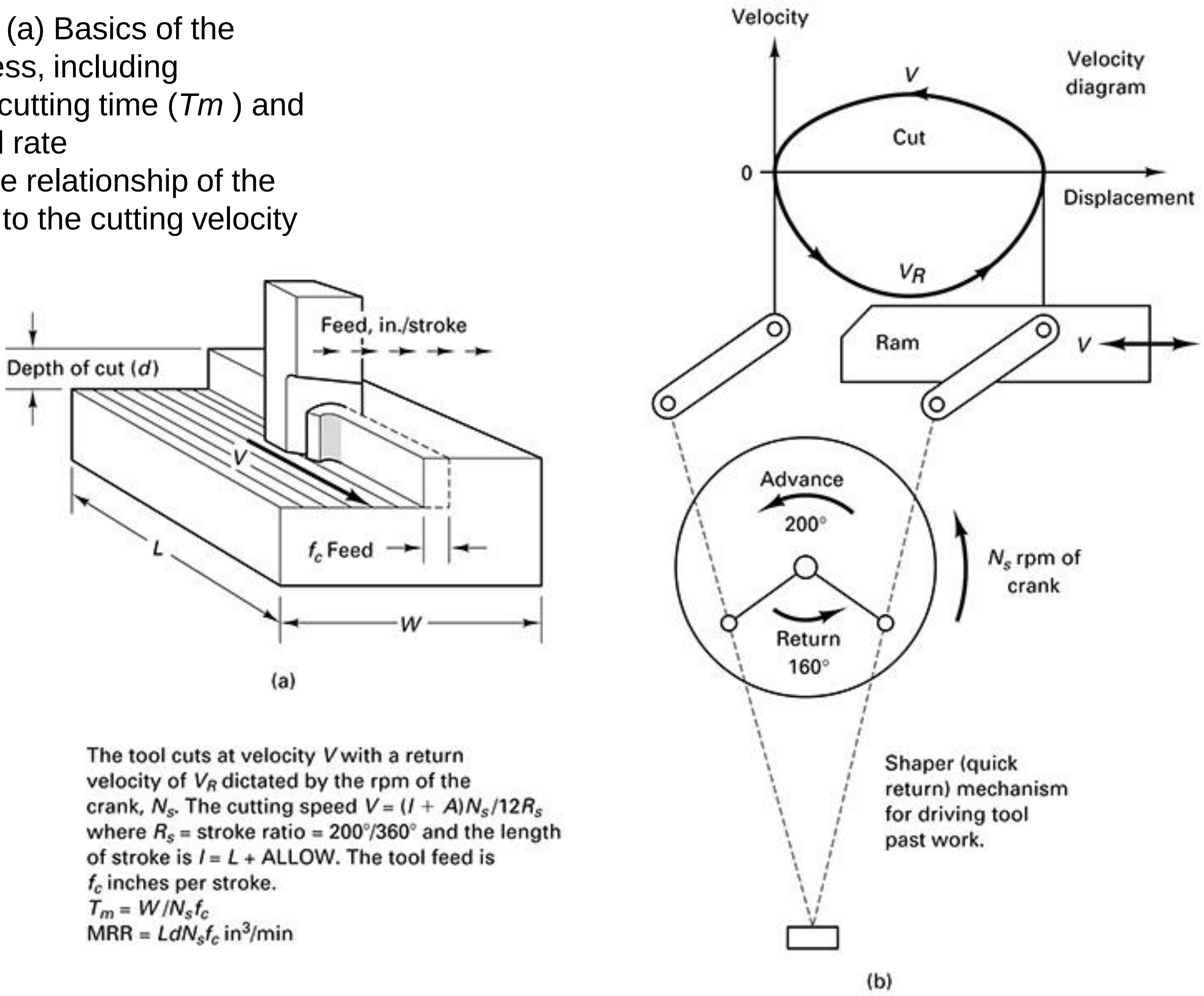
FIGURE 20-7 Basics of the drilling (hole-making) processes, including equations for cutting time and metal removal rate (MRR).



The T_m for broaching is $T_m = L/12V$. The MRR (per tooth) is $12tWV$ in.^{3}/min where V = cutting velocity in fpm, W is the width of cut, t = rise per tooth.

FIGURE 20-8 Process basics of broaching. Equations for cutting time and metal removal rate (MRR) are developed in Chapter 26

FIGURE 20-9 (a) Basics of the shaping process, including equations for cutting time (*Tm*) and metal removal rate (MRR). (b) The relationship of the crank rpm *Ns* to the cutting velocity *V*.



The tool cuts at velocity V with a return velocity of V_R dictated by the rpm of the crank, N_s. The cutting speed $V = (l + A)N_s/12R_s$ where R_s = stroke ratio = 200°/360° and the length of stroke is $l = L + \text{ALLOW}$. The tool feed is f_c inches per stroke.

$T_m = W/N_s f_c$

$\text{MRR} = LdN_s f_c \text{ in}^3/\text{min}$

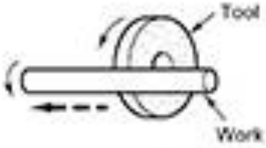
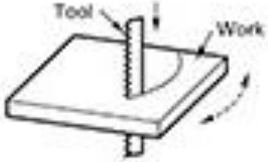
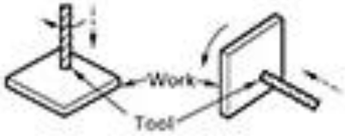
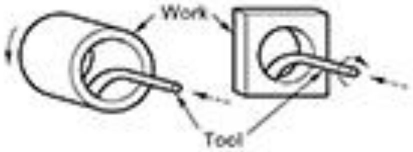
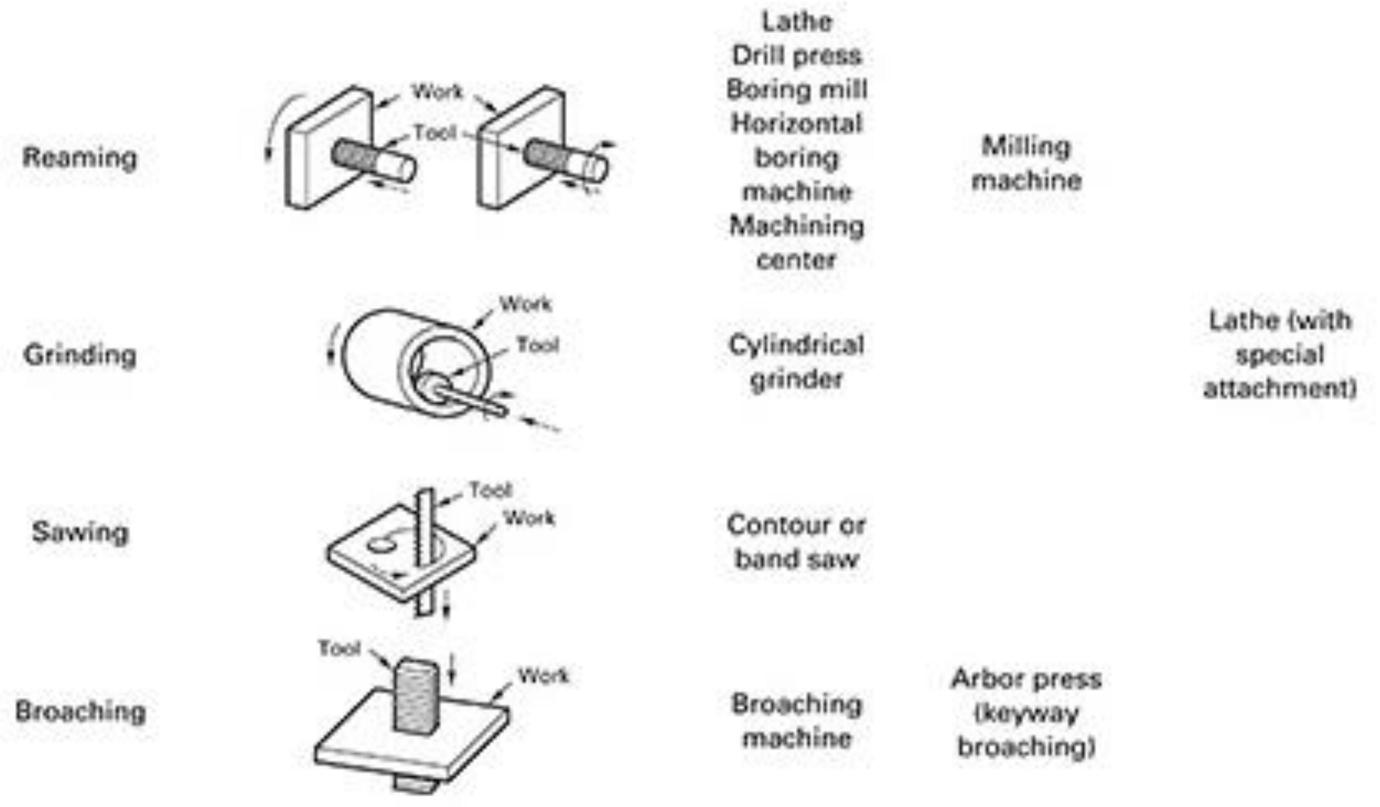
Operation	Block diagram	Most commonly used machines	Machines less frequently used	Machines seldom used
Turning		Lathe NC lathe machining center	Boring mill	Turret lathe
Grinding		Cylindrical grinder		Lathe (with special attachment)
Sawing (of plates and sheets)		Contour or band saw	Laser Flame cutting Plasma arc	
Drilling		Drill press Machining center (nc) Vert. milling machine	Lathe Horizontal boring machine	Horizontal milling machine Boring mill
Boring		Lathe Boring mill Horizontal boring machine Machining center		Milling machine Drill press

FIGURE 20-10 Operations and machines used for machining cylindrical surfaces.



Reaming	Lathe Drill press Boring mill Horizontal boring machine Machining center	Milling machine	
Grinding	Cylindrical grinder		Lathe (with special attachment)
Sawing	Contour or band saw		
Broaching	Broaching machine	Arbor press (keyway broaching)	

FIGURE 20-10 Operations and machines used for machining cylindrical surfaces.

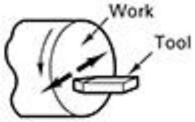
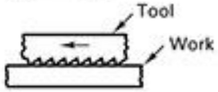
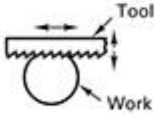
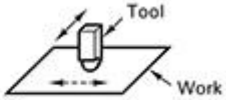
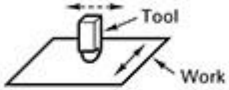
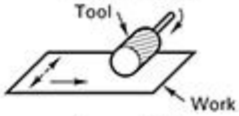
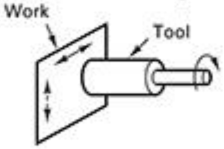
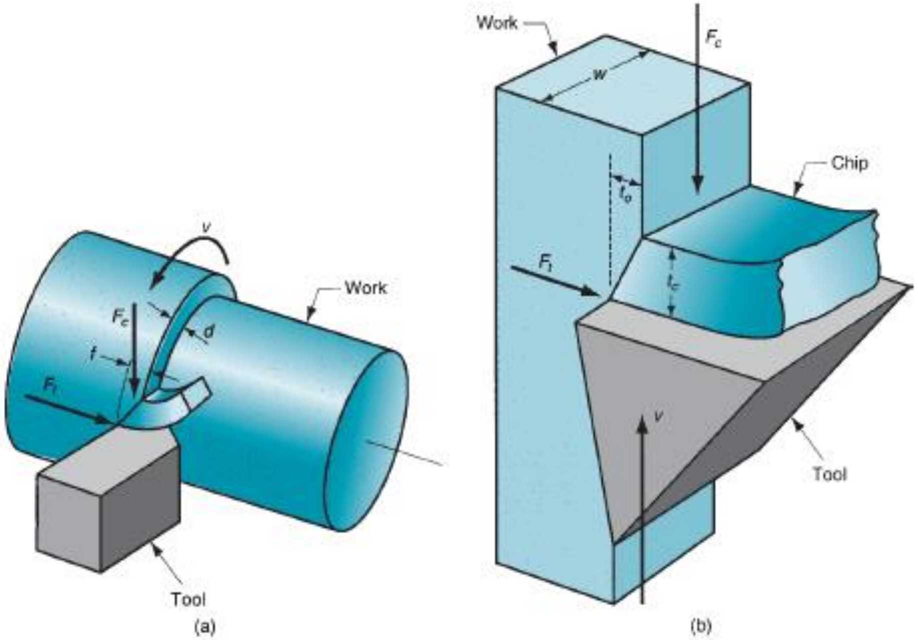
Operation	Block diagram	Most commonly used machines	Machines less frequently used	Machines seldom used
Facing		Lathe	Boring mill	
Broaching		Broaching machine		Turret broach
Grinding		Surface grinder		Lathe (with special attachment)
Sawing		Cutoff saw	Contour saw	
Shaping		Horizontal shaper	Vertical shaper	
Planing		Planer		
Milling	slab milling 	Milling machine	Lathe with special milling tools	
	face milling 	Milling machine Machining center	Lathe with special milling tools	Drill press (light cuts)

FIGURE 20-11 Operations and machines used to generate flat surfaces.

Understanding Chip Formation

- **Oblique machining**: - Three dimensional representation
- - Difficult to analyze
- **Orthogonal machining**: two-dimensional
- used to explain the mechanics of metal cutting
- Chip formation is a shearing process along the shear plane. The mechanics of shearing is: compression, plastic deformation, work hardening, and failure (shearing).

FIGURE 21.13 Approximation of turning by the orthogonal model: (a) turning; and (b) the corresponding orthogonal cutting.



20.3 Energy and Power in Machining

- The three components of forces in Oblique cutting:
- F_c: primary cutting force in the direction of the cutting velocity and it accounts for 99% of the power
- F_f: feed force in the direction of feed v_f and is usually 50% of F_c. It is a small percentage of the power (feed speed is low compared to cutting speed)
- F_r: radial or thrust force and is about 50% of F_f. It contributes very little to power (velocity in its direction is negligible)

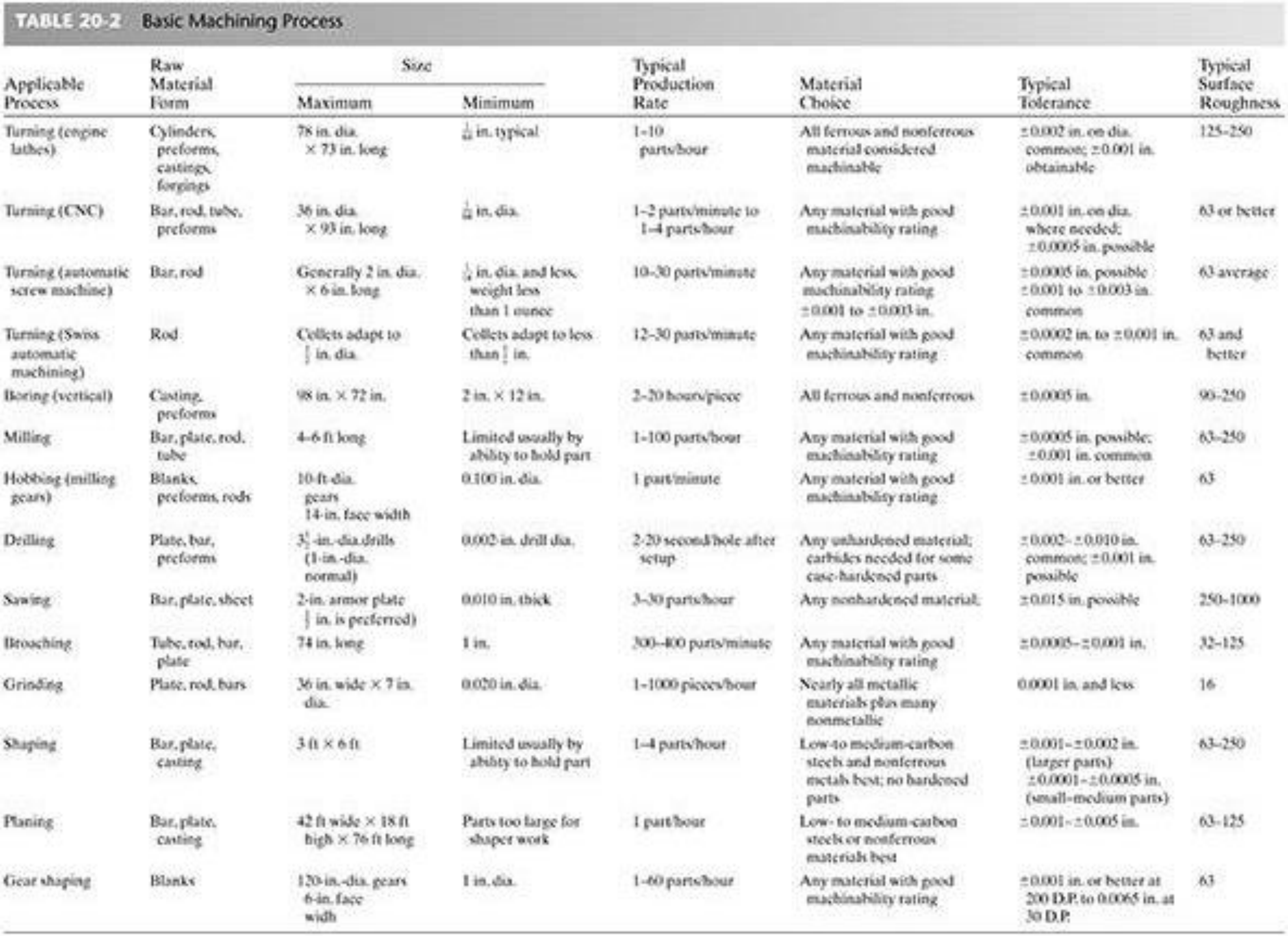
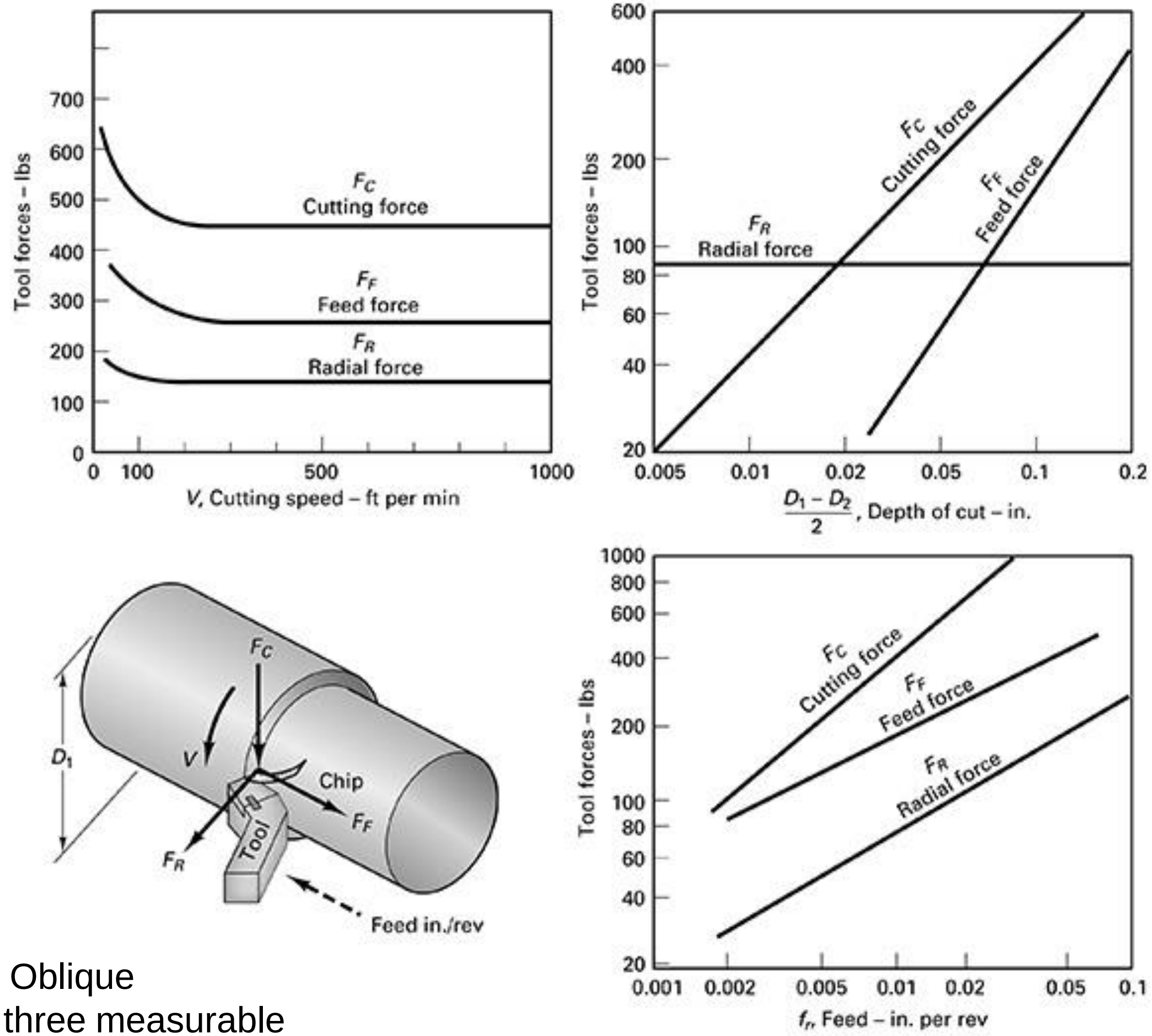


TABLE 20-2 Basic Machining Process

Applicable Process	Raw Material Form	Size		Typical Production Rate	Material Choice	Typical Tolerance	Typical Surface Roughness
		Maximum	Minimum				
Turning (engine lathes)	Cylinders, preforms, castings, forgings	78 in. dia. × 73 in. long	$\frac{1}{64}$ in. typical	1-10 parts/hour	All ferrous and nonferrous material considered machinable	±0.002 in. on dia. common; ±0.001 in. obtainable	125-250
Turning (CNC)	Bar, rod, tube, preforms	36 in. dia. × 93 in. long	$\frac{1}{64}$ in. dia.	1–2 parts/minute to 1–4 parts/hour	Any material with good machinability rating	±0.001 in. on dia. where needed; ±0.0005 in. possible	63 or better
Turning (automatic screw machine)	Bar, rod	Generally 2 in. dia. × 6 in. long	$\frac{1}{4}$ in. dia. and less, weight less than 1 ounce	10-30 parts/minute	Any material with good machinability rating ±0.001 to ±0.003 in.	±0.0005 in. possible ±0.001 to ±0.003 in. common	63 average
Turning (Swiss automatic machining)	Rod	Collets adapt to $\frac{3}{4}$ in. dia.	Collets adapt to less than $\frac{1}{8}$ in.	12–30 parts/minute	Any material with good machinability rating	±0.0002 in. to ±0.001 in. common	63 and better
Boring (vertical)	Casting, preforms	98 in. × 72 in.	2 in. × 12 in.	2-20 hours/piece	All ferrous and nonferrous	±0.0005 in.	90-250
Milling	Bar, plate, rod, tube	4–6 ft long	Limited usually by ability to hold part	1-100 parts/hour	Any material with good machinability rating	±0.0005 in. possible; ±0.001 in. common	63-250
Hobbing (milling gears)	Blanks, preforms, rods	10-ft-dia. gears 14-in. face width	0.100 in. dia.	1 part/minute	Any material with good machinability rating	±0.001 in. or better	63
Drilling	Plate, bar, preforms	$3\frac{1}{2}$-in.-dia drills (1-in.-dia. normal)	0.002 in. drill dia.	2-20 second/hole after setup	Any unhardened material; carbides needed for some case-hardened parts	±0.002-±0.010 in. common; ±0.001 in. possible	63-250
Sawing	Bar, plate, sheet	2-in. armor plate $\frac{1}{2}$ in. is preferred)	0.010 in. thick	3–30 parts/hour	Any nonhardened material;	±0.015 in. possible	250-1000
Broaching	Tube, rod, bar, plate	74 in. long	1 in.	300–400 parts/minute	Any material with good machinability rating	±0.0005–±0.001 in.	32-125
Grinding	Plate, rod, bars	36 in. wide × 7 in. dia.	0.020 in. dia.	1-1000 pieces/hour	Nearly all metallic materials plus many nonmetallic	0.0001 in. and less	16
Shaping	Bar, plate, casting	3 ft × 6 ft	Limited usually by ability to hold part	1–4 parts/hour	Low-to medium-carbon steels and nonferrous metals best; no hardened parts	±0.001–±0.002 in. (larger parts) ±0.0001–±0.0005 in. (small-medium parts)	63-250
Planing	Bar, plate, casting	42 ft wide × 18 ft high × 76 ft long	Parts too large for shaper work	1 part/hour	Low- to medium-carbon steels or nonferrous materials best	±0.001–±0.005 in.	63-125
Gear shaping	Blanks	120-in.-dia. gears 6-in. face width	1 in. dia.	1-60 parts/hour	Any material with good machinability rating	±0.001 in. or better at 200 D.P. to 0.0065 in. at 30 D.P.	63



3 Force

F_C = Cutting force (vertical)
F_R = Radial force (thrust)
F_F = Feed force

FIGURE 20-12 Oblique machining has three measurable components of forces acting on the tool. The forces vary with speed, depth of cut, and feed.

- Power for cutting: $P = F_c V$
- Spindle horsepower: $HP = F_c V/33{,}000$
- Specific horsepower: $HP_s = HP/MRR$ (hp/in^3/min)
- It is the approximate power needed to remove 1 in^3 per minute.
- In turning: $MRR \approx 12 V f_r d$
- Thus $HP_s = F_c V/(33000 \times 12 V f_r d) = F_c/(396000 f_r d)$
- HP_s for various metals are shown in Table HP_s is used to estimate motor *horsepower* HP_m

- Motor horsepower $HP_m = (HP_s \times MRR \times CF) / E$
- CF: correction factor (accounts for variation in speed feed, and rake angle)
- E : machine efficiency (account for power needed for friction, inertia, and moving parts) and is about 80%
- The primary cutting force F_c can be calculated as:

$$F_c \approx (HP_s \times MRR \times 33000) / V$$

- F_c is useful in the analysis of deflection and vibration problems related to machinery in the design of work holding devices.

- In general:

Increase in speed, feed, and depth of cut increase the power.

- Doubling speed → doubles HP
- Doubling feed or depth of cut doubles F_c
- Increasing speed does not increase F_c ??? (puzzle)
- Speed has strong effect on tool life (effect of heat)

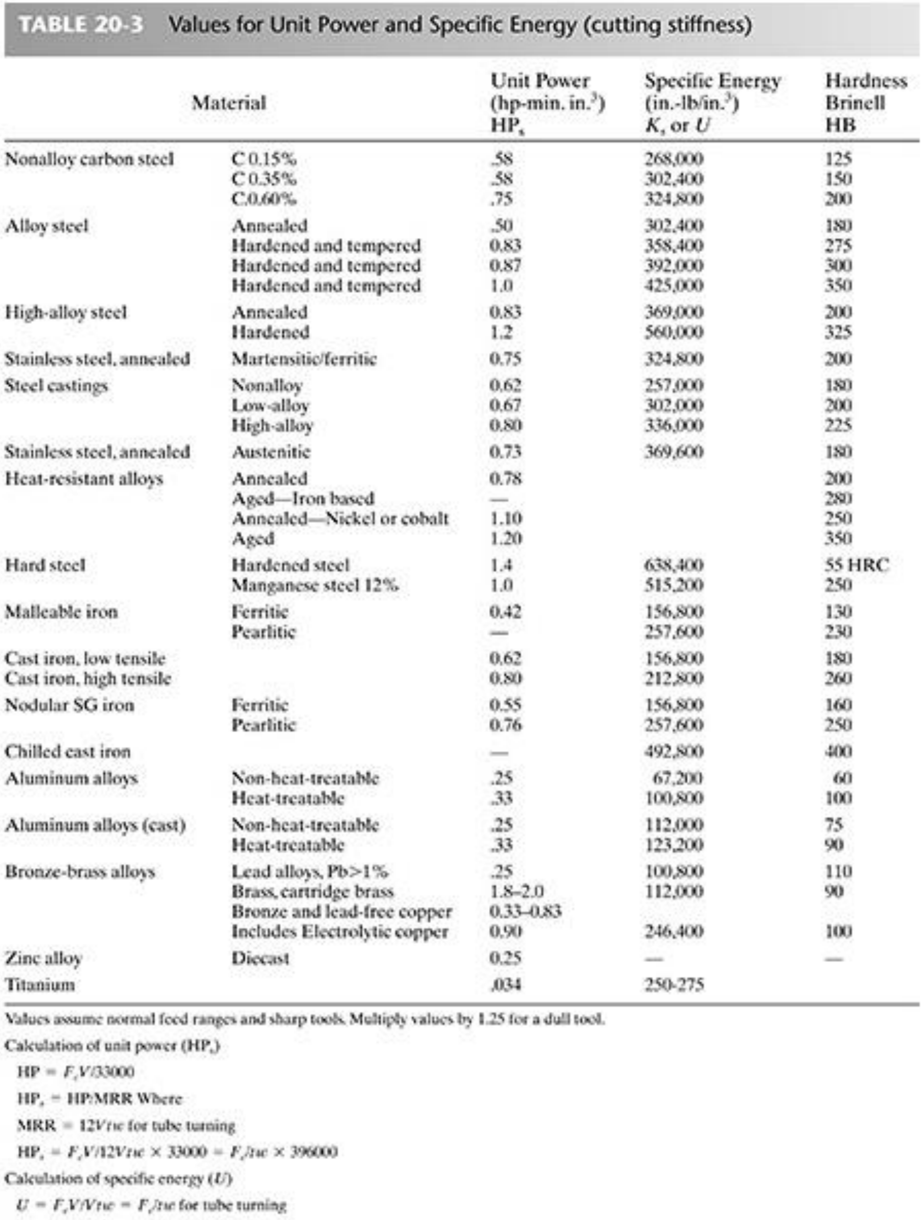


TABLE 20-3 Values for Unit Power and Specific Energy (cutting stiffness)

Material		Unit Power (hp-min. in.^{3}) HP_s	Specific Energy (in.-lb/in.^{3}) K_s or U	Hardness Brinell HB
Nonalloy carbon steel	C 0.15%	.58	268,000	125
	C 0.35%	.58	302,400	150
	C 0.60%	.75	324,800	200
Alloy steel	Annealed	.50	302,400	180
	Hardened and tempered	0.83	358,400	275
	Hardened and tempered	0.87	392,000	300
	Hardened and tempered	1.0	425,000	350
High-alloy steel	Annealed	0.83	369,000	200
	Hardened	1.2	560,000	325
Stainless steel, annealed	Martensitic/ferritic	0.75	324,800	200
Steel castings	Nonalloy	0.62	257,000	180
	Low-alloy	0.67	302,000	200
	High-alloy	0.80	336,000	225
Stainless steel, annealed	Austenitic	0.73	369,600	180
Heat-resistant alloys	Annealed	0.78		200
	Aged—Iron based	—		280
	Annealed—Nickel or cobalt	1.10		250
	Aged	1.20		350
Hard steel	Hardened steel	1.4	638,400	55 HRC
	Manganese steel 12%	1.0	515,200	250
Malleable iron	Ferritic	0.42	156,800	130
	Pearlitic	—	257,600	230
Cast iron, low tensile		0.62	156,800	180
Cast iron, high tensile		0.80	212,800	260
Nodular SG iron	Ferritic	0.55	156,800	160
	Pearlitic	0.76	257,600	250
Chilled cast iron		—	492,800	400
Aluminum alloys	Non-heat-treatable	.25	67,200	60
	Heat-treatable	.33	100,800	100
Aluminum alloys (cast)	Non-heat-treatable	.25	112,000	75
	Heat-treatable	.33	123,200	90
Bronze-brass alloys	Lead alloys, Pb>1%	.25	100,800	110
	Brass, cartridge brass	1.8–2.0	112,000	90
	Bronze and lead-free copper	0.33–0.83		
	Includes Electrolytic copper	0.90	246,400	100
Zinc alloy	Diecast	0.25	—	—
Titanium		.034	250-275	

Values assume normal feed ranges and sharp tools. Multiply values by 1.25 for a dull tool.

Calculation of unit power (HP_s)

$HP = F_c V/33000$

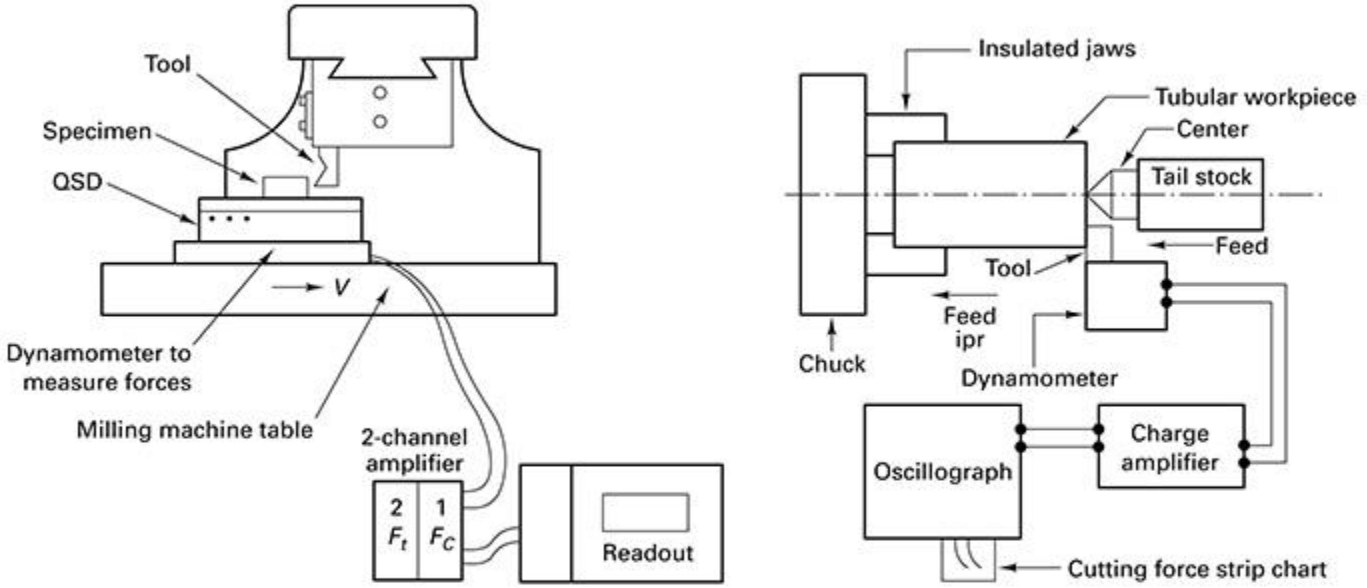
$HP_s = HP/MRR$ Where

$MRR = 12Vt_{ue}$ for tube turning

$HP_s = F_c V/12Vt_{ue} \times 33000 = F_c/t_{ue} \times 396000$

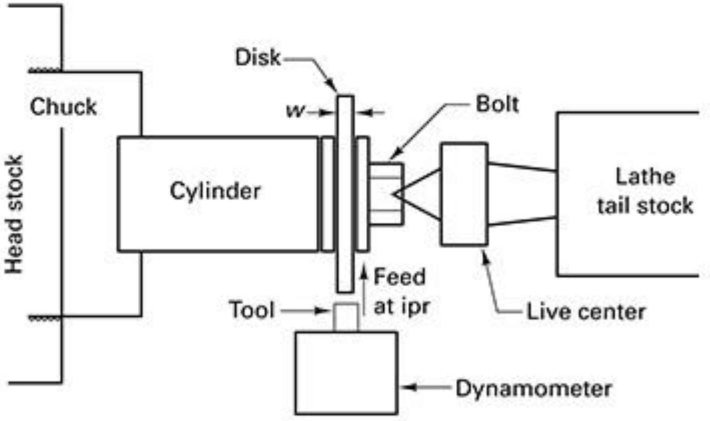
Calculation of specific energy (U)

$U = F_c V/Vt_{ue} = F_c/t_{ue}$ for tube turning



(a) OPM *V* (Front view) See Figure 21-14

(b) OTT (Top view) See Figure 21-15



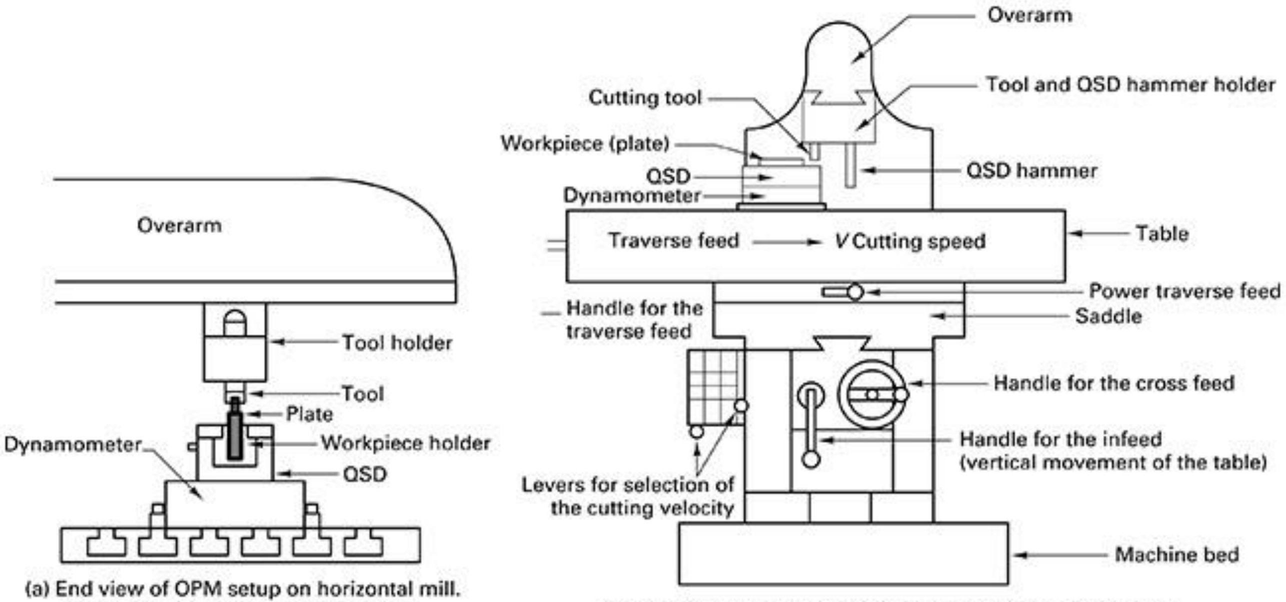
(c) ODM (Top view)

FIGURE 20-13 Three ways to perform orthogonal machining. (a) Orthogonal plate machining on a horizontal milling machine, good for low-speed cutting. (b) Orthogonal tube turning on a lathe; high-speed cutting (see Figure 20-16). (c) Orthogonal disk machining on a lathe; very high-speed machining with tool feeding (ipr) in the facing direction

20.4 Orthogonal Machining (Two Forces)

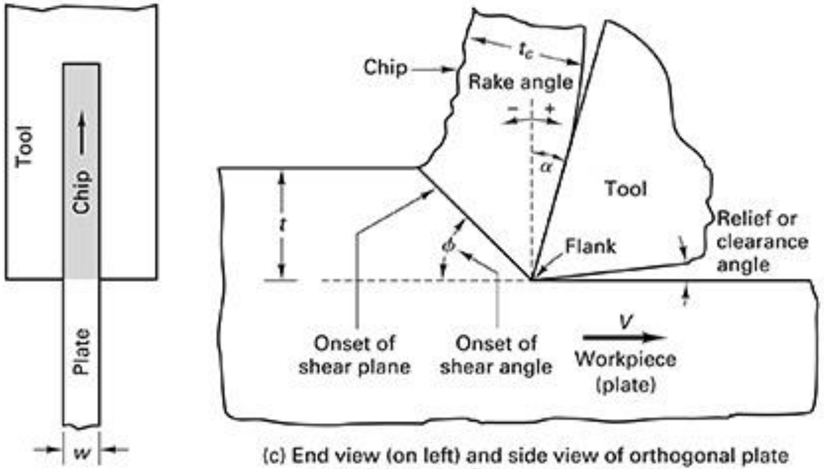
Assumptions for orthogonal cutting :

- single narrow shear plane
- perfectly sharp edge



(a) End view of OPM setup on horizontal mill. Table feed is used for cutting speed.

(b) Horizontal milling setup for OPM using QSD. Front view.



(c) End view (on left) and side view of orthogonal plate machining with fixed tool and moving plate.

FIGURE 20-14 Schematics of the orthogonal plate machining setups. (a) End view of table, quick-stop device (QSD), and plate being machined for OPM. (b) Front view of horizontal milling machine. (c) Orthogonal plate machining with fixed tool, moving plate. The feed mechanism of the mill is used to produce low cutting speeds. The feed of the tool is *t* and the DOC is *w*, the width of the plate.

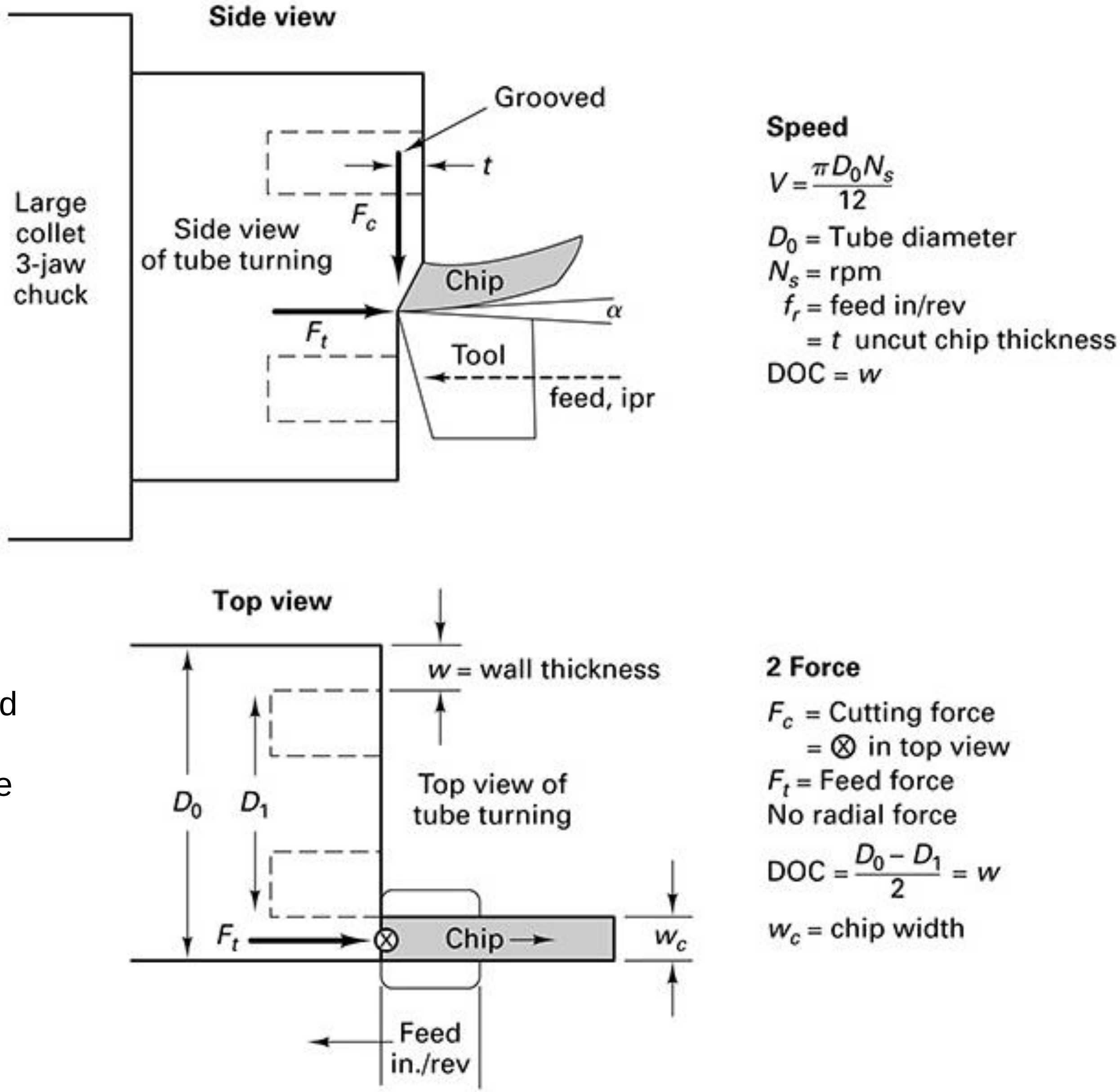


FIGURE 20-15 Orthogonal tube turning (OTT) produces a two-force cutting operation at speeds equivalent to those used in most oblique machining operations. The slight difference in cutting speed between the inside and outside edge of the chip can be neglected.

FIGURE 20-16 Videograph made from the orthogonal plate machining process.

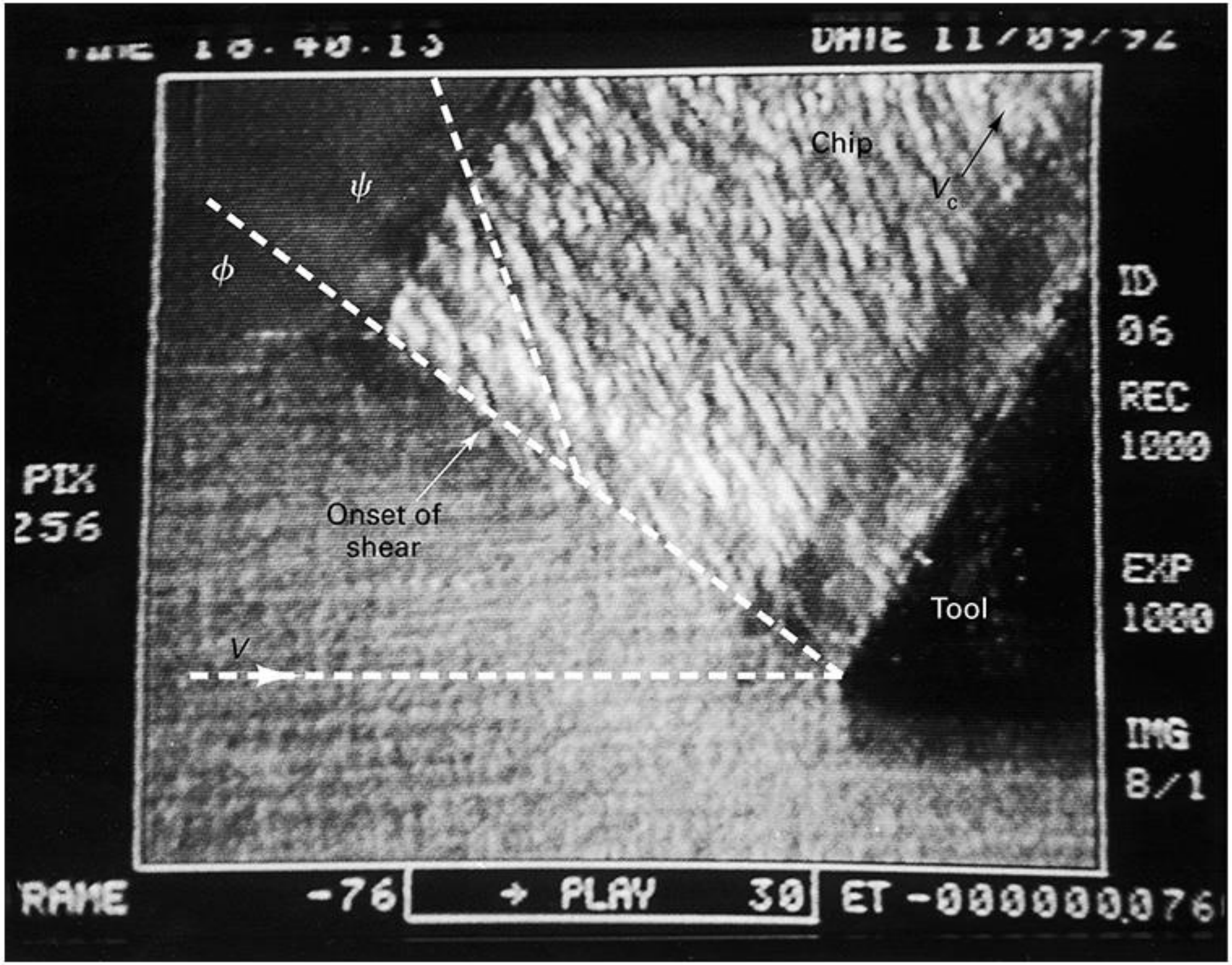
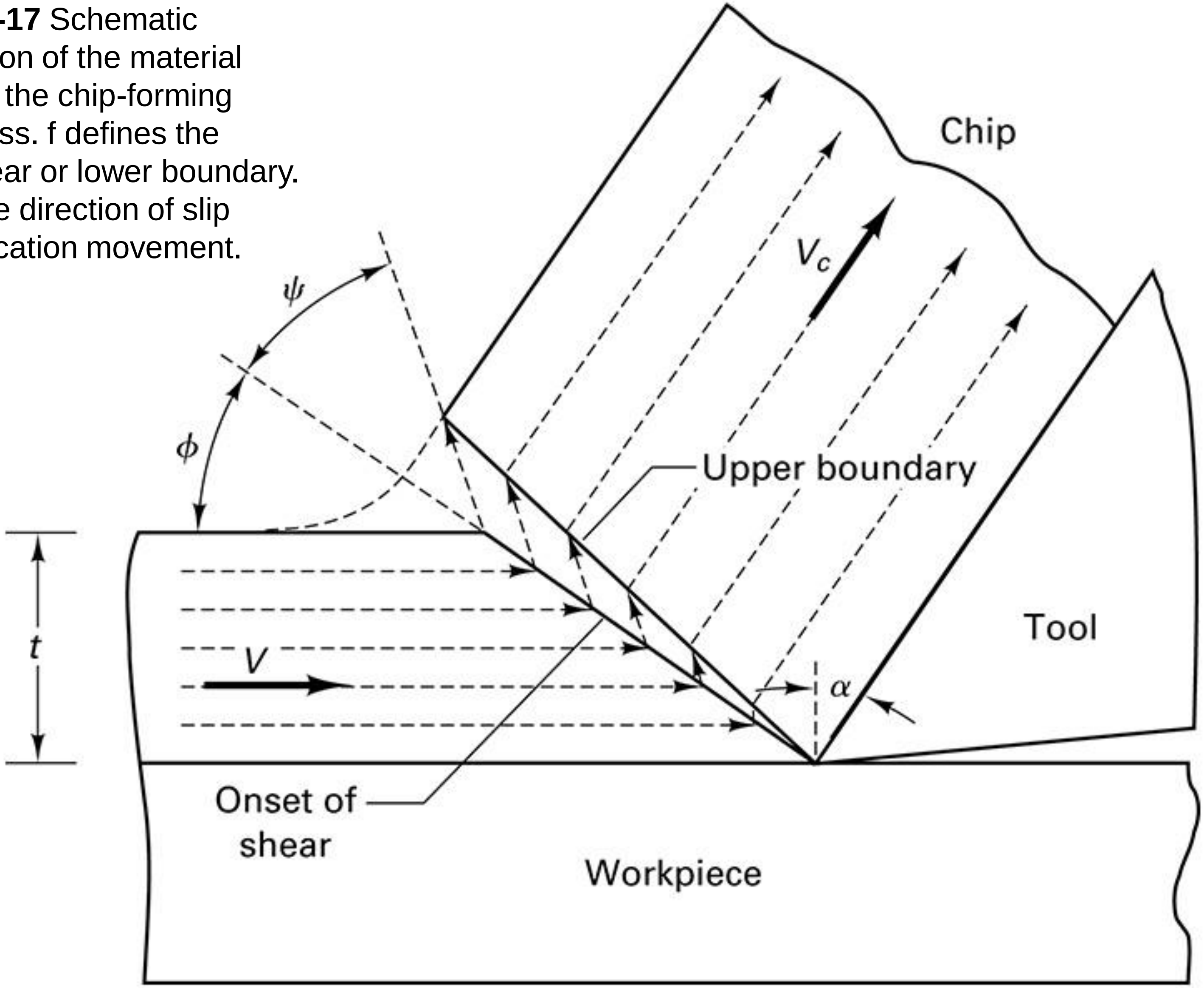


FIGURE 20-17 Schematic representation of the material flow, that is, the chip-forming shear process. f defines the onset of shear or lower boundary. c defines the direction of slip due to dislocation movement.



- **Effect of work material properties:**

High strength material is characterized by:

- large forces
- greater tool deflection
- increased friction (heat generation)
- greater work input

Ductile material is characterized by extensive plastic deformation (increase work, heat, and temperature), and longer and continuous chip.

Brittle material produces discontinuous or segmented chip.

- Built-up edge (BUE) is characterized by:
  - ductile material
  - high temp. and pressure
  - weld effect
  - protection of tool from wear
  - change in tool geometry
- and can be eliminated by:
  - reduced depth of cut
  - change in cutting speed
  - positive rake angle
  - use of coolant
  - change of cutting tool material

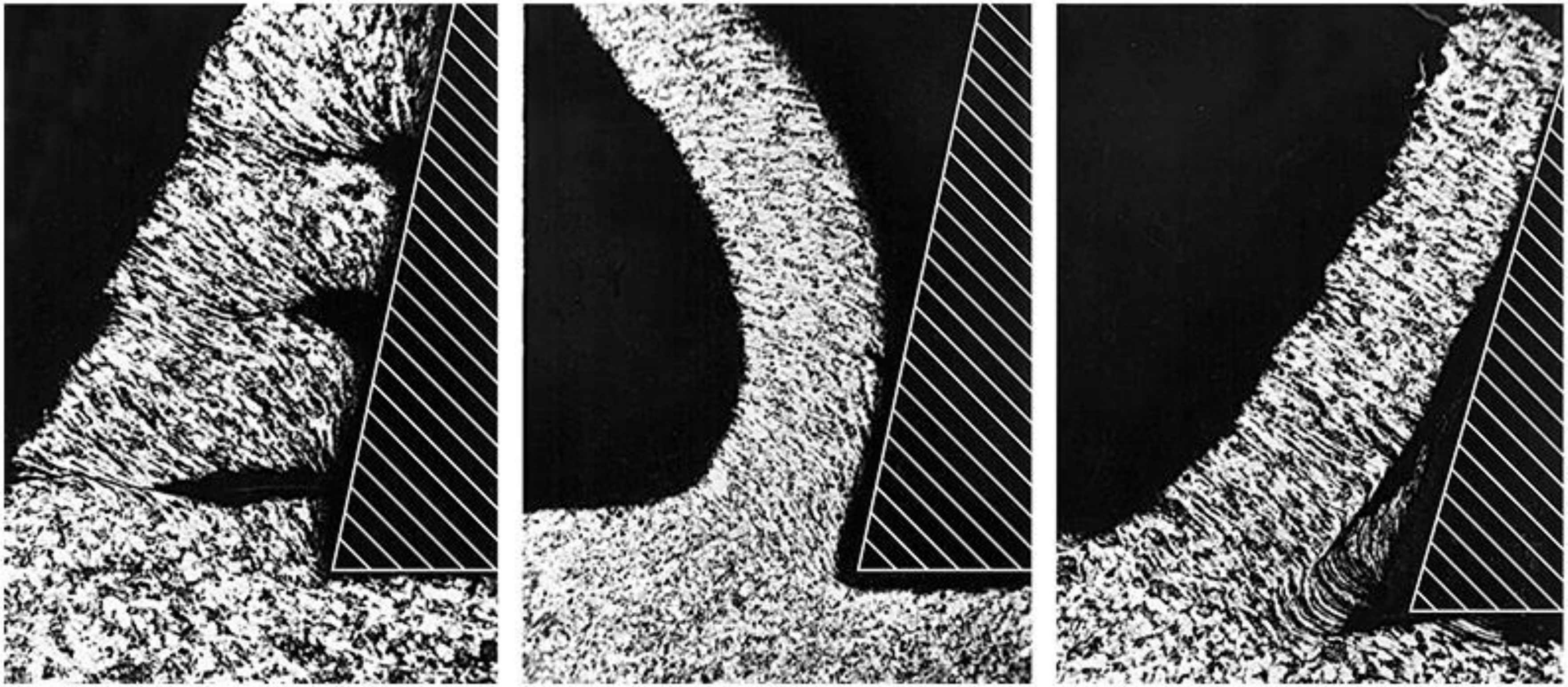


FIGURE 20-18 Three characteristic types of chips. (Left to right) Discontinuous, continuous, and continuous with built-up edge. Chip samples produced by quick-stop technique. *(Courtesy of Eugene Merchant (deceased) at Cincinnati Milacron, Inc., Ohio.)*

20.5 Merchant's Model

- The speed relations as represented by Figure 20.19
- V: cutting speed
- V_c: chip velocity
- V_s: shear process velocity
- t: uncut chip thickness
- t_c: chip thickness
- α: back rake angle
- γ: clearance angle
- chip thickness ratio: $r_c = t/ t_c$
- Equations 6, 7, 8, and 9 will be used for solving problems.

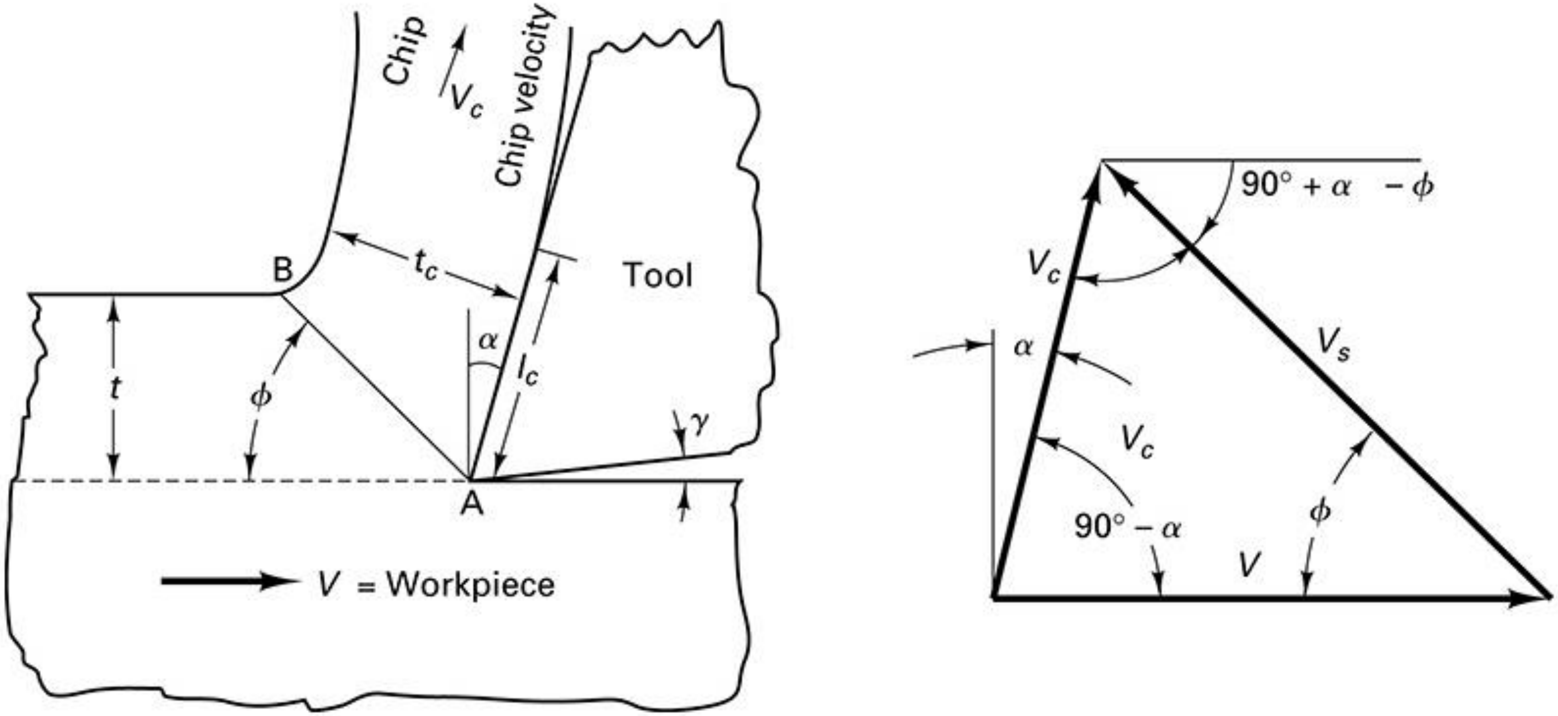


FIGURE 20-19 Velocity diagram associated with Merchant’s orthogonal machining model.

20.6 Mechanics of Machining (Statics)

- F: friction force
- N: normal force acting on tool/chip interface
- F_s: sheer force
- F_n: normal force acting on shear plane
- The above forces cannot be measured.
- The Force dynamometer is used to measure:
- F_c: cutting force
- F_t: tangential (normal) force
- μ: friction coefficient on tool chip interface

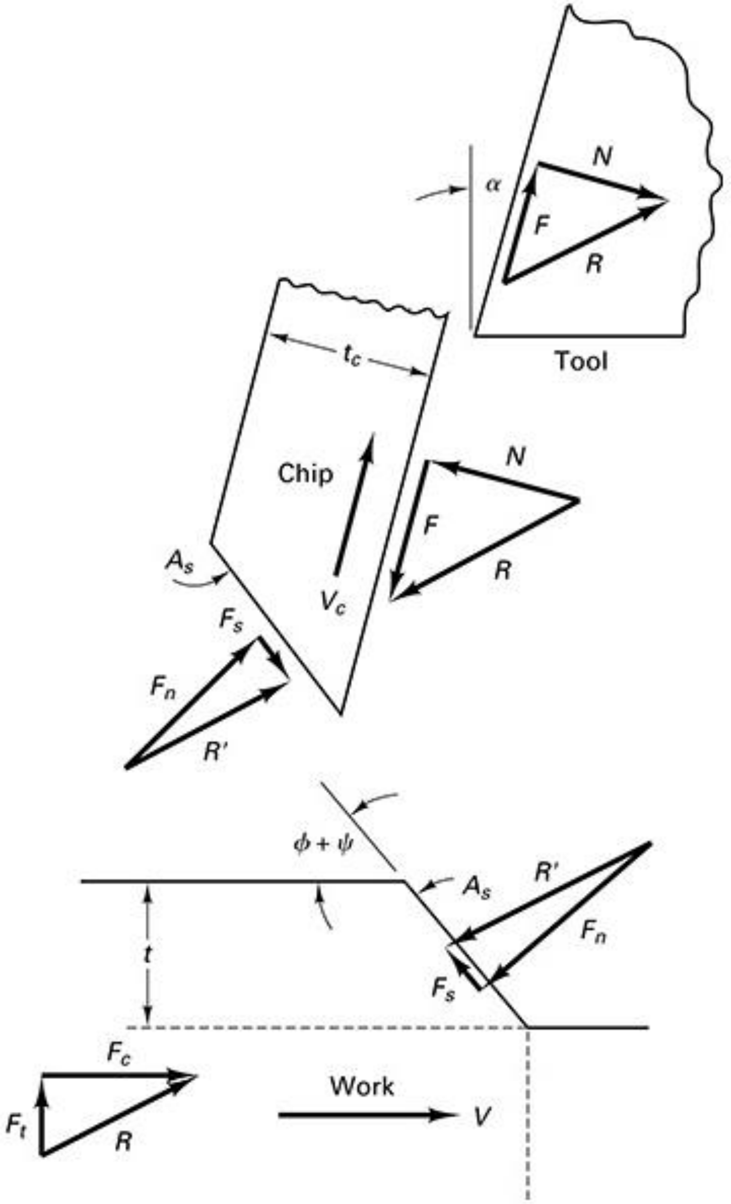


FIGURE 20-20 Free-body diagram of orthogonal chip formation process, showing equilibrium condition between resultant forces *R* and *R*.

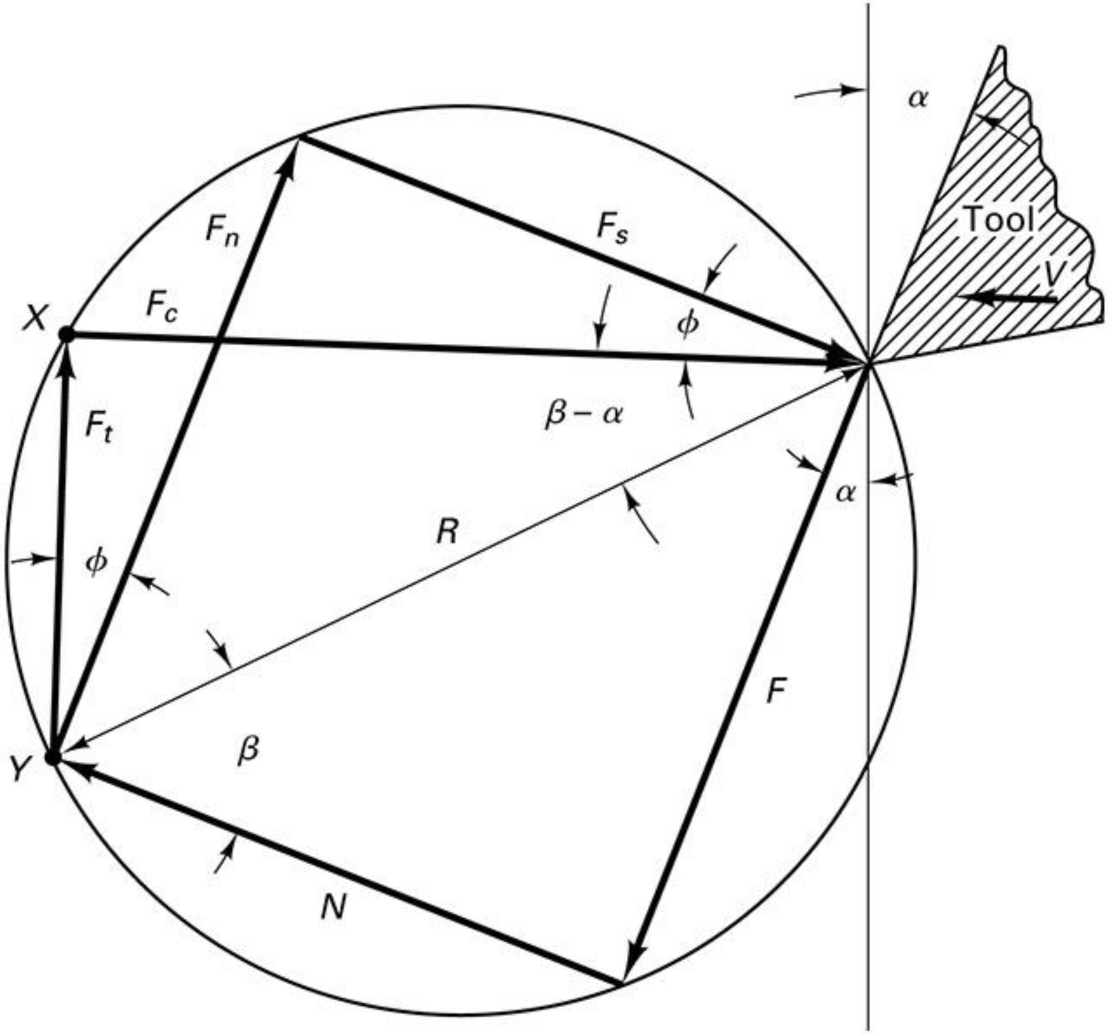
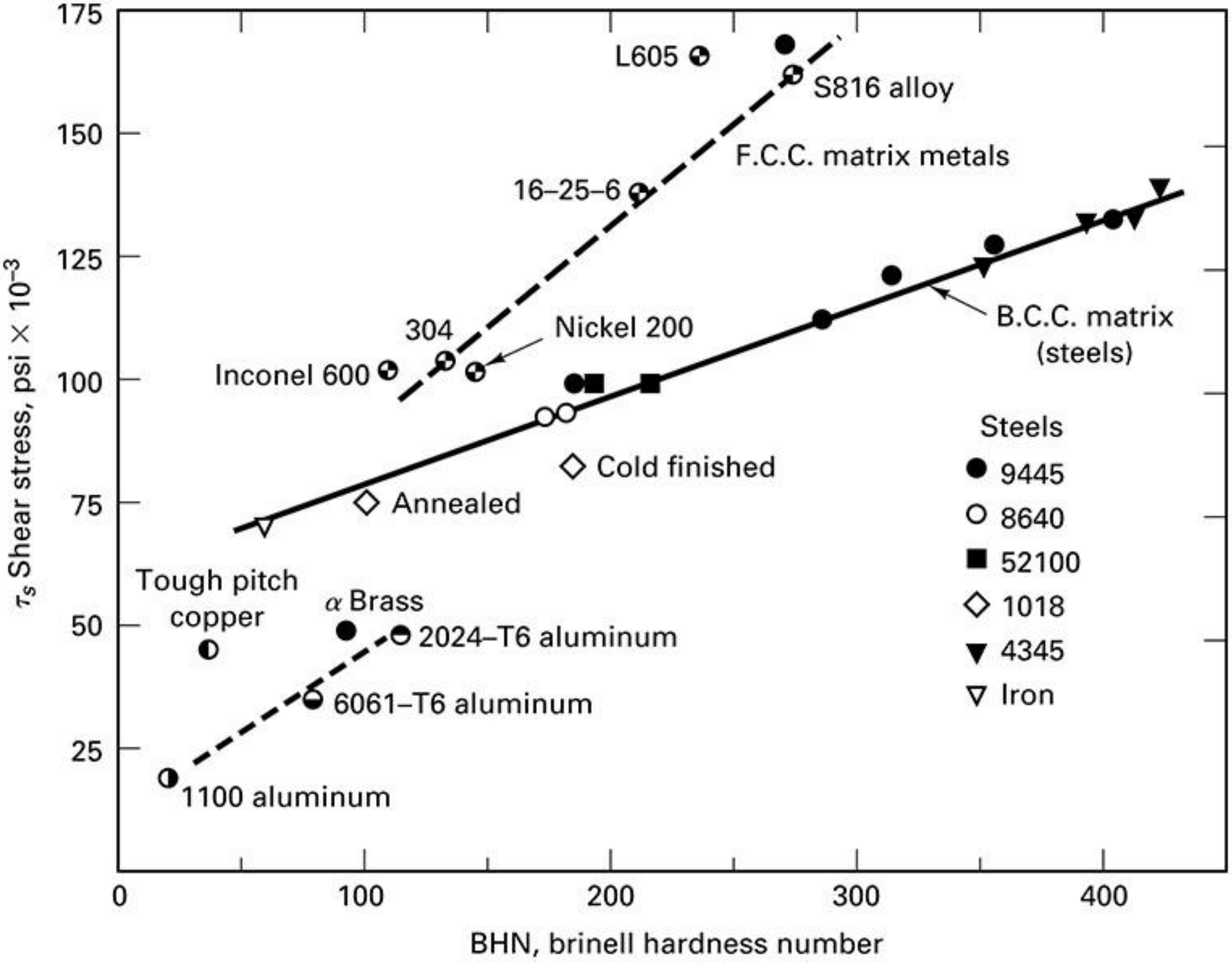
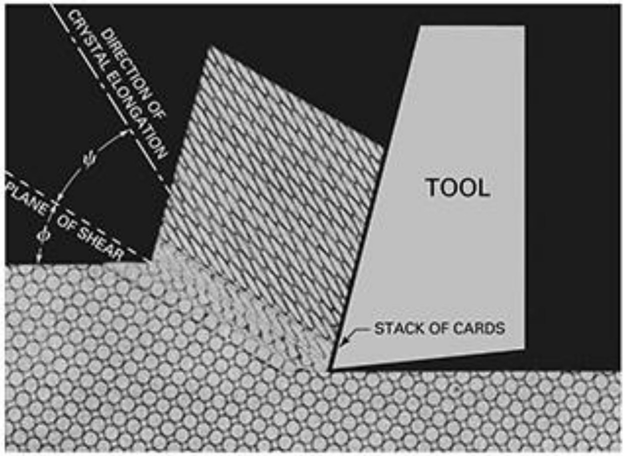


FIGURE 20-21 Merchant's circular force diagram used to derive equations for Fs , Fr , Ft , and N as functions of Fc, Fr , f, a, and b.

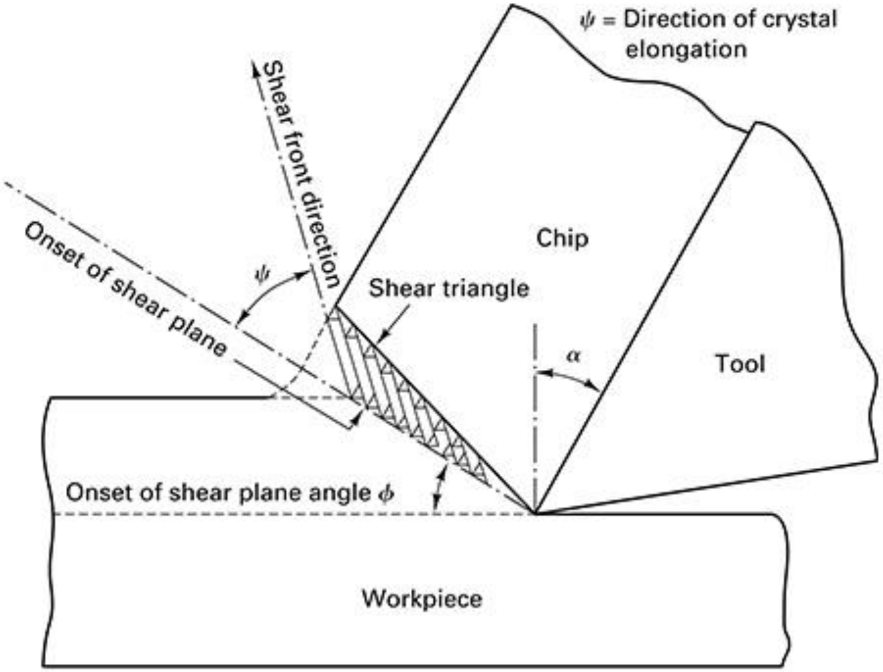
20.7 Shear Strain and Shear Front Angle

FIGURE 20-22 Shear stress ts variation with the Brinell hardness number for a group of steels and aerospace alloys. Data of some selected fcc metals are also included. *(Adapted with permission from S. Ramalingham and K. J. Trigger,* Advances in Machine Tool Design and Research, *1971, Pergamon Press.)*

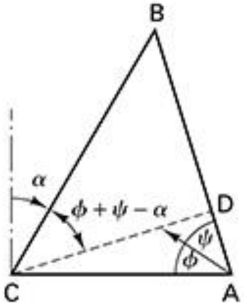




Mechant's bubble
model of chip formation



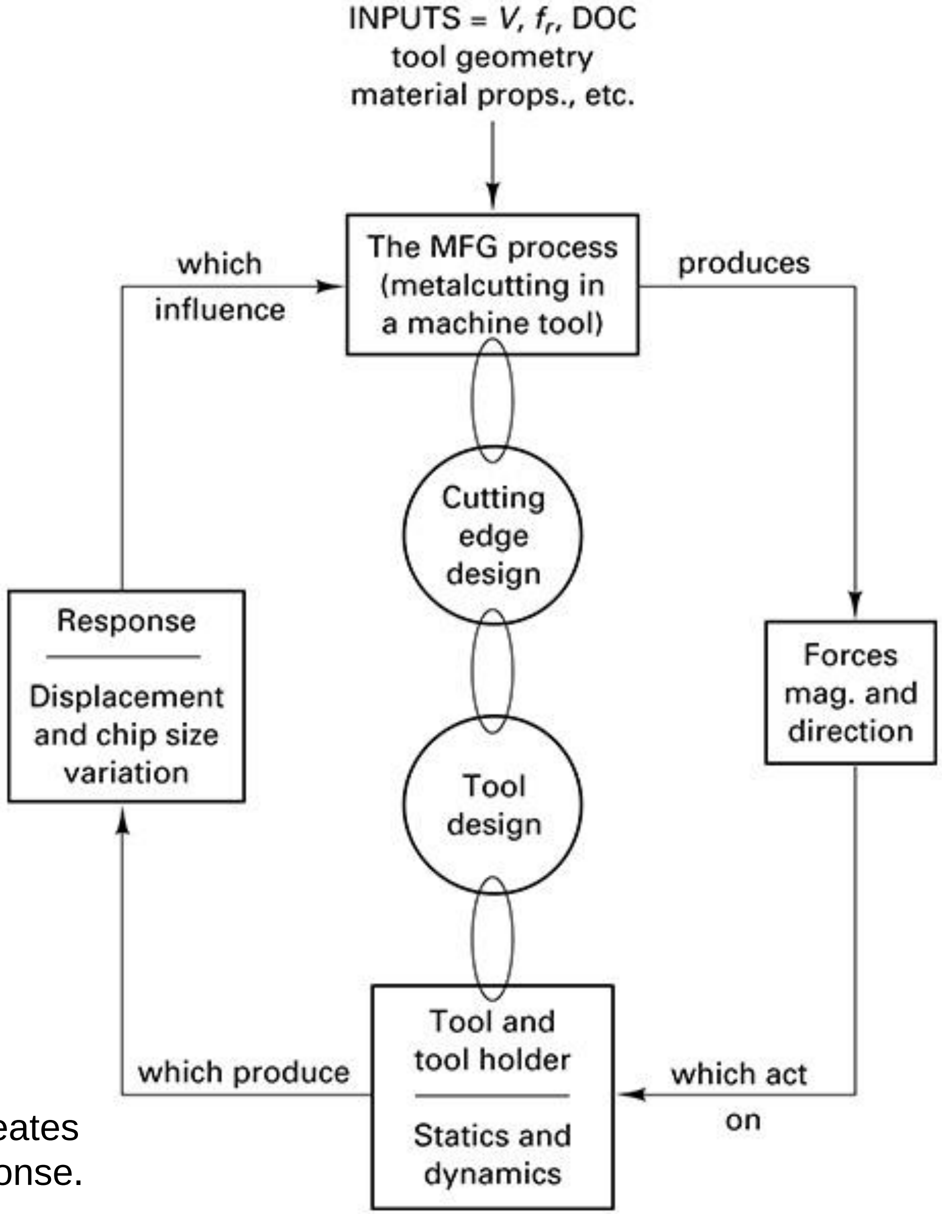
Black-Huang stack-of-cards model



The shaded shear triangle
on the right is used to
develop the basic
equation for shear
strain, γ.

FIGURE 20-23 The Black–Huang “stack-of-cards” model for calculating shear strain in metal cutting is based on Merchant’s bubble model for chip formation, shown on the left.

20.8 Mechanics of Machining (Dynamics)



INPUTS = V, f_r, DOC
tool geometry
material props., etc.

The MFG process (metalcutting in a machine tool)

produces

Forces mag. and direction

which act on

Tool and tool holder

Statics and dynamics

which produce

Response

Displacement and chip size variation

which influence

Cutting edge design

Tool design

FIGURE 20-24 Machining dynamics is a closed-loop interactive process that creates a force-displacement response.

- **Free Vibration** The response to an initial condition or sudden change. The amplitude of the vibration decreases with time and occurs at the natural frequency of the system often produced by interrupted machining. Often appears as lines or shadows following a surface discontinuity.

- **Forced Vibration** The response to a periodic (repeating with time) input. The response and input occur at the same frequency. The amplitude of the vibration remains constant for a set input condition and is nonlinearly related to speed. Unbalance, misalignment, tooth impacts, and resonance of rotating systems are the most common examples.

- **Self-Excited Vibration** The periodic response of the system to a constant input. The vibration may grow in amplitude (unstable) and occurs near the natural frequency of the system regardless of the input. Chatter due to the regeneration of surface waviness is the most common metal cutting example.

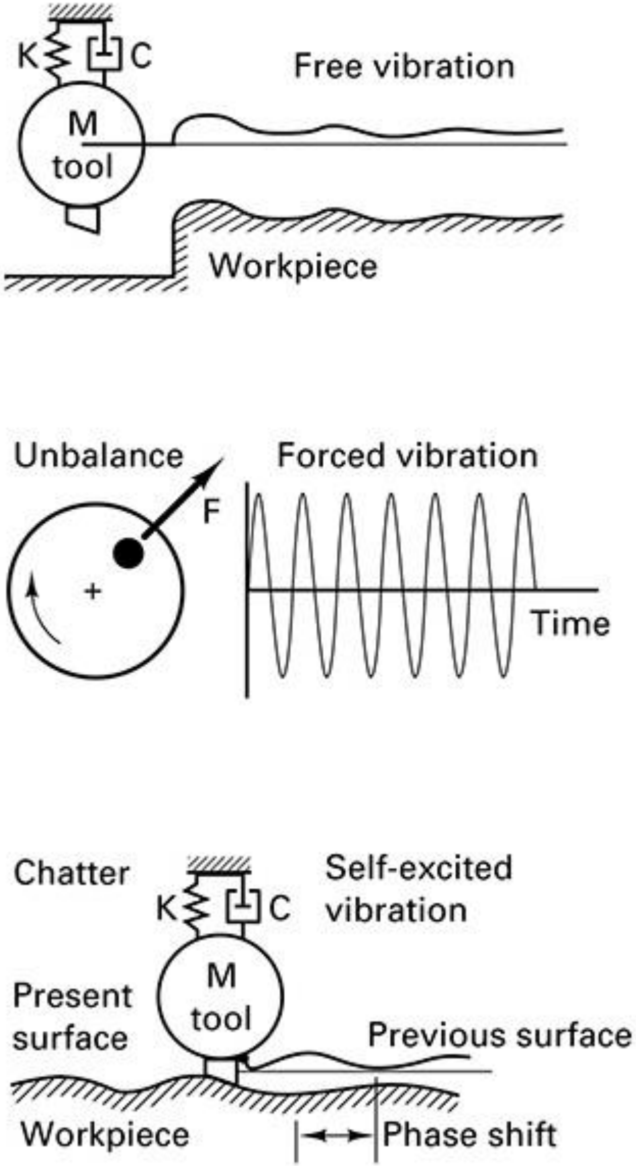


FIGURE 20-25 There are three types of vibration in machining.

FIGURE 20-26 Some examples of chatter that are visible on the surfaces of the workpiece.

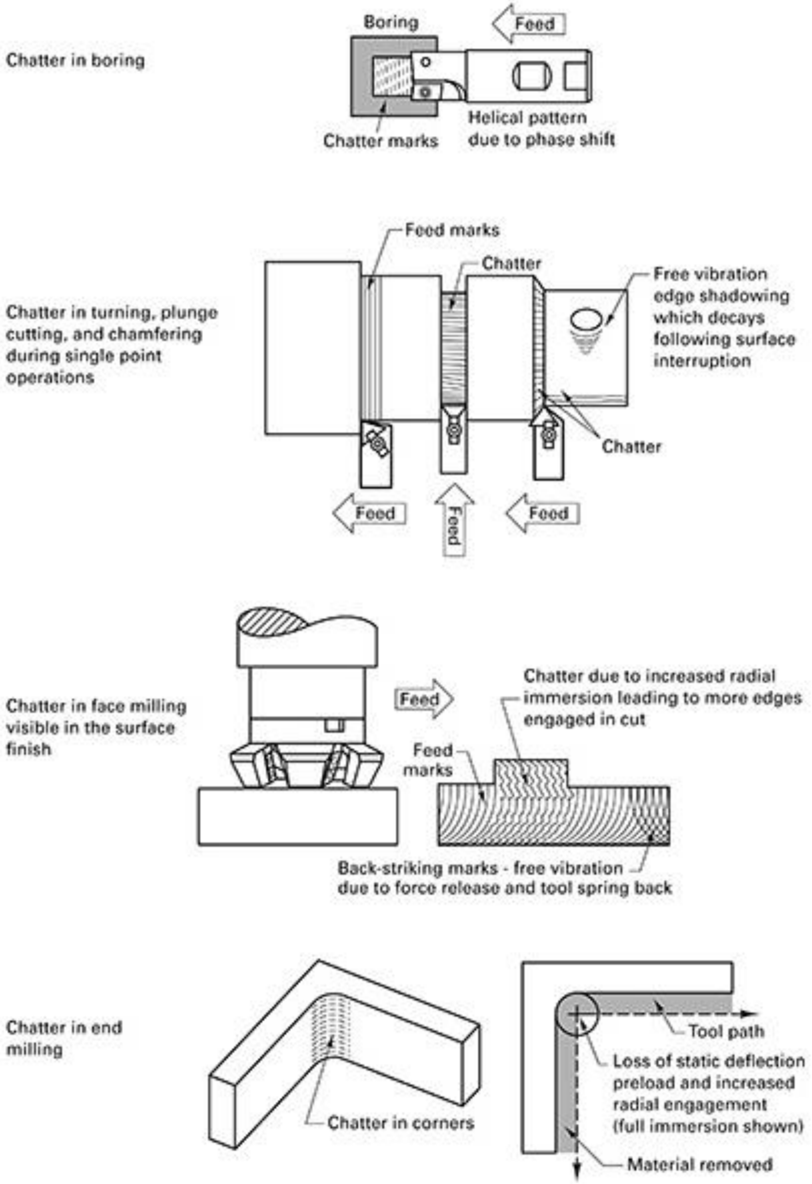
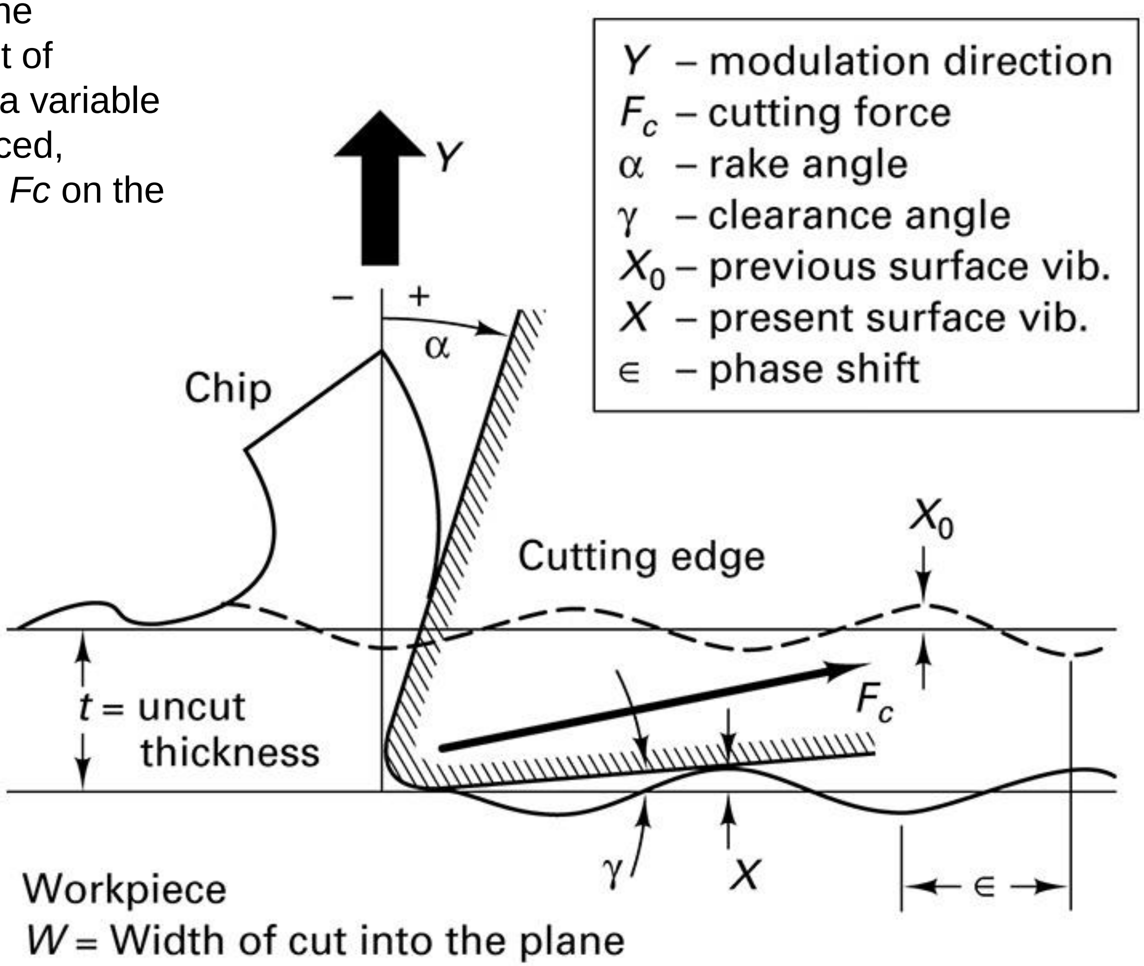


FIGURE 20-27 When the overlapping cuts get out of phase with each other, a variable chip thickness is produced, resulting in a change in *Fc* on the tool or workpiece.



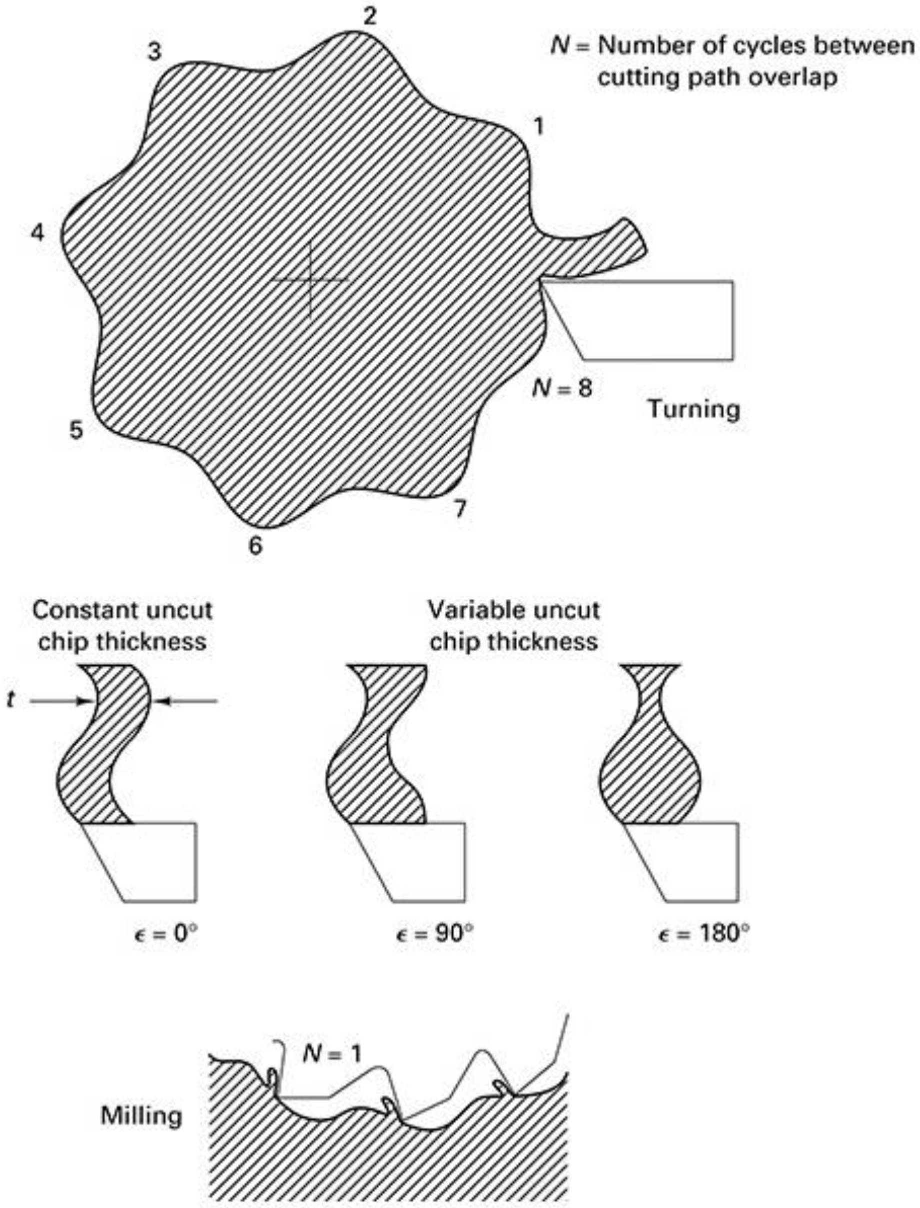


FIGURE 20-28 Regenerative chatter in turning and milling produced by variable uncut chip thickness.

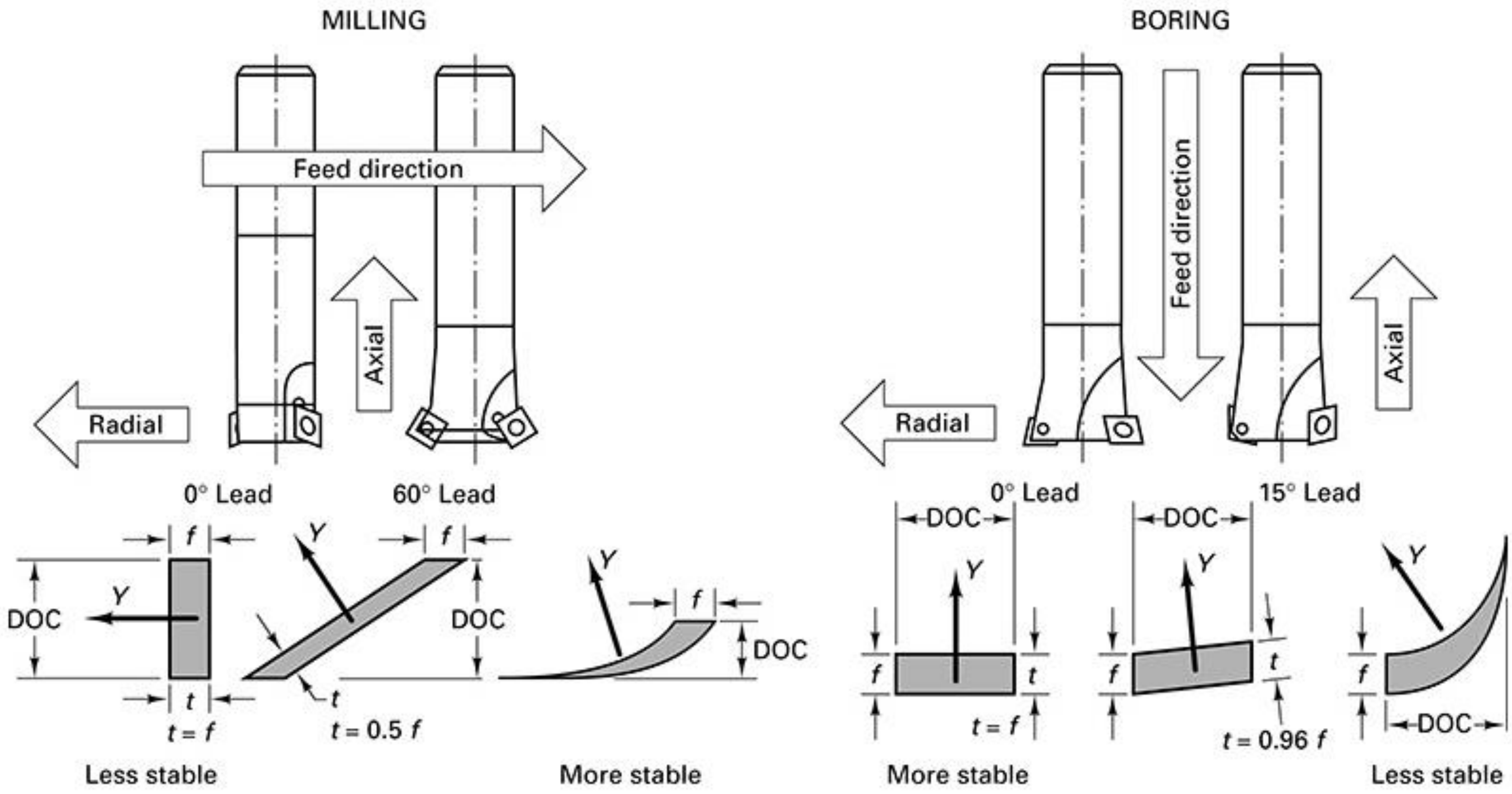
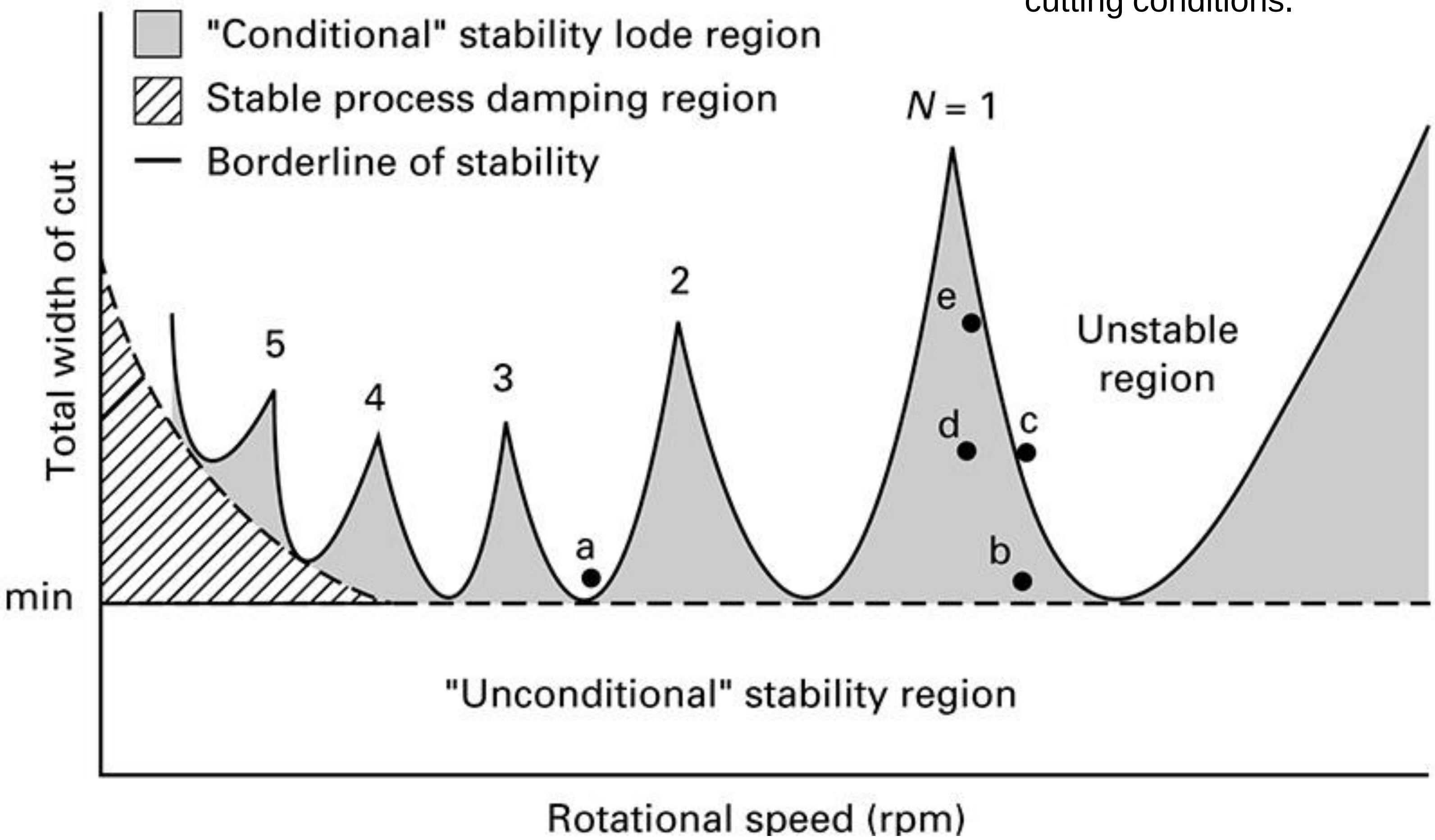


FIGURE 20-29 Milling and boring operations can be made more stable by correct selection of insert geometry.

FIGURE 20-30 Dynamic analysis of the cutting process produces a stability lobe diagram, which defines speeds that produce stable and unstable cutting conditions.



Heat and Temperature in Metal cutting

- Power is converted to heat: w.p, tool, chip
- **Three sources of heat: (see Figure)**

1-from shearing: plastic deformation results in the major heat source (most of this heat stays in the chip)

2-chip-tool interface: additional plastic deformation and friction produces more heat

3-rubbing the tool with the freshly produced workpiece surface.

- **Tool material must be:**

- hard to resist wear
- tough to resist cratering and chipping
- resist impact loading
- sustain hardening at elevated temp.

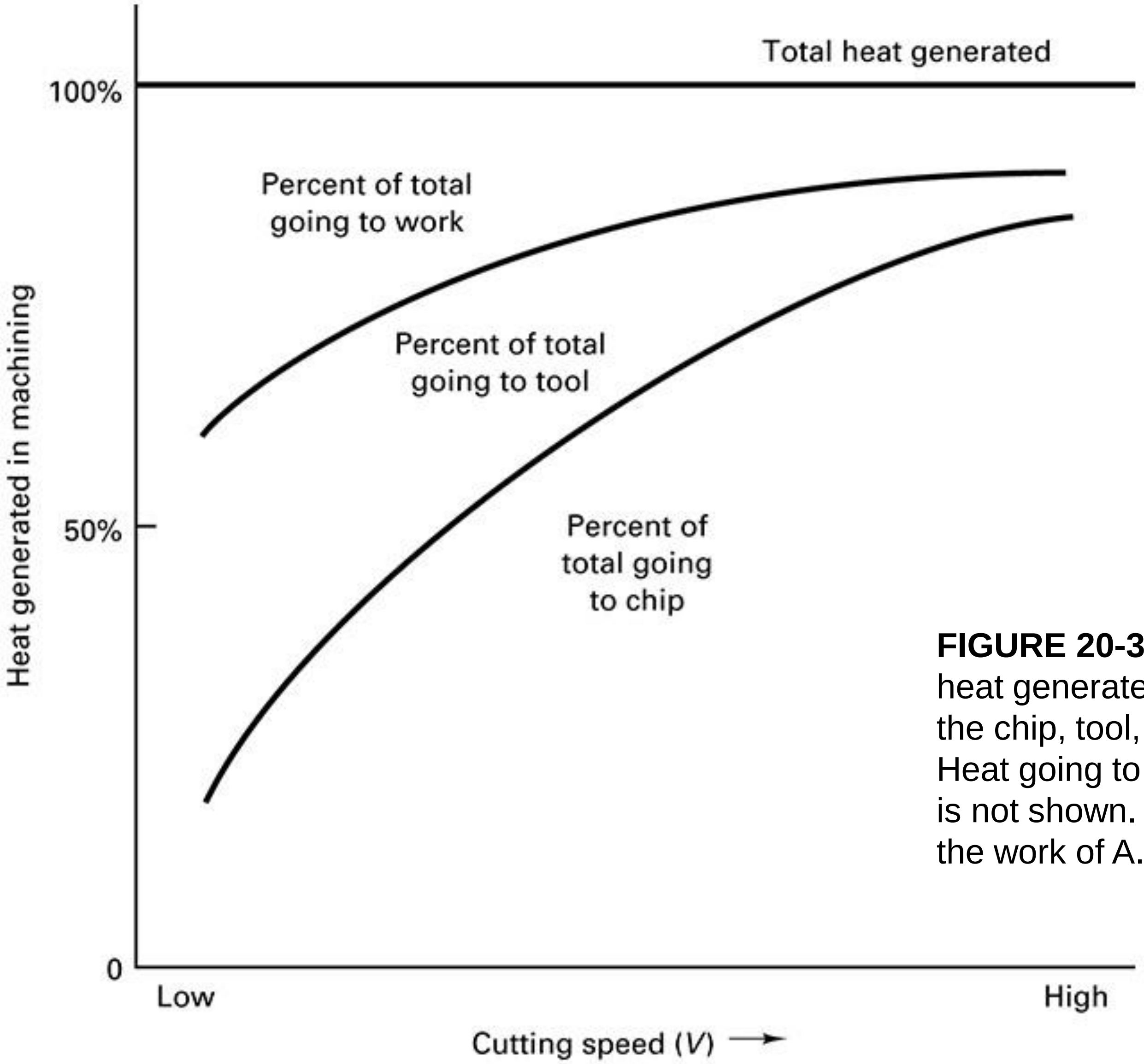


FIGURE 20-31 Distribution of heat generated in machining to the chip, tool, and workpiece. Heat going to the environment is not shown. Figure based on the work of A. O. Schmidt.

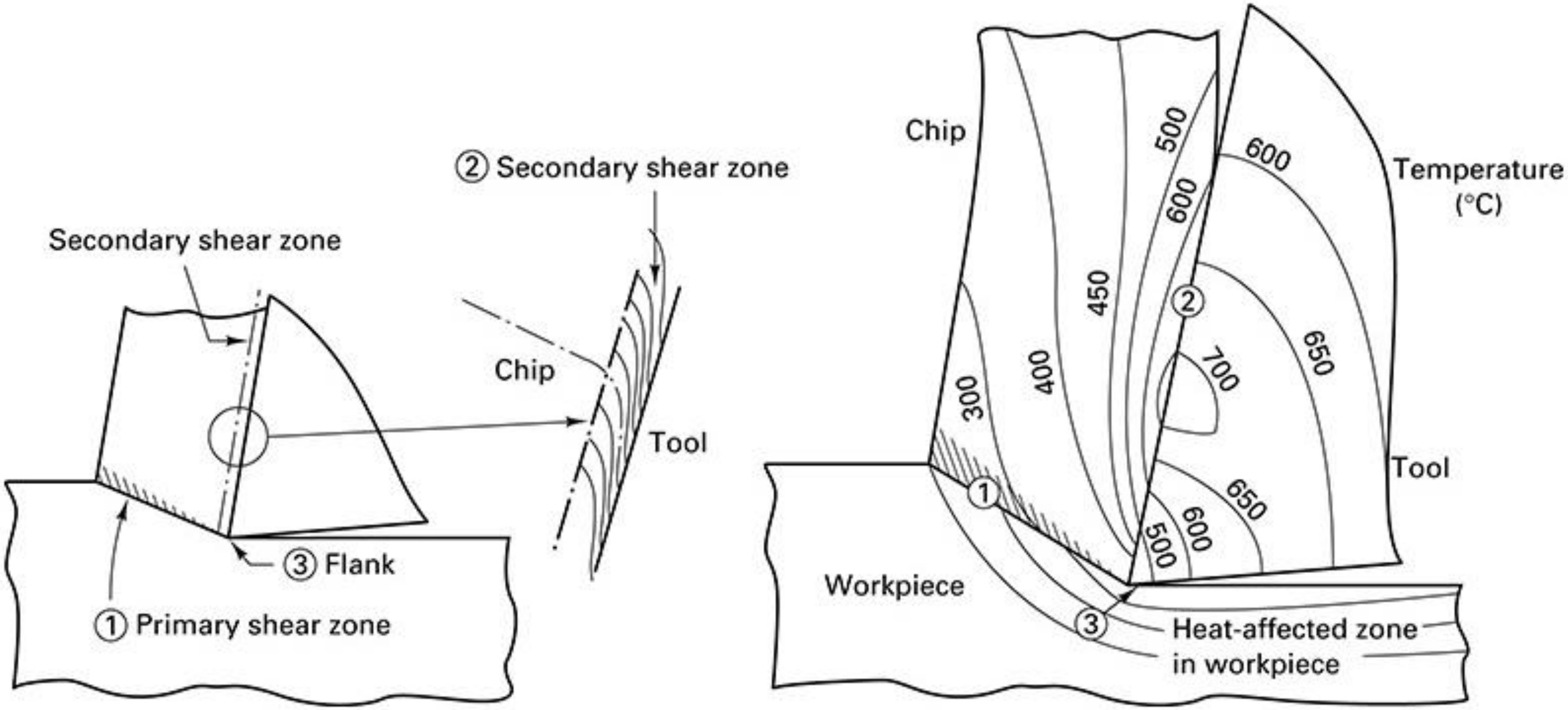


FIGURE 20-32 There are three main sources of heat in metal cutting. (1) Primary shear zone. (2) Secondary shear zone tool–chip (T–C) interface. (3) Tool flank. The peak temperature occurs at the center of the interface, in the shaded region.

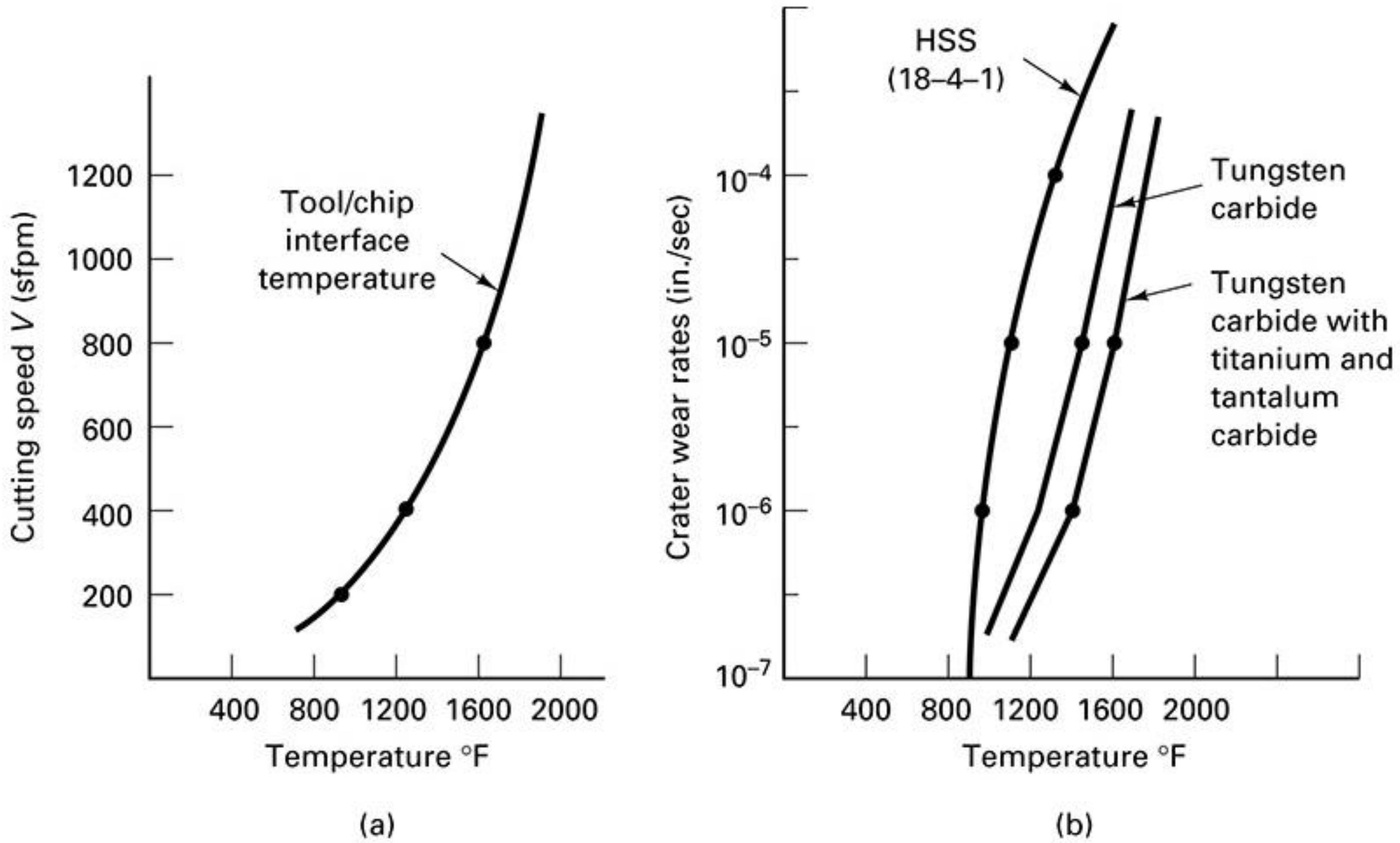


FIGURE 20-33 The typical relationship of temperature at the tool–chip interface to cutting speed shows a rapid increase. Correspondingly, the tool wears at the interface rapidly with increased temperature, often created by increased speed.

20.9 Summary

Chapter 22:
Cutting Tools for Machining

DeGarmo’s Materials and Processes in Manufacturing

21.1 Introduction

- Cutting tool Characteristics:

1. High hardness
2. Resistance to abrasion, wear, chipping
3. High hot hardness
4. Strength to resist bulk deformation
5. High toughness
6. Good chemical stability
7. Adequate thermal properties
8. High elastic modulus
9. Consistent tool life
10. Correct geometry and surface finish.

Improvements in Cutting Tools

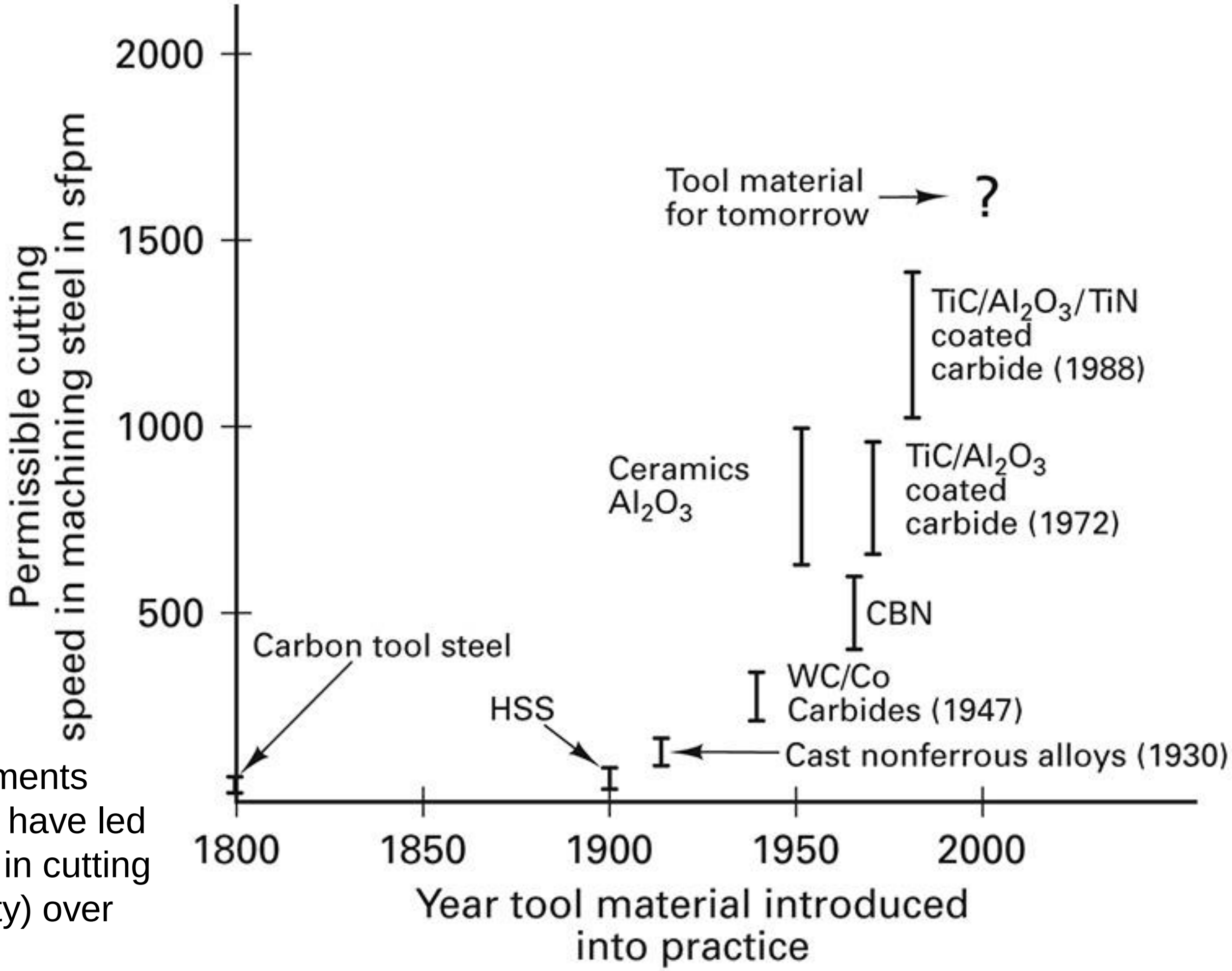


FIGURE 21-1 Improvements in cutting tool materials have led to significant increases in cutting speeds (and productivity) over the years.

Selection of Cutting Tool Materials

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

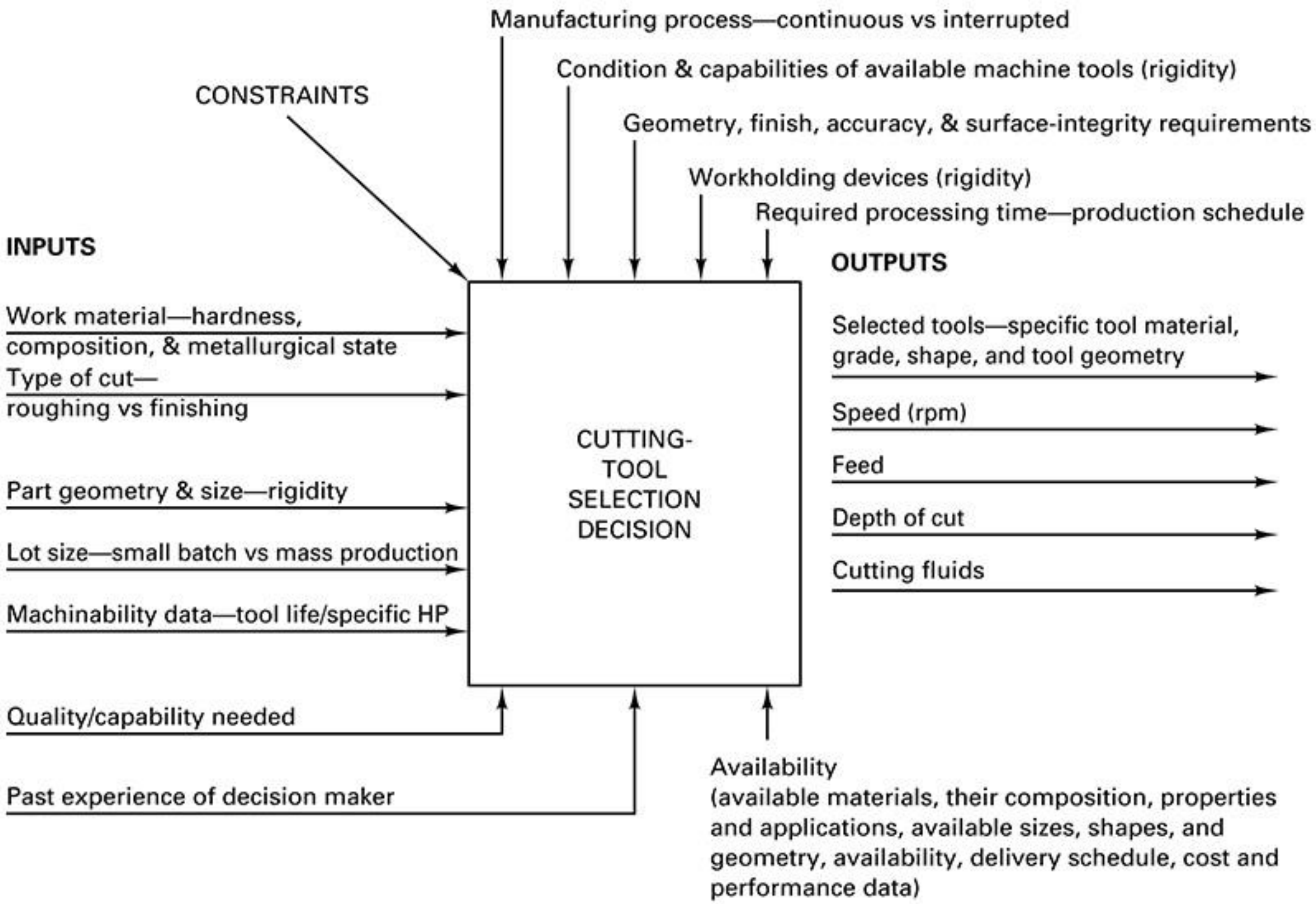


FIGURE 21-3 (a) Hardness of cutting materials and (b) decreasing hardness with increasing temperature, called hot hardness. Some materials display a more rapid drop in hardness above some temperatures. *(From* Metal Cutting Principles, *2nd ed. Courtesy of Ingersoll Cutting Tool Company.)*

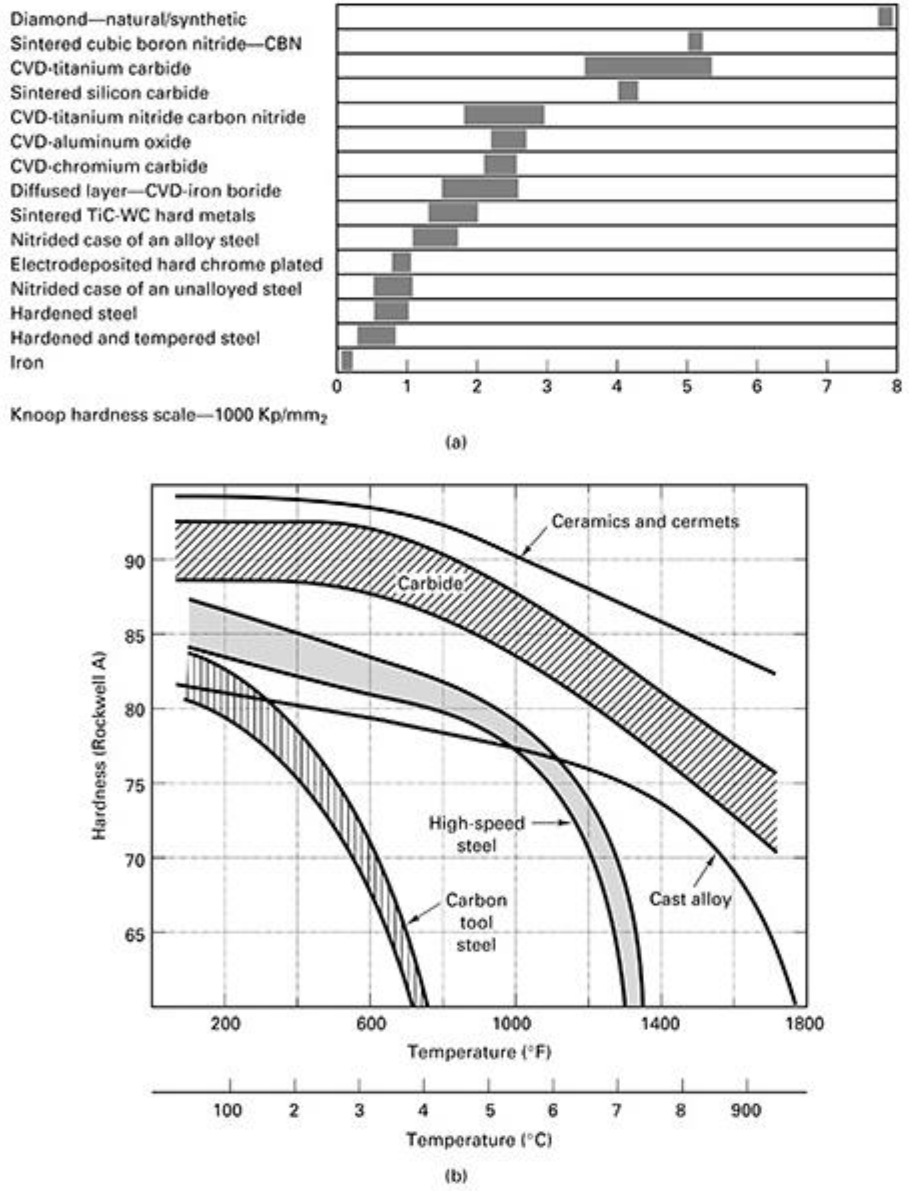
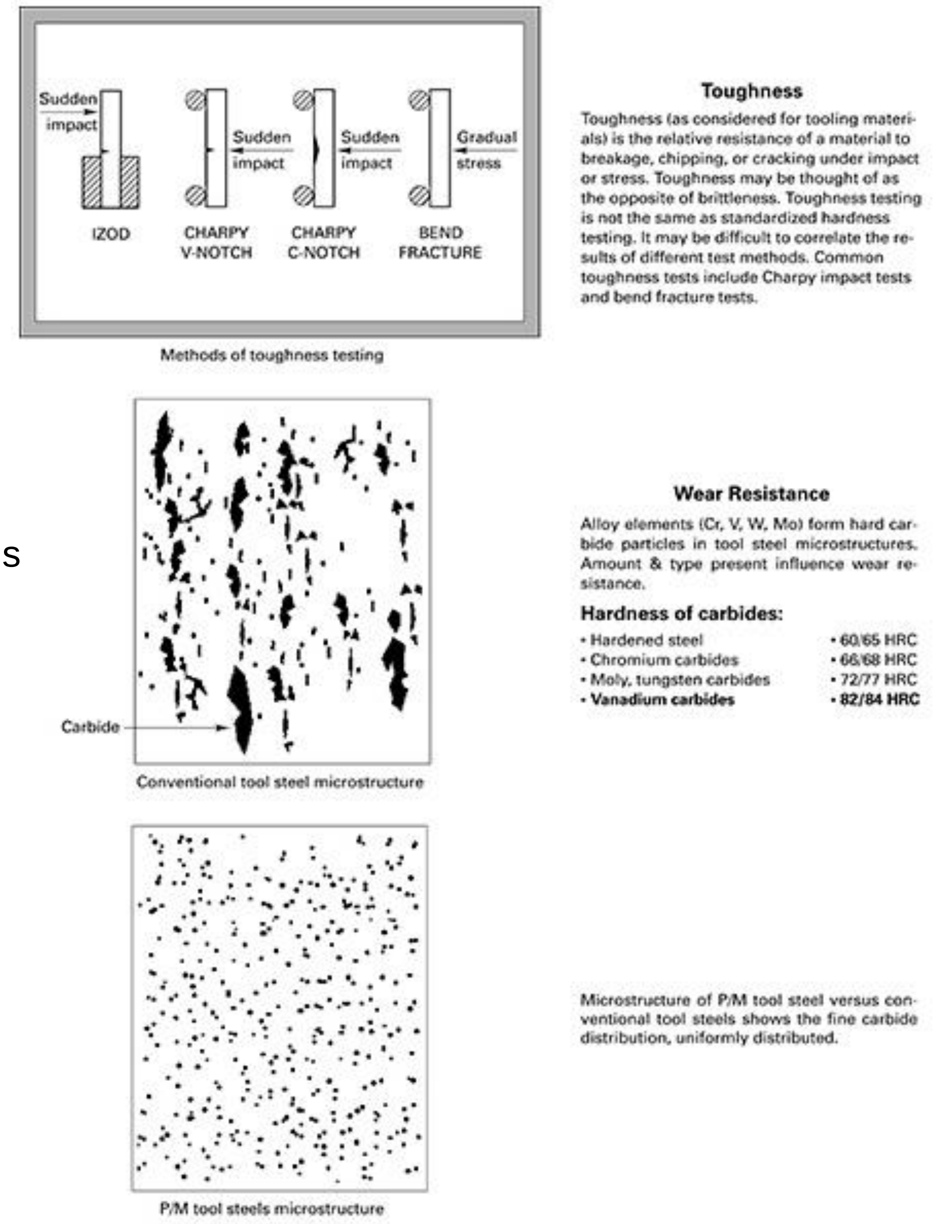


FIGURE 21-4 The most important properties of tool steels are:
1. Hardness—resistance to deforming and flattening
2. Toughness—resistance to breakage and chipping
3. Wear resistance—resistance to abrasion and erosion.



Methods of toughness testing

Toughness

Toughness (as considered for tooling materials) is the relative resistance of a material to breakage, chipping, or cracking under impact or stress. Toughness may be thought of as the opposite of brittleness. Toughness testing is not the same as standardized hardness testing. It may be difficult to correlate the results of different test methods. Common toughness tests include Charpy impact tests and bend fracture tests.

Conventional tool steel microstructure

Wear Resistance

Alloy elements (Cr, V, W, Mo) form hard carbide particles in tool steel microstructures. Amount & type present influence wear resistance.

Hardness of carbides:

• Hardened steel	• 60/65 HRC
• Chromium carbides	• 66/68 HRC
• Moly, tungsten carbides	• 72/77 HRC
• **Vanadium carbides**	• **82/84 HRC**

P/M tool steels microstructure

Microstructure of P/M tool steel versus conventional tool steels shows the fine carbide distribution, uniformly distributed.

Properties of Cutting Tool Materials

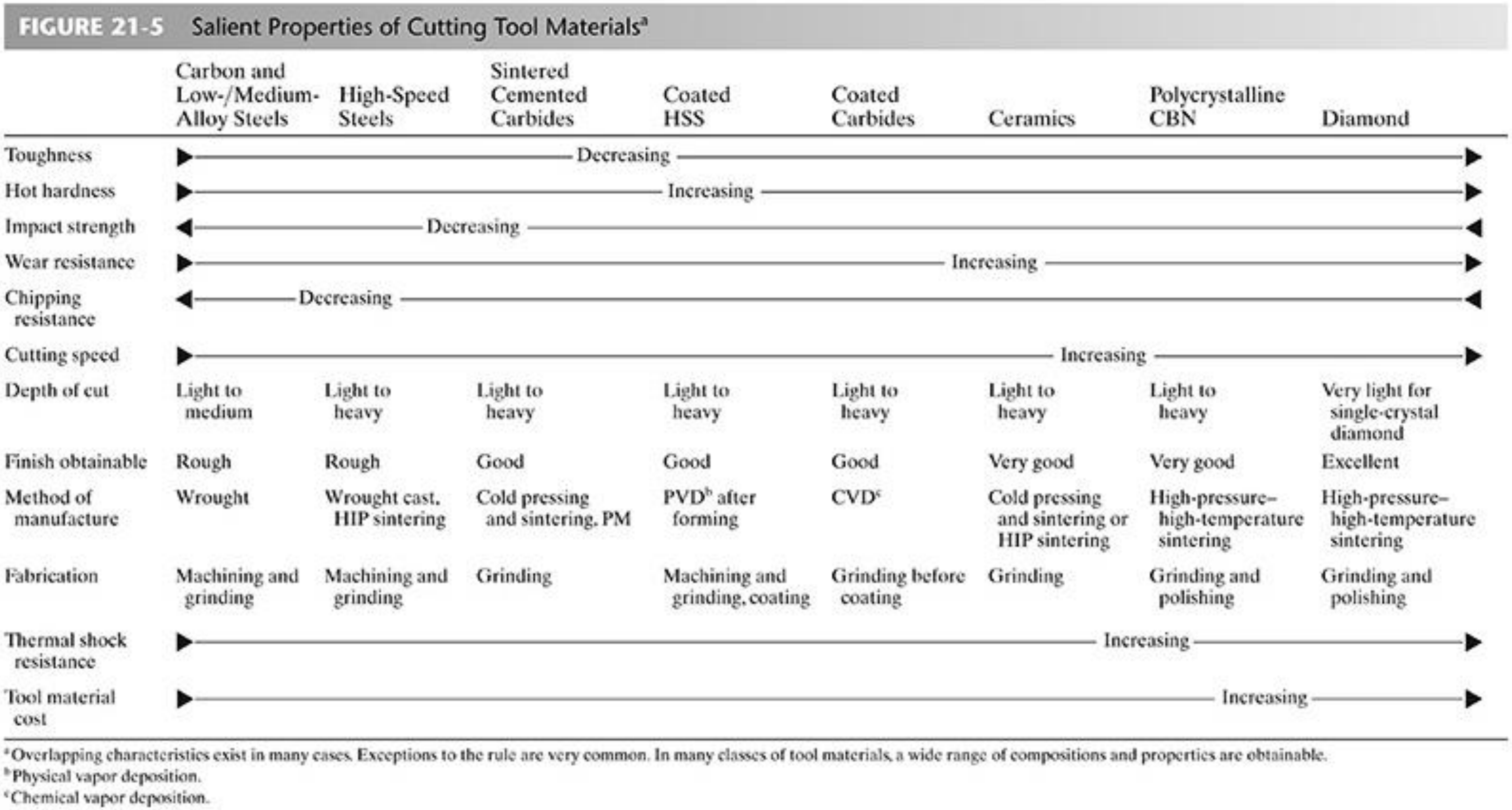


FIGURE 21-5 Salient Properties of Cutting Tool Materials[a]

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

---

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

[b] Physical vapor deposition.

[c] Chemical vapor deposition.

21.2 Cutting-Tools Materials

- Speed and feed are limited by the tool material, they should be low enough for better tool life and productivity.
- Coated and uncoated High Speed Steel (HSS) and carbides are used most.
- Coated tools cost 15 to 20 % more. Thus, their use should justify the need.
- Diamond and CBN are used when cost is justified.
- Cast Cobalt is characterized by high raw material cost.
- Ceramics and Cermits have lower cost than Cast Cobalt.

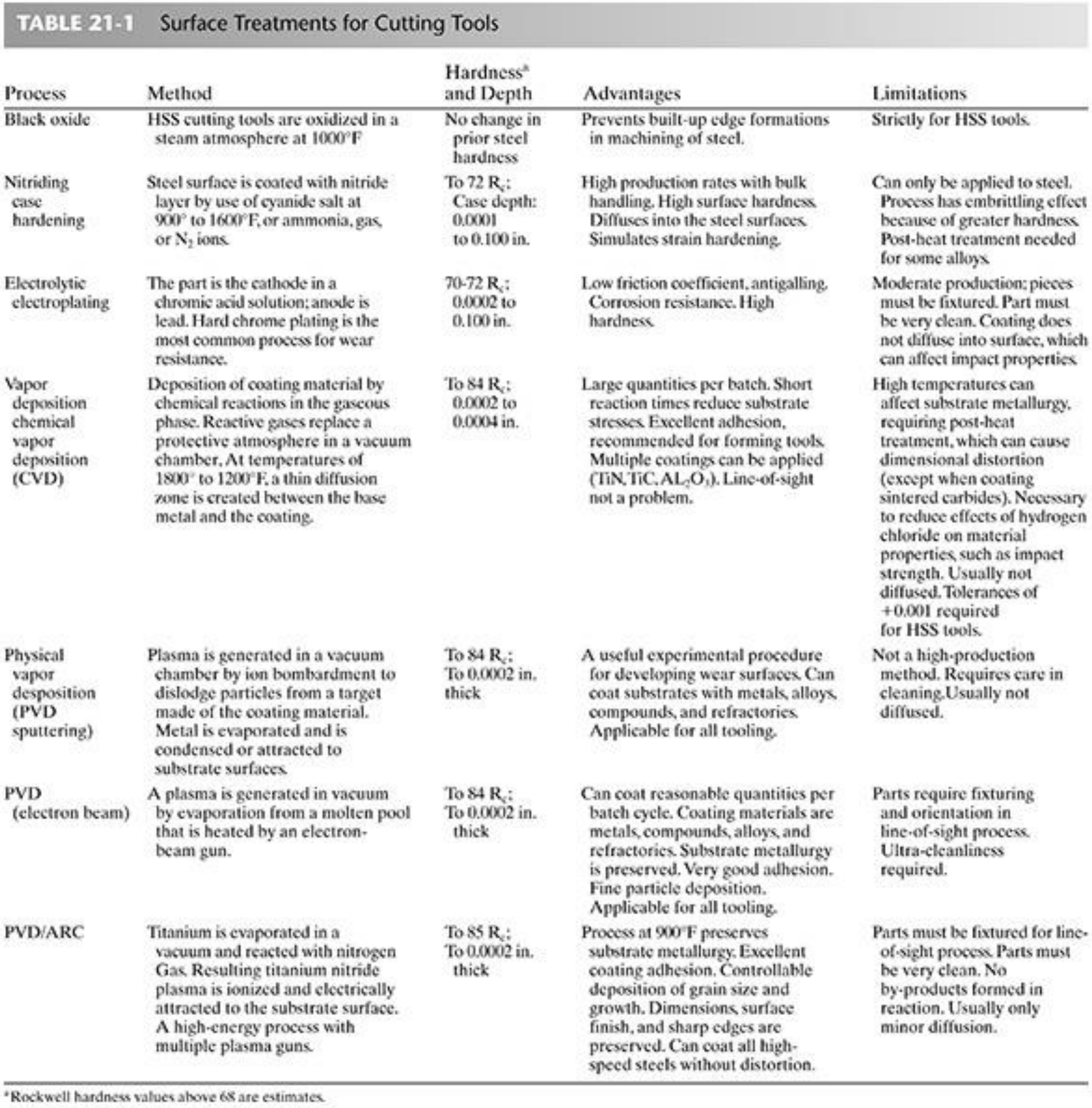


TABLE 21-1 Surface Treatments for Cutting Tools

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

[a] Rockwell hardness values above 68 are estimates.

Tool Steels:

Made from carbon steel and low/medium alloy steel

- Plain Carbon Steel(0.9 to 1.3%C) is hardened and tempered: good hardness, strength, toughness. Loose hardness at above 200C.
- Low/medium alloy steel used with (Mo, Cr for hardenability) or (tungsten W, and Mo for wear resistance).
- loose hardness at 150 to 350 C
- limited abrasion resistance
- used in drills, taps, dies, reamers, and broaches

High Speed Steel

- Contain solid solution of (W, Mo, Co, V, Cr) + (Fe and C)
- Retain properties at temp. up to 600C, “red hardness”
- Typical composition 18-4-1 called T1 (tungsten 18%, Cr 4%, V 1% See table)
- used in drills, milling cutters, and single point tools
- produced by either casting or powder metallurgy PM

Cast Cobalt Alloy

- cobalt- rich + Cr-W carbon cast alloy
- retain hardness at higher temp. thus used at high cutting speed
- cannot be soften or heat treated
- cast to shape and finished to size by grinding
- available in simple shapes
- high manufacturing cost, thus not used often

Carbides or Sintered Carbides

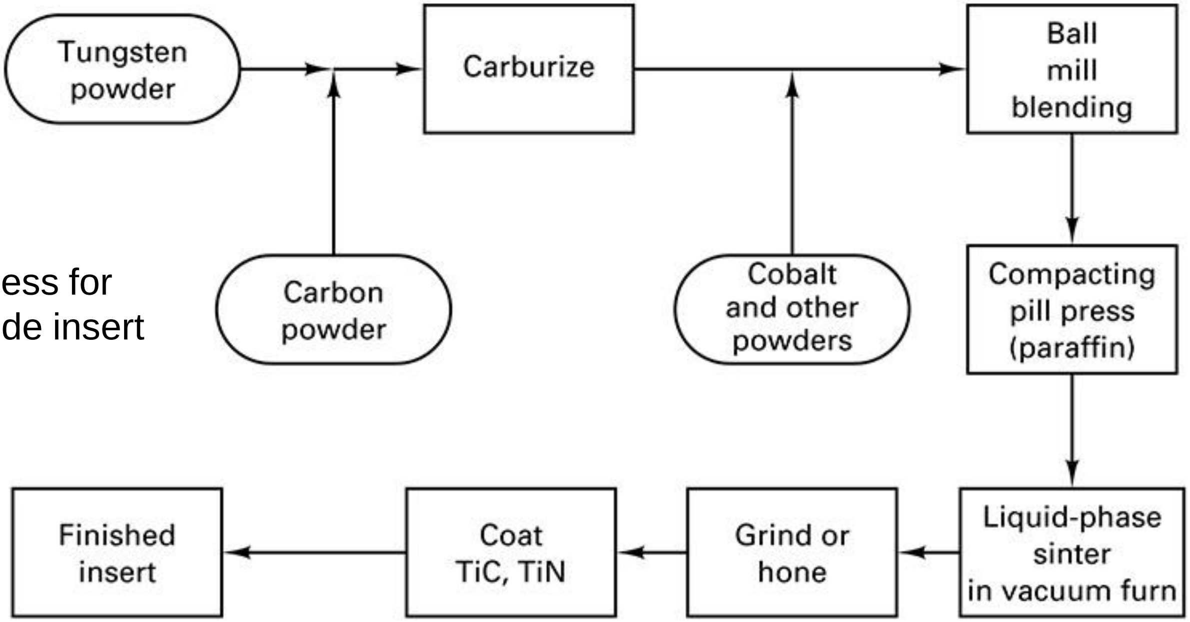
- non ferrous alloy
- called sintered or cemented carbides because of the manufacturing method by PM (see Fig)
- Most contain W-Ti or W-Ti-Ta or WC with cobalt as binder
- Much harder, better hot hardness, high stiffness, lower friction, operate at higher speed than HSS, more brittle and expensive

Carbides or Sintered Carbides

- Available as inserts (brazed or clamped)
- A small radius sharp edge may chip or break thus, can be made in increased radius to withstand cutting forces
- Tool can have grove as shown in Fig to reduce forces and work as chip breaker
- For interrupted cutting as in milling cobalt can be added to improve toughness

Cemented Carbide Inserts

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



Tungsten powder

Carbon powder

Carburize

Cobalt and other powders

Ball mill blending

Compacting pill press (paraffin)

Liquid-phase sinter in vacuum furn

Grind or hone

Coat TiC, TiN

Finished insert

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

Ceramics

- pure aluminum oxide, Al_2O_3
- made from fine particles by PM in the form of disposable tips
- can use 2 to 3 times the cutting speed of carbides
- completely resistant to cratering
- requires no coolant
- more brittle than carbides
- poor thermal and mechanical shock resistance, thus is not used in interrupted cutting

Boring Head

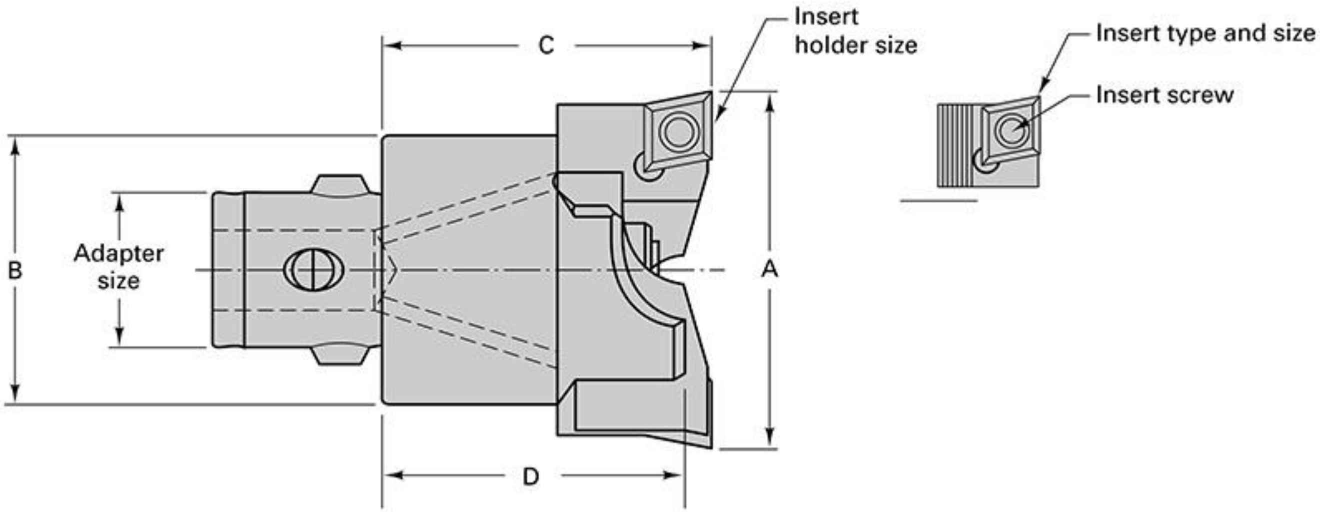
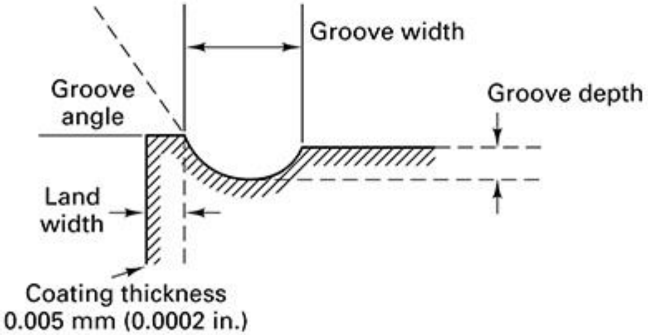


FIGURE 21-7 Boring head with carbide insert cutting tools. These inserts have a chip groove that can cause the chips to curl tightly and break into small, easily disposed lengths.



Coated Carbide Tools

A composite tool (see Fig.) made from a thin chemically stable hard refractory coating (abrasive resistant) of (TiC, TiN, Al_2O_3). The Bulk of the tool is made from a material characterized by:

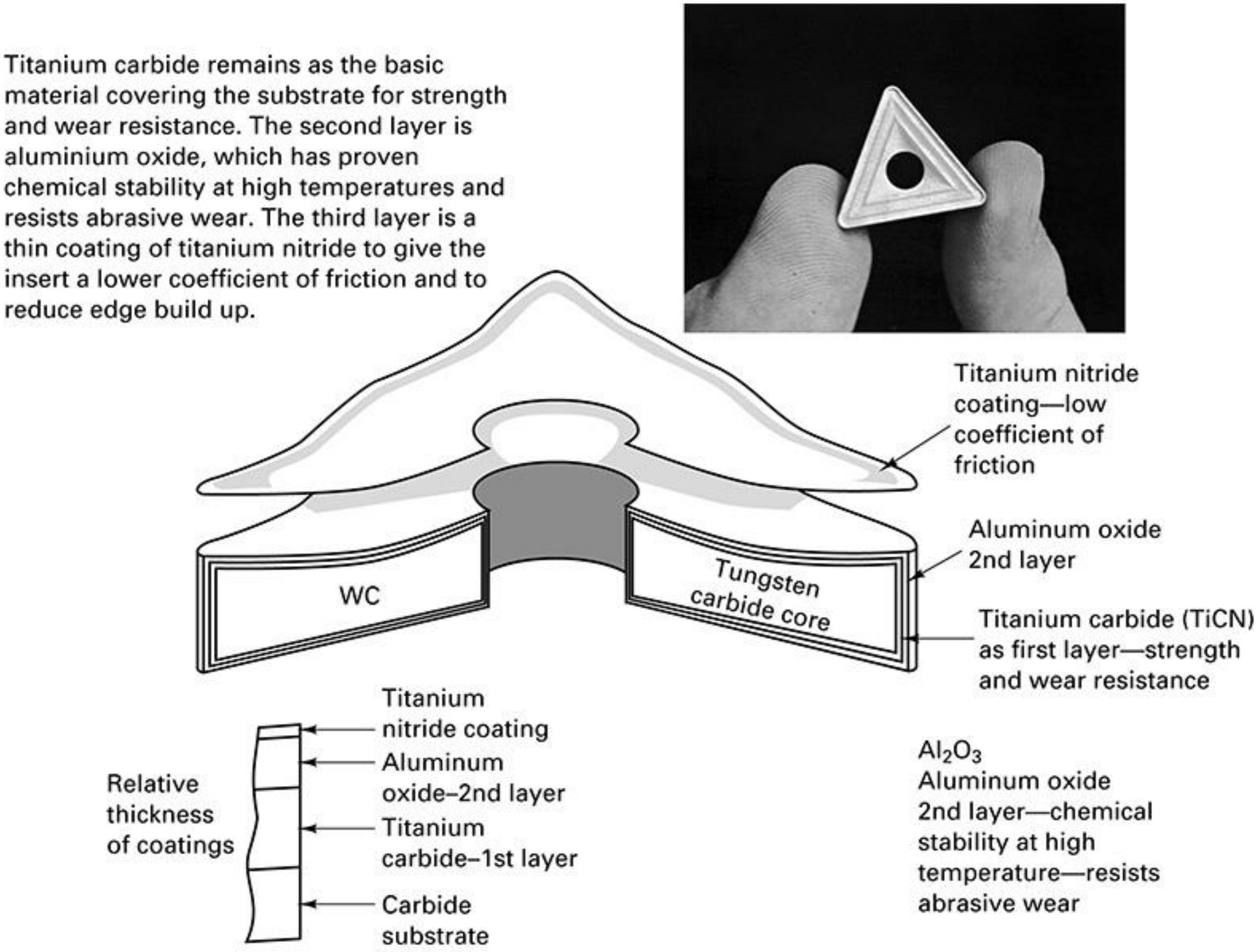
- tough
- shock resistant
- withstand high temp. and plastic deformation
- resist breakage

The result is an improved tool life 200 to 300%

The tool is coated by a chemical vaporization

Triple Coated Carbide Tools

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



Titanium carbide remains as the basic material covering the substrate for strength and wear resistance. The second layer is aluminium oxide, which has proven chemical stability at high temperatures and resists abrasive wear. The third layer is a thin coating of titanium nitride to give the insert a lower coefficient of friction and to reduce edge build up.

Triple Coated Carbide Tools

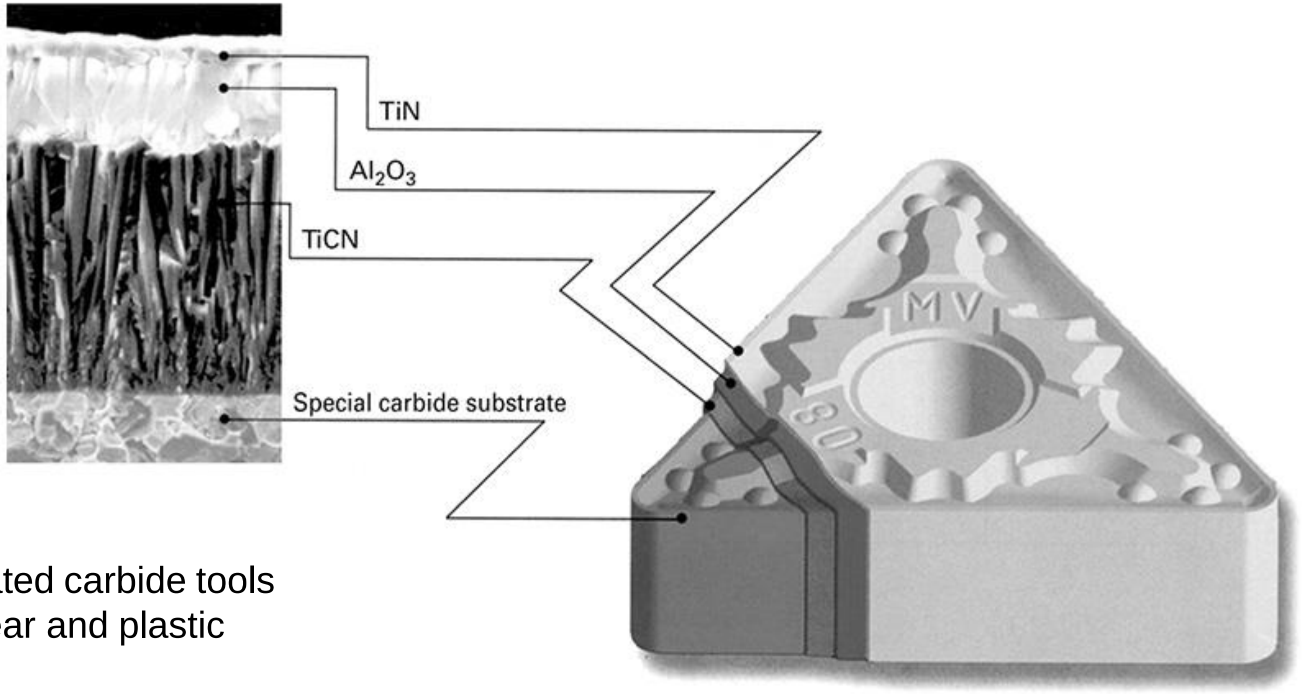


FIGURE 21-8 Triple-coated carbide tools provide resistance to wear and plastic deformation in machining of steel, abrasive wear in cast iron, and built-up edge formation.

TiN-Coated High-Speed Steel

- The best process for coating is the Physical Vapor Deposition(PVD), and variation of this process are given in Table.
- Advantages:1- reduced tool wear 2- higher hardness
- Used in making hobs, gear-shaper cutters, drills, reamers, taps, broaches, saws, and milling cutters.

Cutting Tool Material Properties

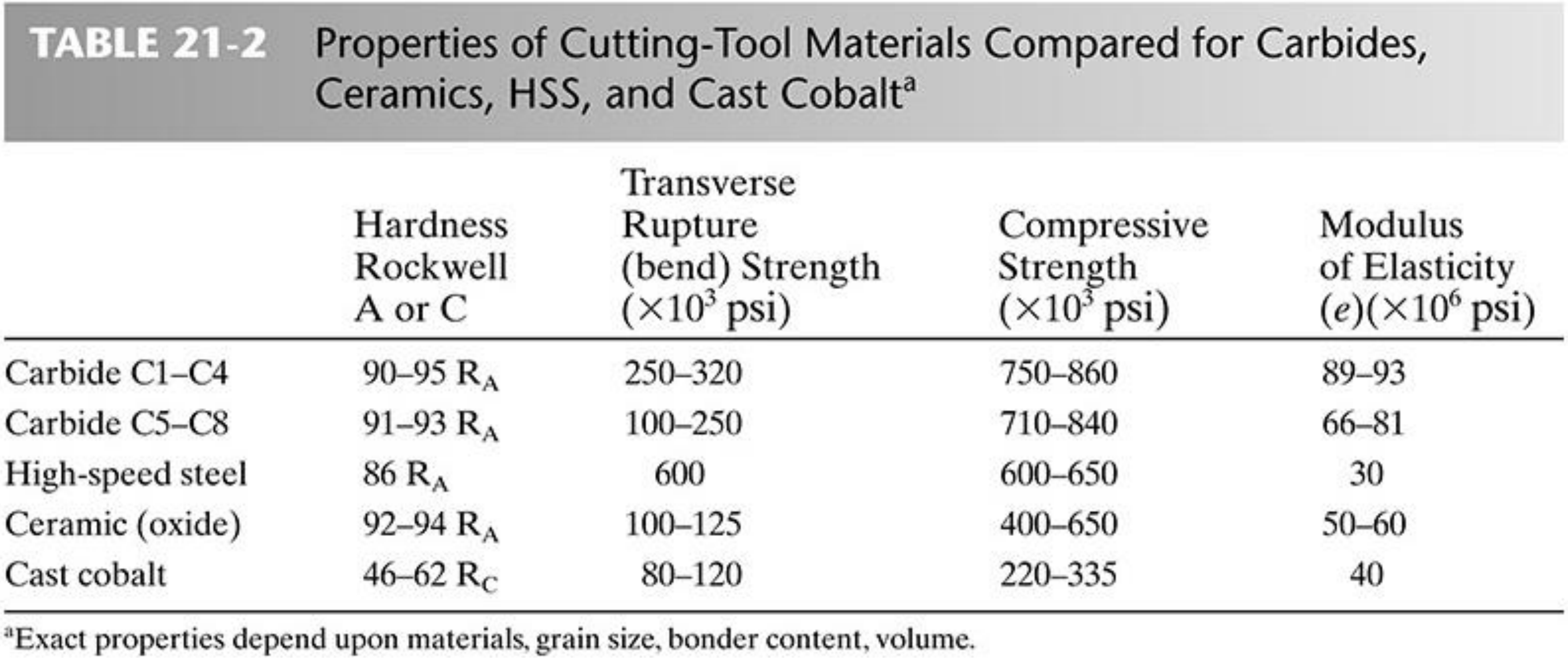


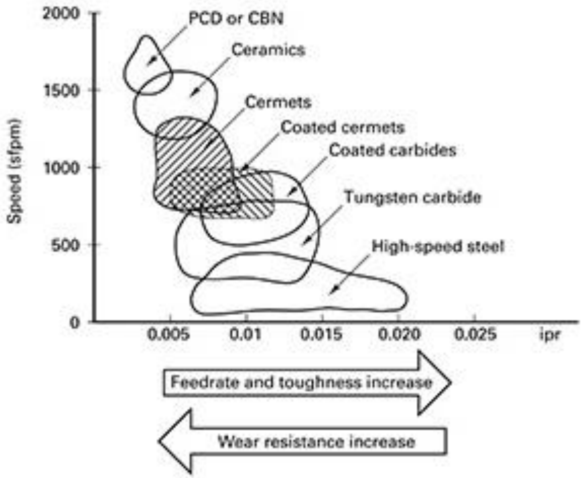
TABLE 21-2 Properties of Cutting-Tool Materials Compared for Carbides, Ceramics, HSS, and Cast Cobalt[a]

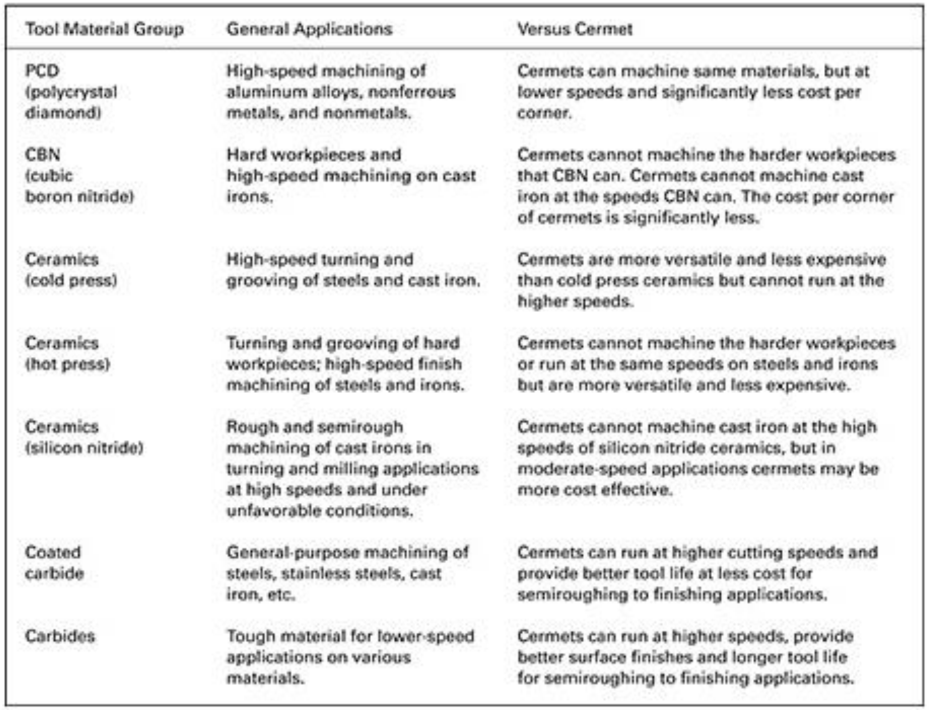
	Hardness Rockwell A or C	Transverse Rupture (bend) Strength ($\times 10^3$ psi)	Compressive Strength ($\times 10^3$ psi)	Modulus of Elasticity (e)($\times 10^6$ psi)
Carbide C1–C4	90–95 R_A	250–320	750–860	89–93
Carbide C5–C8	91–93 R_A	100–250	710–840	66–81
High-speed steel	86 R_A	600	600–650	30
Ceramic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

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

Cermits

- made from ceramic and metal binder(TiC, nickel, cobalt, tantalum nitrides, TiN, and others)
- Used for finishing purposes
- Higher hot hardness and oxidation resistance than cemented carbides
- Less toughness, lower thermal conductivity, and greater thermal expansion(thermal cracking during interrupted cuts)





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

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

Diamonds

- hardest material known
- use industrial diamond(polycrystalline compacts). Fine grain size diamond particles sintered together and metallurgic ally bonded to a cemented carbide substance
- used in machining aluminum, bronze, and plastics
- operate at high speed with fine feed

- properties:
  - high hardness, good thermal conductivity
  - very low friction, nonadherence to most materials
  - ability to maintain sharp edge for long time
  - good wear resistance
- shortcomings:
  - tendency to interact chemically with elements
  - wear rapidly when machining mild steel
  - convert at high temp.(700C) to graphite and/or oxides in air
  - very brittle
  - difficult to shape

Polycrystalline Diamond Tools

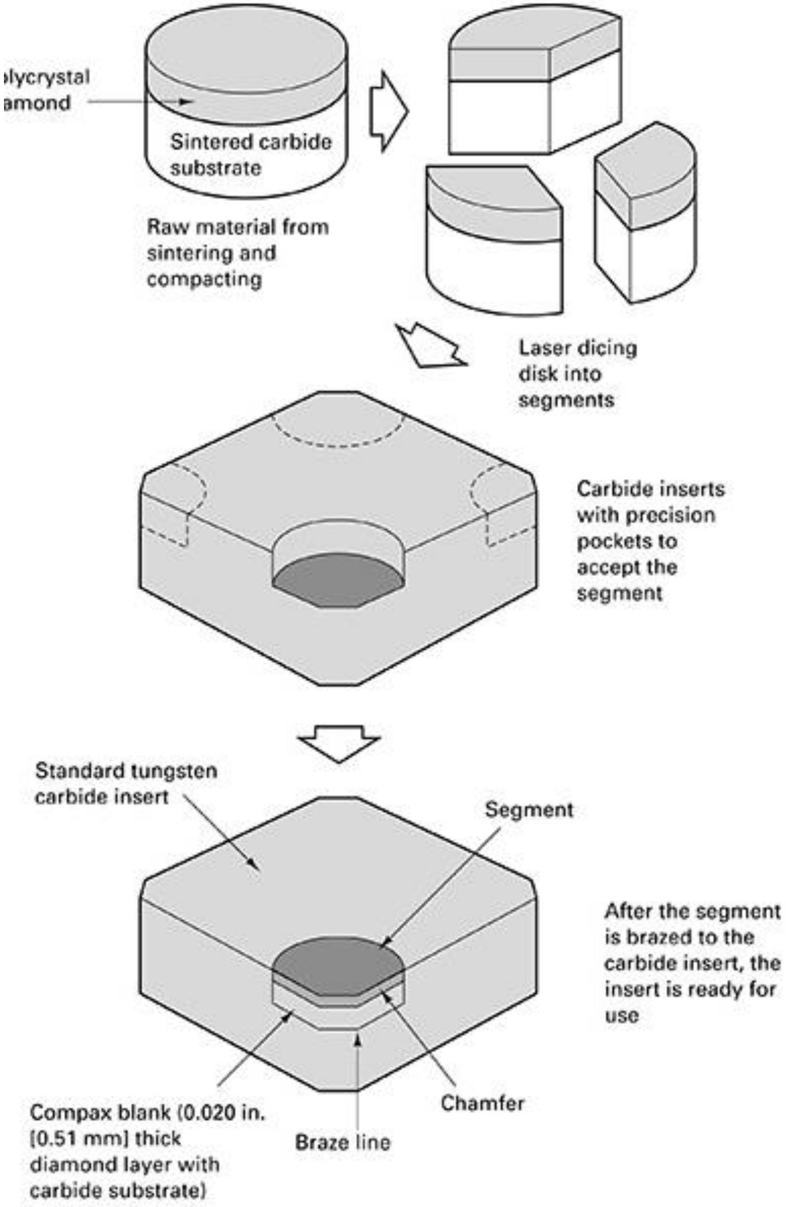


FIGURE 21-10 Polycrystalline diamond tools are carbides with diamond inserts. They are restricted to simple geometries.

Polycrystalline Cubic Boron Nitrides (PCBN)

- used in auto. Industry for machining hardened steel and superalloys
- retain hardness at elevated temp.
- lower chemical reaction
- less hard than diamond

Cost Comparison

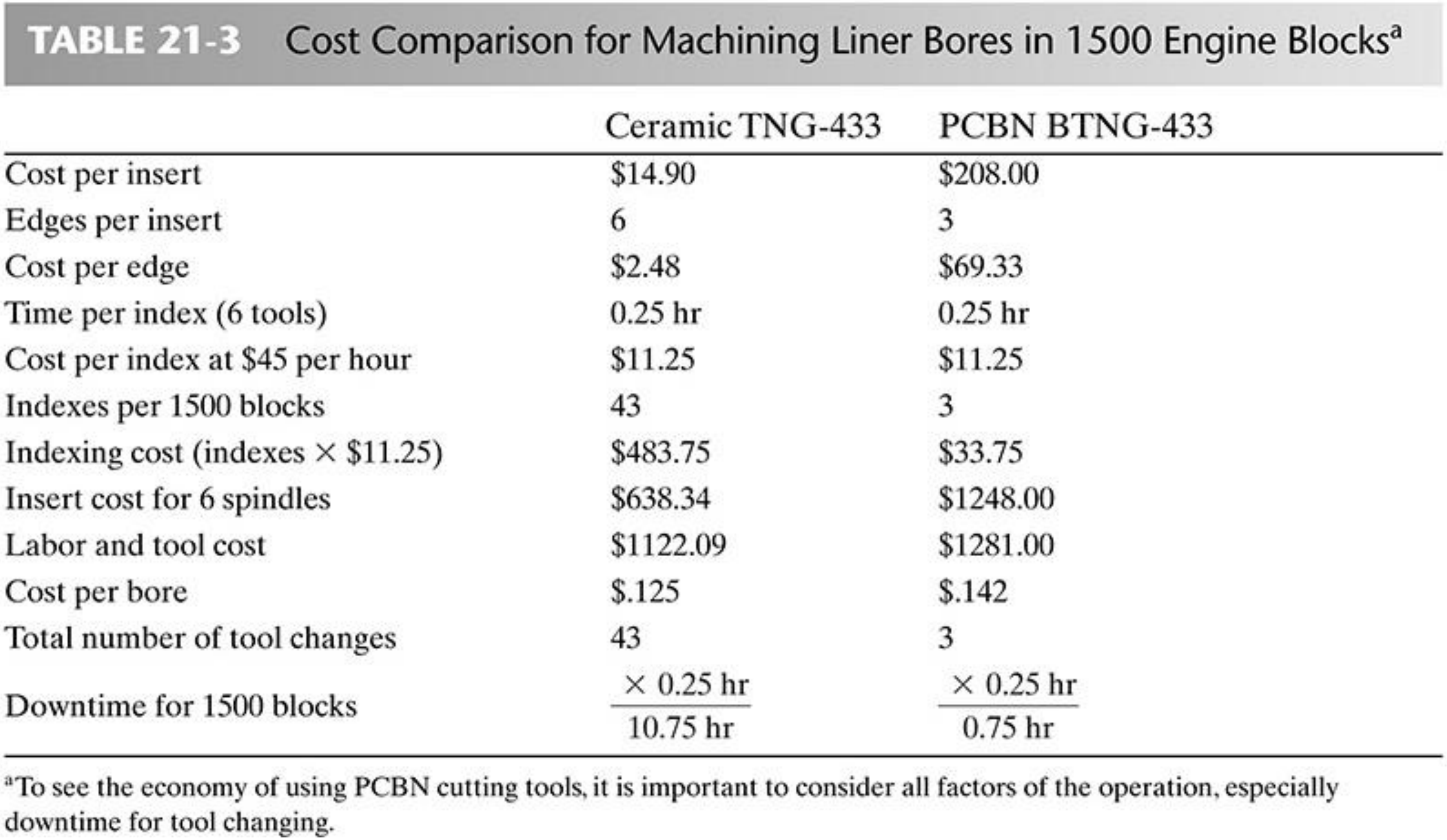


TABLE 21-3 Cost Comparison for Machining Liner Bores in 1500 Engine Blocks[a]

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

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

Application Comparison

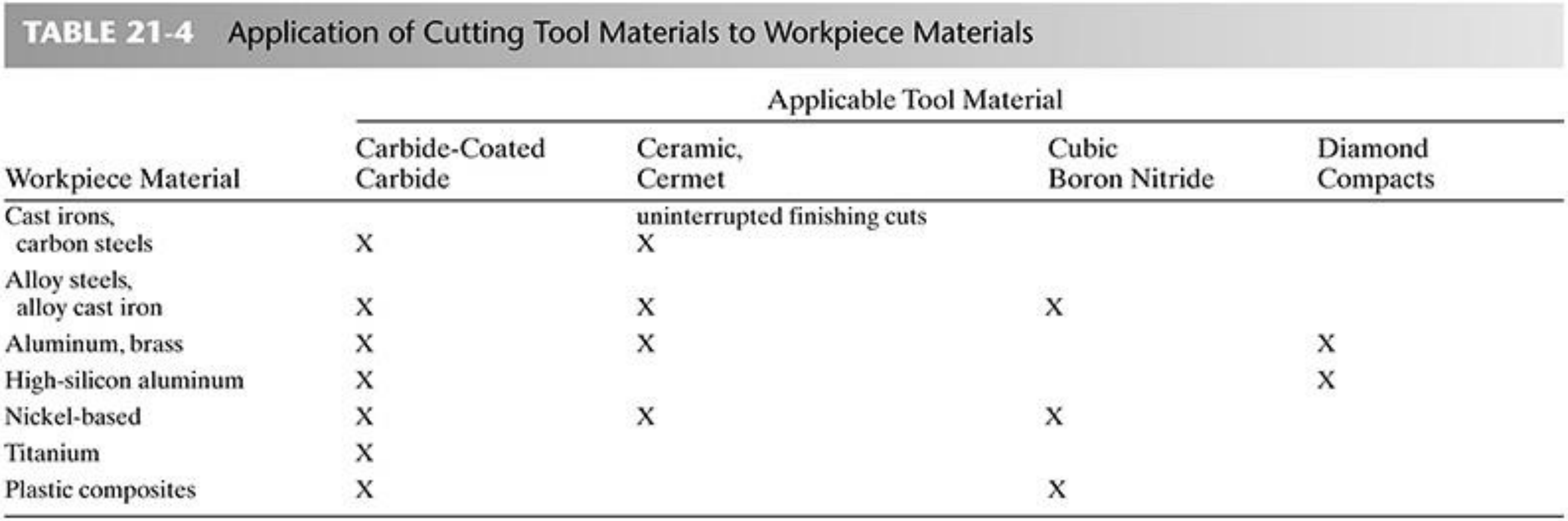


TABLE 21-4 Application of Cutting Tool Materials to Workpiece Materials

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

21.3 Tool Geometry

- Tool geometry depends on: tool material and work material
- Most important angles: rake, end and side relief

Relief angle:

- affect tool life and surface quality
- large angle gives good surface quality
- ranges from 5 to 10 degrees

Back rake angle:

- ability to shear work material
- +ve rake, reduce cutting force and thus smaller deflection of work and tool
- -ve rake, for hard material, increase tool force , but give good support specially for interrupted cuts
- the angle for carbide tools ranges from –6 to +6
- the angle for HSS is generally positive
- small rake gives high compression, high tool forces, and high friction
- large rake can weeken the tool
- Grooved tools provide increased rake which increases the shear angle and thus the force and power are lowered which means that higher cutting speed can be used

Tool Geometry Terminology

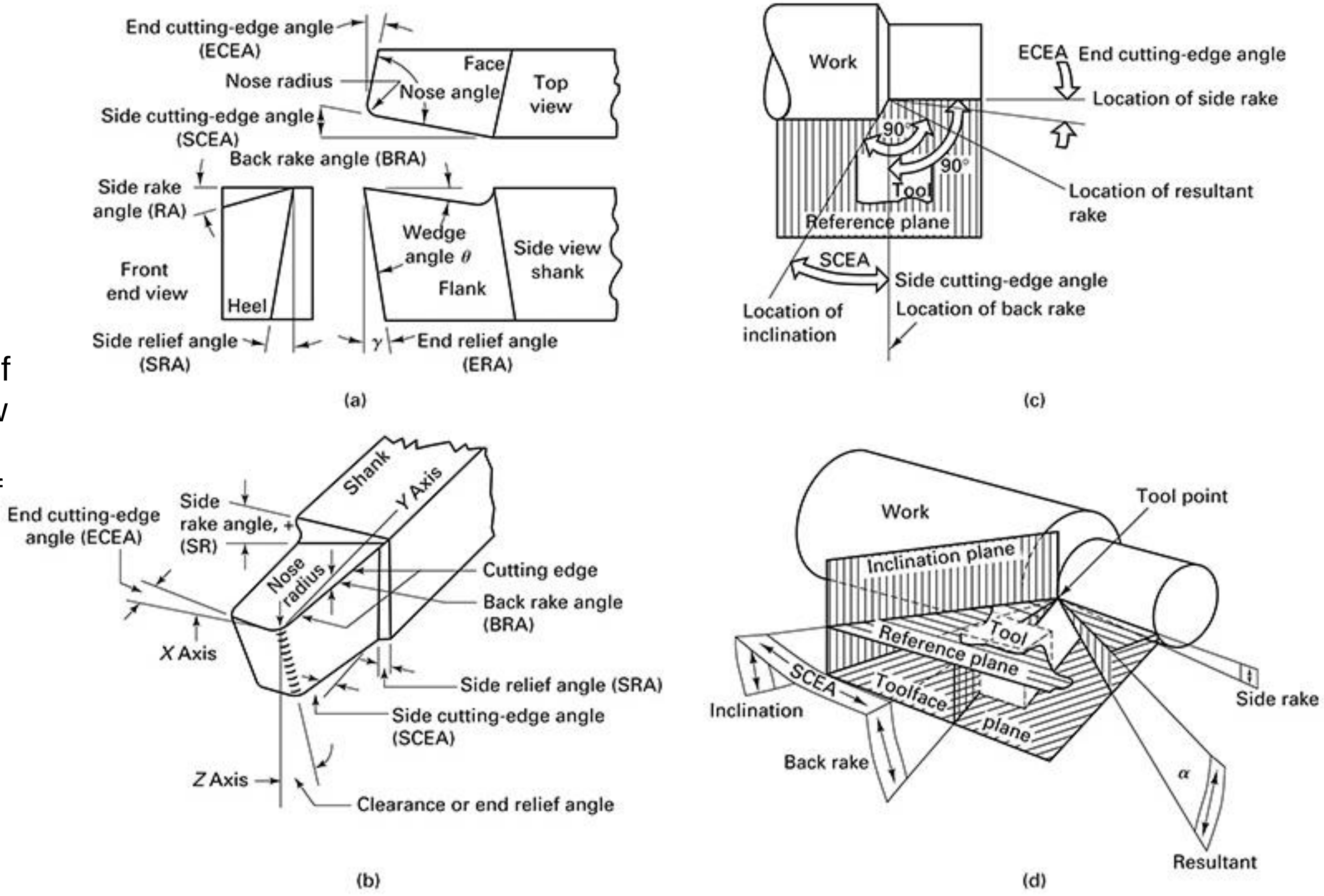
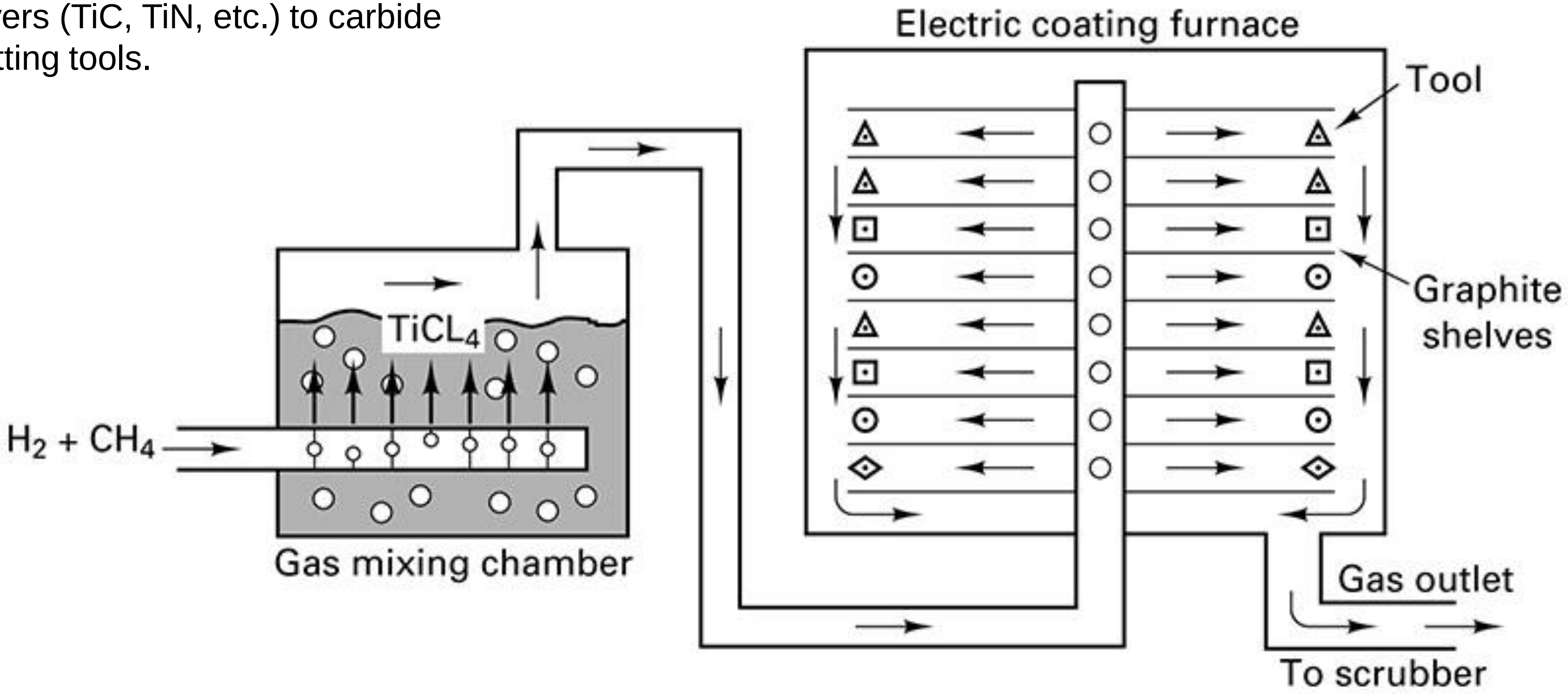


FIGURE 21-11 Standard terminology to describe the geometry of single-point tools: (a) three dimensional views of tool, (b) oblique view of tool from cutting edge, (c) top view of turning with single-point tool, (d) oblique view from shank end of single-point turning tool.

21.4 Tools Coating Processes

CVD Process

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



PVC Arc Process

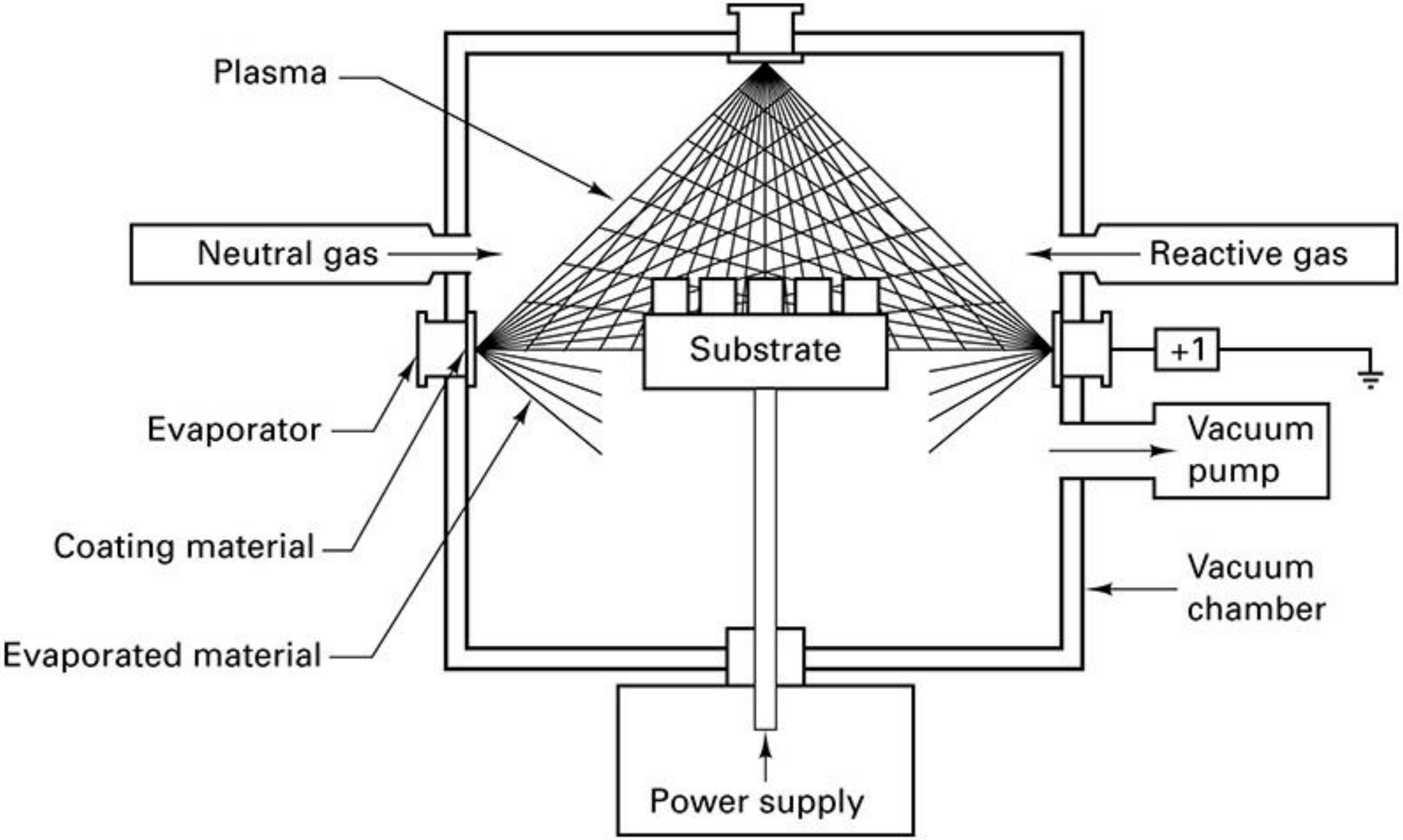
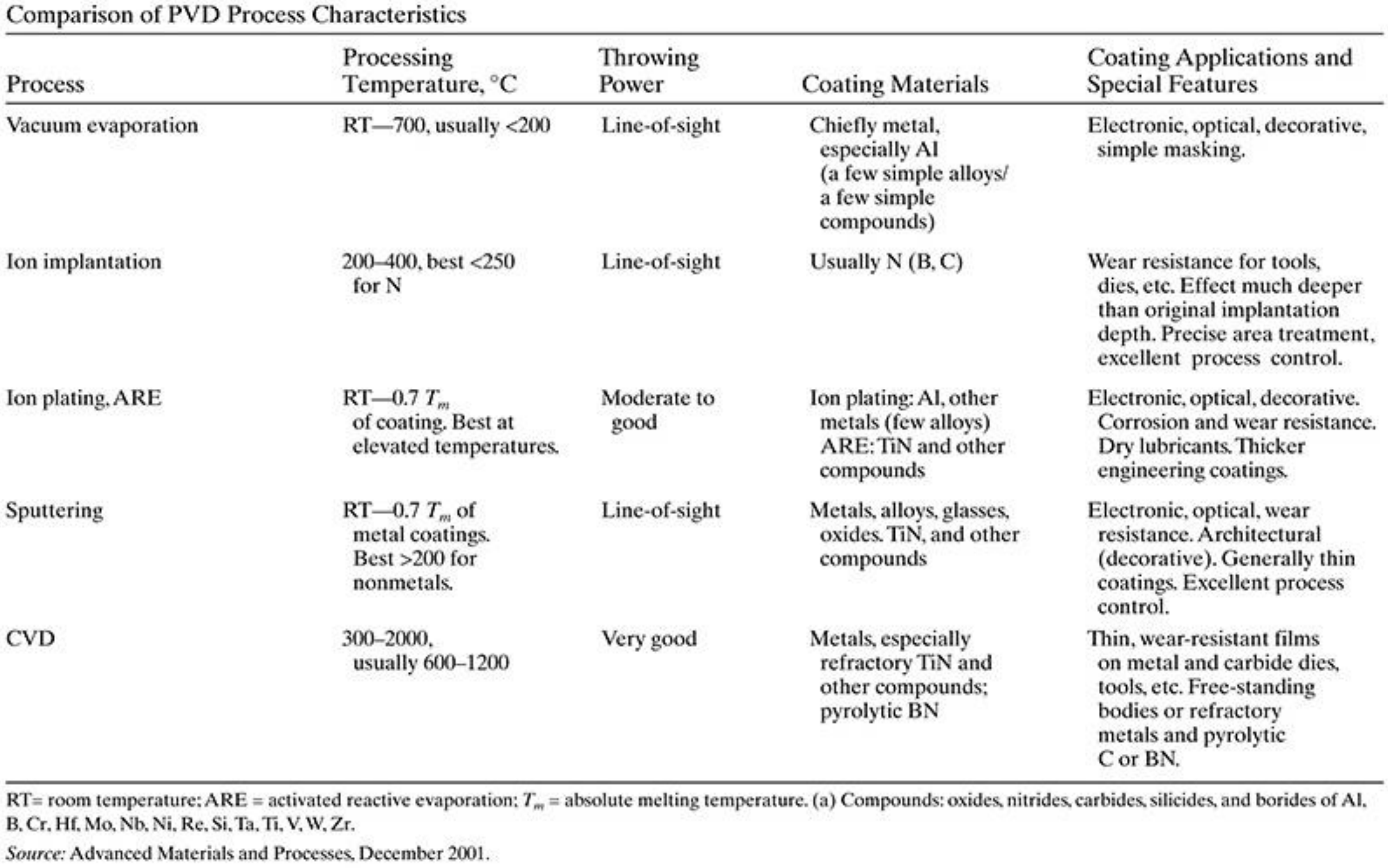


FIGURE 21-13 Schematic of PVC arc evaporation process

Comparison of PVD Processes



Comparison of PVD Process Characteristics

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

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

Source: Advanced Materials and Processes, December 2001.

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

21.5 Tool Failure and Tool Life

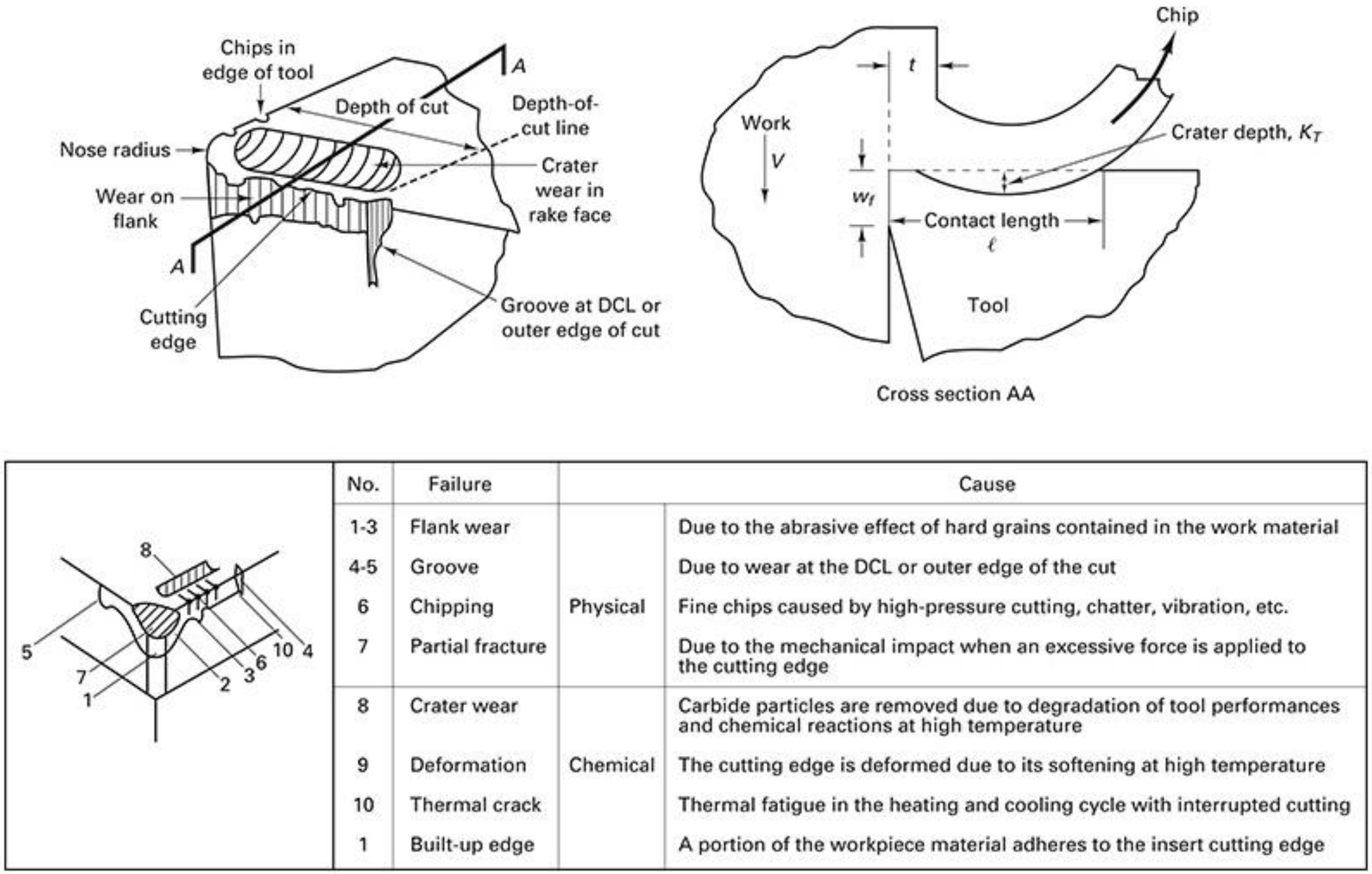
- Tool failure is due to :

1- slow death mechanism (flank wear and crater wear)

2- Sudden death (unpredictable)

- Changing in tool geometry due to failure affects:
- power
- surface finish
- dimensional accuracy
- dynamic stability

Tool Failure



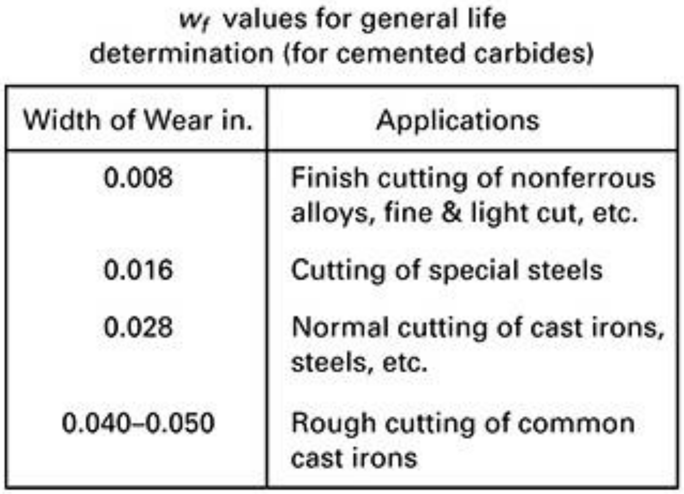
No.	Failure	Cause	
1-3	Flank wear	Physical	Due to the abrasive effect of hard grains contained in the work material
4-5	Groove		Due to wear at the DCL or outer edge of the cut
6	Chipping		Fine chips caused by high-pressure cutting, chatter, vibration, etc.
7	Partial fracture		Due to the mechanical impact when an excessive force is applied to the cutting edge
8	Crater wear	Chemical	Carbide particles are removed due to degradation of tool performances and chemical reactions at high temperature
9	Deformation		The cutting edge is deformed due to its softening at high temperature
10	Thermal crack		Thermal fatigue in the heating and cooling cycle with interrupted cutting
1	Built-up edge		A portion of the workpiece material adheres to the insert cutting edge

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

- Wear mechanisms are:
- abrasive
- adhesion
- diffusion
- chemical interaction

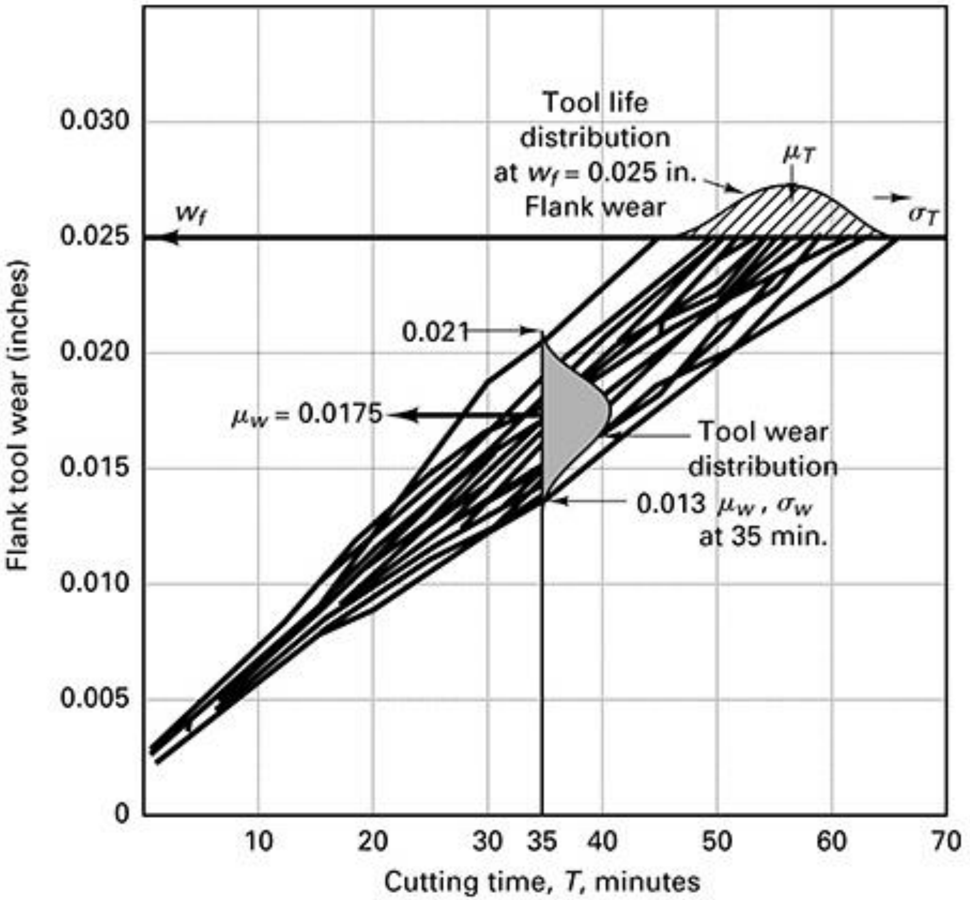
Tools Wear

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



w_f values for general life determination (for cemented carbides)

Width of Wear in.	Applications
0.008	Finish cutting of nonferrous alloys, fine & light cut, etc.
0.016	Cutting of special steels
0.028	Normal cutting of cast irons, steels, etc.
0.040–0.050	Rough cutting of common cast irons



Typical Tool Wear Curves

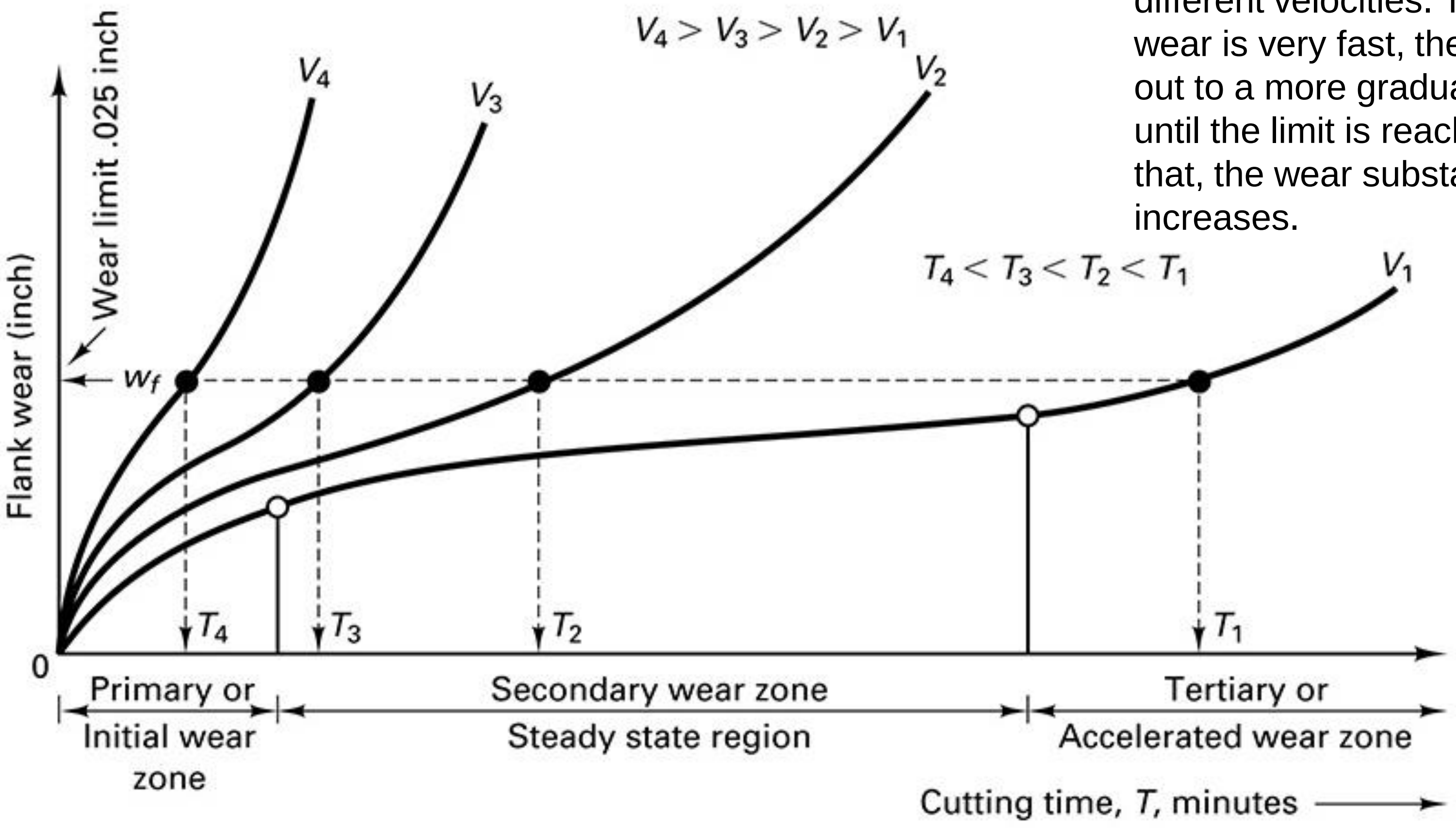


FIGURE 21-17 Typical tool wear curves for flank wear at different velocities. The initial wear is very fast, then it evens out to a more gradual pattern until the limit is reached; after that, the wear substantially increases.

Taylor’s Tool Life Model

- $VT^n = C$

n depends on tool material

C depends on input parameters

- Log V + n log T = log C

Can draw a log log graph for this equation as shown in Fig. 21.18

- It can be seen from Figure that C= V at a tool life of one min.
-
- Fig. 21.19 tool life for different work materials
-

Taylor Tool Life Curves

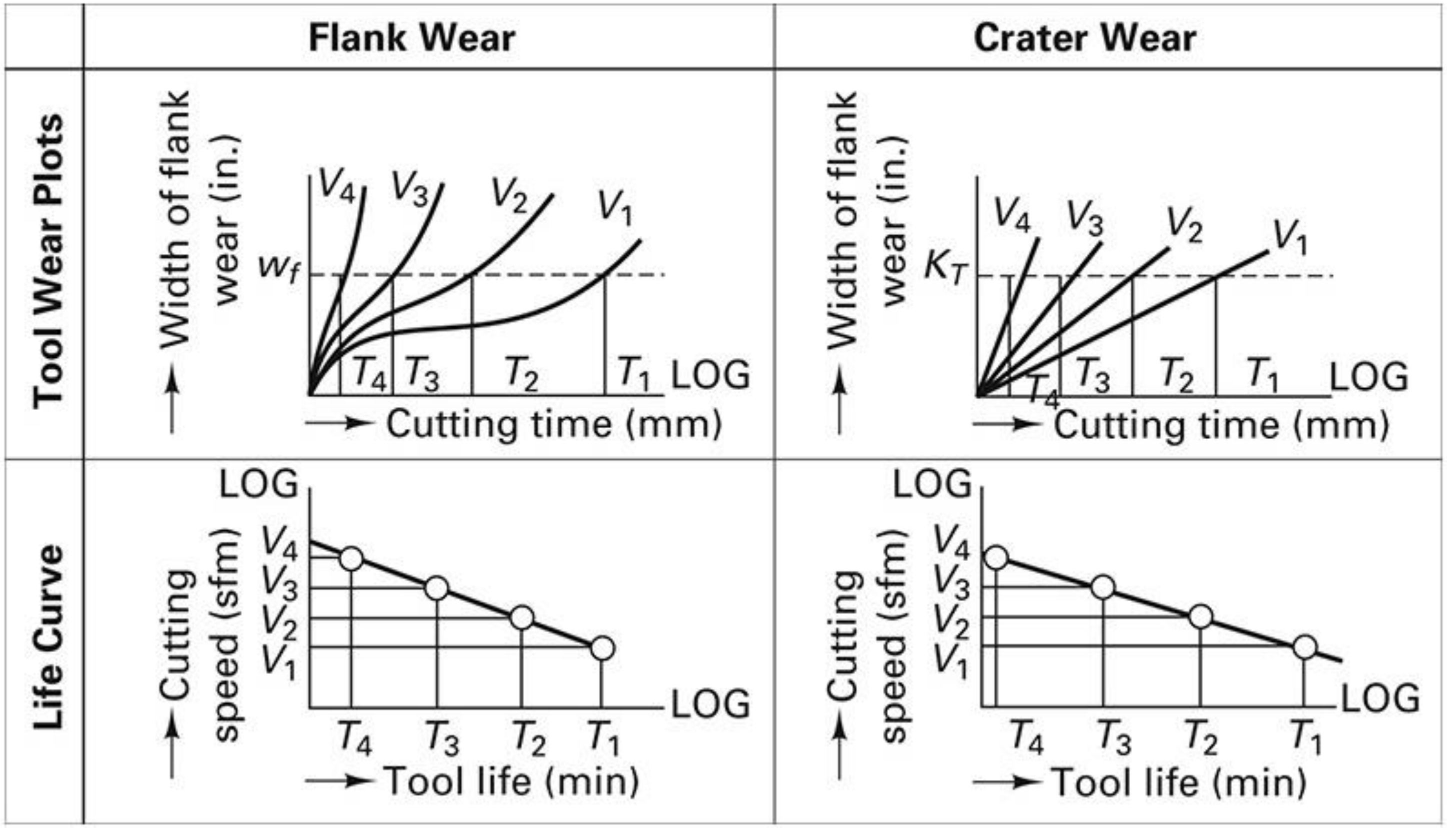


FIGURE 21-18 Construction of the Taylor tool life curve using data from deterministic tool wear plots like those of Figure 21-17. Curves like this can be developed for both flank and crater wear.

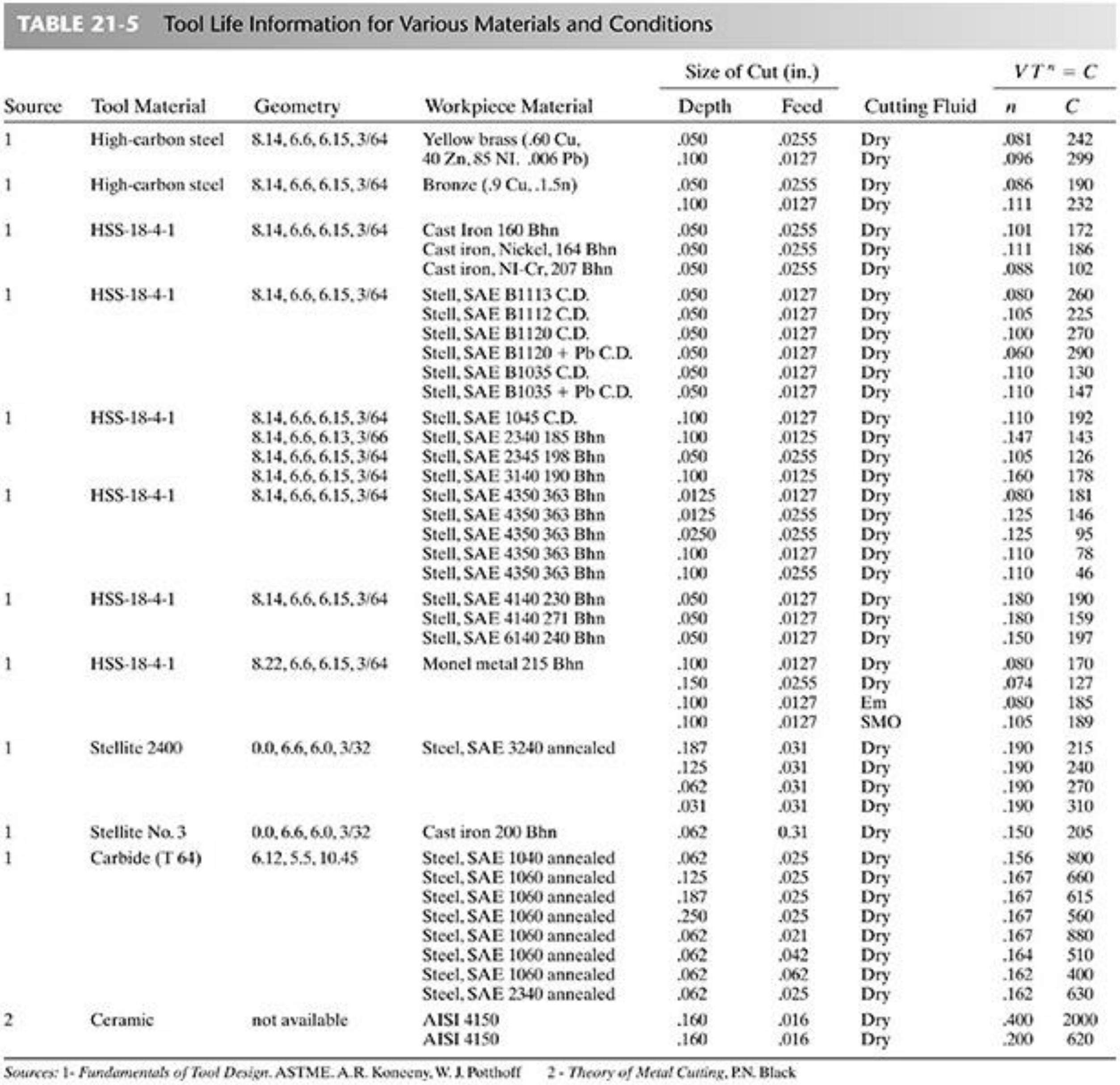


TABLE 21-5 Tool Life Information for Various Materials and Conditions

				Size of Cut (in.)			$VT^n = C$	
Source	Tool Material	Geometry	Workpiece Material	Depth	Feed	Cutting Fluid	n	C
1	High-carbon steel	8.14, 6.6, 6.15, 3/64	Yellow brass (.60 Cu, 40 Zn, 85 NI. .006 Pb)	.050	.0255	Dry	.081	242
				.100	.0127	Dry	.096	299
1	High-carbon steel	8.14, 6.6, 6.15, 3/64	Bronze (.9 Cu, .1.5n)	.050	.0255	Dry	.086	190
				.100	.0127	Dry	.111	232
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Cast Iron 160 Bhn	.050	.0255	Dry	.101	172
			Cast iron, Nickel, 164 Bhn	.050	.0255	Dry	.111	186
			Cast iron, NI-Cr, 207 Bhn	.050	.0255	Dry	.088	102
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE B1113 C.D.	.050	.0127	Dry	.080	260
			Stell, SAE B1112 C.D.	.050	.0127	Dry	.105	225
			Stell, SAE B1120 C.D.	.050	.0127	Dry	.100	270
			Stell, SAE B1120 + Pb C.D.	.050	.0127	Dry	.060	290
			Stell, SAE B1035 C.D.	.050	.0127	Dry	.110	130
			Stell, SAE B1035 + Pb C.D.	.050	.0127	Dry	.110	147
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 1045 C.D.	.100	.0127	Dry	.110	192
		8.14, 6.6, 6.13, 3/66	Stell, SAE 2340 185 Bhn	.100	.0125	Dry	.147	143
		8.14, 6.6, 6.15, 3/64	Stell, SAE 2345 198 Bhn	.050	.0255	Dry	.105	126
		8.14, 6.6, 6.15, 3/64	Stell, SAE 3140 190 Bhn	.100	.0125	Dry	.160	178
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 4350 363 Bhn	.0125	.0127	Dry	.080	181
			Stell, SAE 4350 363 Bhn	.0125	.0255	Dry	.125	146
			Stell, SAE 4350 363 Bhn	.0250	.0255	Dry	.125	95
			Stell, SAE 4350 363 Bhn	.100	.0127	Dry	.110	78
			Stell, SAE 4350 363 Bhn	.100	.0255	Dry	.110	46
1	HSS-18-4-1	8.14, 6.6, 6.15, 3/64	Stell, SAE 4140 230 Bhn	.050	.0127	Dry	.180	190
			Stell, SAE 4140 271 Bhn	.050	.0127	Dry	.180	159
			Stell, SAE 6140 240 Bhn	.050	.0127	Dry	.150	197
1	HSS-18-4-1	8.22, 6.6, 6.15, 3/64	Monel metal 215 Bhn	.100	.0127	Dry	.080	170
				.150	.0255	Dry	.074	127
				.100	.0127	Em	.080	185
				.100	.0127	SMO	.105	189
1	Stellite 2400	0.0, 6.6, 6.0, 3/32	Steel, SAE 3240 annealed	.187	.031	Dry	.190	215
				.125	.031	Dry	.190	240
				.062	.031	Dry	.190	270
				.031	.031	Dry	.190	310
1	Stellite No. 3	0.0, 6.6, 6.0, 3/32	Cast iron 200 Bhn	.062	0.31	Dry	.150	205
1	Carbide (T 64)	6.12, 5.5, 10.45	Steel, SAE 1040 annealed	.062	.025	Dry	.156	800
			Steel, SAE 1060 annealed	.125	.025	Dry	.167	660
			Steel, SAE 1060 annealed	.187	.025	Dry	.167	615
			Steel, SAE 1060 annealed	.250	.025	Dry	.167	560
			Steel, SAE 1060 annealed	.062	.021	Dry	.167	880
			Steel, SAE 1060 annealed	.062	.042	Dry	.164	510
			Steel, SAE 1060 annealed	.062	.062	Dry	.162	400
			Steel, SAE 2340 annealed	.062	.025	Dry	.162	630
2	Ceramic	not available	AISI 4150	.160	.016	Dry	.400	2000
			AISI 4150	.160	.016	Dry	.200	620

Sources: 1- *Fundamentals of Tool Design*. ASTME. A.R. Koneeny, W. J. Potthoff 2 - *Theory of Metal Cutting*, P.N. Black

Tool Life Plots

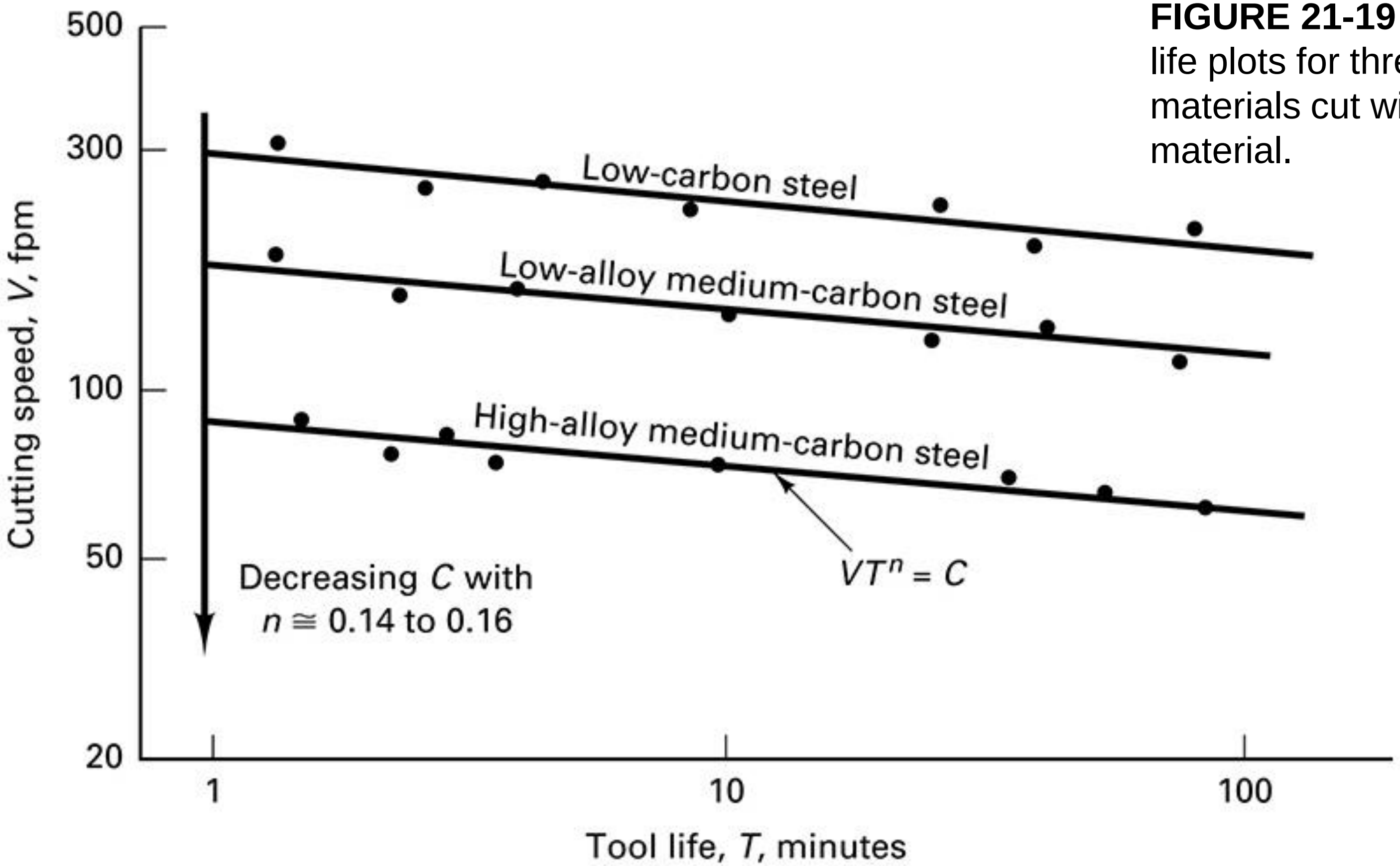


FIGURE 21-19 Log-log tool life plots for three steel work materials cut with HSS tool material.

Tools Life

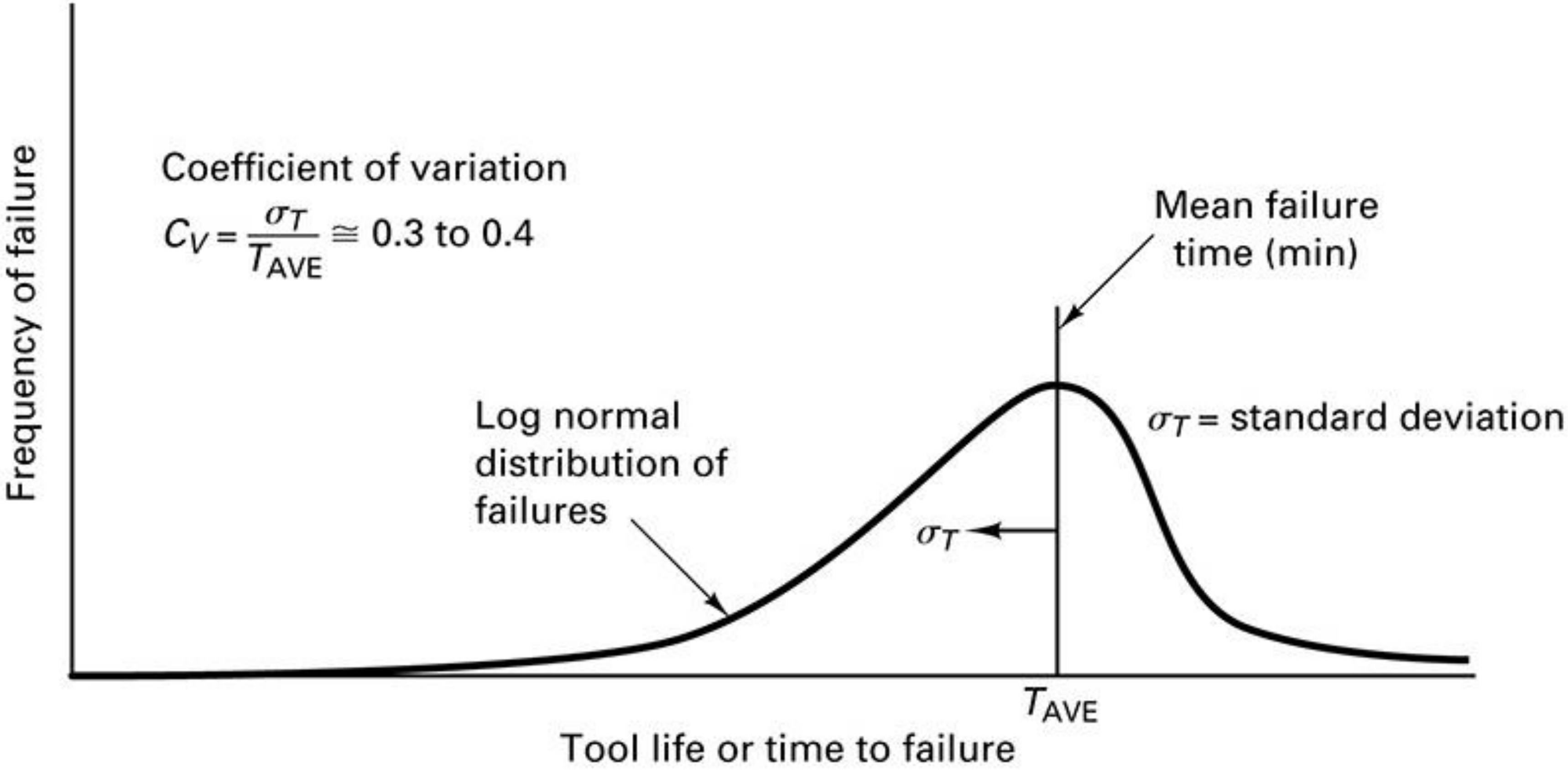
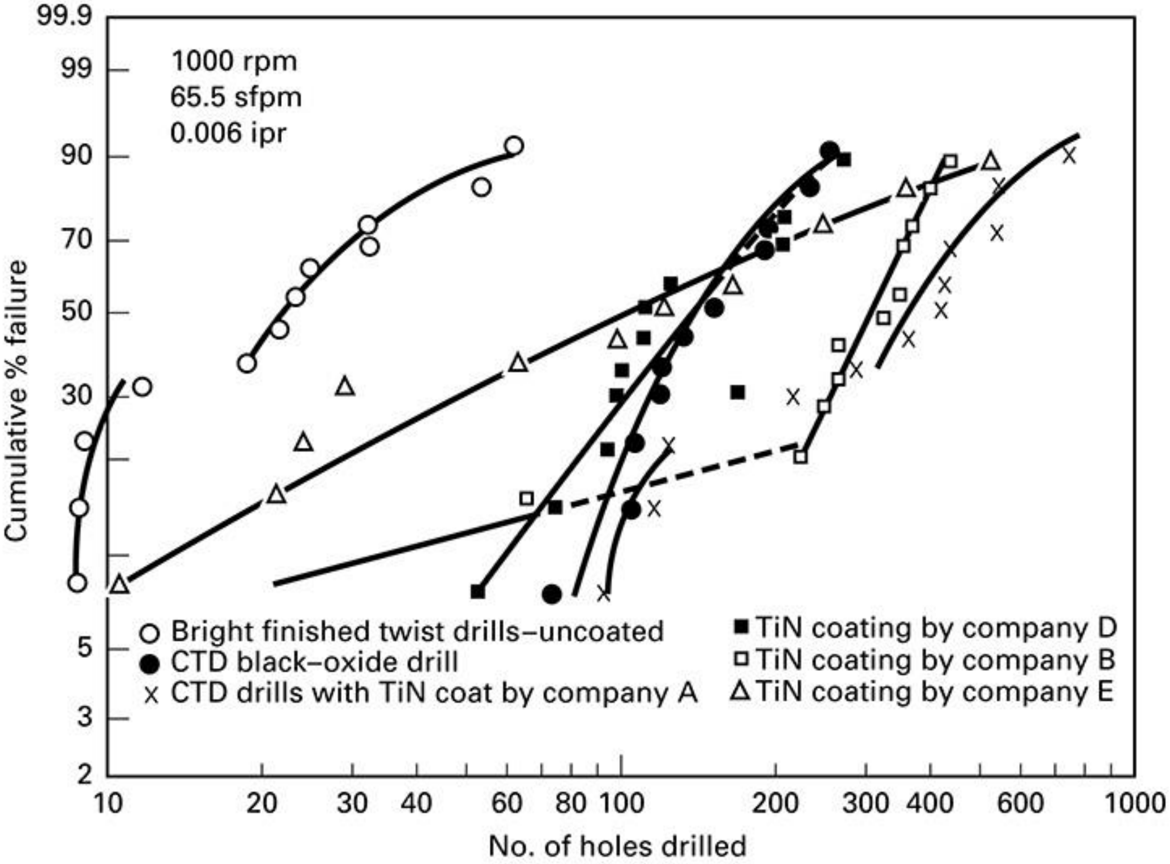


FIGURE 21-20 Tool life viewed as a random variable has a log normal distribution with a large coefficient of variation.

Tool Life Data

FIGURE 21-21 Tool life test data for various coated drills. TiN-coated HSS drills outperform uncoated drills. Life based on the number of holes drilled before drill failure.



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

21.7 Economics of Machining

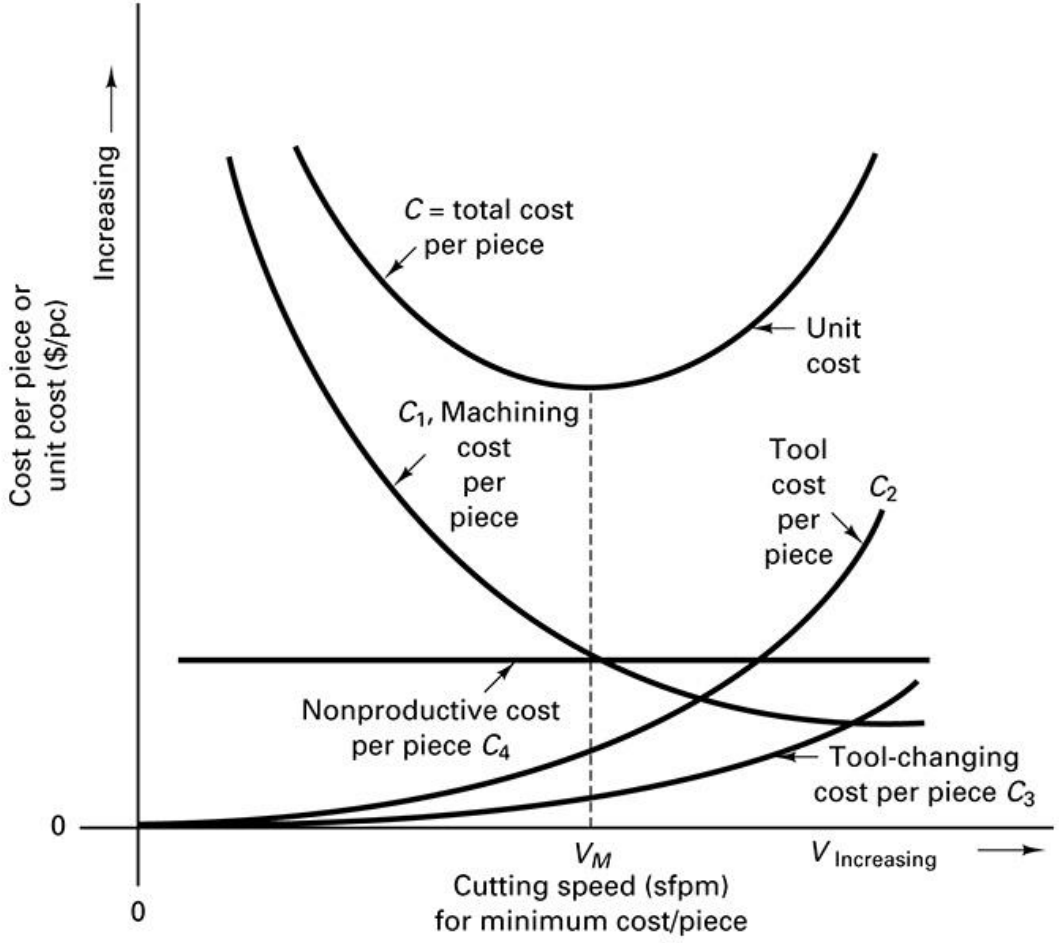
- Cutting speed has greater influence on tool life, 50% increase in speed decreases tool life by 90%.

DIFFINITIONS:

- machining cost
- tool cost
- tool changing cost
- handling cost
- velocity for minimum cost per piece V_M
- tool changing time t_c

Cost per Unit

FIGURE 21-22 Cost per unit for a machining process versus cutting speed. Note that the "*C*" in this figure and related equations is not the same "*C*" used in the Taylor tool life (equation 21-3).



Cost Comparison

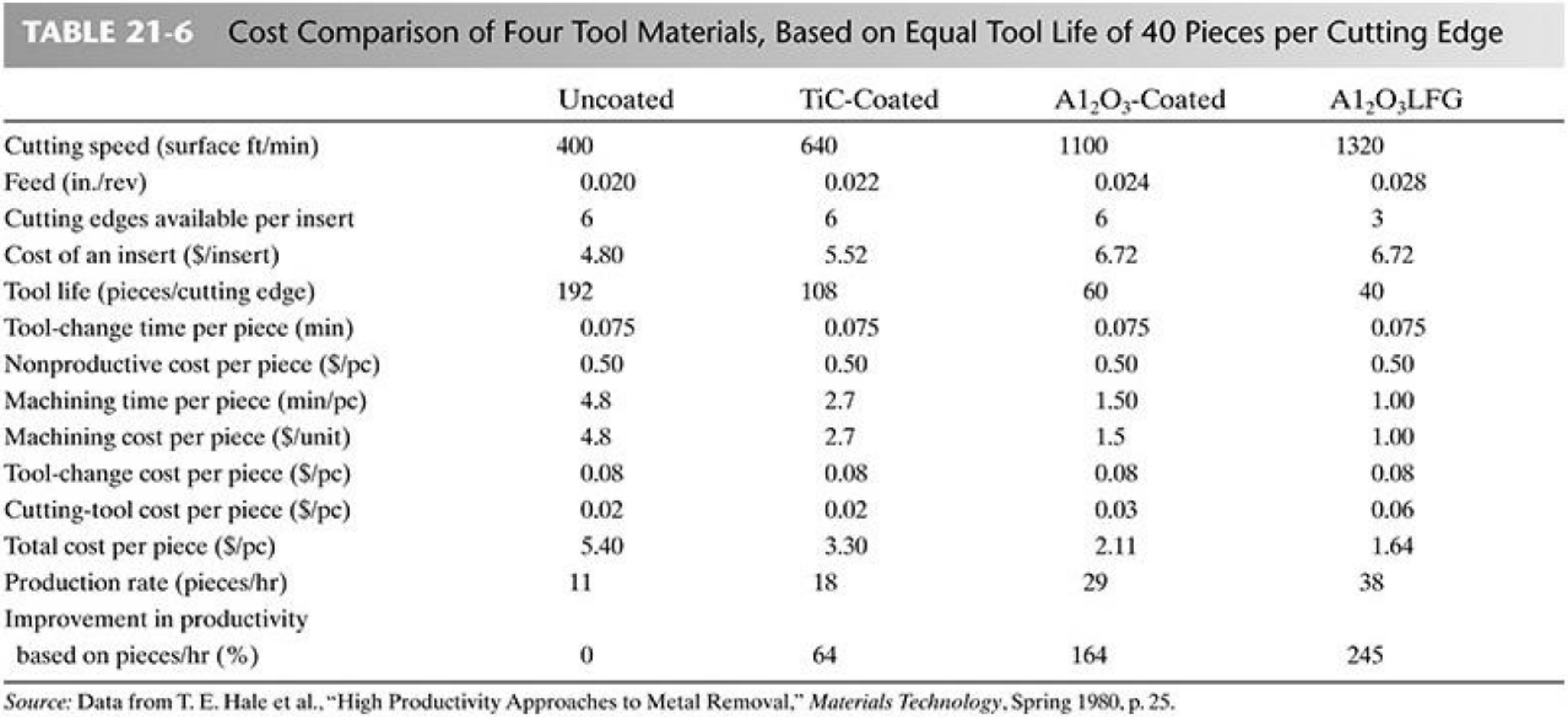


TABLE 21-6 Cost Comparison of Four Tool Materials, Based on Equal Tool Life of 40 Pieces per Cutting Edge

	Uncoated	TiC-Coated	$A1_2O_3$-Coated	$A1_2O_3$LFG
Cutting speed (surface ft/min)	400	640	1100	1320
Feed (in./rev)	0.020	0.022	0.024	0.028
Cutting edges available per insert	6	6	6	3
Cost of an insert ($/insert)	4.80	5.52	6.72	6.72
Tool life (pieces/cutting edge)	192	108	60	40
Tool-change time per piece (min)	0.075	0.075	0.075	0.075
Nonproductive cost per piece ($/pc)	0.50	0.50	0.50	0.50
Machining time per piece (min/pc)	4.8	2.7	1.50	1.00
Machining cost per piece ($/unit)	4.8	2.7	1.5	1.00
Tool-change cost per piece ($/pc)	0.08	0.08	0.08	0.08
Cutting-tool cost per piece ($/pc)	0.02	0.02	0.03	0.06
Total cost per piece ($/pc)	5.40	3.30	2.11	1.64
Production rate (pieces/hr)	11	18	29	38
Improvement in productivity based on pieces/hr (%)	0	64	164	245

Source: Data from T. E. Hale et al., "High Productivity Approaches to Metal Removal," *Materials Technology*, Spring 1980, p. 25.

Machinability Rating

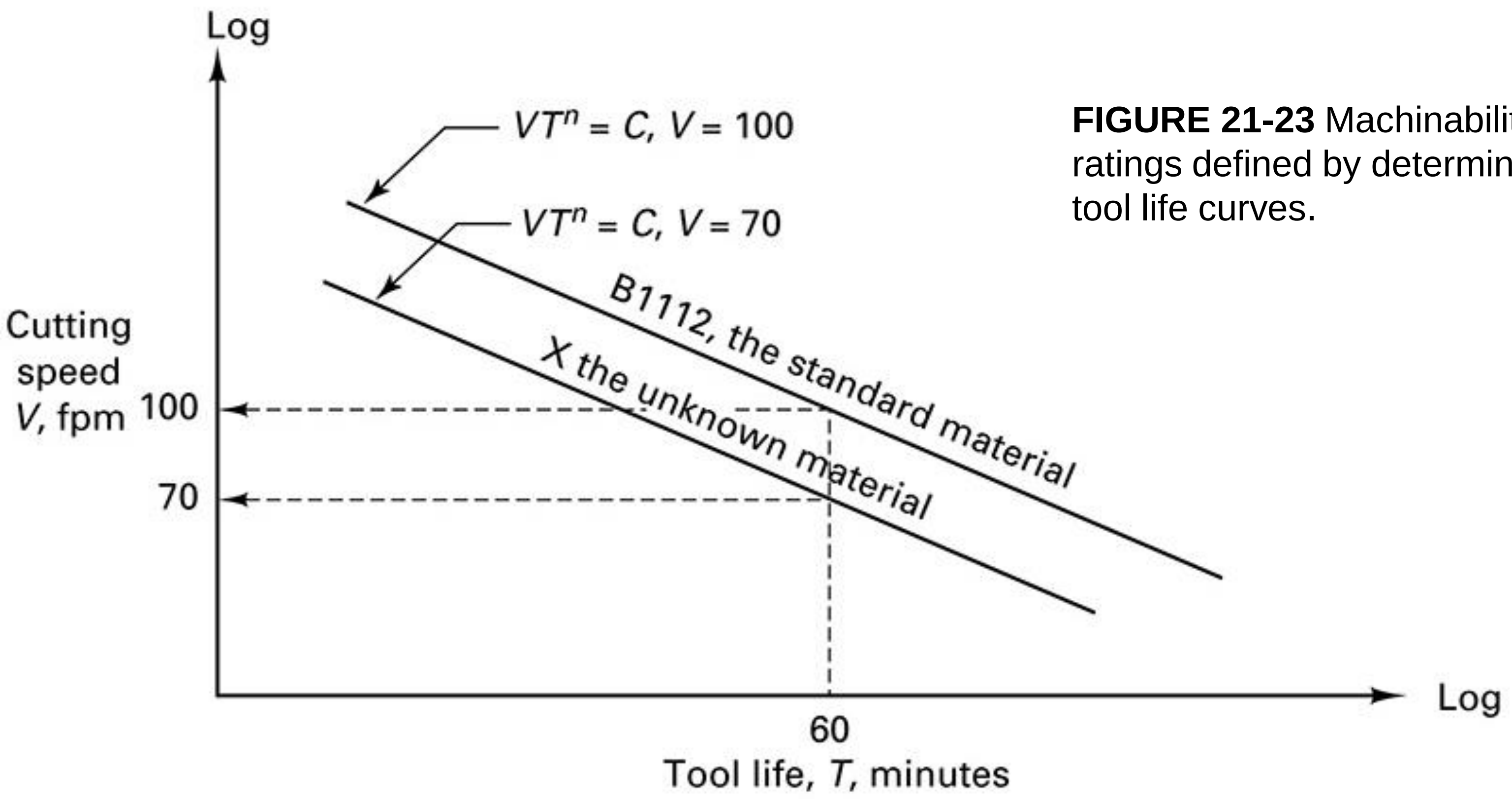


FIGURE 21-23 Machinability ratings defined by deterministic tool life curves.

Machinability

- Has different meanings; the one which is used most, is ease of machining.

Other definitions:

- ease or difficulty with which the material can be machined
- speed for a given tool life
- max. cutting speed for tool satisfactory performance
- ease of chip removal

21.8 Cutting Fluids

- Speed is doubled or tripled when using cutting fluid.
- Its functions:
- coolant (primarily)
- lubricant
- carry away the chip

- Water is the best coolant but it is rust hazard. Oil is less effective coolant but do not cause rust.

- Can use combination of oil and water or wax and water.
- Chemicals can be added to provide:
- ❑ wetting agents
- ❑ detergents
- ❑ rust inhabitance

Cutting Fluid Contaminants

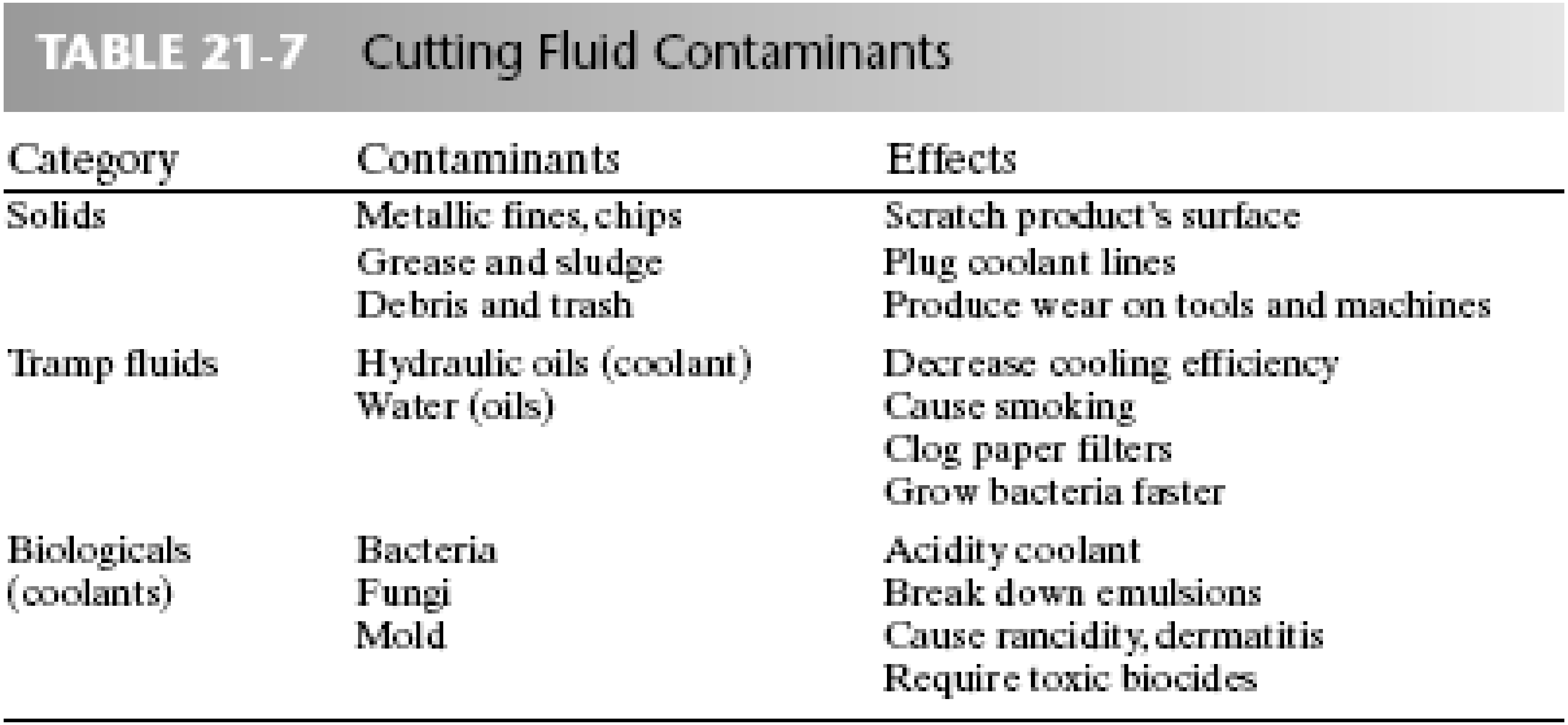
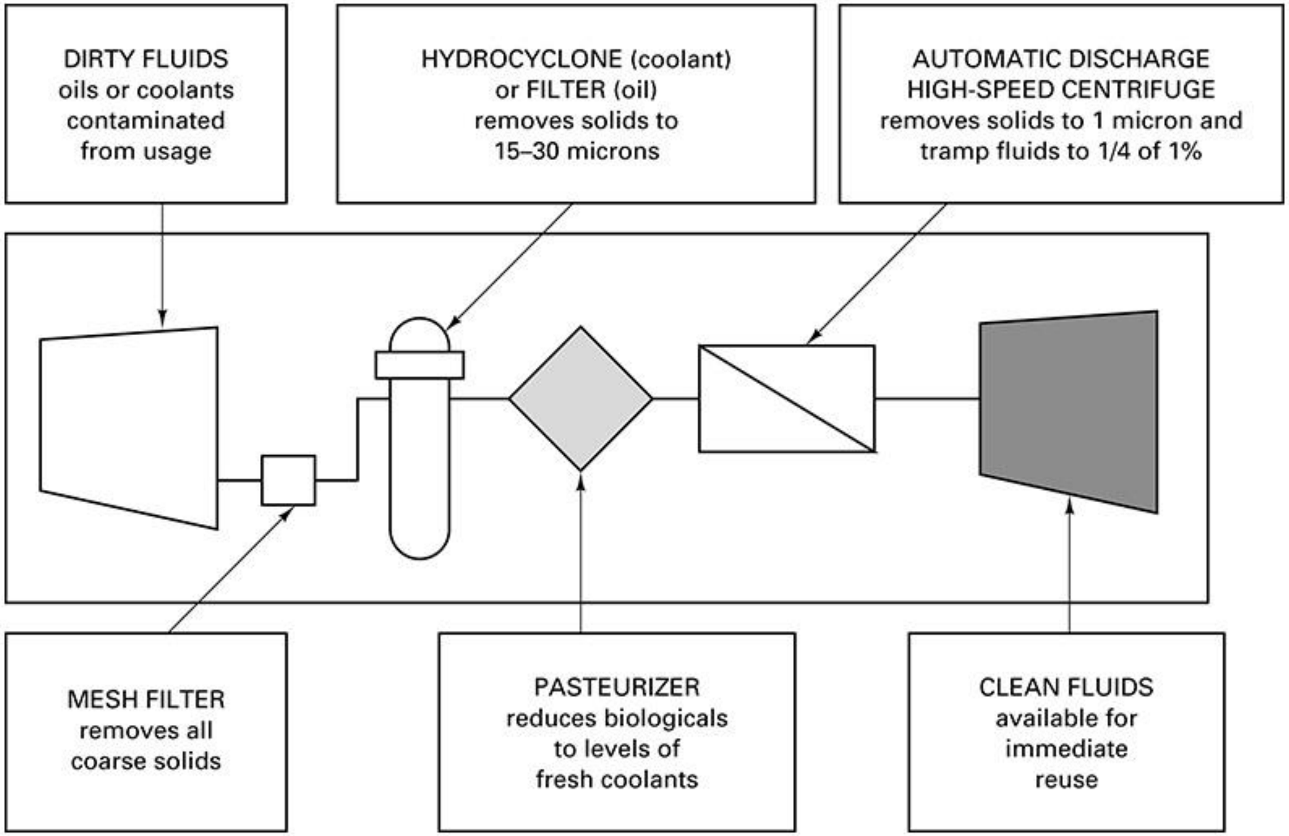


TABLE 21-7 Cutting Fluid Contaminants

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

Fluid Recycling System

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



DIRTY FLUIDS
oils or coolants
contaminated
from usage

HYDROCYCLONE (coolant)
or FILTER (oil)
removes solids to
15–30 microns

AUTOMATIC DISCHARGE
HIGH-SPEED CENTRIFUGE
removes solids to 1 micron and
tramp fluids to 1/4 of 1%

MESH FILTER
removes all
coarse solids

PASTEURIZER
reduces biologicals
to levels of
fresh coolants

CLEAN FLUIDS
available for
immediate
reuse

Chapter 23:
Turning and Boring Processes

DeGarmo’s Materials and Processes in Manufacturing

22.1 Introduction

- Turning is the process of machining external cylindrical and conical surfaces.
- Boring is a variant of turning were the machining results in an internal cylindrical or conical surface.
- Turning and Boring are performed on a lathe were a single point tool is moved across the rotating workpeice

Standard Engine Lathe

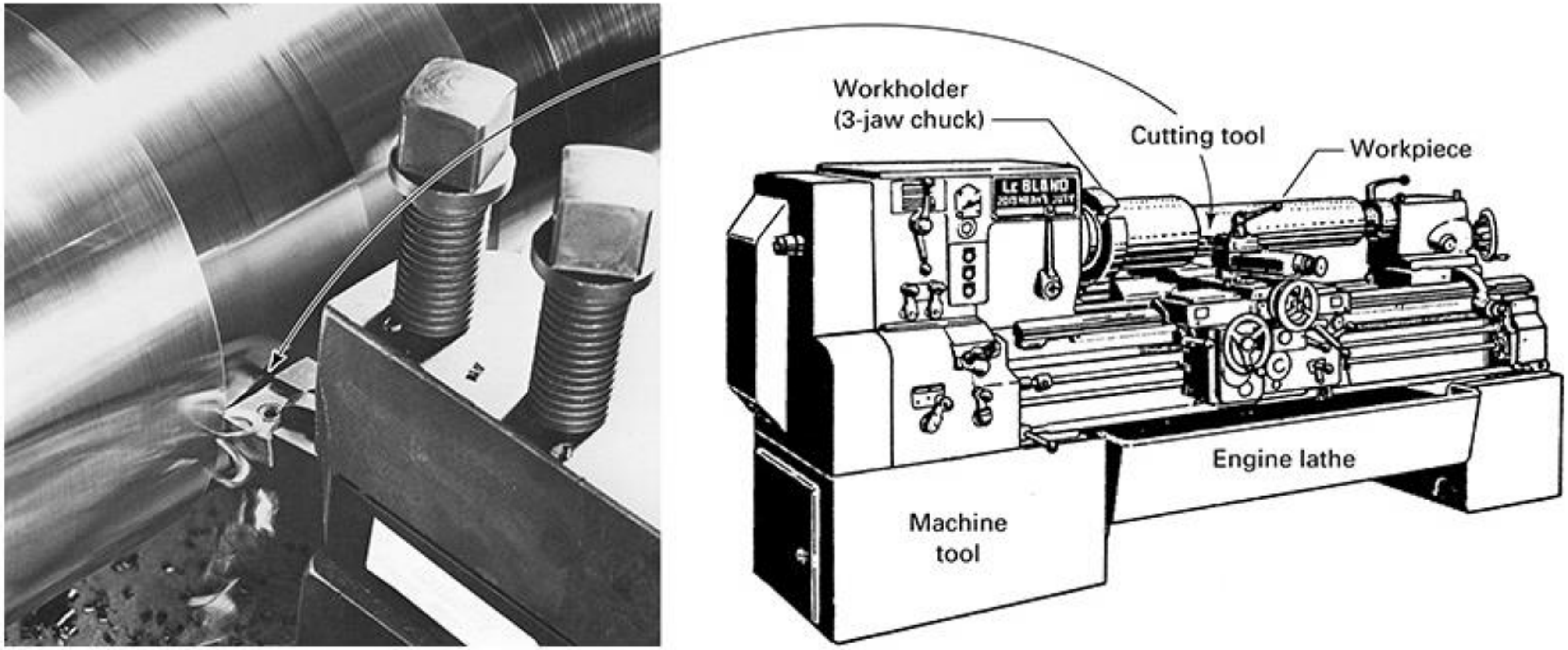


FIGURE 22-1 Schematic of a standard engine lathe performing a turning operation, with the cutting tool shown in inset.

Basic Turning Operations

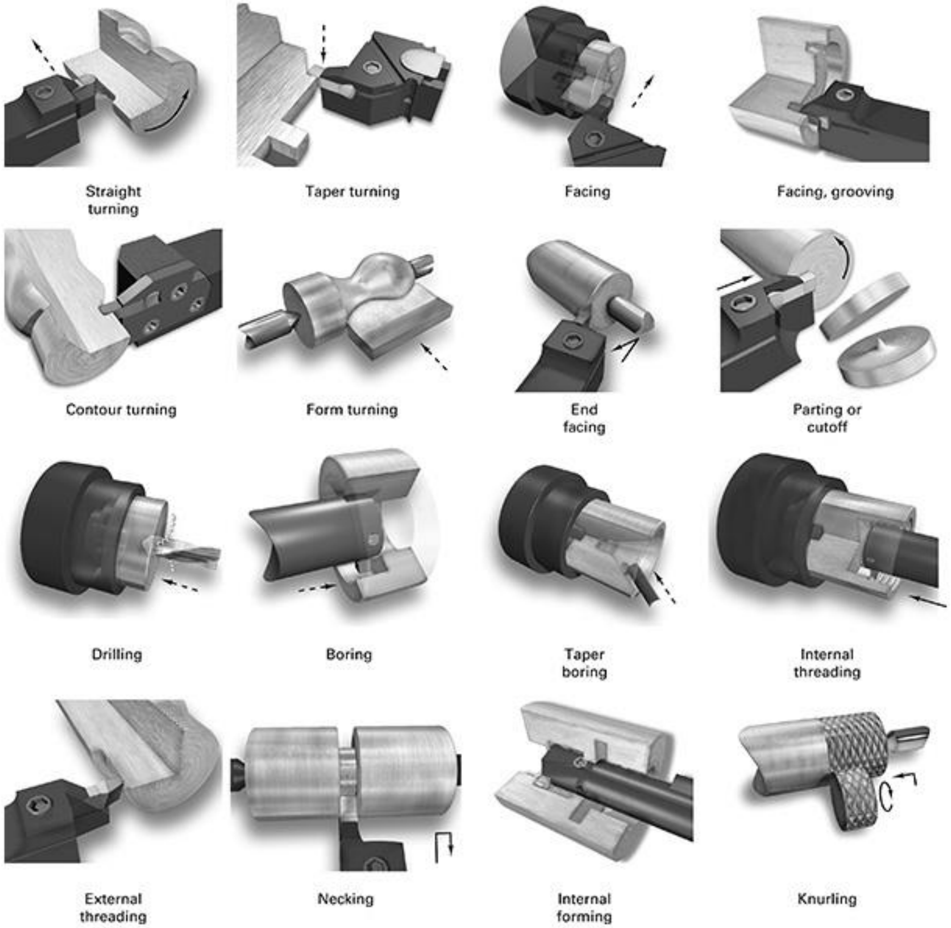


FIGURE 22-2 Basic turning machines can rotate the work and feed the tool longitudinally for turning and can perform other operations by feeding transversely. Depending on what direction the tool is fed and on what portion of the rotating workpiece is being machined, the operations have different names. The dashed arrows indicate the tool feed motion relative to the workpiece.

Basic Operations:

- Turning
- Boring
- Facing
- Parting
- Drilling
- Reaming
- Knurling

- **Turning and Boring Tapers**
- Four methods are used for taper turning:

1. Using the compound rest for short lengths with a graduated scale on the base of the compound rest
2. Using taper attachment
3. Setting over the tail stock
4. Numerically controlled Lathe.

22.2 Fundamentals of Turning, Boring, and Facing Operations

- Turning constitutes the majoring of lathe work and is summarized in two categories.
  - Roughing: Used to remove large amounts of material using large depth of cuts and slow speeds. Requires less time to remove material, though dimensional accuracy and surface finish quality are lost.
  - Finishing: Uses light passes with speeds as fine as necessary to produce the desired finish. One to two passes are usually required to produce a smooth finish.

Turning Calculations

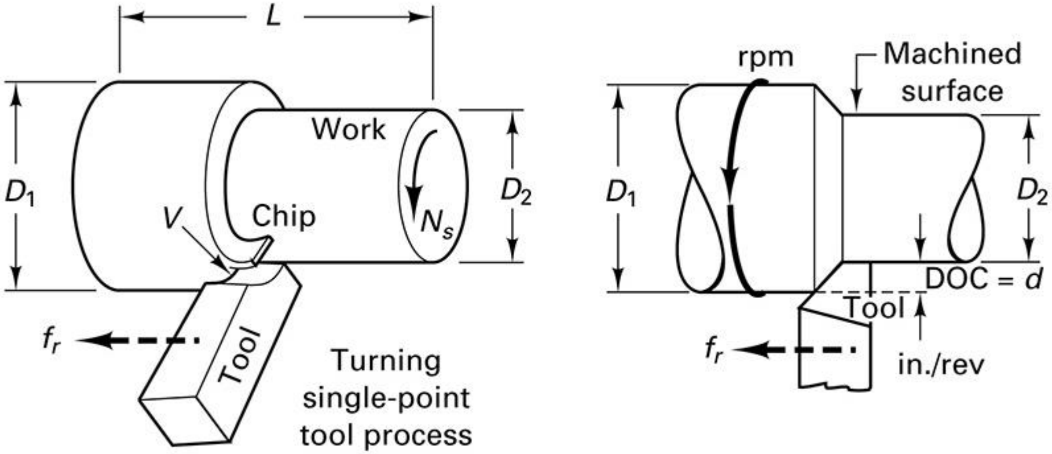


FIGURE 22-3 Basics of the turning process normally done on a lathe. The dashed arrows indicate the feed motion of the tool relative to the work.

Depth of Cut

$$d = \text{DOC} = \frac{D_1 - D_2}{2} \text{ inches}$$

Lathe rpm

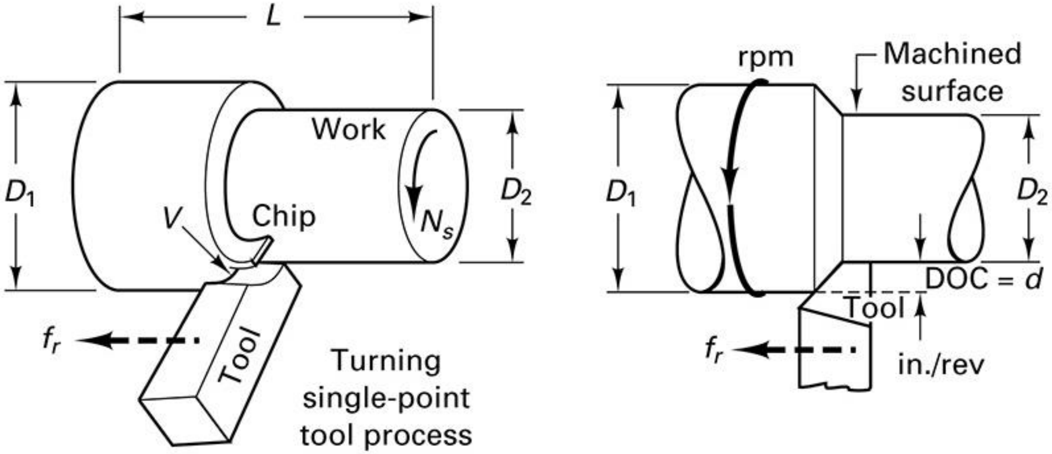
$$N_s = \frac{12V}{\pi D_1}$$

Cutting Time

$$T_m = \frac{L + A}{f_r N_s}$$

Turning Calculations, cont.

FIGURE 22-3 Basics of the turning process normally done on a lathe. The dashed arrows indicate the feed motion of the tool relative to the work.



Metal Removal Rate, MRR

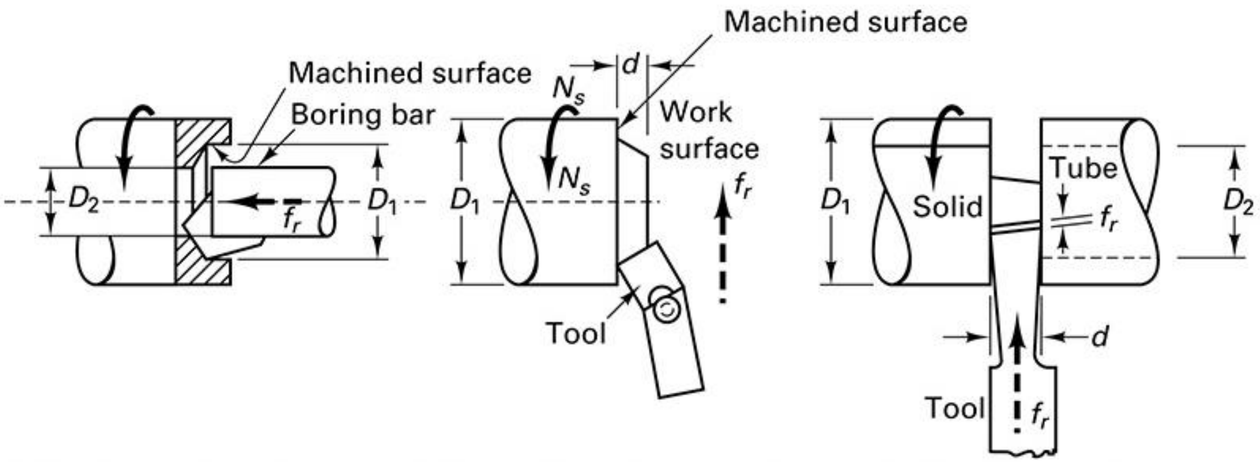
$$\mathrm{MRR} = \frac{\text{volume removed}}{\text{time}} = \frac{(\pi D_1^2 - \pi D_2^2)L}{4L/f_r N}$$

Alternate equation for MRR

$$\mathrm{MRR} \cong 12\, V f_r d \text{ in.}^3/\text{min}$$

Boring Calculations

FIGURE 22-4 Basic movement
of boring, facing,
and cutoff (or
parting) process.



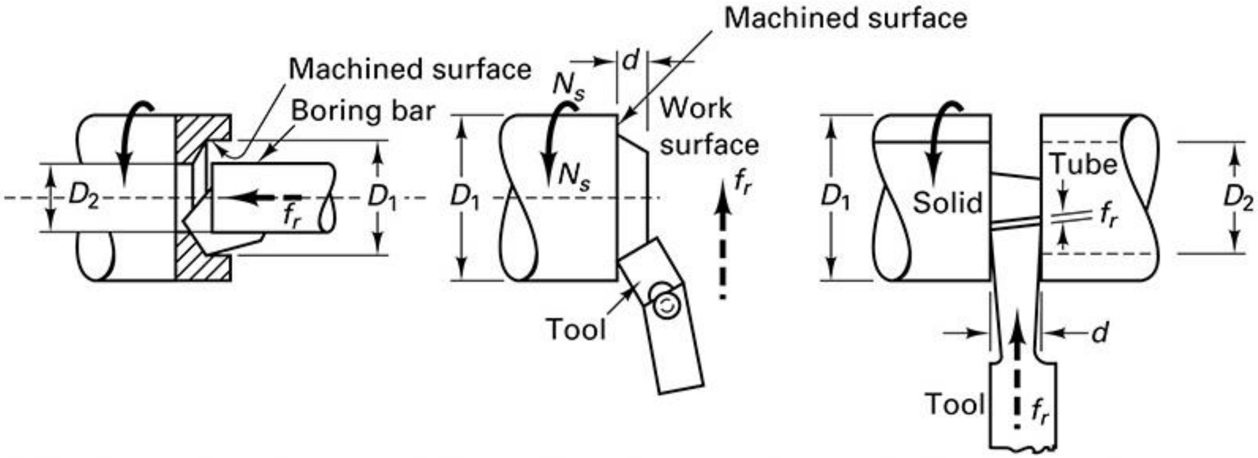
(a) Boring a drilled hole (b) Facing from the cross side (c) Cutoff or parting

- Cutting time $$T_m = \frac{L + A}{f_r N_s}$$

- Material Removal Rate $$\text{MRR} = \frac{L(\pi D_1^2 - \pi D_2^2)/4}{L/f_r N}$$

or $$\text{MRR} \cong 12\, V f_r d$$

Facing Calculations



(a) Boring a drilled hole (b) Facing from the cross side (c) Cutoff or parting

FIGURE 22-4 Basic movement of boring, facing, and cutoff (or parting) process.

- Cutting time

$$T_m = \text{cutting time} = \frac{L + A}{f_r N} \text{ minutes} = \frac{\frac{D_1}{2} + A}{f_r N}$$

- Material Removal Rate

$$\text{MRR} = \frac{\text{VOL}}{T_m} = \frac{\pi D_1^2 d f_r N}{4L} = 6V f_r d \quad \text{in.}^3/\text{min}$$

Deflection in Boring, Facing, and Cutoff Operations

- The speed, feed and depth of cut are less in Boring, Facing and Cutoff operations because of the large overhang of the tools. Basic deflection calculations for the tool are:

$$\delta = \frac{Pl^3}{3EI} = \frac{F_c l^3}{3EI}$$

E = modulus of elasticity

I = moment of inertia of cross section of tool

$P = F_c$ = applied load or cutting force

$I = \pi D_1^2/64$ solid round bar

$I = \pi(D_1^4 - (D_2^4))/64$ bar with hole

D_1 = diameter of tube or bar

D_2 = inside diameter of the tube

Other Lathe Operations

- Precision Boring: Bored holes often are bell mouthed due to tool deflection. To compensate a pilot bushing is used within the chuck as shown:

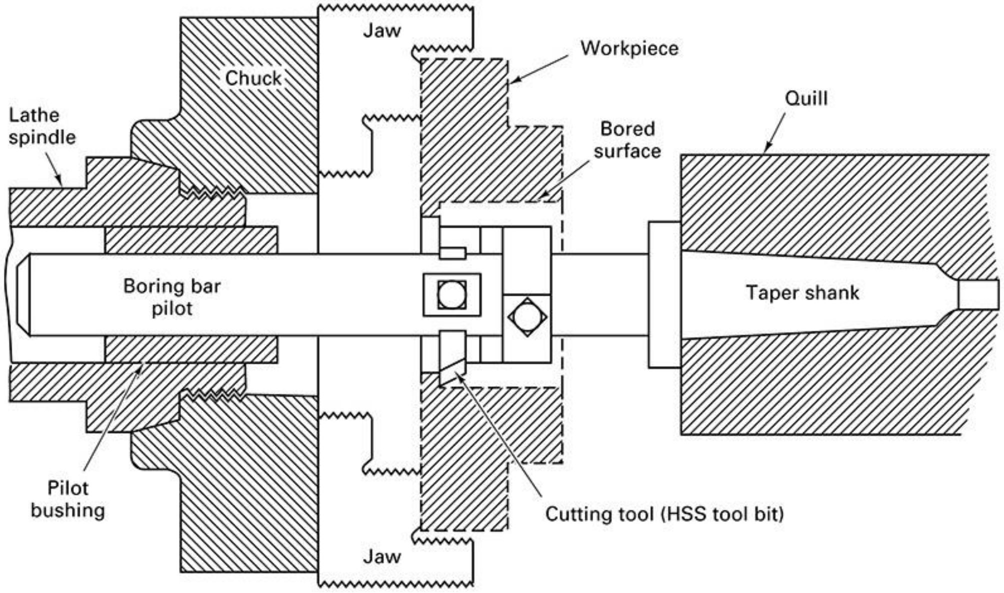
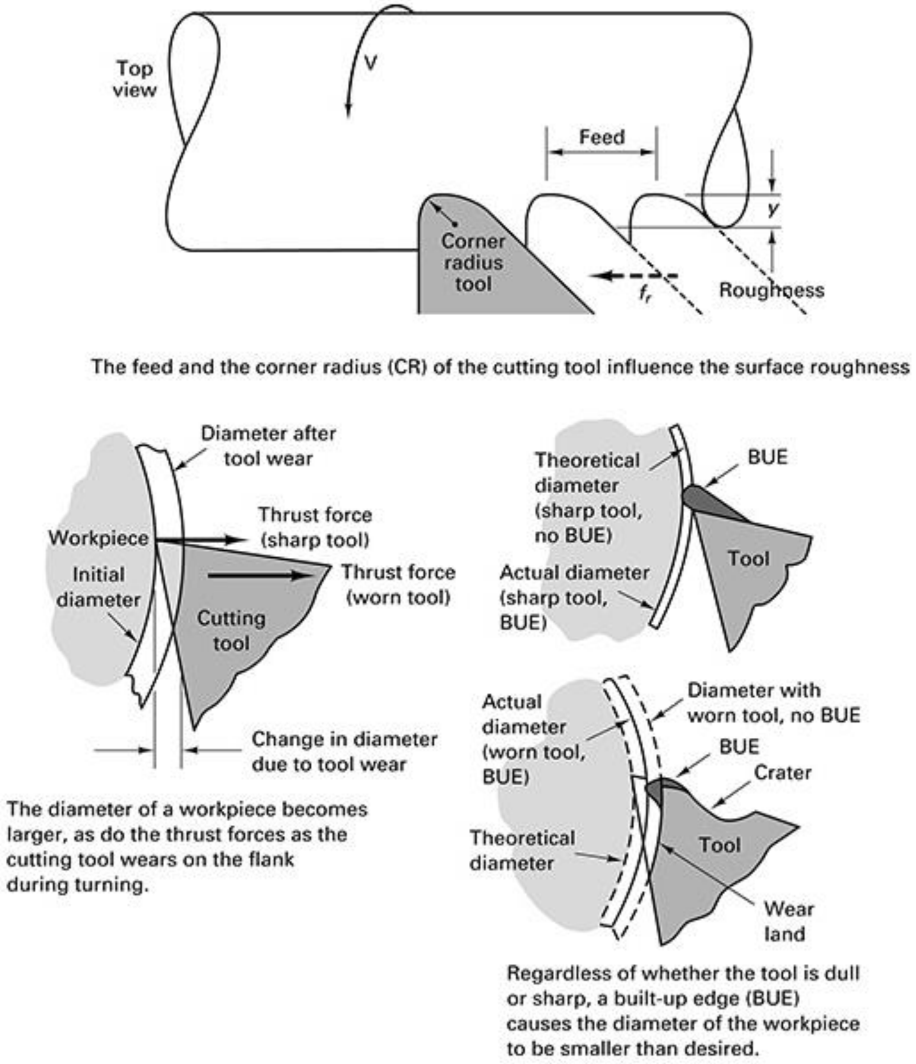


FIGURE 22-5 Pilot boring bar mounted in tailstock of lathe for precision boring large hole in casting. The size of the hole is controlled by the rotation diameter of the cutting tool.

Dimensional Accuracy in Turning



The feed and the corner radius (CR) of the cutting tool influence the surface roughness

The diameter of a workpiece becomes larger, as do the thrust forces as the cutting tool wears on the flank during turning.

Regardless of whether the tool is dull or sharp, a built-up edge (BUE) causes the diameter of the workpiece to be smaller than desired.

FIGURE 22-7 Accuracy and precision in turning is a function of many factors, including tool wear and BUE.

22.3 Lathe Design and Terminology

- Lathe Engine essential components:
  - Bed
    - Gray cast for vibration dampening
  - Headstock assembly
    - Spindle
    - Transmission
    - Drive motor
  - Tailstock assembly
    - Longitudinal way clamp
    - Transverse way clamp
    - Quill for cutting tools, live centers, or dead centers

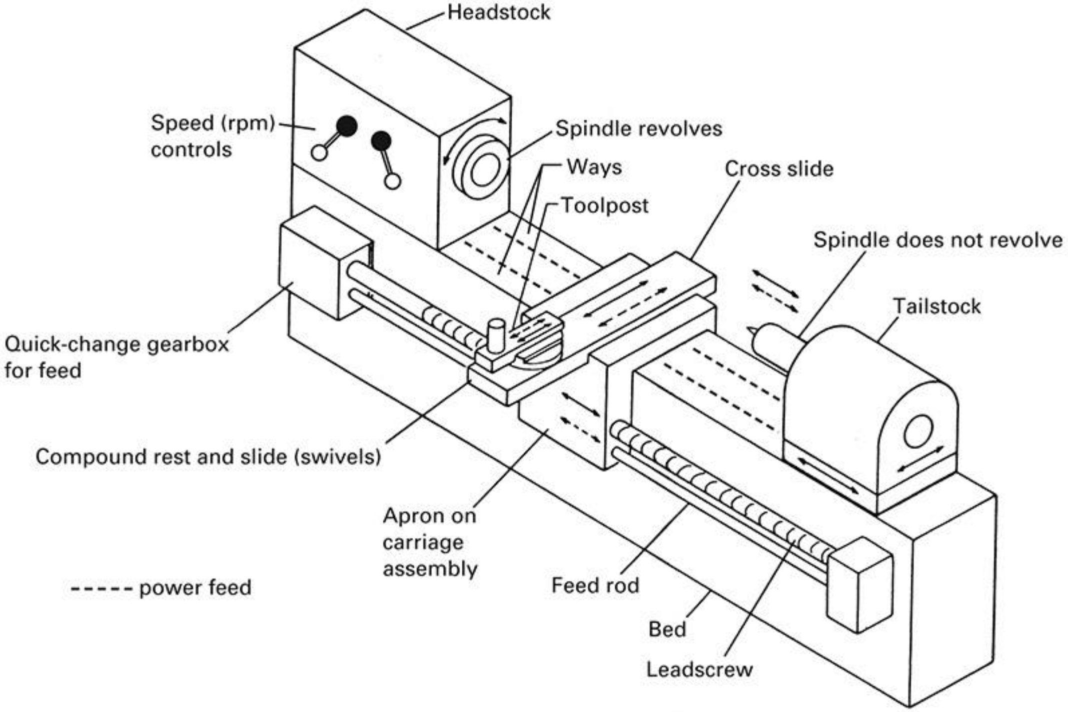


FIGURE 22-8 Schematic diagram of an engine lathe, showing basic components.

22.3 Lathe Design and Terminology

- Lathe Engine essential components:
  - Quick-change gearbox
    - Powers Carriage Assembly movement with lead screw
  - Carriage Assembly
    - Fixed to cross slide
    - Holds tool post at variable orientations
    - Provides longitudinal and transverse movement of tooling
  - Ways
    - Provides precise guidance to carriage assembly and tailstock

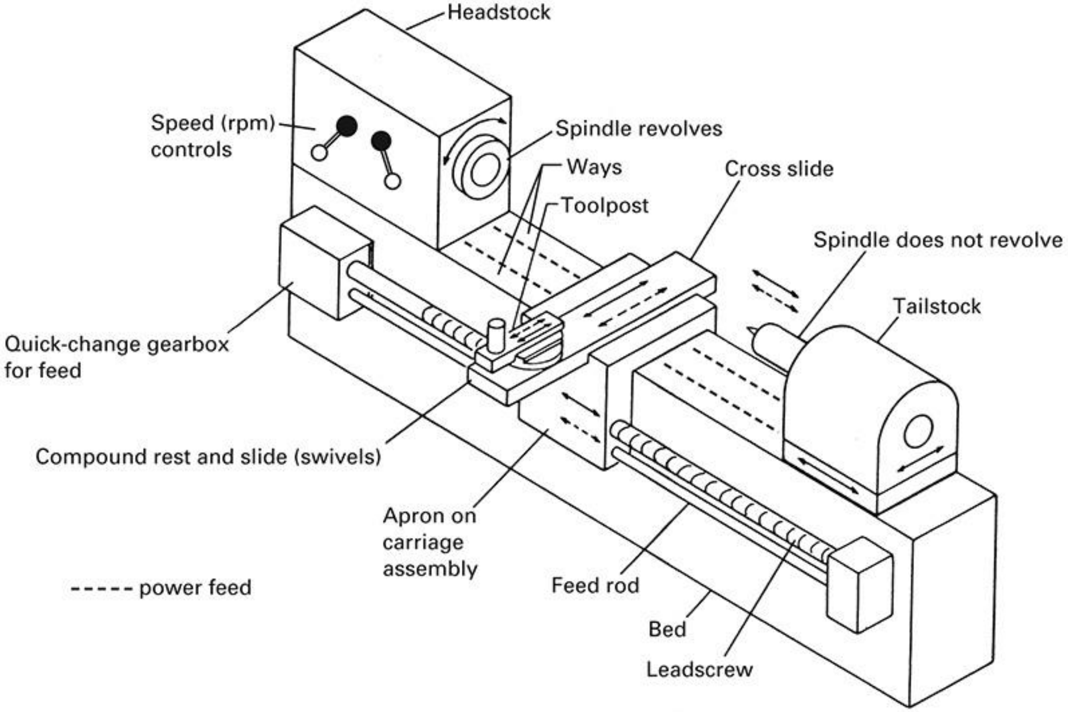


FIGURE 22-8 Schematic diagram of an engine lathe, showing basic components.

Types of Lathes

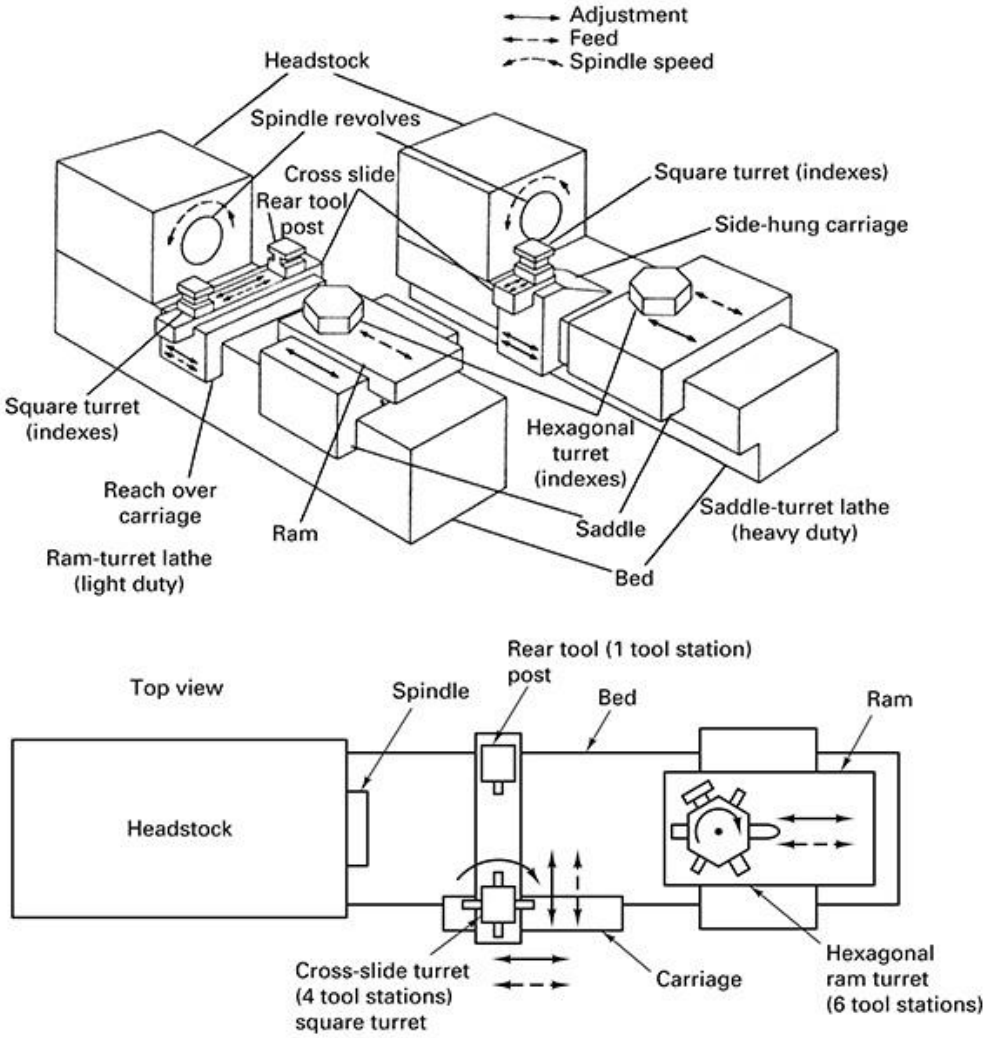
- Speed Lathes
  - Limited to headstock, tailstock, and simple tool post.
  - Limited to 3-4 speeds
  - High spindle speeds,
  - For light work such a wood turning, metal polishing, or metal spinning
- Engine Lathes
  - Most common type
  - Variable in design from low to high power designs
  - Broad range of lengths up to 60ft long
  - Features as described in Figure 22.8

Types of Lathes, cont.

- Toolroom Lathes
  - Specialized Engine lathe with greater accuracy.
  - Broader range of speeds and feeds
  - Greater versatility for tool and die manufacturing
- Turret Lathes
  - Turret on tool post rotates to position a variety of tools
  - Capstan wheel used to pull to away from work piece to position next tool
  - A number of tools set up on machine, each brought up in quick succession to complete the part in a single setup

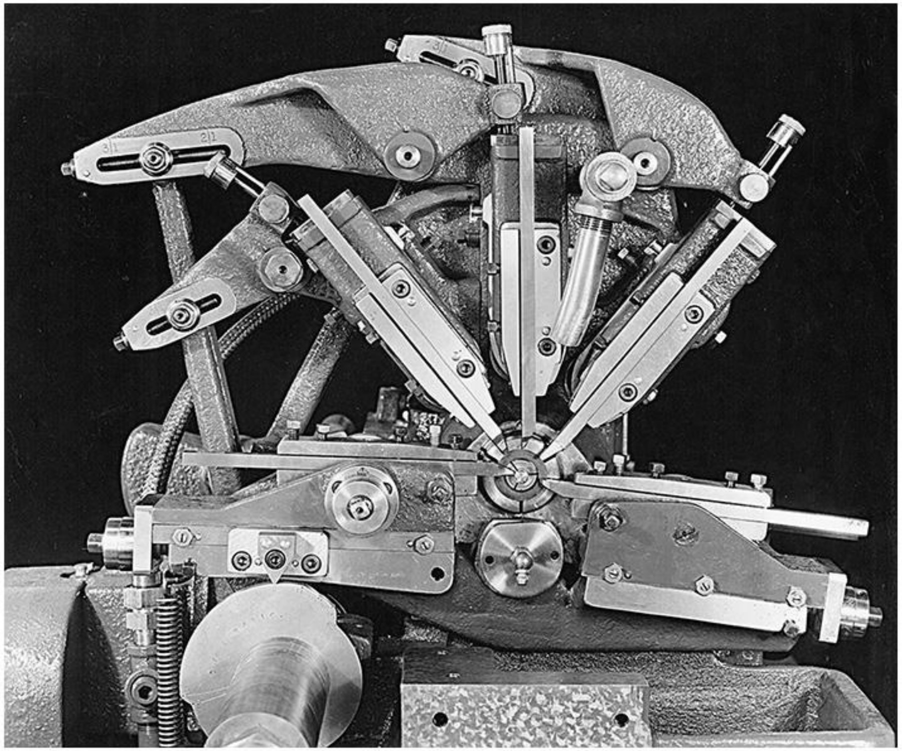
Types of Lathes, Turret Lathes

- **FIGURE 22-12** Block diagrams of ram- and saddle-turret lathe.



Types of Lathes

- Automatic Lathes
  - Also called Swiss Screw machine
  - A specialized type of automatic turret lathe
  - Rod stock is automatically fed into th collet



- **Size Designation of Lathes**
- The size of a lathe is designed by two dimensions:

1. The swing, which is the max. diameter of the work.
2. The max. distance between centers.

22.4 Cutting Tools for Lathes

- Tools consists of cutting surface and support
  - Cutting surfaces can be of same material as support or a separate insert
  - Supports materials must be rigid and strong enough to prevent tool deflection during cutting
  - Cutting materials are typically carbides, carbide coatings, ceramics, or high carbon steels
  - Inserts are used to decrease cost in that the insert is disposed of, and the support reused.

Typical Tool Holders

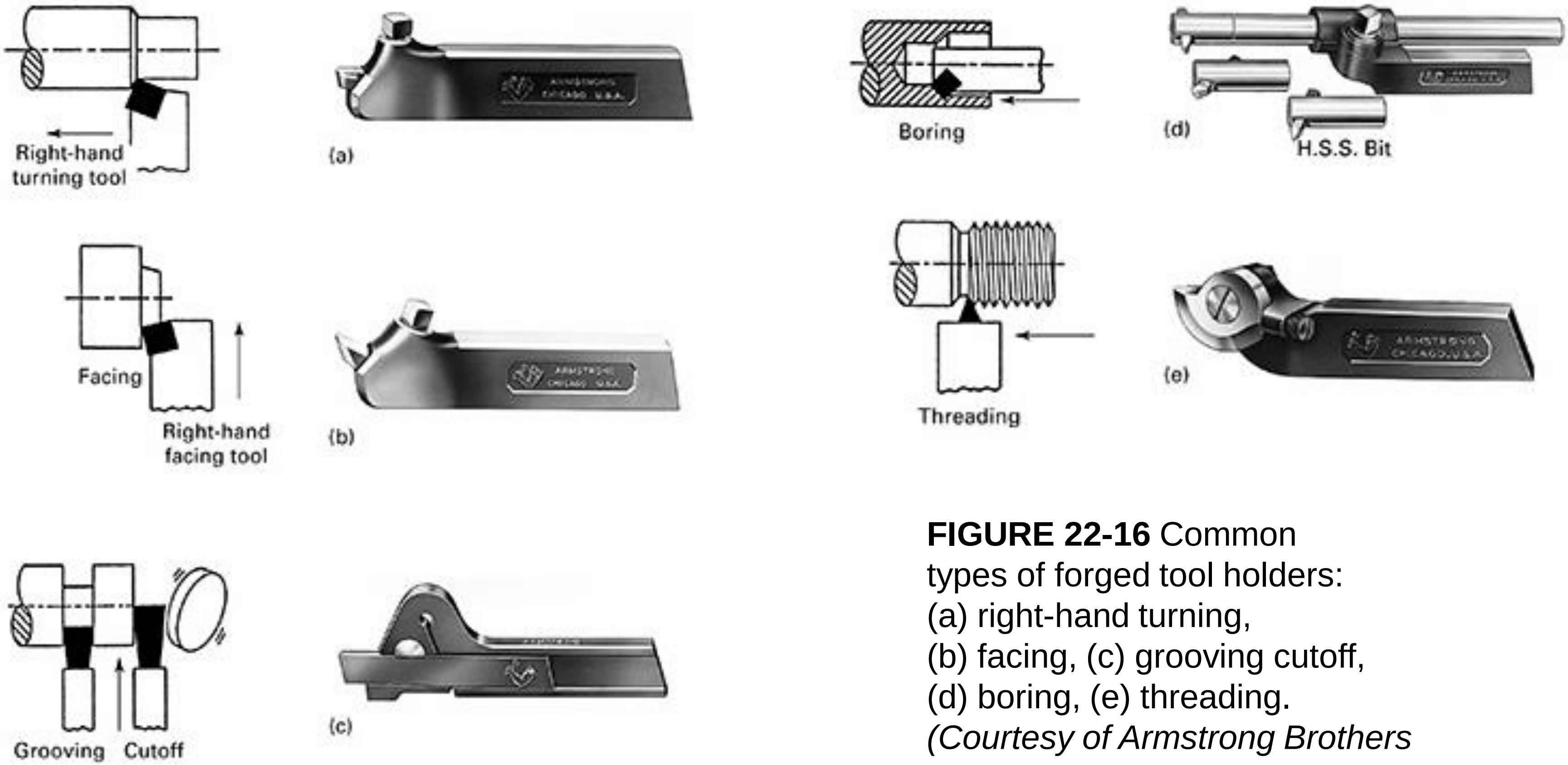
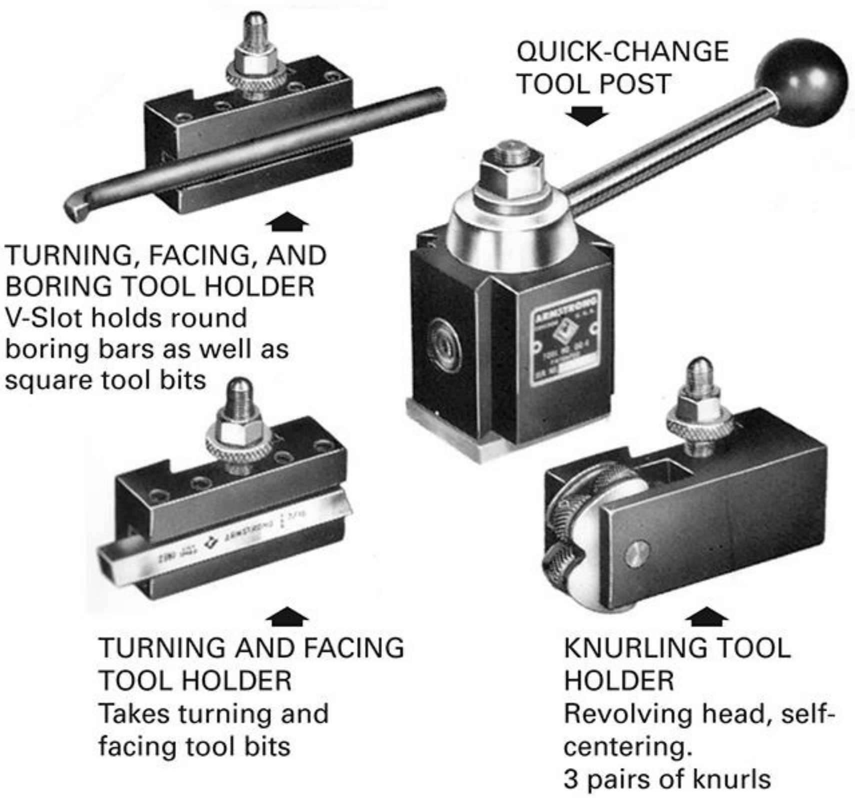


FIGURE 22-16 Common types of forged tool holders:
(a) right-hand turning,
(b) facing, (c) grooving cutoff,
(d) boring, (e) threading.
(Courtesy of Armstrong Brothers Tool Company.)

Quick Change Tool Holders

- Tool changing can take over 50% of manual lathe operations
- Quick Change holders are used to reduce manual tool change time and increase production



QUICK-CHANGE TOOL POST

TURNING, FACING, AND BORING TOOL HOLDER
V-Slot holds round boring bars as well as square tool bits

TURNING AND FACING TOOL HOLDER
Takes turning and facing tool bits

KNURLING TOOL HOLDER
Revolving head, self-centering.
3 pairs of knurls

22.5 Workholding Devices for Lathes

- Work pieces can be held by various methods
  - Work piece mounted between centers
  - Work piece mounted within a single chuck
  - Work piece mounted within a collet
  - Work piece mounted on a faceplate

Lathe Centers

- A lathe center hold the end of the work piece, providing support to preventing the work piece from deflecting during machining
- Lather centers can be mounted in the spindle hole, or in the tailstock quill
- Lathe centers fall into two categories
  - Dead Center: solid steel tip that work piece spins against
  - Live Center: centers contact point is mounted on bearings and allowed to spin with work piece

Lathe Centers

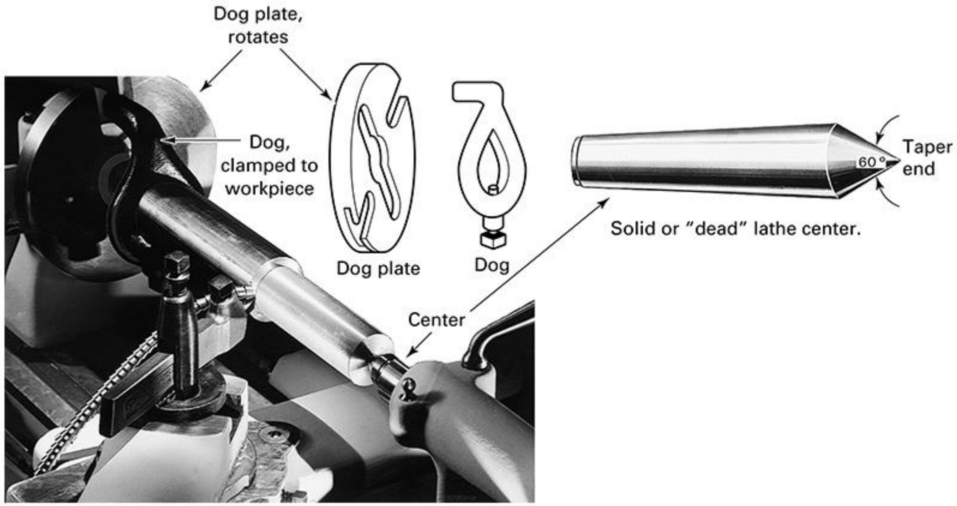


FIGURE 22-21 Work being turned between centers in a lathe, showing the use of a dog and dog plate. *(Courtesy of South Bend Lathe.)*

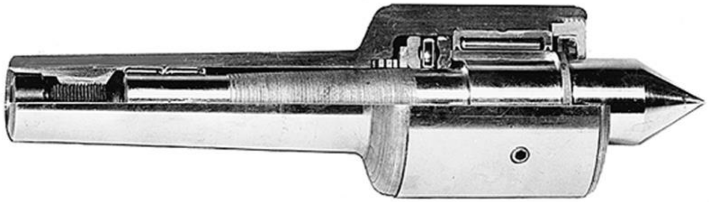


FIGURE 22-22 Live lathe center can rotate with the part.

Lathe Chucks

- Lathe Chucks are adjustable mechanical vises that hold the work piece and transfer rotation motion from the drive motor to the work piece
- Lathe Chucks come in two basic types
  - Three-jaw self-centering chucks
    - Used to center round or hexagonal stock
  - Four-jaw independent chucks
    - Each jaw moves independently to accommodate various work piece shapes

Lathe Chucks

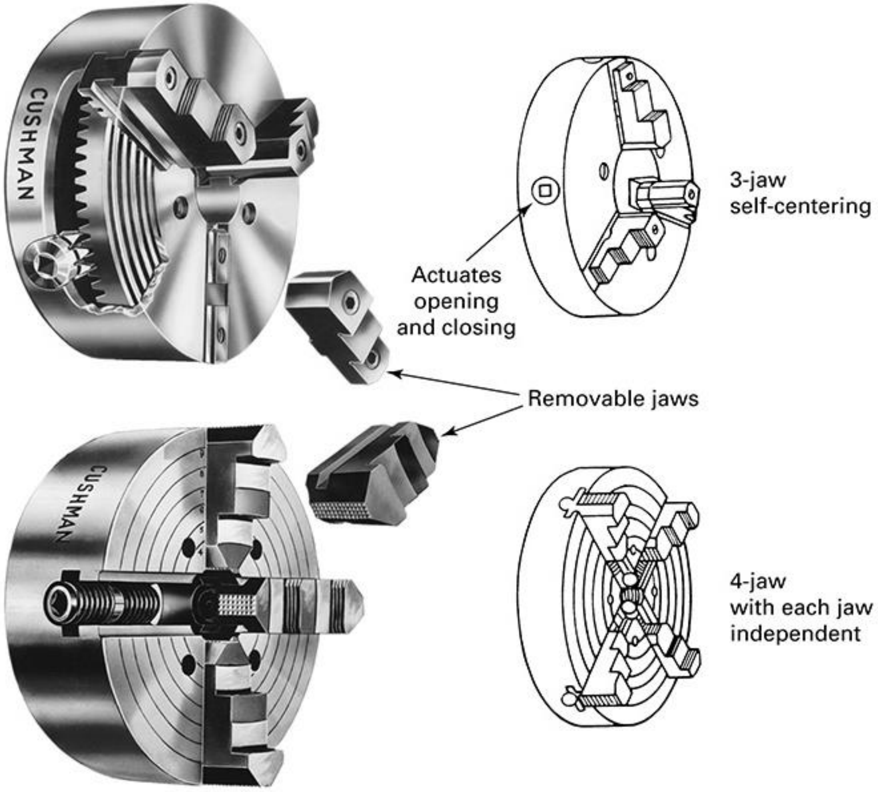


FIGURE 22-24 The jaws on chucks for lathes (four-jaw independent or three-jaw selfcentering) can be removed and reversed.

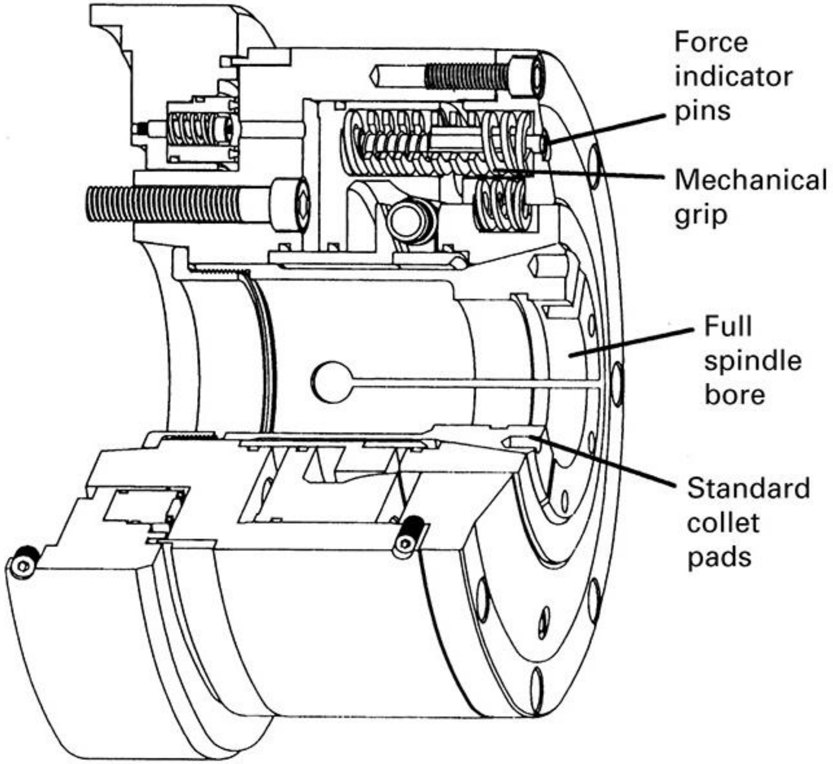


FIGURE 22-25 Hydraulically actuated through-hole three-jaw power chuck shown in section view to left and in the spindle of the lathe above connected to the actuator.

Lathe Collets

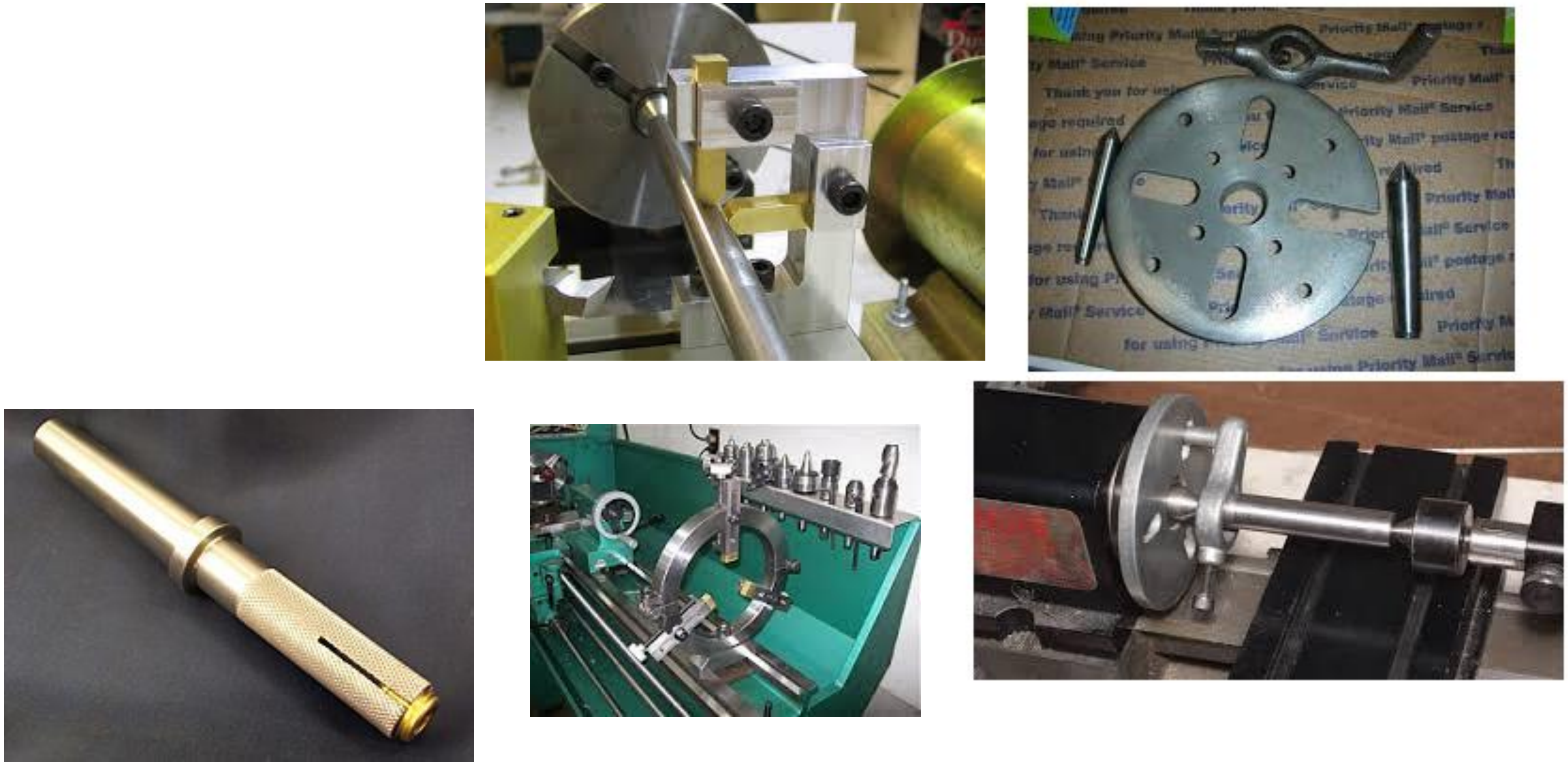
- Collets are used to hold round stock of standard sizes
- Most accurate holding method for round stock
  - Run out less than 0.0005 inch
  - Stock should be no more than 0.002 inch larger or 0.005 smaller than the collet
  - Typically used for drill-rod, cold-rolled, extruded, or previously machined stock

Lathe Collets

FIGURE 22-26 Several types of lathe collets. *(Courtesy of South Bend Lathe.)*

Face Plates

- Face plates are used to mount irregular work pieces that can not be gripped with a chuck
- Face plates are typically custom built to each work piece
- The face plate is mounted to a center, or mounted in a chuck



- **Mandrels**
- For mounting work.
- Thee types:

1. plain solid
2. gang
3. cone

- **Steady and follow rest:**
- For turning long, slender piece between centers.
- **Mounting Work on the Carriage:**
- Boring tools will be mounted between centers and driven by means of a dog

Summary

- Lathes are used for turning, boring, drilling and facing
- Lathe typically holds the work piece in a rotating chuck, with the opposite end supported by a center held in the tailstock
- A wide variety of lathe types, and tool types are available depending upon the application and the rate of production

Chapter 24:
Drilling and Related Hole-Making Processes

DeGarmo's Materials and Processes in Manufacturing

23.1 Introduction

- Drilling is most common single machining operation
- Drilling makes up 25% of machining
- Drilling occurs at the end of a tool within the material, four actions take place a the drill tip
    - **1.** A small hole is formed by the web—chips are not cut here in the normal sense.
    - **2.** Chips are formed by the rotating lips.
    - **3.** Chips are removed from the hole by the screw action of the helical flutes.
    - **4.** The drill is guided by lands or margins that rub against the walls of the hole

Nomenclature and Geometry of a Drill

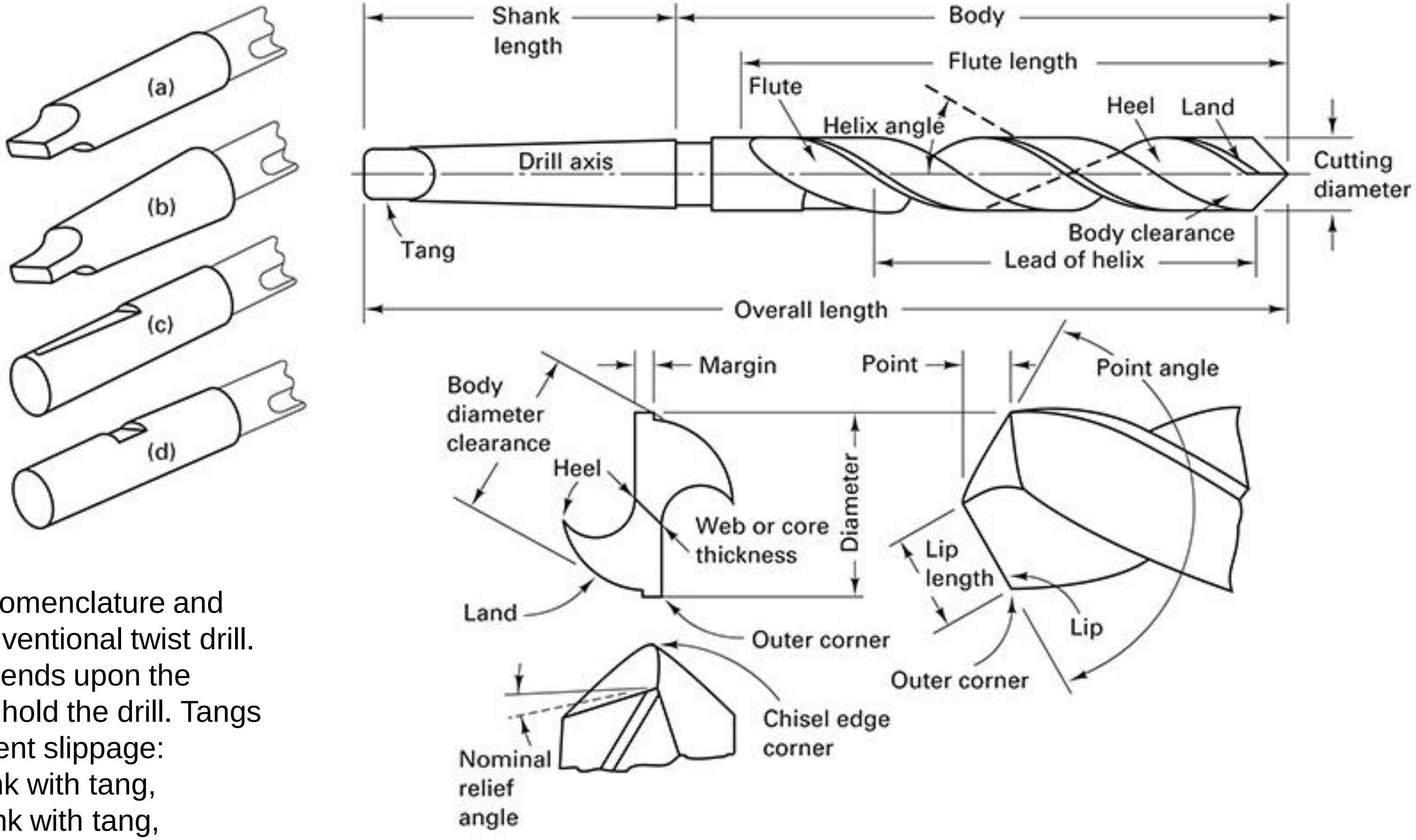


FIGURE 23-1 Nomenclature and geometry of conventional twist drill. Shank style depends upon the method used to hold the drill. Tangs or notches prevent slippage:
(a) straight shank with tang,
(b) tapered shank with tang,
(c) straight shank with whistle notch,
(d) straight shank with flat notch.

23.2 Fundamentals of the Drilling Process

- A conventional two-flute drill, with drill of diameter *D*, has two principal cutting edges rotating at an rpm rate of *N* and feeding axially.
- The rpm of the drill is established by the selected cutting velocity or cutting speed with *V* in surface feet per minute and *D* in inches.

$$N_s = \frac{12V}{\pi D}$$

Conventional Drill Geometry

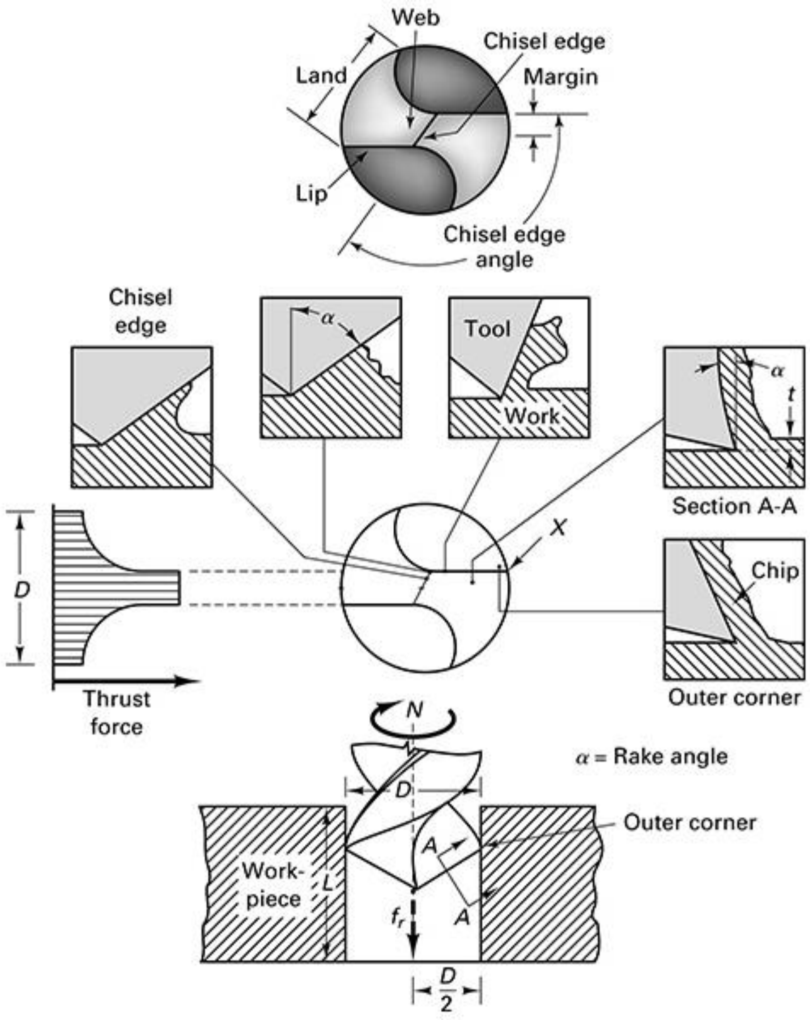


FIGURE 23-2 Conventional drill geometry viewed from the point showing how the rake angle varies from the chisel edge to the outer corner along the lip. The thrust force increases as the web is approached.

Material Removal Rate

- The material removal rate (MRR) for drilling is:

$$\text{MRR} = \frac{\text{volume}}{T_m} = \frac{\pi D^2 L/4}{L/f_r N_s} \text{(omitting allowances)}$$

- Which reduces to

$$\text{MRR} = (\pi D^2/4) f_r N_s \text{ in.}^3$$ or $$\text{MRR} \cong 3DVf_r$$

Were T_m is cutting time, f_r is feed rate, and L is depth of the hole.

23.3 Types of Drills

- The most common drills are twist drills
- Twist drills have three parts
    - The body: consisting of spiral grooves called flutes, separated by lands
    - The point: a wide variety of geometry are used, but typically have a cone angel of 118°, and a rake angle of 24°
    - The shank: a straight or tapered section where the drill is clamped.

Types of Twist Drills

FIGURE 23-3 Types of twist drills and shanks. Bottom to top: Straight-shank, three-flute core drill; straight-shank; taper-shank; bit-shank; straight-shank, high-helix angle; straight-shank, straight-flute; taper-shank, subland drill.

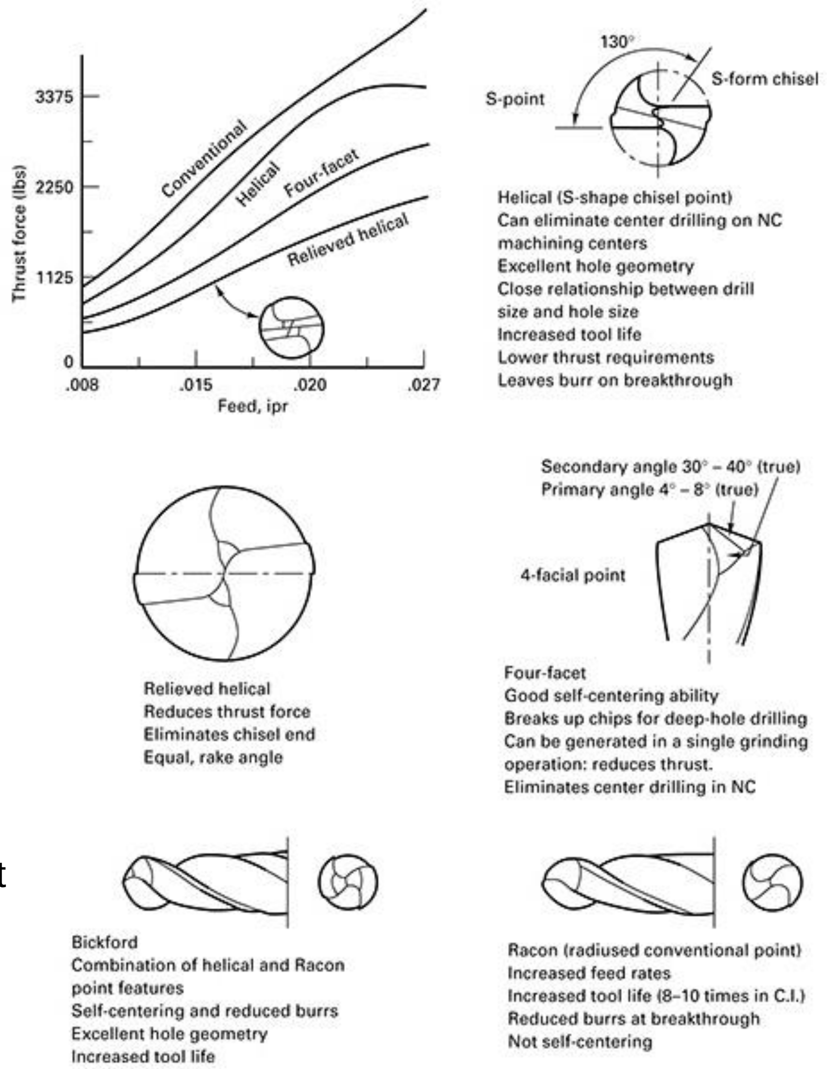
Drill Walking

- Standard drills have a straight line chisel point.
- This point caused drills to “walk” along the surface
- This effect is counter by using centering techniques
  - Center punches
  - Pre-drilled guide holes for large holes
- Specialized methods of grinding the point address walking

Specialized Tips

- Specialized tips are used to produce self centering holes where hole position is critical.
  - Helical tips
  - Four-facet tips
  - Racon
  - Bickford
  - Center core, or slot drills
- Used in machining centers and high speed automatic NC systems where manual center punching is impractical

Drill Point Geometry



Helical (S-shape chisel point)
Can eliminate center drilling on NC machining centers
Excellent hole geometry
Close relationship between drill size and hole size
Increased tool life
Lower thrust requirements
Leaves burr on breakthrough

Relieved helical
Reduces thrust force
Eliminates chisel end
Equal, rake angle

Four-facet
Good self-centering ability
Breaks up chips for deep-hole drilling
Can be generated in a single grinding operation: reduces thrust.
Eliminates center drilling in NC

Bickford
Combination of helical and Racon point features
Self-centering and reduced burrs
Excellent hole geometry
Increased tool life

Racon (radiused conventional point)
Increased feed rates
Increased tool life (8–10 times in C.I.)
Reduced burrs at breakthrough
Not self-centering

FIGURE 23-4 As the drill advances, it produces a thrust force. Variations in the drill-point geometry are aimed at reducing the thrust force.

Center Core Drill

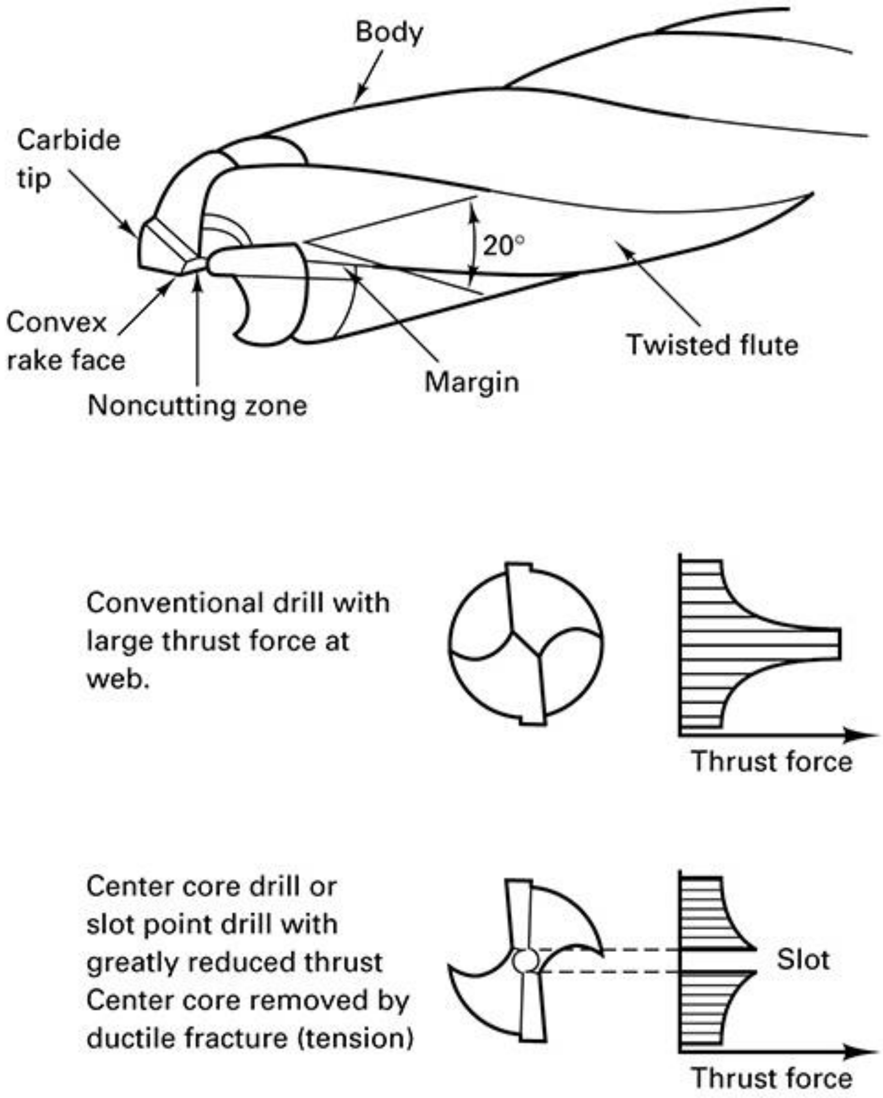
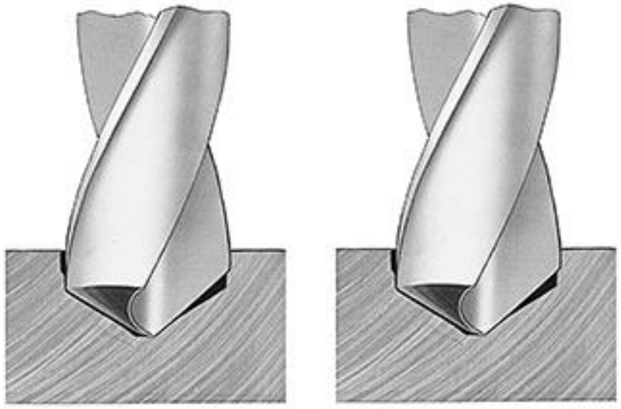


FIGURE 23-5 Center core drills can greatly reduce the thrust force.

Typical Causes of Drilling Problems



(a) Angle unequal (b) Length unequal

Outer corners break down: Cutting speed too high; hard spots in material; no cutting compound at drill point; flutes clogged with chips

Cutting lips chip: Too much feed; lip relief too great

Checks or cracks in cutting lips: Overheated or too quickly cooled while sharpening or drilling

Chipped margin: Oversize jig bushing

Drill breaks: Point improperly ground; feed too heavy; spring or backlash in drill press, fixture, or work; drill is dull; flutes clogged with chips

Tang breaks: Imperfect fit between taper shank and socket caused by dirt or chips or by burred or badly worn sockets

Drill breaks when drilling brass or wood: Wrong type drill; flutes clogged with chips

Drill spilts up center: Lip relief too small; too much feed

Drill will not enter work: Drill is dull; web too heavy; lip relief too small

Hole rough: Point improperly ground or dull; no cutting compounds at drill point; improper cutting compound; feed too great; fixture not rigid

Hole oversize: Unequal angle of the cutting edges; unequal length of the cutting edges; see part (a)

Chip shape changes while drilling: Dull drill or cutting lips chipped

Large chip coming from one flute, small chip from the other: Point improperly ground, one lip doing all the cutting

Depth-to-Diameter Ratio

- Standard drills typically are used to produce holes with a depth to diameter ratio of 3:1
- Deeper holes result in drift of the tool decreasing hole straightness
- Specialized drills called deep-hole drills or gundrills are used for greater ratios
- Gundrills are single tipped tools with a coolant channel delivering coolant to the tip and flushing chips to the surface
- Ratios of 100:1 are possible with gundrills

Gundrills Geometry

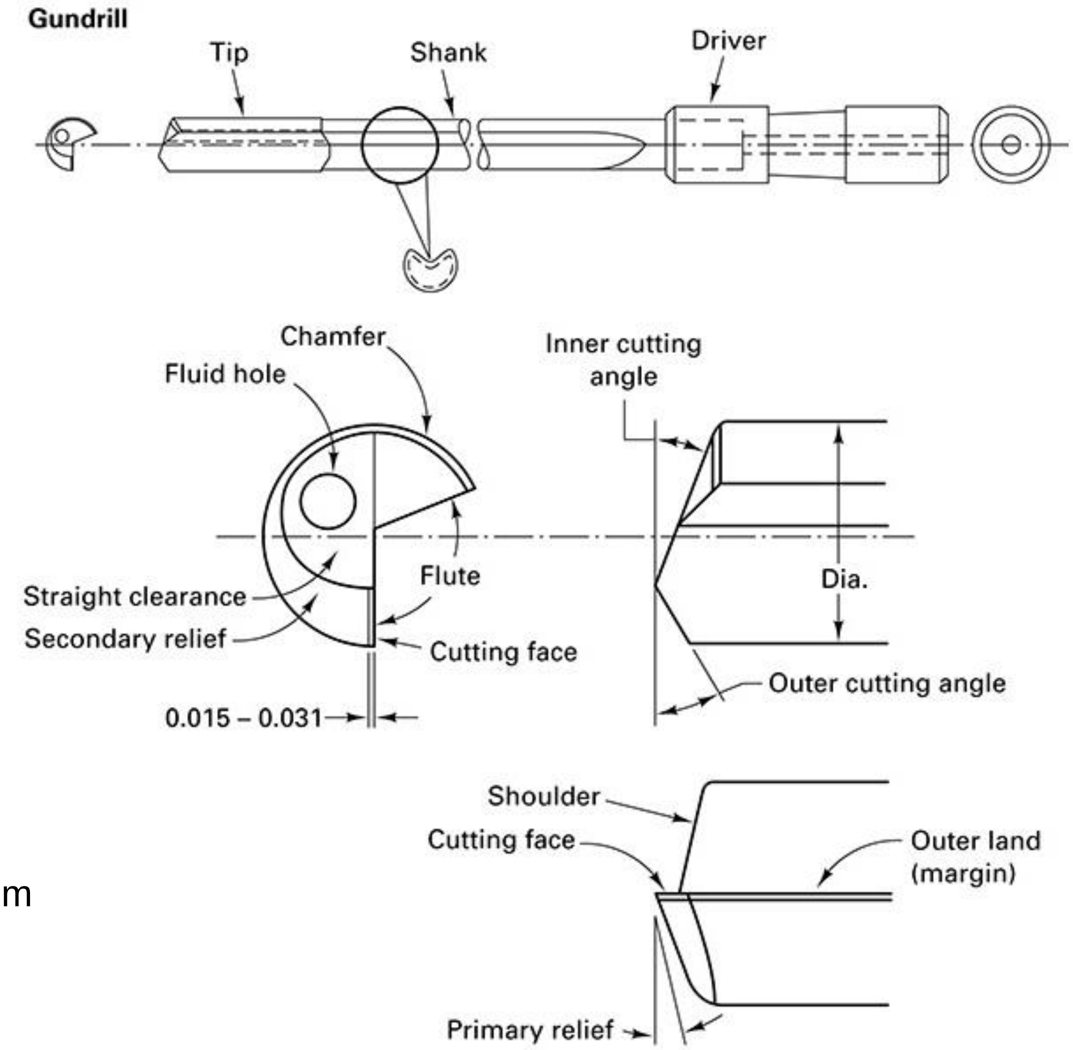
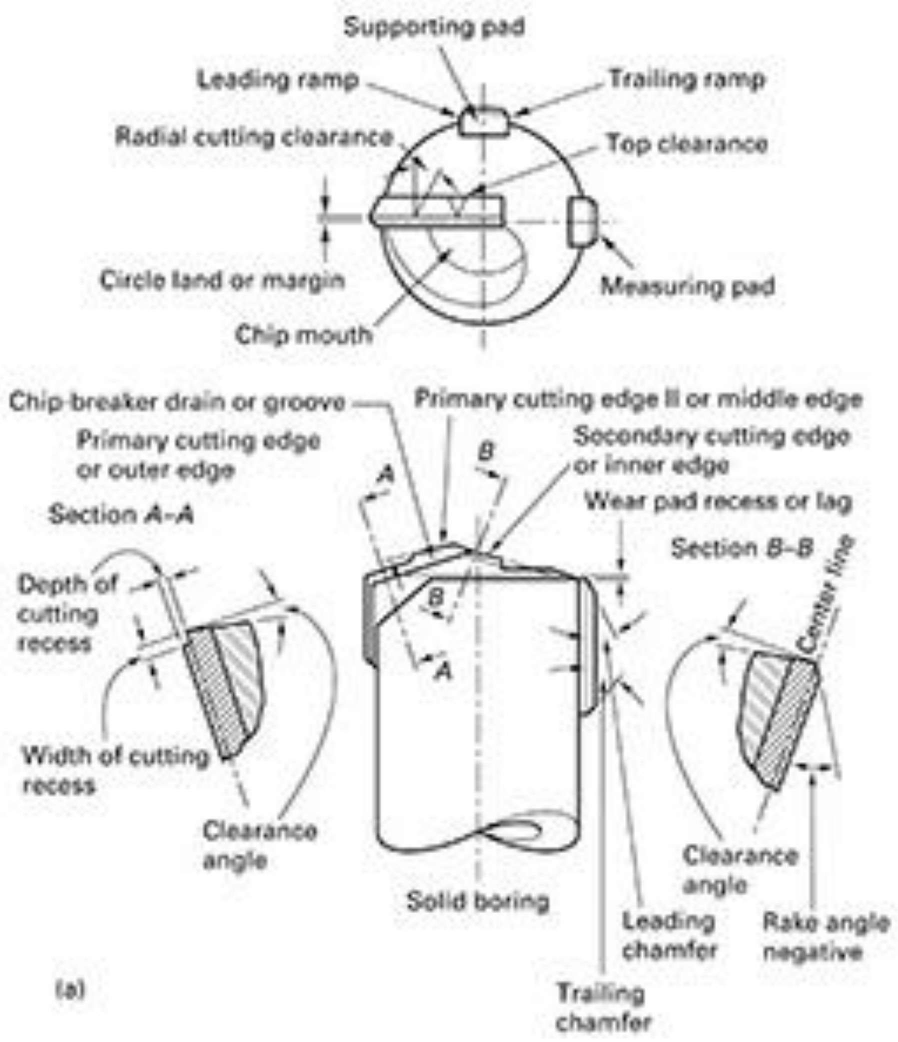


FIGURE 23-7 The gundrill geometry is very different from that of conventional drills.

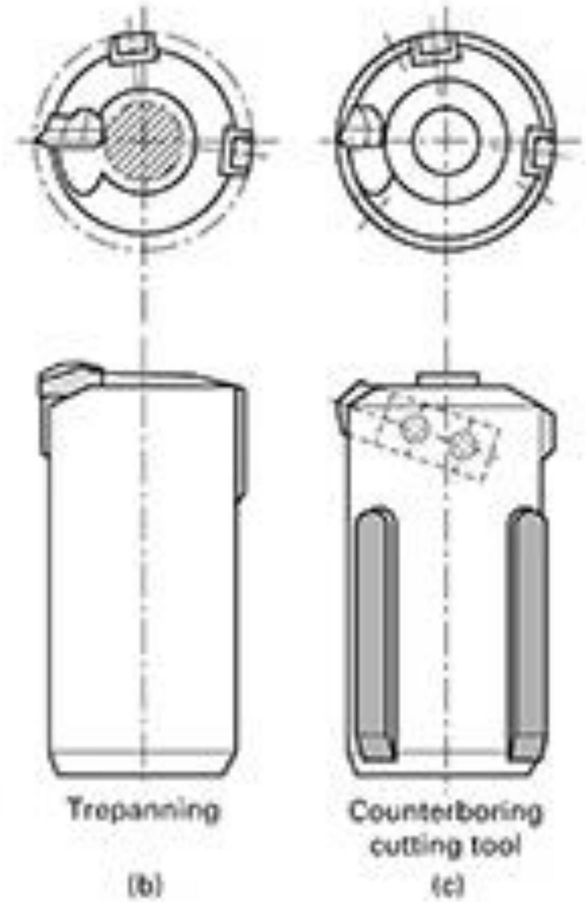
Boring Trepanning Association (BTA)

- BTA drills are a another form of deep-boring drills
- BTA drills are also referred to as ejector drills
- Depth of hole is limited to the torsional rigidity of the drill shank
- BTA drills have a hollow center where the chips are carried way from the cutting surface

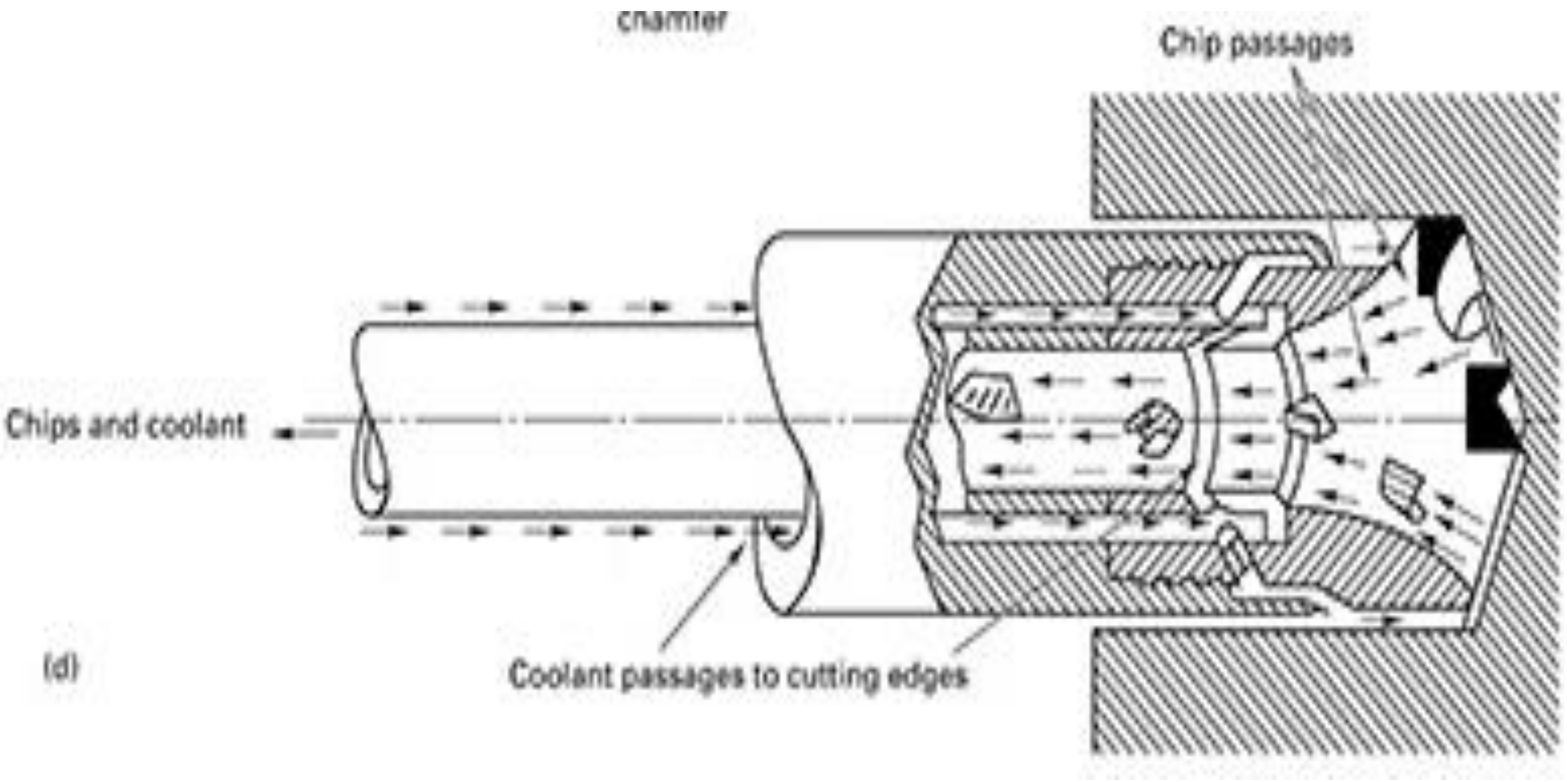
BTA Drills for Boring



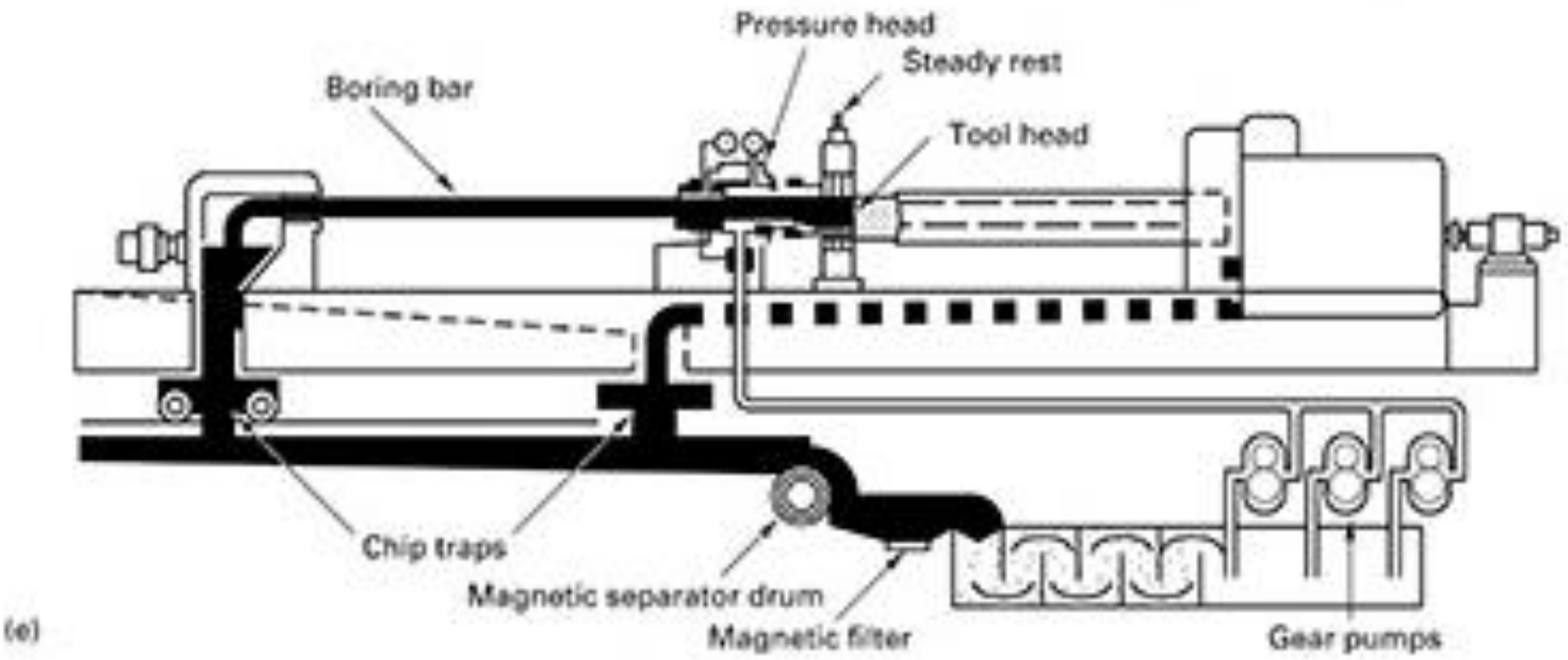
BTA for Trepanning and Counterboring



BTA for Deep-hole Drilling with Ejector Drill



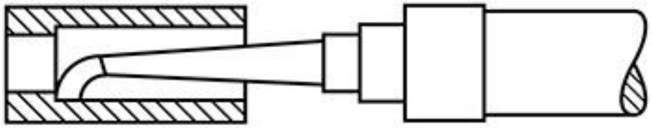
BTA for Horizontal Deep-drilling Machine



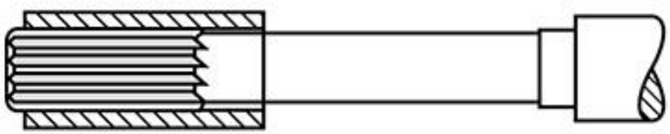
Steps to High Accuracy Holes with Conventional Drills

Step 1 Centering and countersinking with a combination center drill and countersink.
(Courtesy of Chicago-Latrobe)

Step 2 Drilling with a standard twist drill.



Step 3 Truing hole by boring.



Step 4 Final sizing and finishing with a reamer.

FIGURE 23-10 To obtain a hole that is accurate as to size and aligned on center (located), this 4 step sequence of operations is usual.

Specialty Drills

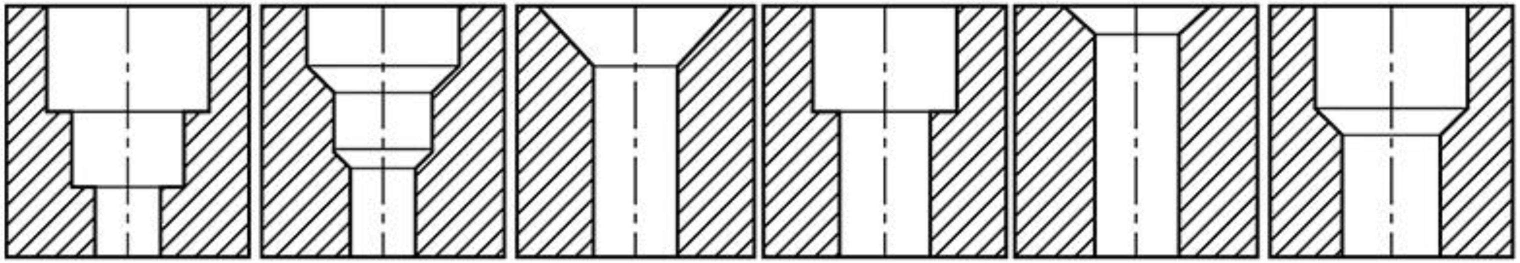
- Hole cutters: used for holes in sheet stock
- Subland drills: used for multi diameter holes
- Spade drills: used for holes over 1 inch
- Indexable drills: used for high speed shallow holes in solid stock
- Micro drills (pivot drills): used for holes 0.02 to 0.0001 inch diameter where grain boundaries and inclusion produce non-uniform material properties

Hole Cutters for Used Sheets

- When cutting large holes in sheet stock, a hole cutter is used
- Hole cutters have a pilot drill in the center used to accurately locate the center
- Also called a hole saw

Subland Drill

Subland drill



Drill multiple diameters

Multiple drill countersink and counterbore

Drill and countersink

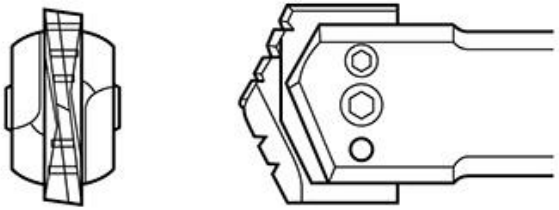
Drill and counterbore

Drill and chamfer

Drill, countersink, and counterbore

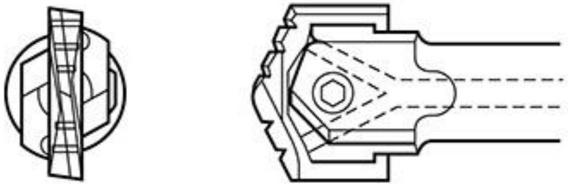
FIGURE 23-11 Special purpose subland drill (above), and some of the operations possible with other combination drills (below).

Spade Drills

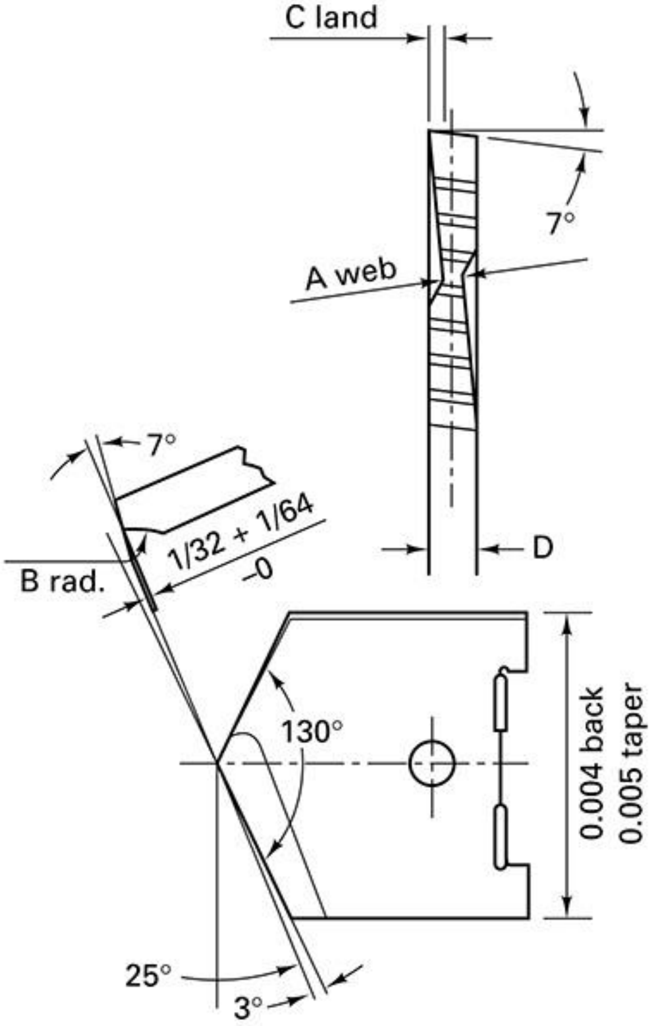


Regular spade drill

FIGURE 23-12 (Top) Regular spade drill; (middle) spade drill with oil holes; (bottom) spade drill geometry, nomenclature.



Spade drill with oil holes



- Spade Drills are used:
  - for making holes larger than one inch
  - at low speed and high feed
  - can drill deep holes in solid material without having an existing hole
  - body is made from ordinary steel
  - drill point is made from carbide material
  - have central hole for cooling and chip removal

Indexable Drills

FIGURE 23-13 One- and two lipped indexable insert drills are widely used for holes over 1 inch in diameter. *(Courtesy of Waukesha.)*

Microdrills

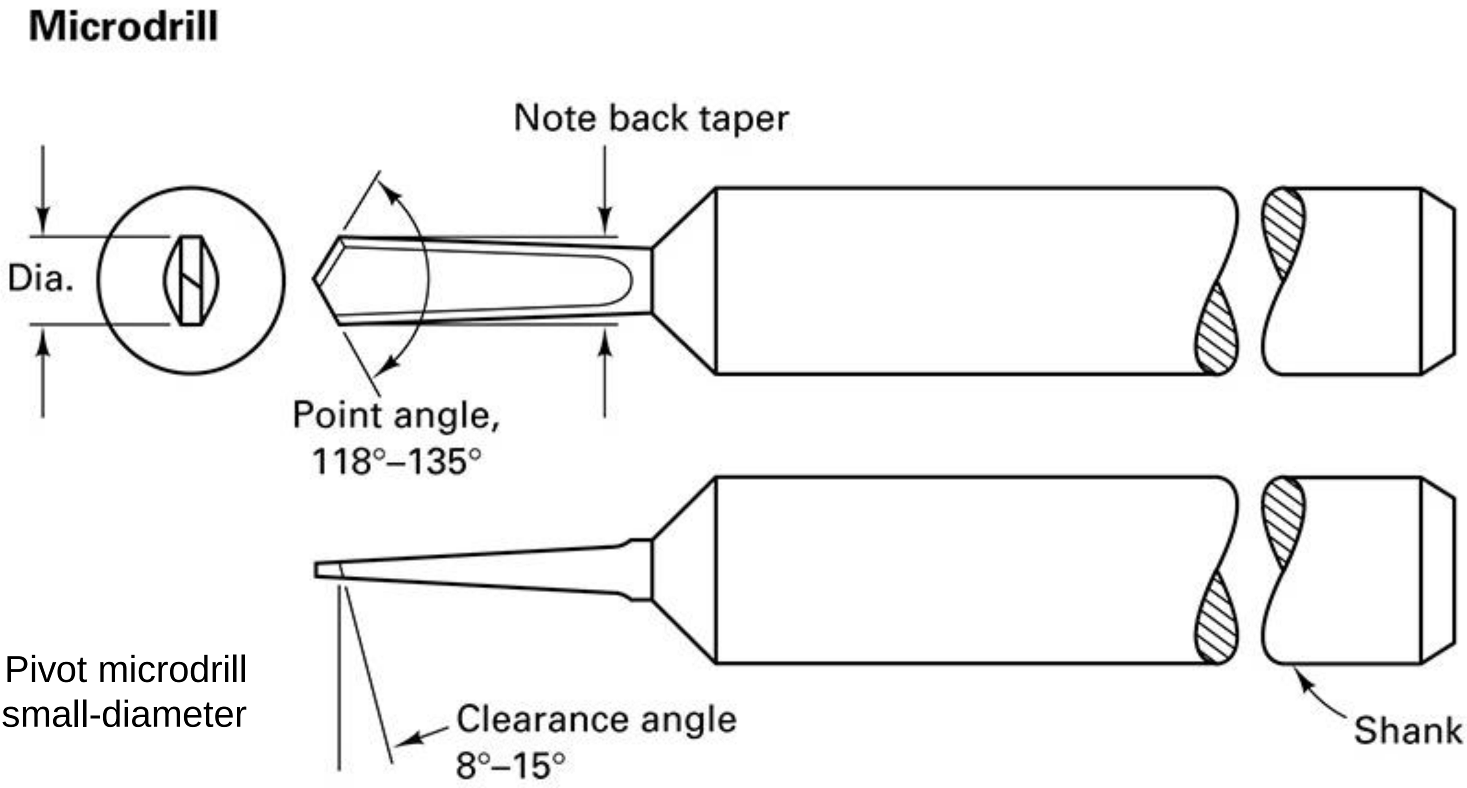


FIGURE 23-15 Pivot microdrill for drilling very-small-diameter holes.

23.4 Tool Holders for Drills

- Straight-shank drills are typically held in chucks
  - Three-jaw jacobs chucks: used on manual drill presses, require used of a key
  - Collet chuck: used with carbide tools where high bearing thrust is used
  - Quick change chucks: used were rapid change is needed
- Tapered shank drills held in mores taper of the machine spindle

Drill Chucks

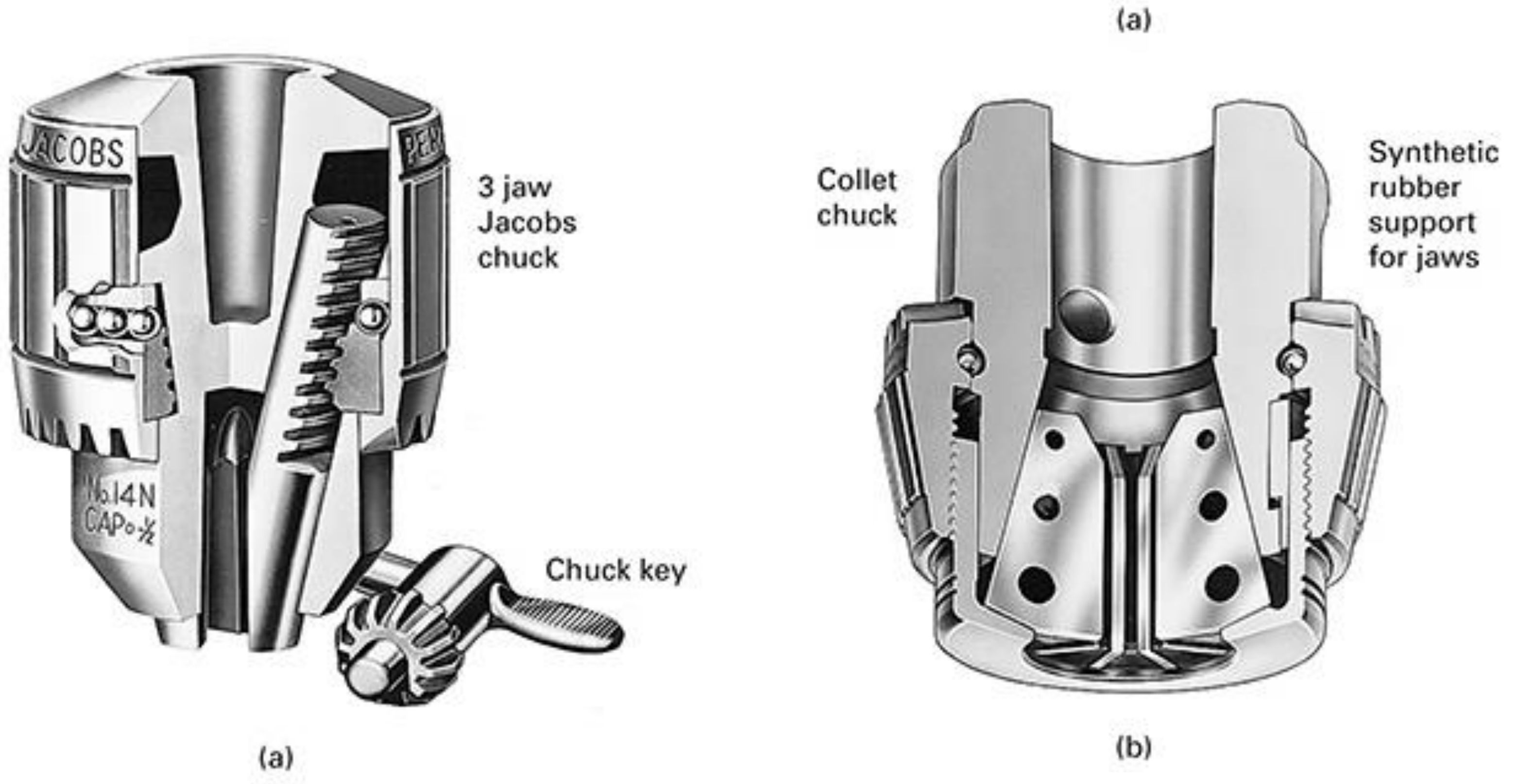


FIGURE 23-16 Two of the most commonly used types of drill chucks are the 3-jaw Jacobs chuck (above) and the collet chuck with synthetic rubber support for jaws. *(Courtesy of Jacobs Manufacturing Company.)*

Correct Chucking of Carbide Drills

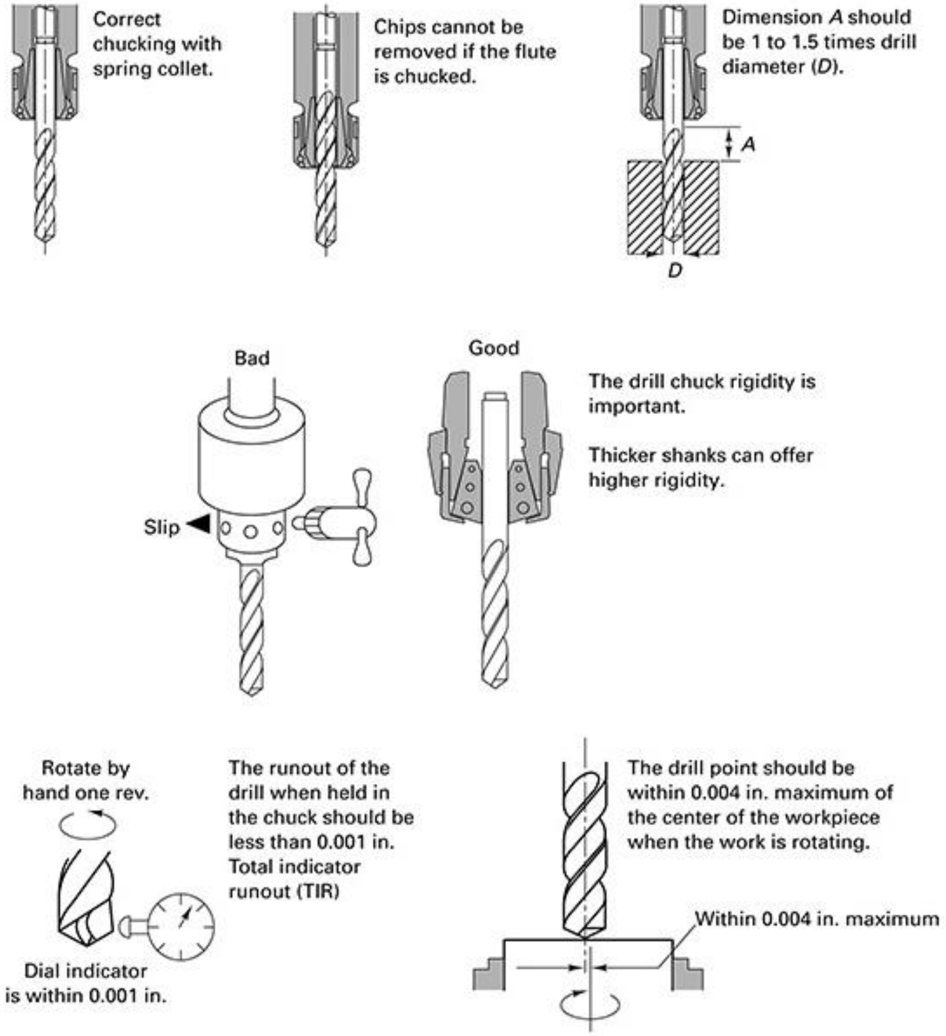


FIGURE 23-17 Here are some suggestions for correct chucking of carbide drills.

23.5 Workholding for Drilling

- For prototype pieces, stock material is held in simple clamping vises
- For high production rates, custom jigs are used
- Stock material is never to be held on the work table by hand

23.6 Machine Tools for Drilling

- Drilling can be performed on:
  - Lathes
  - Vertical mills
  - Horizontal mills
  - Boring machines
  - Machine centers
- Specialized machines designed specifically for drilling called “drill presses”

Requirements of a Drill Press

- Drill presses must have sufficient power and thrust to perform cut
- Drill presses must be rigid enough to prevent chatter
- Drill press consist of a base, a work table, and a column that supports the powerhead and spindle

Specialized Drill Presses

- Gang-drilling machines: independent columns, each with different drilling operation, work piece slid from one column to next
- Turret-type, upright drilling machines: used when numerous drilling operation are required in rapid succession, turret rotates needed tool into position for each operation
- Radial drilling machines: used on large workpieces, spindle mounts on radial arm, allowing drilling operations anywhere along the arm lenght

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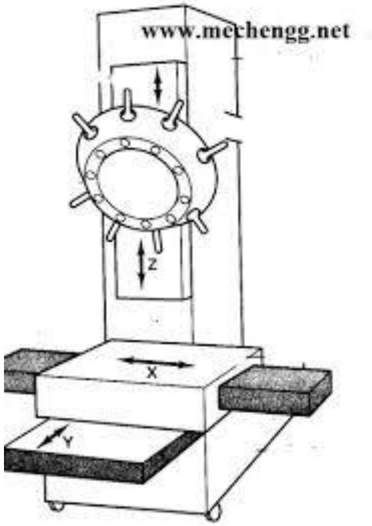

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Specialized Drill Presses

- Semiuniversal and universal machines: On a universal machine the spindle head can be rotated about the horizontal axis to any angle, semiuniversal can be rotated to a limited degree
- Multiple-spindle drilling machines: Single powerhead operates multiple spindles enabling multiple holes at one time, each hole can be unique
- Deep-hole drilling machines


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23.7 Cutting Fluids for Drilling

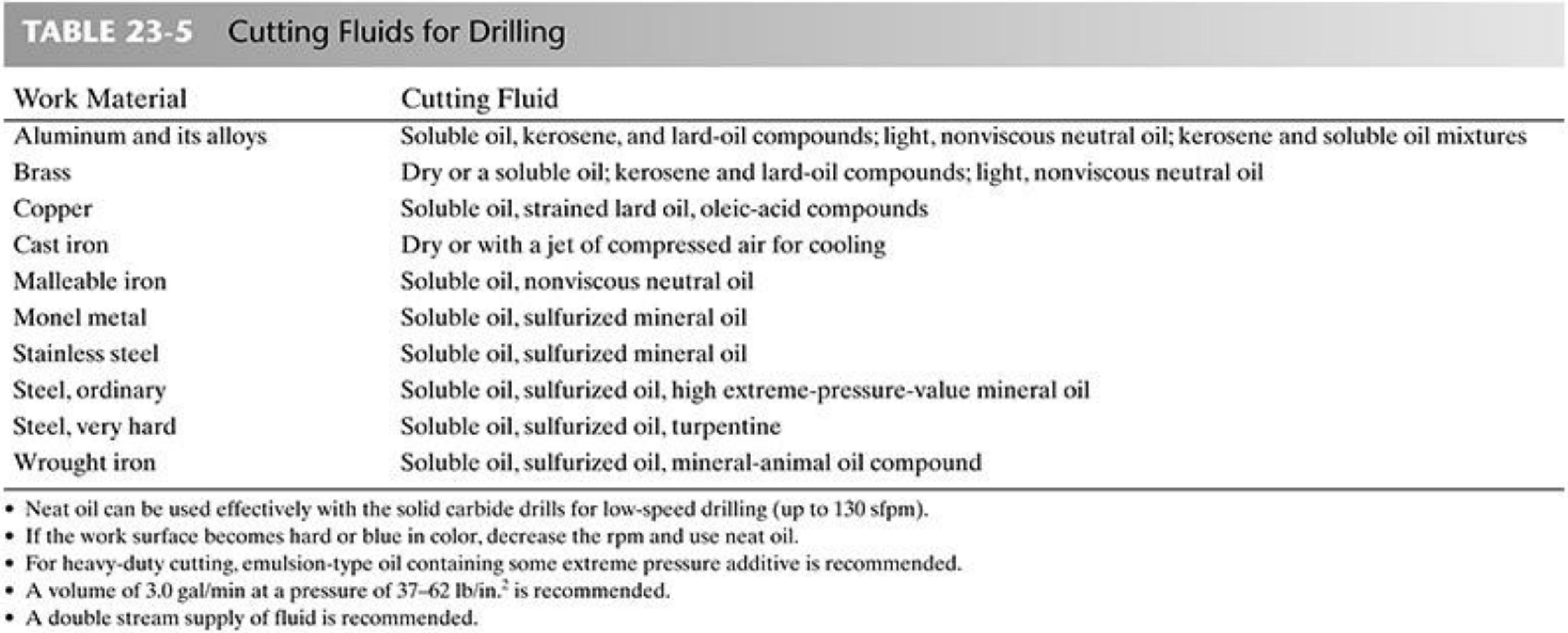


TABLE 23-5 Cutting Fluids for Drilling

Work Material	Cutting Fluid
Aluminum and its alloys	Soluble oil, kerosene, and lard-oil compounds; light, nonviscous neutral oil; kerosene and soluble oil mixtures
Brass	Dry or a soluble oil; kerosene and lard-oil compounds; light, nonviscous neutral oil
Copper	Soluble oil, strained lard oil, oleic-acid compounds
Cast iron	Dry or with a jet of compressed air for cooling
Malleable iron	Soluble oil, nonviscous neutral oil
Monel metal	Soluble oil, sulfurized mineral oil
Stainless steel	Soluble oil, sulfurized mineral oil
Steel, ordinary	Soluble oil, sulfurized oil, high extreme-pressure-value mineral oil
Steel, very hard	Soluble oil, sulfurized oil, turpentine
Wrought iron	Soluble oil, sulfurized oil, mineral-animal oil compound

- Neat oil can be used effectively with the solid carbide drills for low-speed drilling (up to 130 sfpm).
- If the work surface becomes hard or blue in color, decrease the rpm and use neat oil.
- For heavy-duty cutting, emulsion-type oil containing some extreme pressure additive is recommended.
- A volume of 3.0 gal/min at a pressure of 37–62 lb/in.^{2} is recommended.
- A double stream supply of fluid is recommended.

23.8 Counterboring, Countersinking, and Spot Facing

- Counterboring: Follows a drilling operation, or in with drilling with a custom tool. Purpose is to produce a flat bottom so that bolt head or nut is below the surface with enough clearance for a tool.
- Countersinking: Similar to counterboring, but with a 60°, 82°, or 90° beveled bottom to accommodate flat-head screw or rivet.
- Spot facing: Machine minimum depth and diameter around hole to ensure full seating of a bolt head. Used on rough stock surfaces where corrosion or fatigue requirements require full seating

Counterboring and Countersinking Tools

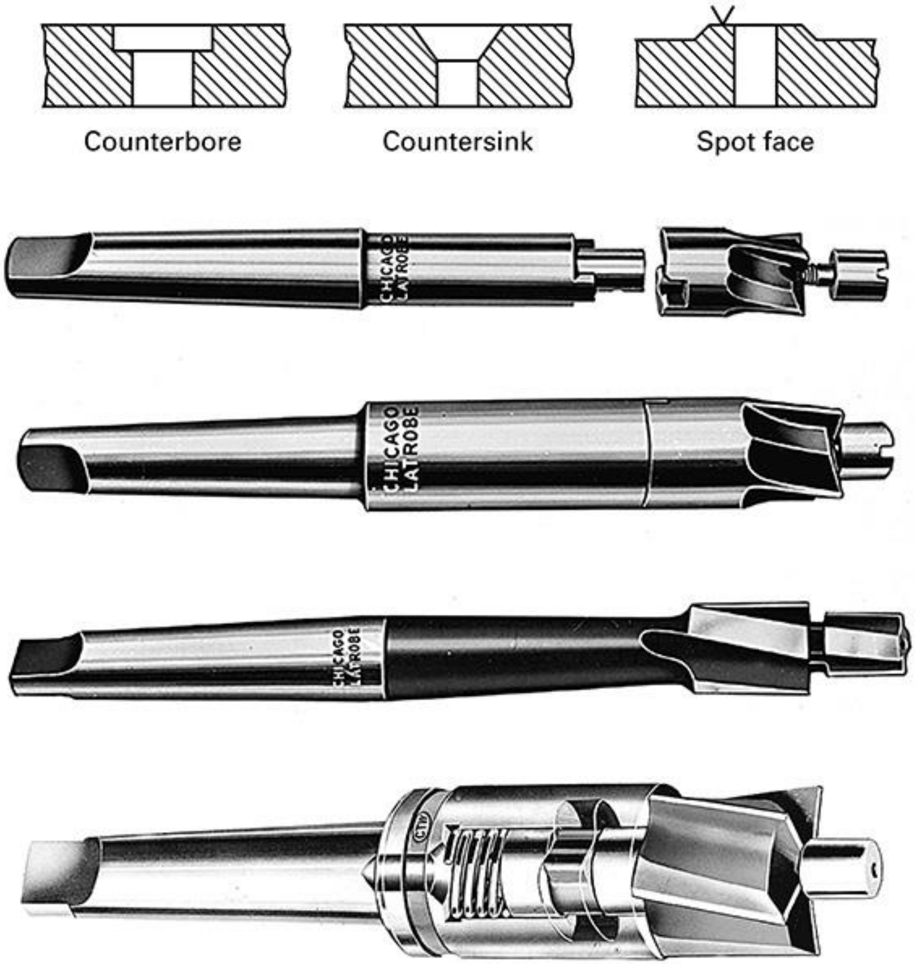


FIGURE 23-21 (a) Surfaces produced by counterboring, countersinking, and spot facing. (b) Counterboring tools: (bottom to top) interchangeable counterbore; solid, taper-shank counterbore with integral pilot; replaceable counterbore and pilot; replaceable counterbore, disassembled. *(Courtesy of Ex-Cell-O Corporation and Chicago Latrobe Twist Drill Works.)*

23.9 Reaming

- Reams remove small amounts of material to ensure exact hole size and improve hole surface finish
- Reams are either hand operated or machined at slow speed
- Ream types
    - Shell reams
    - Expansion reams
    - Adjustable reams
    - Tapered reams

Ream Geometry

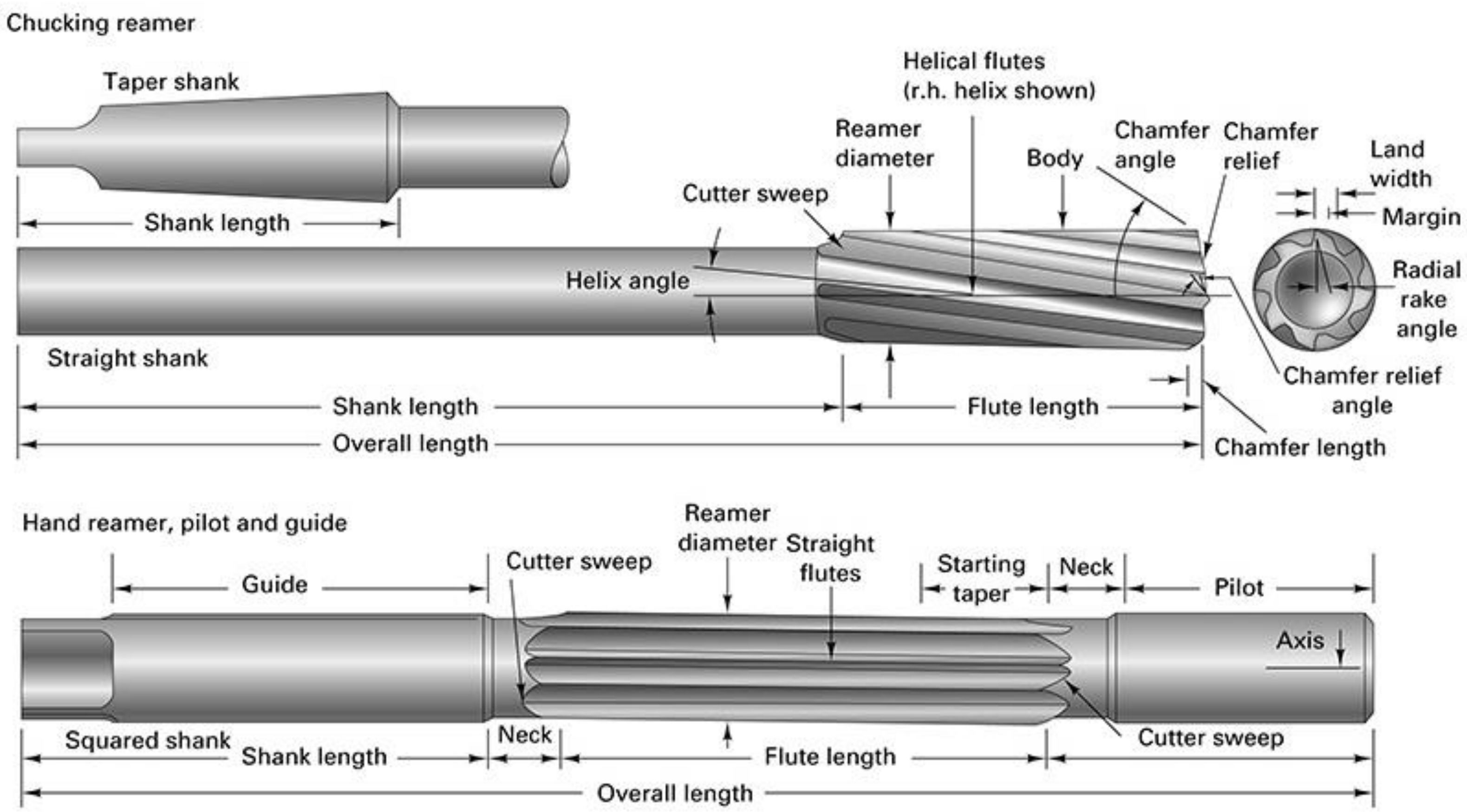
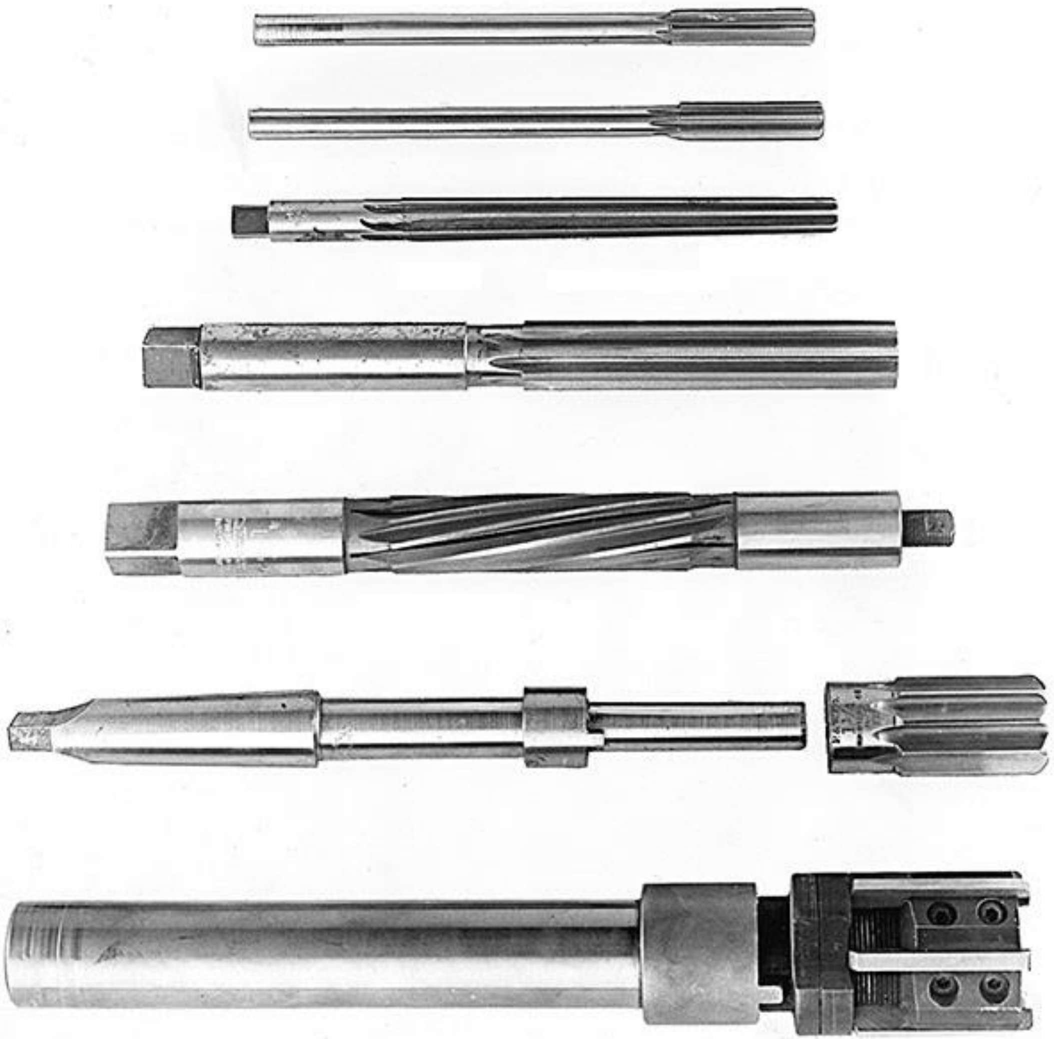


FIGURE 23-22 Standard nomenclature for hand and chucking reamers.

Types of Reams

FIGURE 23-23 Types of reamers: (top to bottom) Straightfluted rose reamer, straight-fluted chucking reamer, straight-fluted taper reamer, straight-fluted hand reamer, expansion reamer, shell reamer, adjustable insertblade reamer.



Summary

- Drilling is the most common machining operation
- Drilling can be performed on a number of machine tools, drill presses are specialized machine tools for drilling only
- Drills come in a wide variety of types and tip geometries depending upon production rate and accuracy needed
- Hole geometries can be adjusted through the use of counterboring, countersinking and reaming

Chapter 25: Milling

DeGarmo's Materials and Processes in Manufacturing

24.1 Introduction

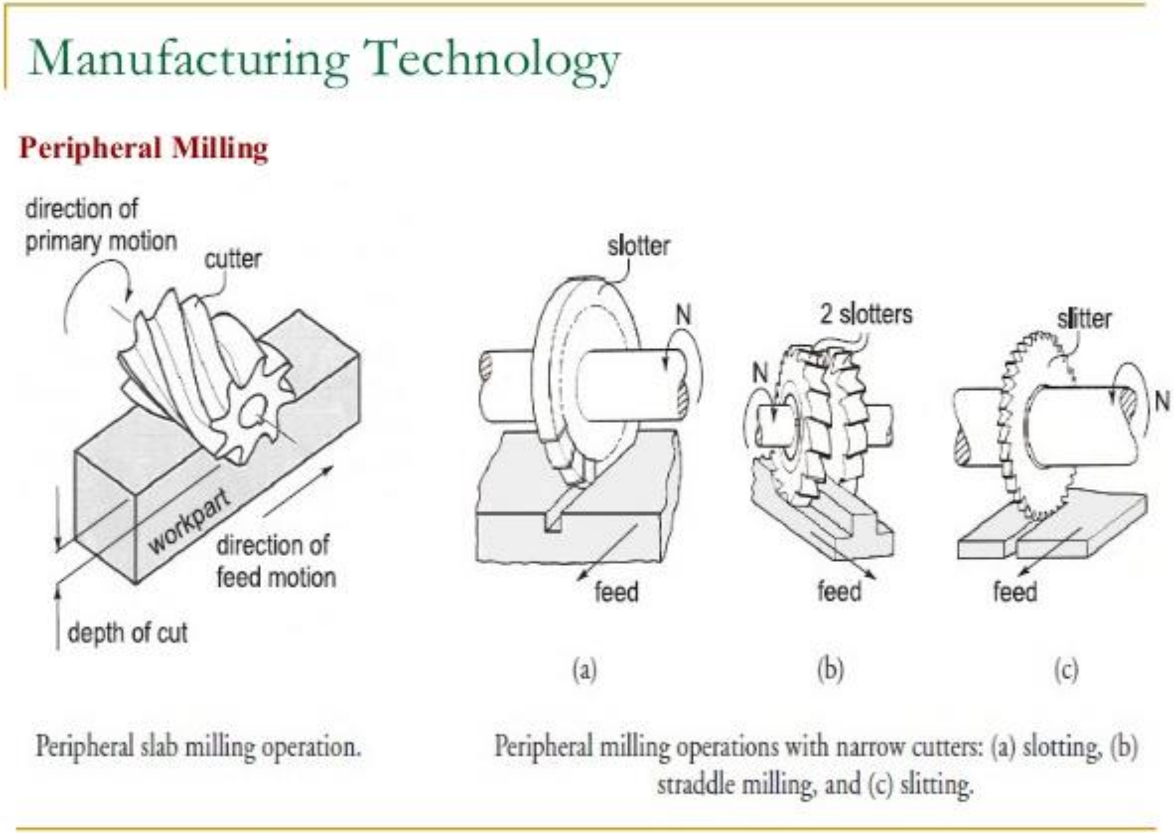
- Milling is the basic process of progressive chip removal to produce a surface.
- Mill cutters have single or multiple teeth that rotate about an axis, removing material.
- Milling can produce the desired surface with a single or multiple passes.
- Milling lends itself easily to mass production.

Process is characterized by:

- rotating cutter, and workpiece is fed
- good surface finish can be obtained
- suited for mass production
- interrupted cutting process

24.2 Fundamentals of Milling Processes

- Milling is classified in two categories:
  - Peripheral milling: the surface is generated by teeth located on the periphery of the cutter body. The surface is parallel with the axis of rotation of the cutter.
  - End milling: also called facing milling, the surface is generated is at a right angle to the cutter axis. Material is removed by the peripheral teeth and the face portion providing finishing action.



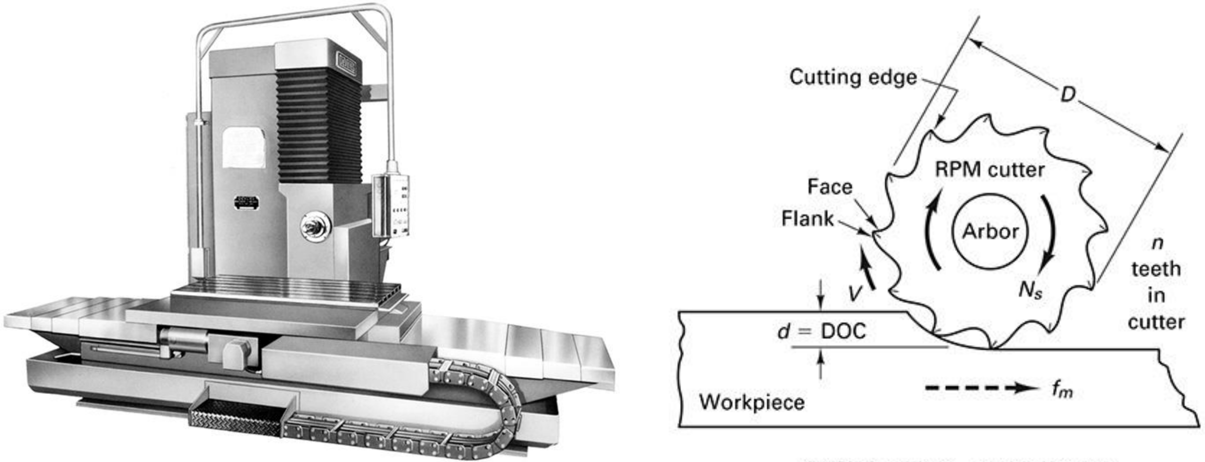
Manufacturing Technology

Peripheral Milling

Peripheral slab milling operation.

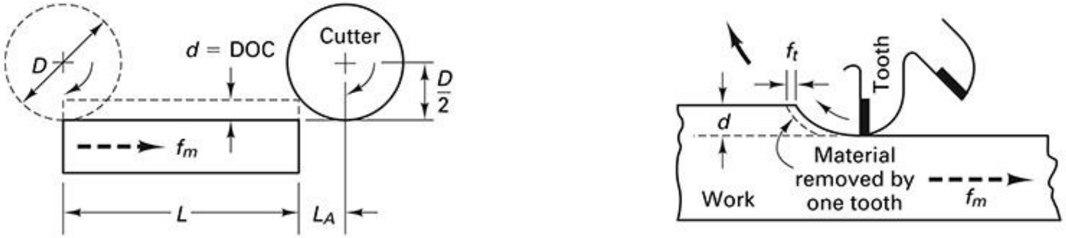
Peripheral milling operations with narrow cutters: (a) slotting, (b) straddle milling, and (c) slitting.

Peripheral Mills



(a) Horizontal-spindle milling machine

(b) Slab milling—multiple tooth



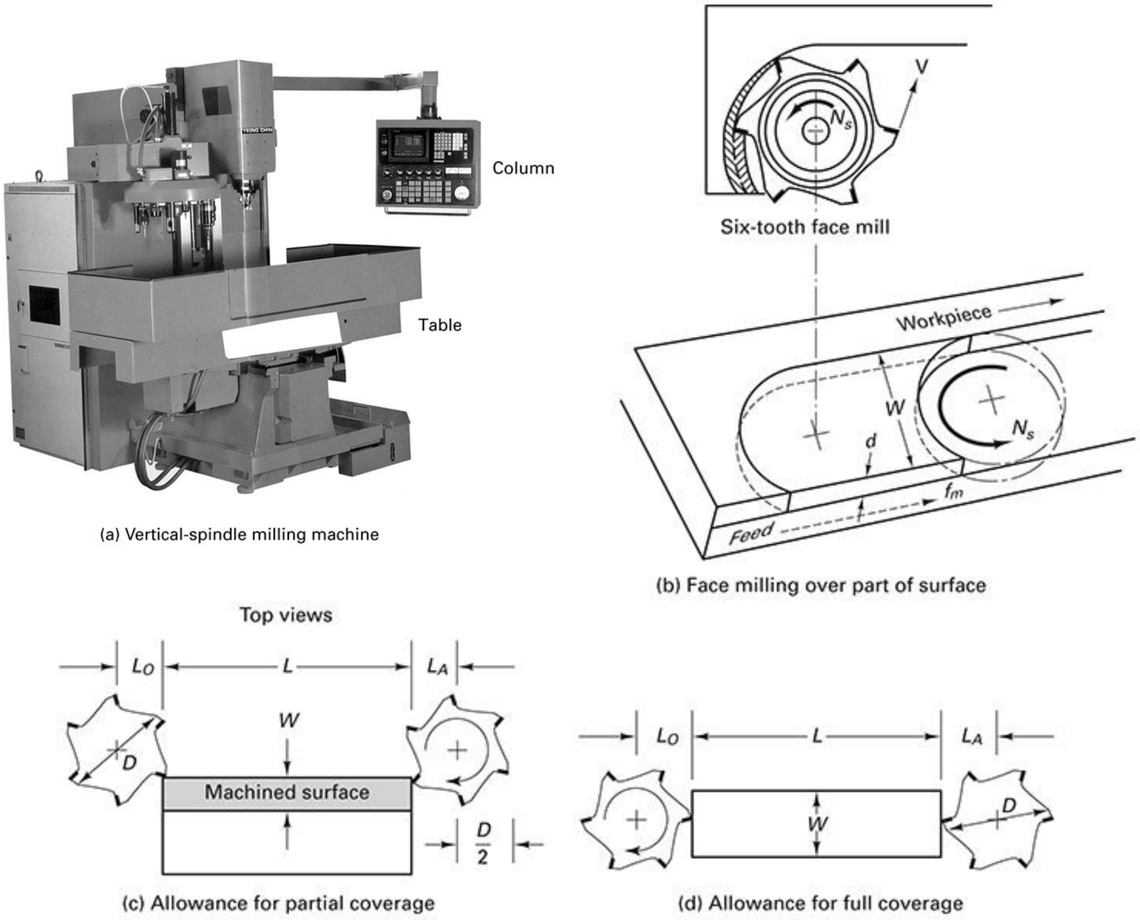
(c) Allowances for cutter approach

(d) Feed per tooth

FIGURE 24-1 Peripheral milling can be performed on a horizontal-spindle milling machine. The cutter rotates at rpm *Ns* , removing metal at cutting speed *V.* The allowance for starting and finishing the cut depends on the cutter diameter and depth of cut, *d.* The feed per tooth, *ft* and cutting speed are selected by the operator or process planner.

Face Mills

FIGURE 24-2 Face milling is often performed on a spindle milling machine using a multiple-tooth cutter (*n* *6* teeth) rotating *Ns* at rpm to produce cutting speed *V.* The workpiece feeds at rate *fm* in inches per minute past the tool. The allowance depends on the tool diameter and the width of cut.



(a) Vertical-spindle milling machine

(b) Face milling over part of surface

(c) Allowance for partial coverage

(d) Allowance for full coverage

Vertical and Horizontal Cutters

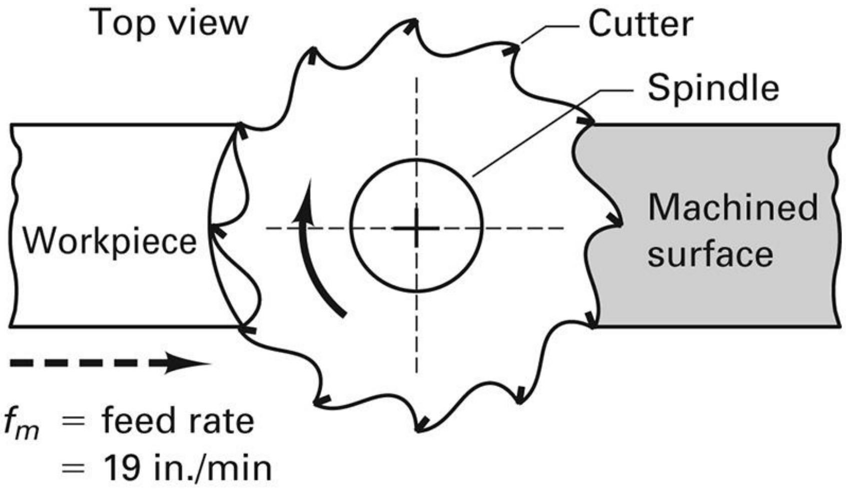


FIGURE 24-3 Face milling viewed from above with vertical spindle-machine.

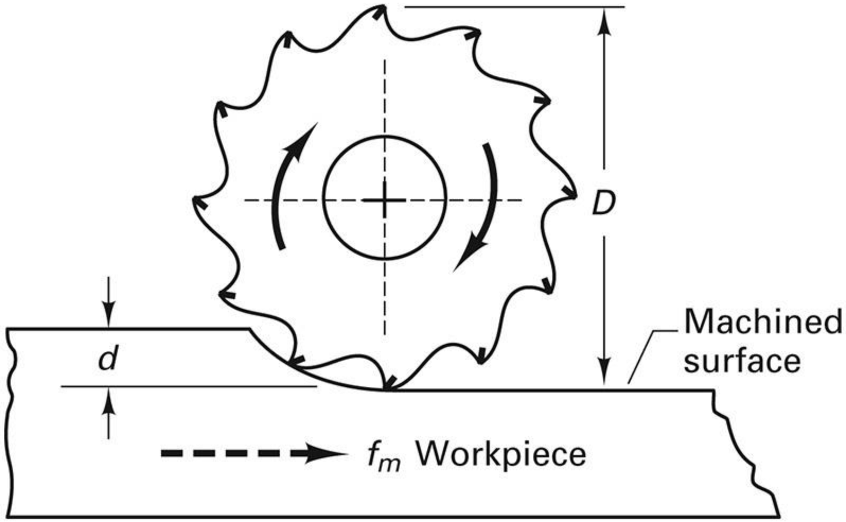
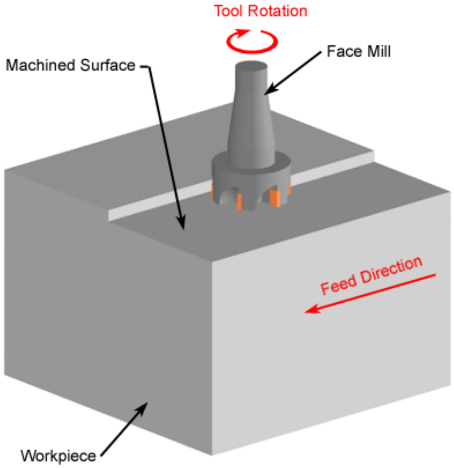
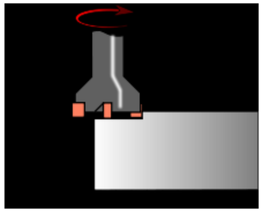


FIGURE 24-4 Slab or side milling being done as a down milling process with horizontal spindle-machine.

Face Milling





End Milling

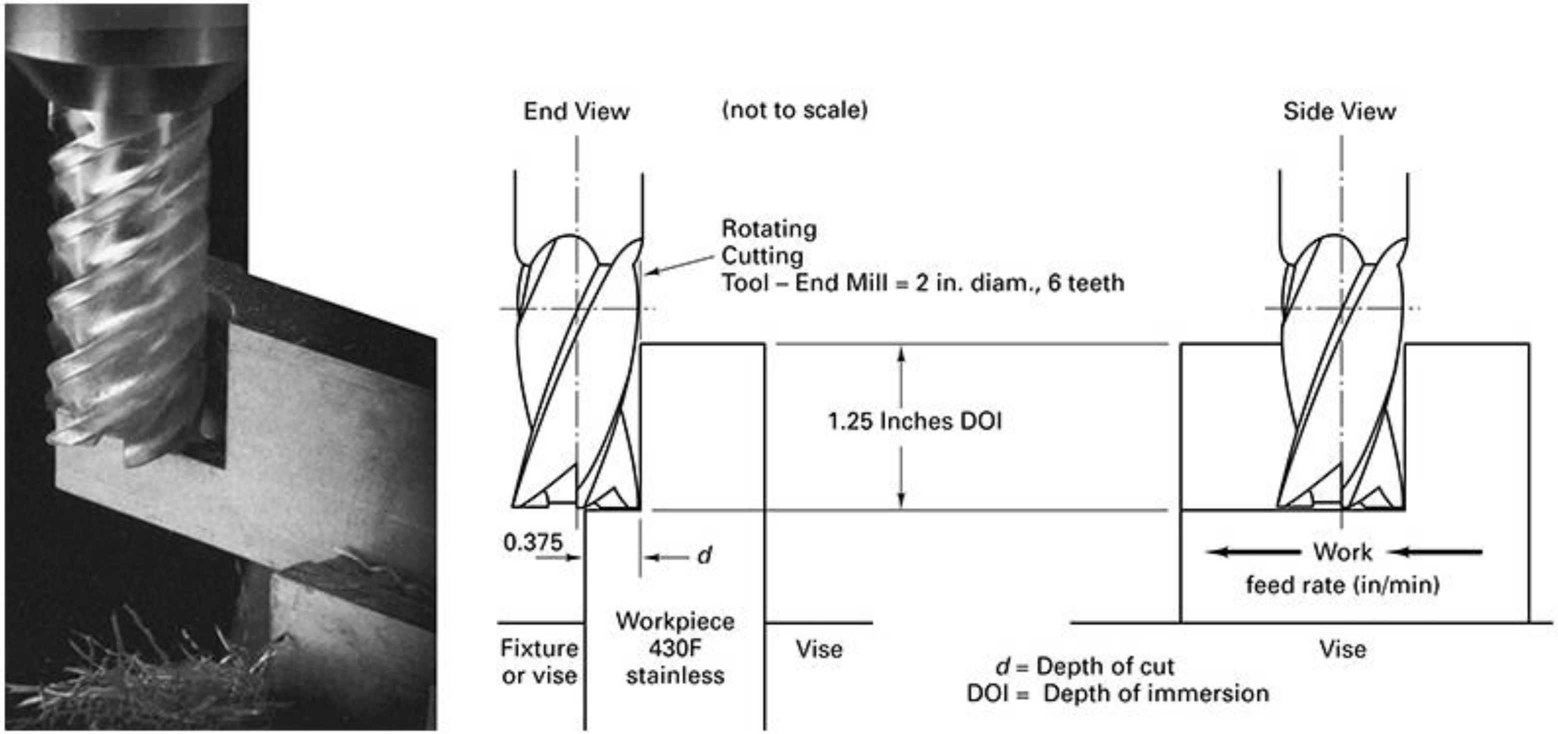


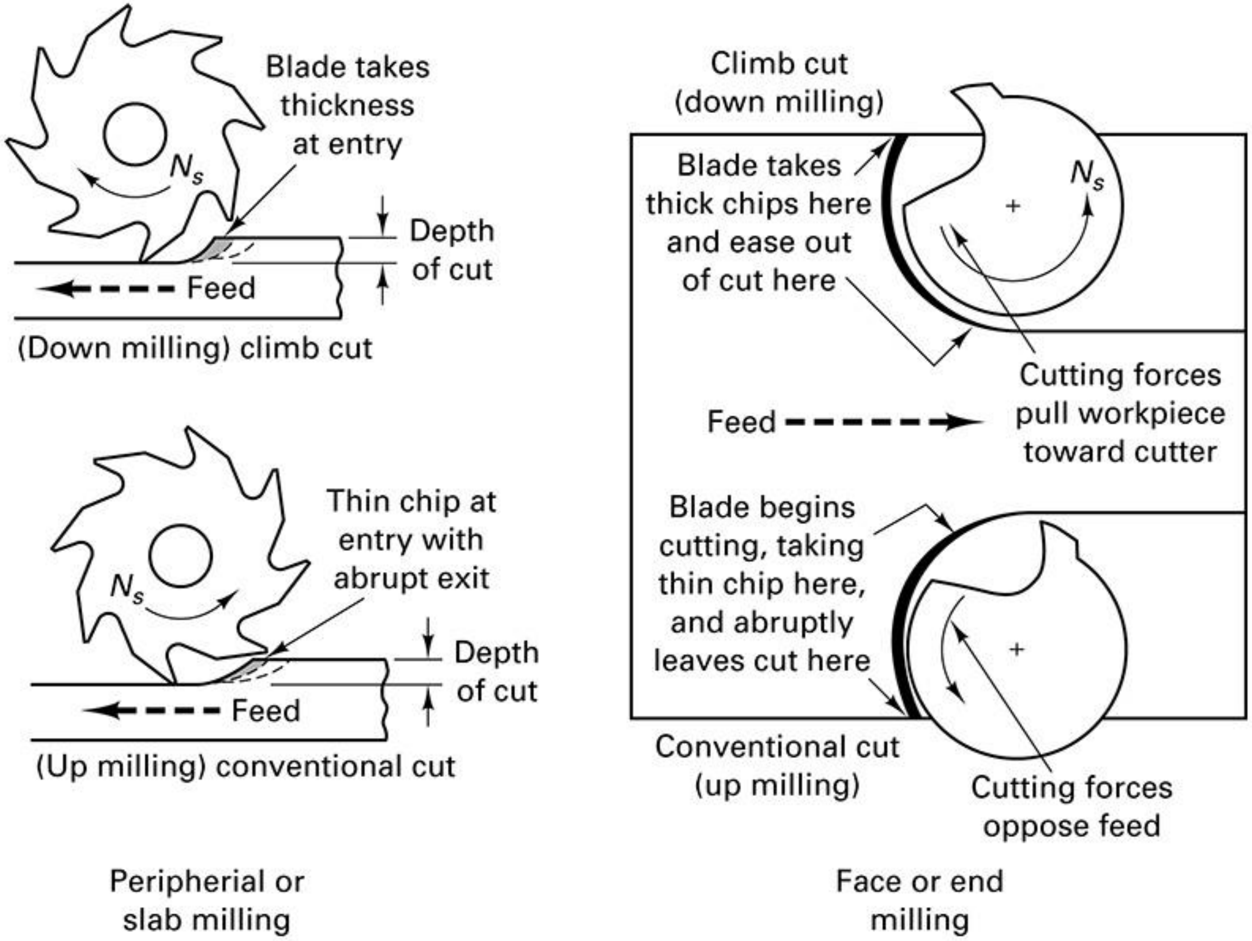
FIGURE 24-5 End milling a step feature in a block using a flat-bottomed, end mill cutter in a vertical spindle-milling machine. On left, photo. In middle, end view, table moving the block into the cutter. On right, side view, workpiece feeding right to left into tool.

Up Versus Down Milling

- Conventional milling is called up milling
    - The cutter rotates against the direction of feed of the workpeice.
    - The Chip is very thin at the beginning and increased along its length.
    - The cutter tends to push the work along and lift it upwards from the table.
- Down milling the cutter rotation is the same as the direction of feed
    - The maximum chip thickness is at the point of tooth contact with the work piece. Dulling the teeth more quickly
    - The work piece is pulled into the cutter, eliminating any effects from looseness of the work table feed screw.

Climbing versus Conventional Mills

FIGURE 24-6 Climb cut or down milling versus conventional cut or up milling for slab or face or end milling.



24.3 Milling Tools and Cutters

- There are a variety of mills used, the most common being face mills and end mills
  - End mills are either HSS or have indexable inserts (Figure 8)
  - End Mills come in a variety of geometries
    - Plain End Mills
    - Shell End Mills
    - Hollow End Mills

Shell End Mills

Other Mill Cutter Types

- Face mills have indexable inserts along the periphery (Figure 7)
- Face Mills come in a variety of geometry (Figure 9)
  - Center hole for arbor mounting
  - Side mill (Figure 10)
  - Staggered-tooth
  - Straddle milling
  - Interlocking slot cutters
  - Slitting cutters

Milling Cutters

Facing Mill

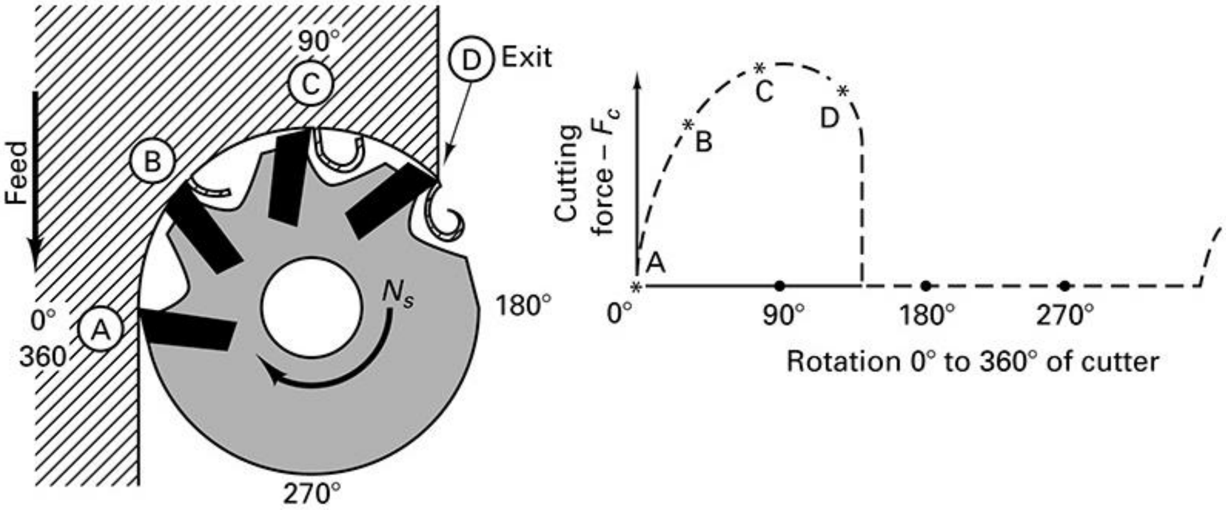


FIGURE 24-7 Conventional face milling (left) with cutting force diagram for *Fc* (right) showing the interrupted nature of the process. *(From* Metal Cutting Principles, *2nd ed., Ingersoll Cutting Tool Company.)*

Typical Cutter Problems

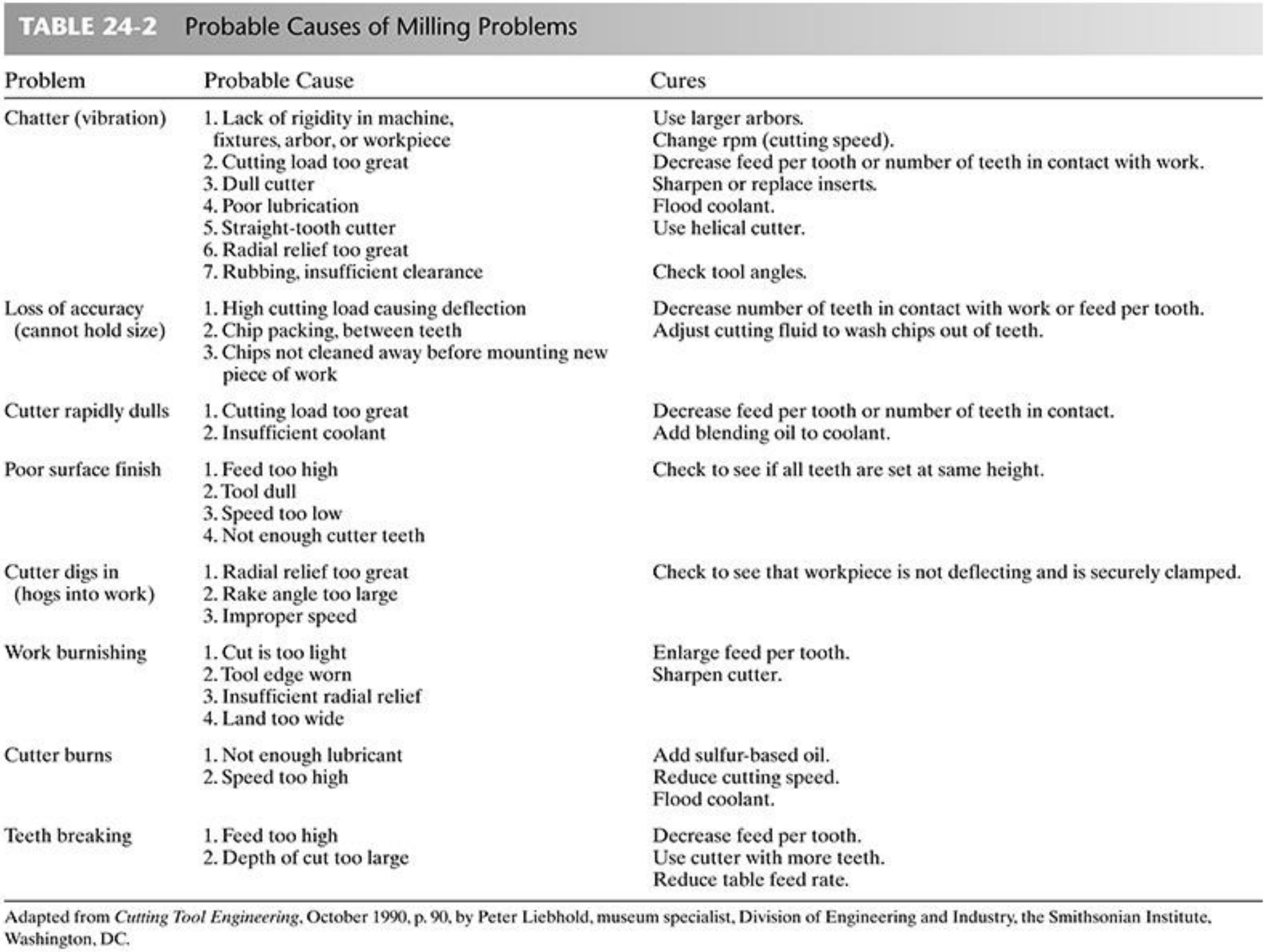


TABLE 24-2 Probable Causes of Milling Problems

Problem	Probable Cause	Cures
Chatter (vibration)	1. Lack of rigidity in machine, fixtures, arbor, or workpiece	Use larger arbors.
	2. Cutting load too great	Change rpm (cutting speed).
	3. Dull cutter	Decrease feed per tooth or number of teeth in contact with work.
	4. Poor lubrication	Sharpen or replace inserts.
	5. Straight-tooth cutter	Flood coolant.
	6. Radial relief too great	Use helical cutter.
	7. Rubbing, insufficient clearance	Check tool angles.
Loss of accuracy (cannot hold size)	1. High cutting load causing deflection	Decrease number of teeth in contact with work or feed per tooth.
	2. Chip packing, between teeth	Adjust cutting fluid to wash chips out of teeth.
	3. Chips not cleaned away before mounting new piece of work	
Cutter rapidly dulls	1. Cutting load too great	Decrease feed per tooth or number of teeth in contact.
	2. Insufficient coolant	Add blending oil to coolant.
Poor surface finish	1. Feed too high	Check to see if all teeth are set at same height.
	2. Tool dull	
	3. Speed too low	
	4. Not enough cutter teeth	
Cutter digs in (hogs into work)	1. Radial relief too great	Check to see that workpiece is not deflecting and is securely clamped.
	2. Rake angle too large	
	3. Improper speed	
Work burnishing	1. Cut is too light	Enlarge feed per tooth.
	2. Tool edge worn	Sharpen cutter.
	3. Insufficient radial relief	
	4. Land too wide	
Cutter burns	1. Not enough lubricant	Add sulfur-based oil.
	2. Speed too high	Reduce cutting speed.
		Flood coolant.
Teeth breaking	1. Feed too high	Decrease feed per tooth.
	2. Depth of cut too large	Use cutter with more teeth.
		Reduce table feed rate.

Adapted from *Cutting Tool Engineering*, October 1990, p. 90, by Peter Liebhold, museum specialist, Division of Engineering and Industry, the Smithsonian Institute, Washington, DC.

End Mill Geometry

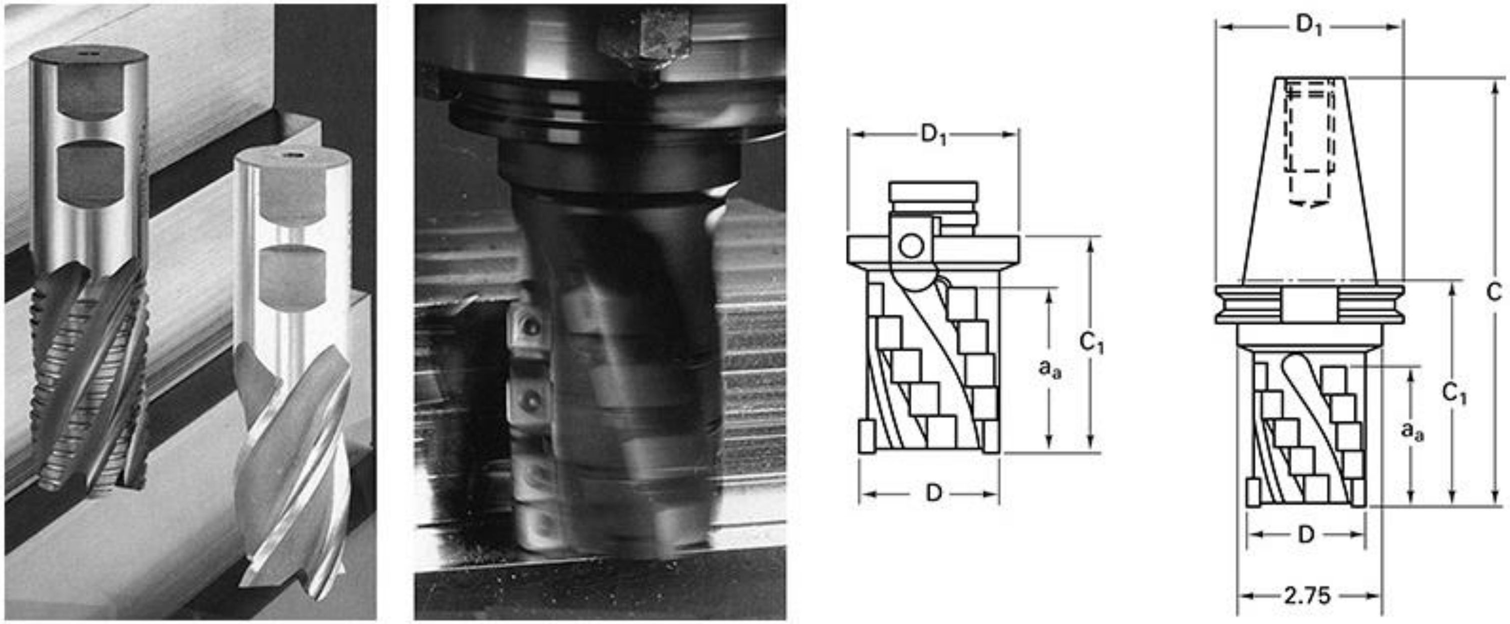


FIGURE 24-8 Solid end mills are often coated. Insert tooling end mills come in a variety of sizes and are mounted on taper shanks.

Facing Mill Geometry

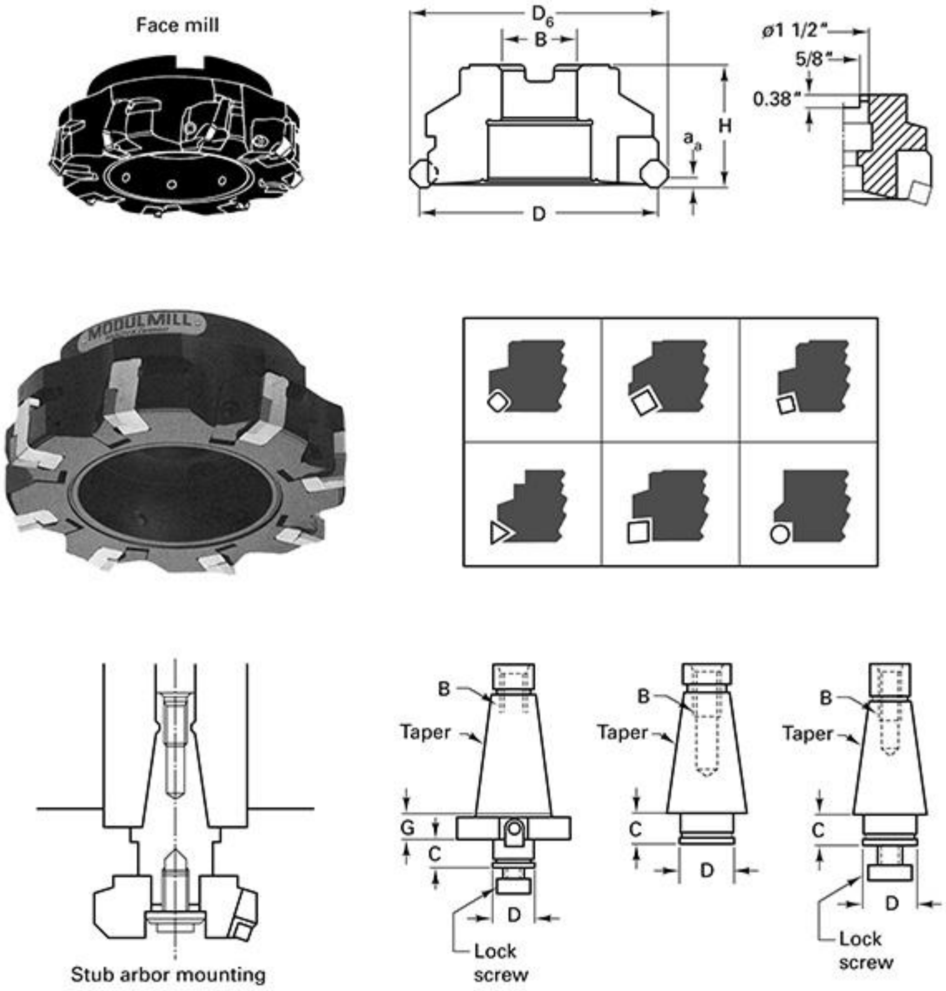
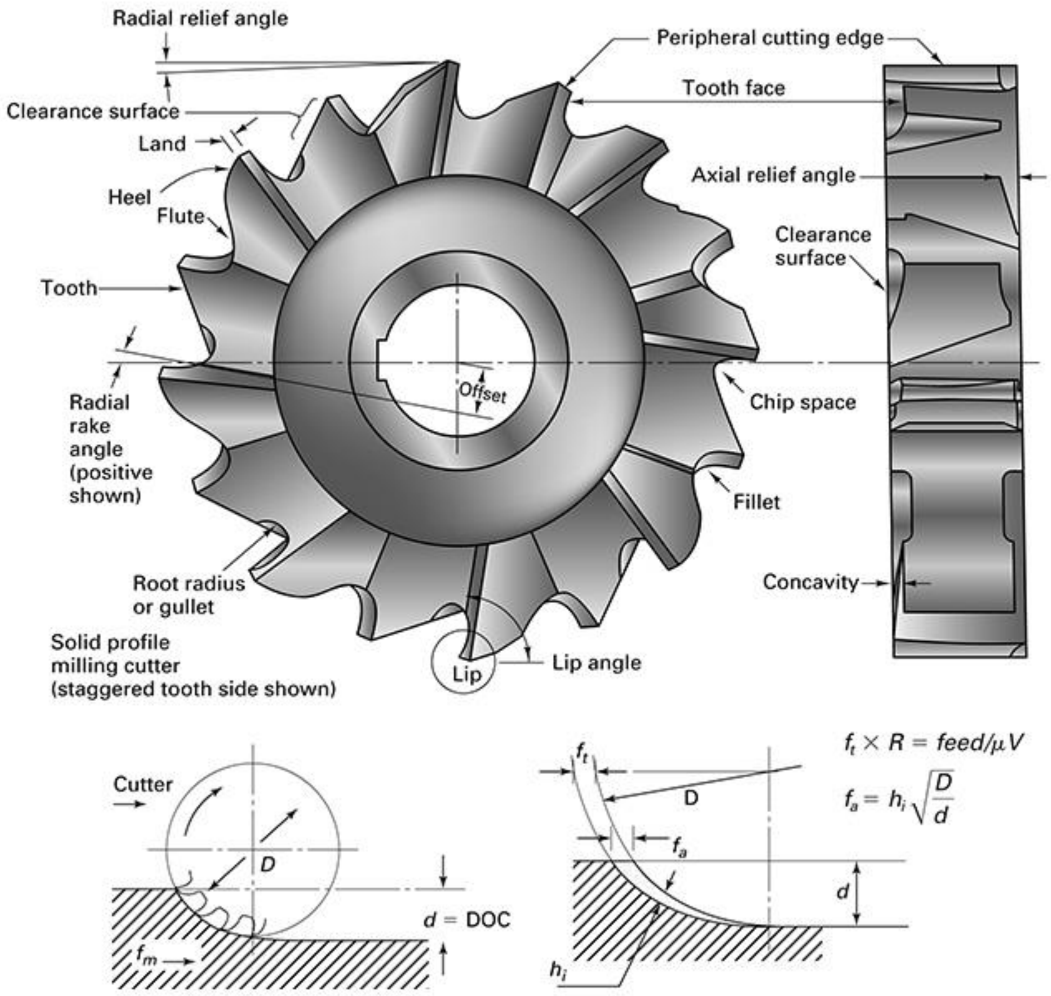


FIGURE 24-9 Face mills come in many different designs using many different insert geometries and different mounting arbors.

Side Milling

FIGURE 24-10 The side-milling cutter can cut on sides and ends of the teeth, so it makes slots or grooves. However, only a few teeth are engaged at any one point in time, causing heavy torsional vibrations. The average chip thickness, *hi*, will be less than the feed per tooth, *ft .* The actual feed per tooth *fa* will be less than feed per tooth selected, *Ft .*



Arbor Milling

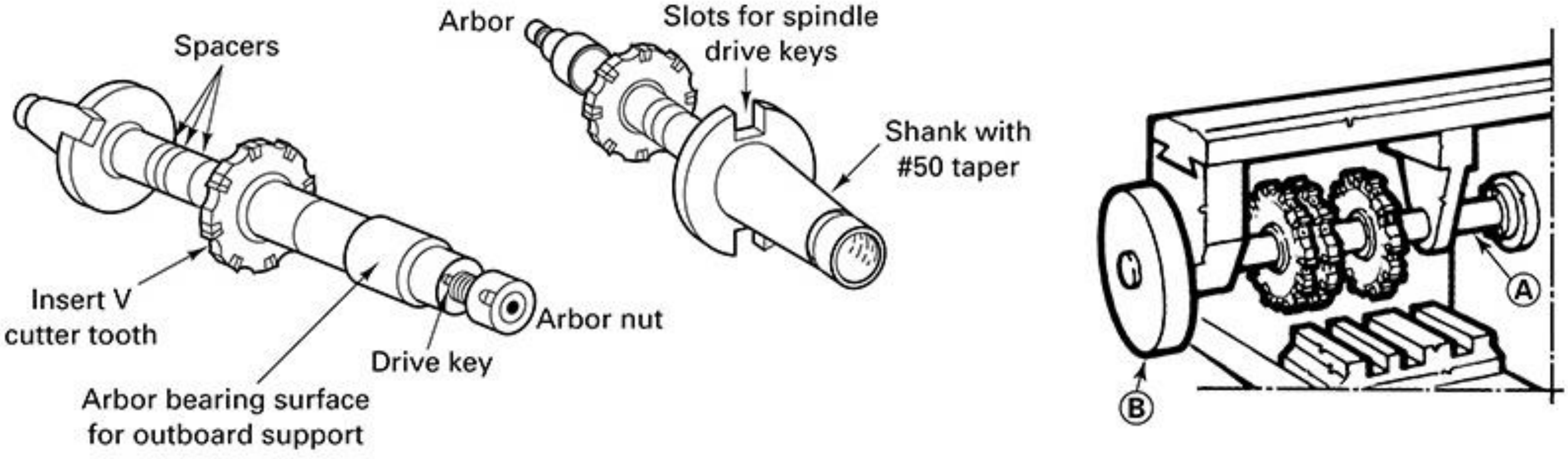


FIGURE 24-11 Arbor (two views) used on a horizontal-spindle milling machine on left. On right, a gangmilling setup showing three side-milling cutters mounted on an arbor (A) with an outboard flywheel (B).

Helical Mills

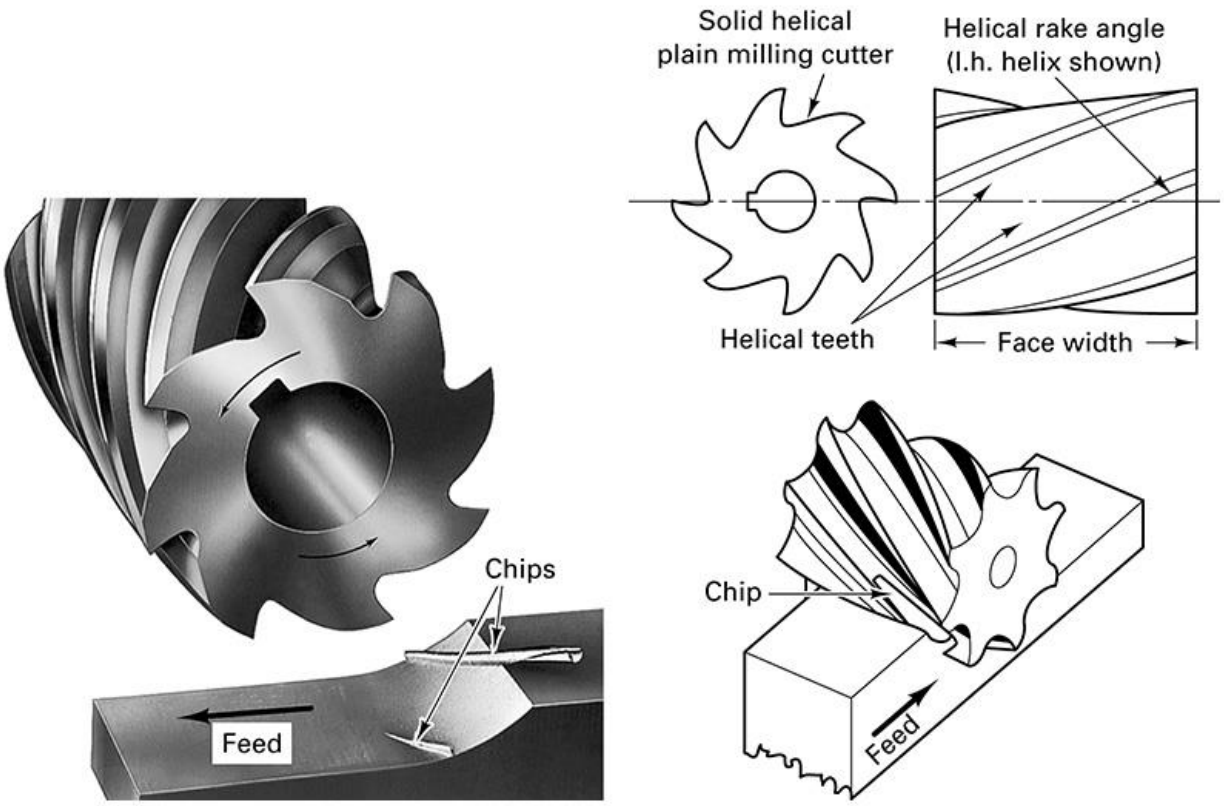
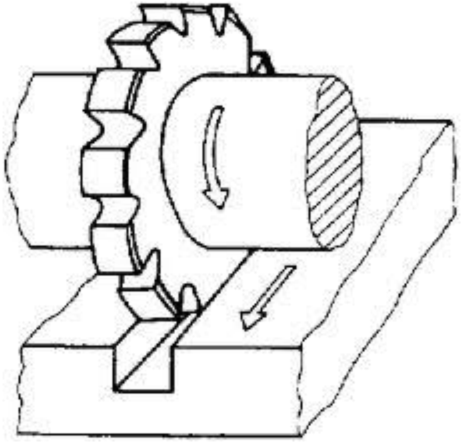


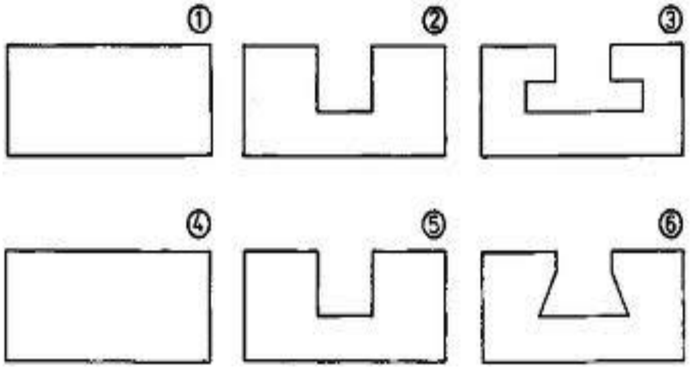
FIGURE 24-12 The chips are formed progressively by the teeth of a plain helical-tooth milling cutter during up milling.

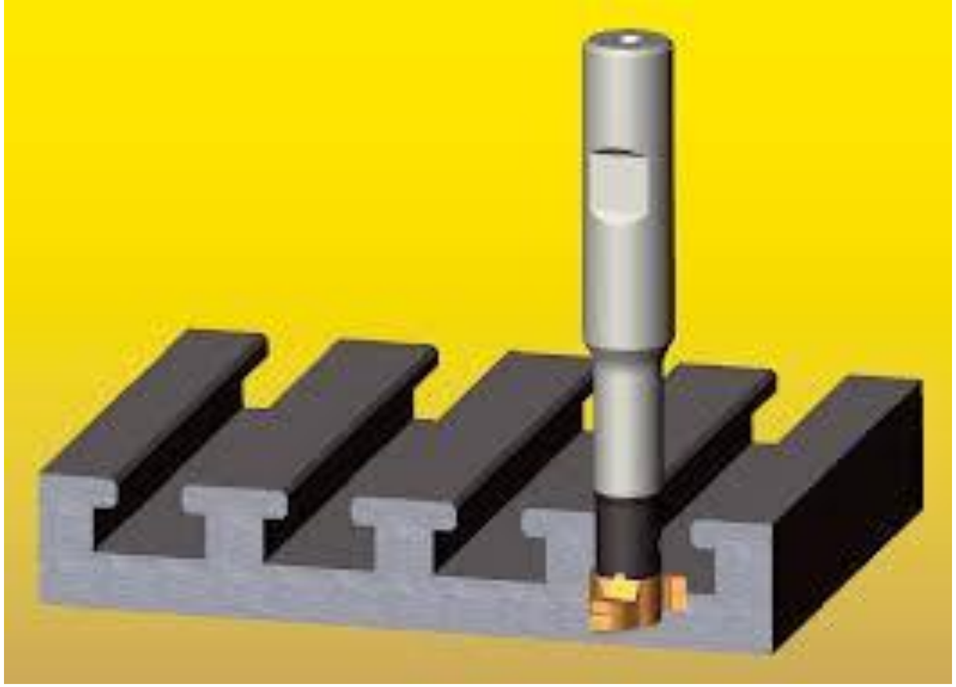
Shaped Cutters

- Form Relieved Cutters are used when intricate shapes are needed.
- T-slot cutters are used to produce slots in material. An end mill is use first to produce the initial groove
- A wooddruf keyseat cutter is used to produce a slot in a shaft and come in standard sizes
- Fly cutters are single toothed face mill cutters, with adjustable radii.

Cutting T- Slot







T- Slot, Wooddruf, and Fly cutters

Relieved Cutter

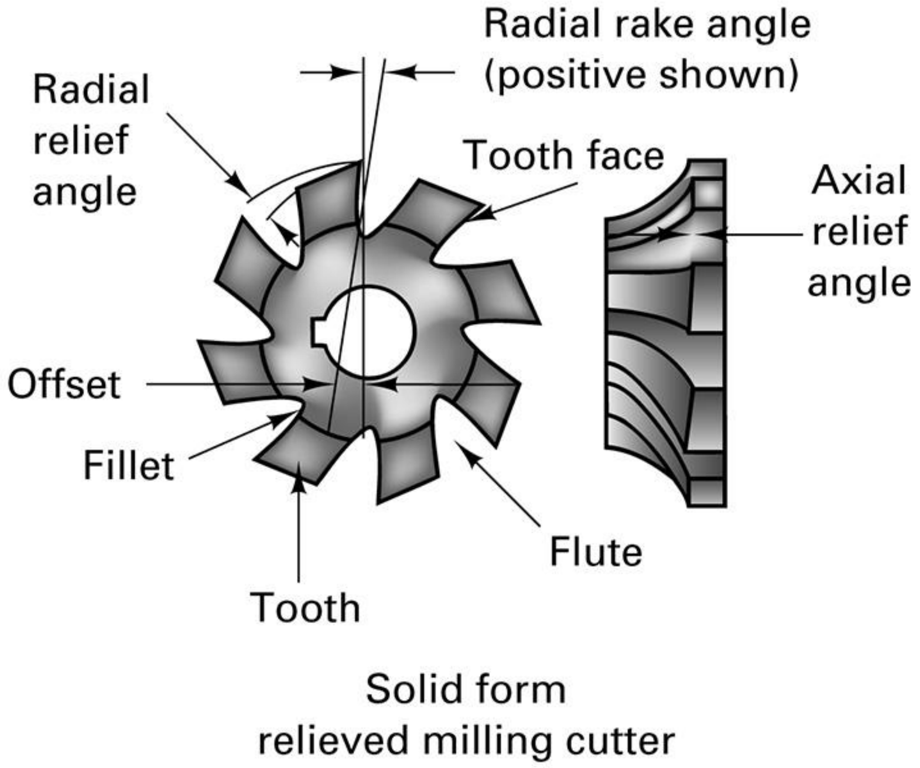


FIGURE 24-13 Solid form relieved milling cutter, would be mounted on an arbor in a horizontal milling machine..

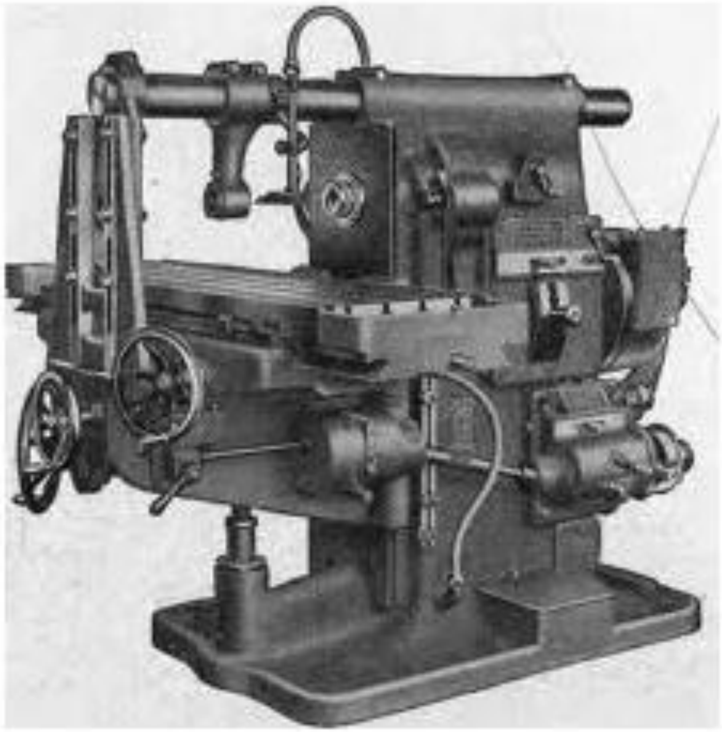
24.4 Machines for Milling

- The four most common types of manually controlled milling machines are listed below in order of increasing power (and therefore metal removal capability):
  - **1.** Ram-type milling machines
  - **2.** Column-and-knee-type milling machines
    - a. Horizontal spindle
    - b. Vertical spindle
  - **3.** Fixed-bed-type milling machines
  - **4.** Planer-type milling machines

Machines for Milling

- Milling machines whose motions are electronically controlled are listed in order of increasing production capacity and decreasing flexibility:
  - **1.** Manual data input milling machines
  - **2.** Programmable CNC milling machines
  - **3.** Machining centers (tool changer and pallet exchange capability)
  - **4.** Flexible Manufacturing Cell and Flexible Manufacturing System
  - **5.** Transfer lines

Milling Machines



Basic Mill Construction

- Most mills consist of column-and-knee designs
  - The column is mounted on a base and the spindle mounted on a knee extending from the column.
  - The knee has vertical movement
  - The material in mounted on a table with longitudinal movement, and the table is mounted on a saddle with transverse movement
- Most common of this type mill is the Ram mill which has a motor and pulley system mounted on the top of the column.

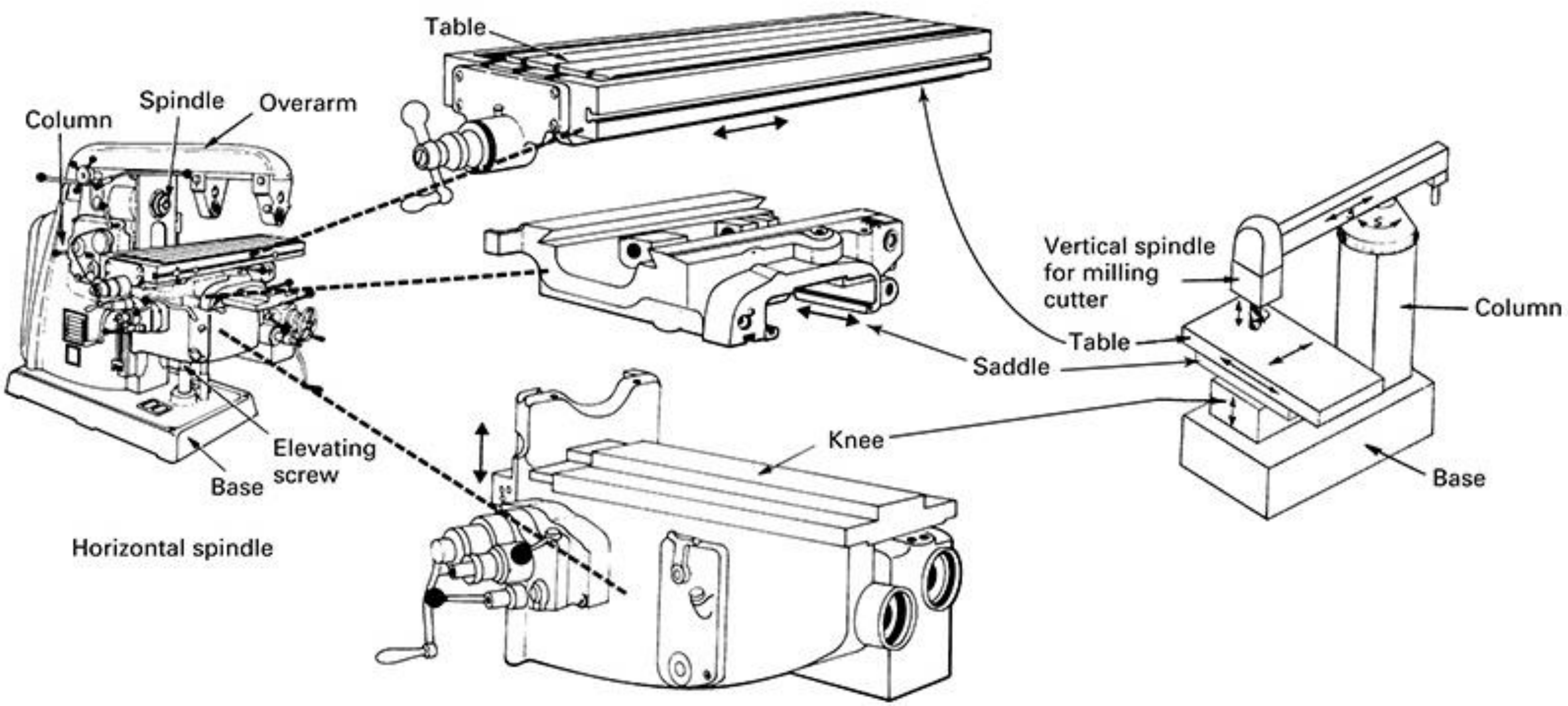
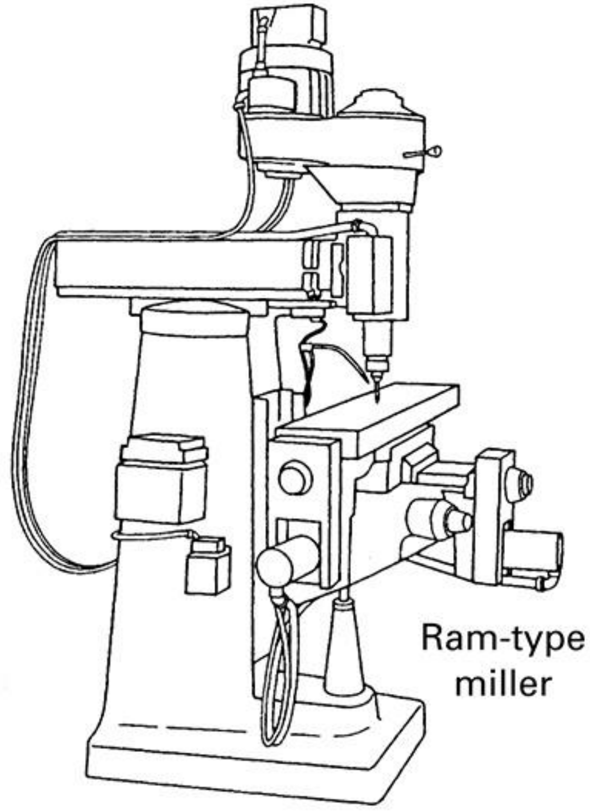


FIGURE 24-14 Major components of a plain column-and-knee-type milling machine, which can have horizontal spindle shown on the left, or a turret type machine with a vertical spindle, shown on the right. The workpiece and workholder on the table can be translated in *X, Y,* and *Z* directions with respect to the tool.

FIGURE 24-15 The ram-type knee-and-column milling machine is one of the most versatile and popular milling machine tools ever designed.



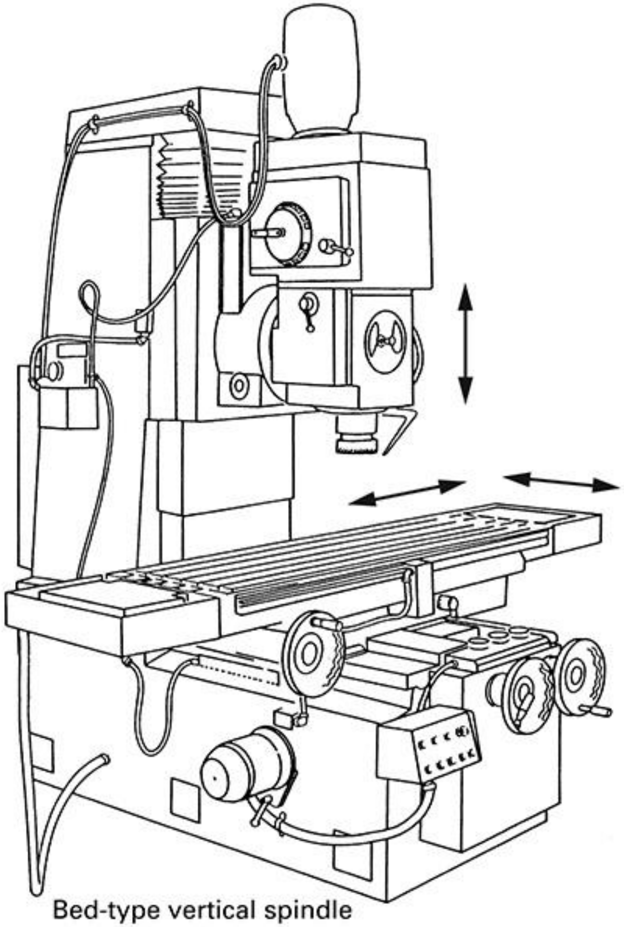
Vertical spindle ram-type

Bed Type Milling Machine

- Made for deep cuts and heavy material removal, the bed only had horizontal movement
- Once the bed is set up, the spindle height is not changed during operation.
- These machines are very common due to their ease of use.

Bed Type Mill

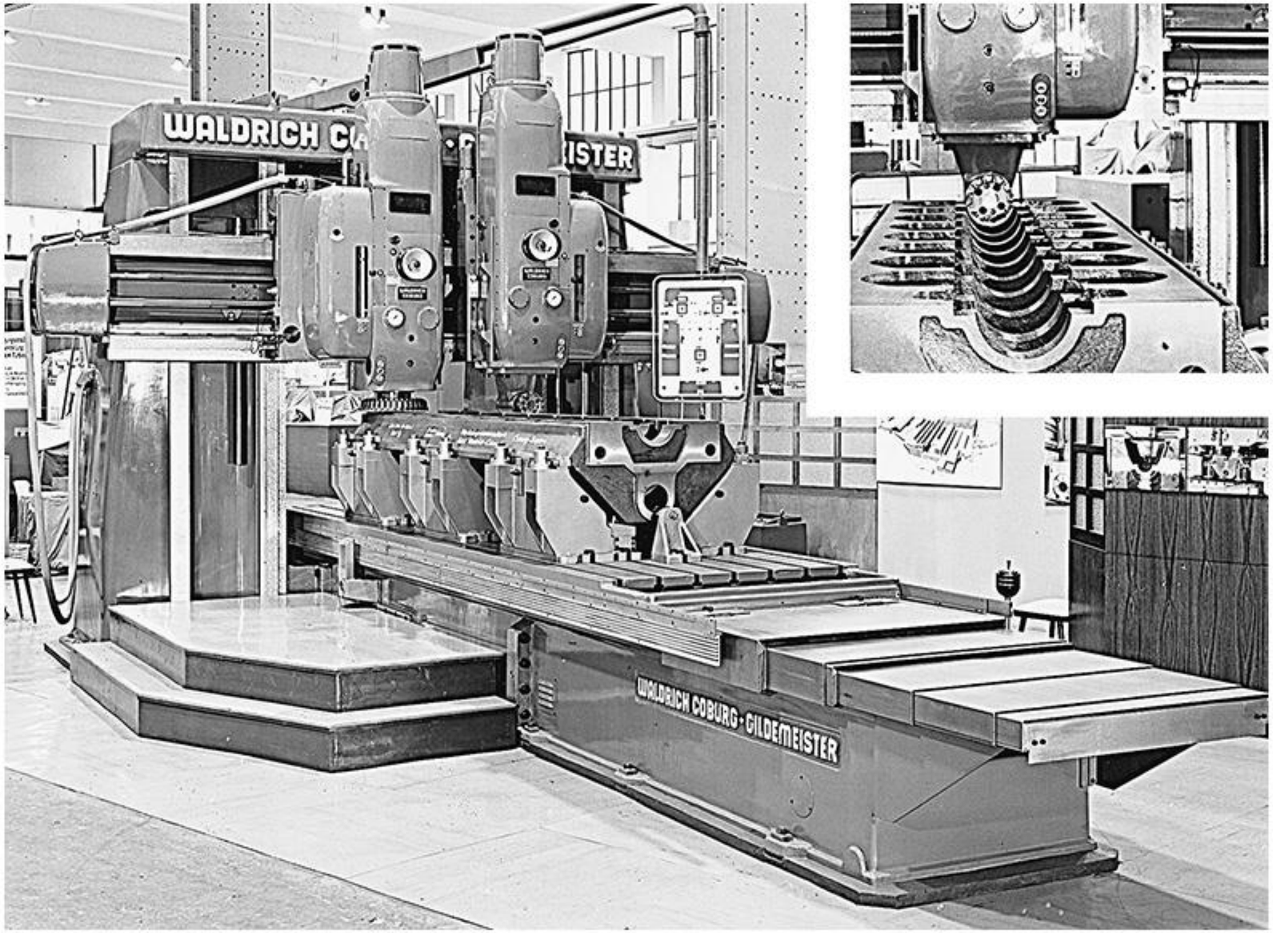
FIGURE 24-16 Bed-type vertical-spindle heavy-duty production machine tools for milling usually have three axes of motion.



Planer Type Mill

- Planer type mills can have several heads to remove large amounts of material while the material is fed slowly into the machine.
- Systems are setup typically for single pass operations.
- These are advantageous for large work pieces requiring heavy material removal.

FIGURE 24-17 Large planertype milling machine. Inset shows 90° head being used. *(Courtesy of Cosa Corporation.)*



Milling Machine Selection

- When purchasing or using a milling machine, consider the following issues:
  - **1.** Spindle orientation and rpm
  - **2.** Machine capability (accuracy and precision)
  - **3.** Machine capacity (size of workpieces)
  - **4.** Horsepower available at spindle (usually 70% of machine horsepower)
  - **5.** Automatic tool changing

Rotary-Table Milling Machines

- Used for some type of face milling in mass production.
- Roughing and finishing cuts can be made in succession utilizing several cutters while the workpiece is held in a rotary table.

Profilers and Duplicators

- Profilers (tracers) duplicates in two dimensions. Utilizes hydraulic tracers and stylus.
- Duplicators forms in three dimensions.

Accessories for milling Machines

- Vertical milling attachment used on a horizontal milling machines.
- Universal milling attachment: its head can be swiveled and can cut at any angle.
- Universal dividing head: used for holding and indexing work., the workpiece rotates one revolution for 40 revolutions of the crank.
- An index plate contains a number of holes, arranged in concentric circles and equally spaced, with each circle having a different number of holes. A plunger pin …. (see book).

Dividing Head

- Example : If the number of holes at the concentric circles are 34, 30, 28, 25, 24. It is required to machine a gear with 14 teethes. How do you index the dividing head?
- Number of turns of crank = 40/ 14 = 2 &12/14 = 2 &6/7
- We look at a circle that contain a number of holes that divides by 7.
- So, we choose 28.
- Holes to be indexed = 6/7 X 28 = 24
- Thus to machine one teeth we have to turn the crank 2 full revolutions and then turn the crank and count for 24 holes and fix at this position.
-
- The above will be repeated for each tooth.

Chapter 26: Other Machining Operations

DeGarmo’s Materials and Processes in Manufacturing

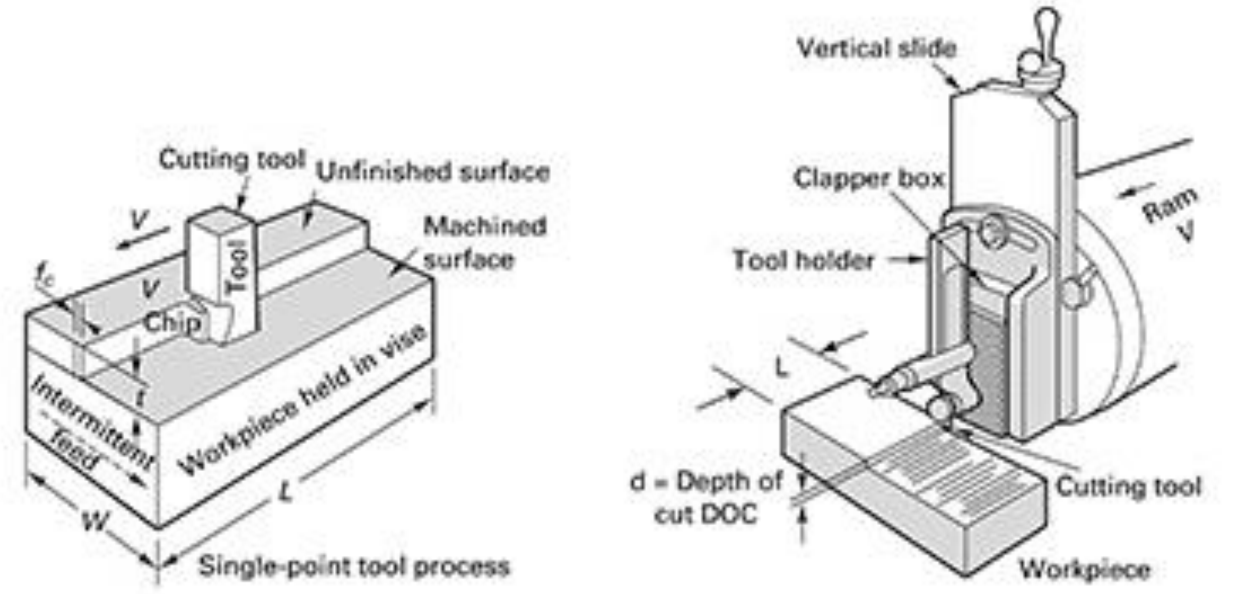
27.1 Introduction

- This chapter covers:
  - Shaping
  - Planing
  - Broaching
  - Sawing
  - Filing

27.2 Introduction to Shaping and Planing

- Shaping and Planing among the oldest techniques
    - Shaping is where the workpiece is fed at right angles to the cutting motion between successive strokes of the tool.
    - Planing the workpiece is reciprocated and the tool is fed at right angles to the cutting motion.
- These process require skilled operators and for the most part have been replaced by other processes

Basics of Shaping



(a) Basic geometry for shaping and planing

(c) Shaper tool holder, clapper box and workpiece

FIGURE 27-1 Basics of shaping and planing. (a) The cutting speed, *V,* and feed per stroke *fc*. (c) The cutting tool is held in a clapper box so the tool does not damage the workpiece on the return stroke.

Basics of Shaping

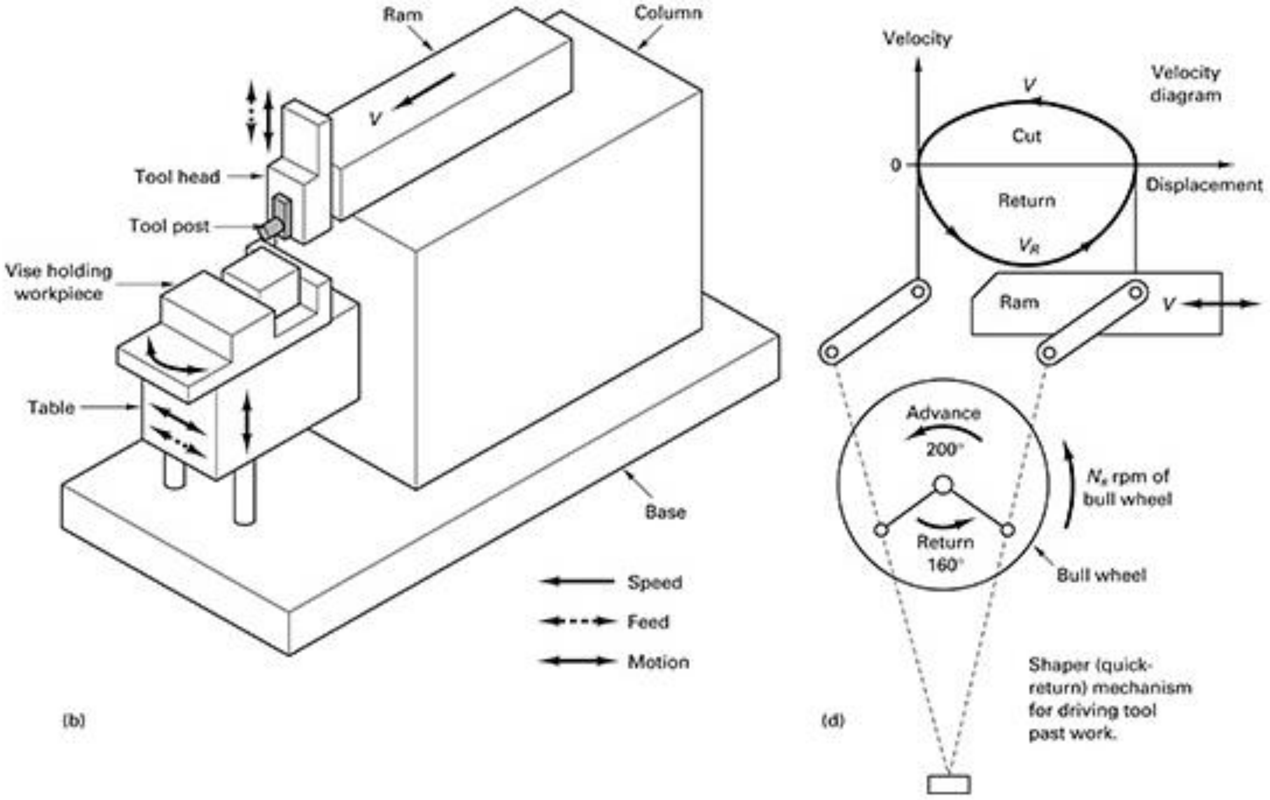


FIGURE 27-1 Basics of shaping and planing. (b) Block diagram of the machine tool. (d) The ram of the shaper carries the cutting tool at cutting velocity *V* and reciprocates at velocity *VR* by the rotation of a bull wheel turning at rpm *ns*.

Common Shaping and Planing Geometry

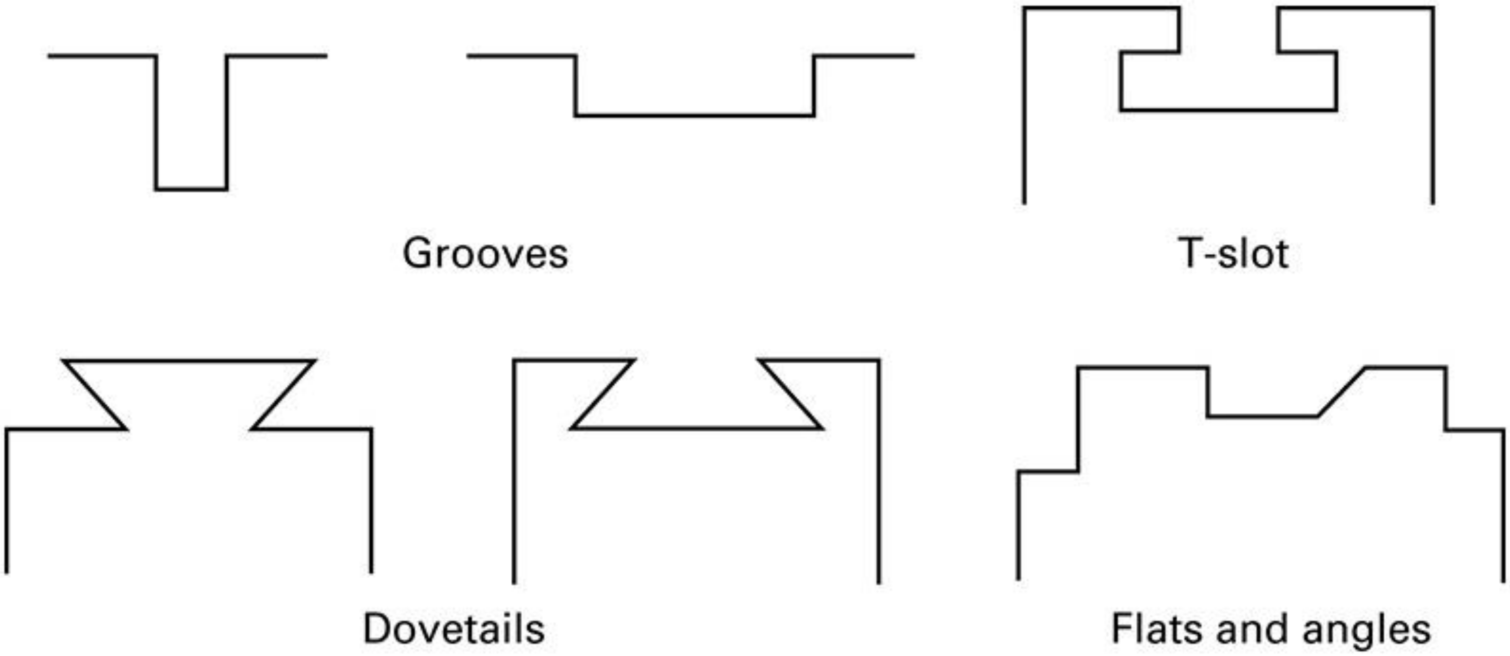


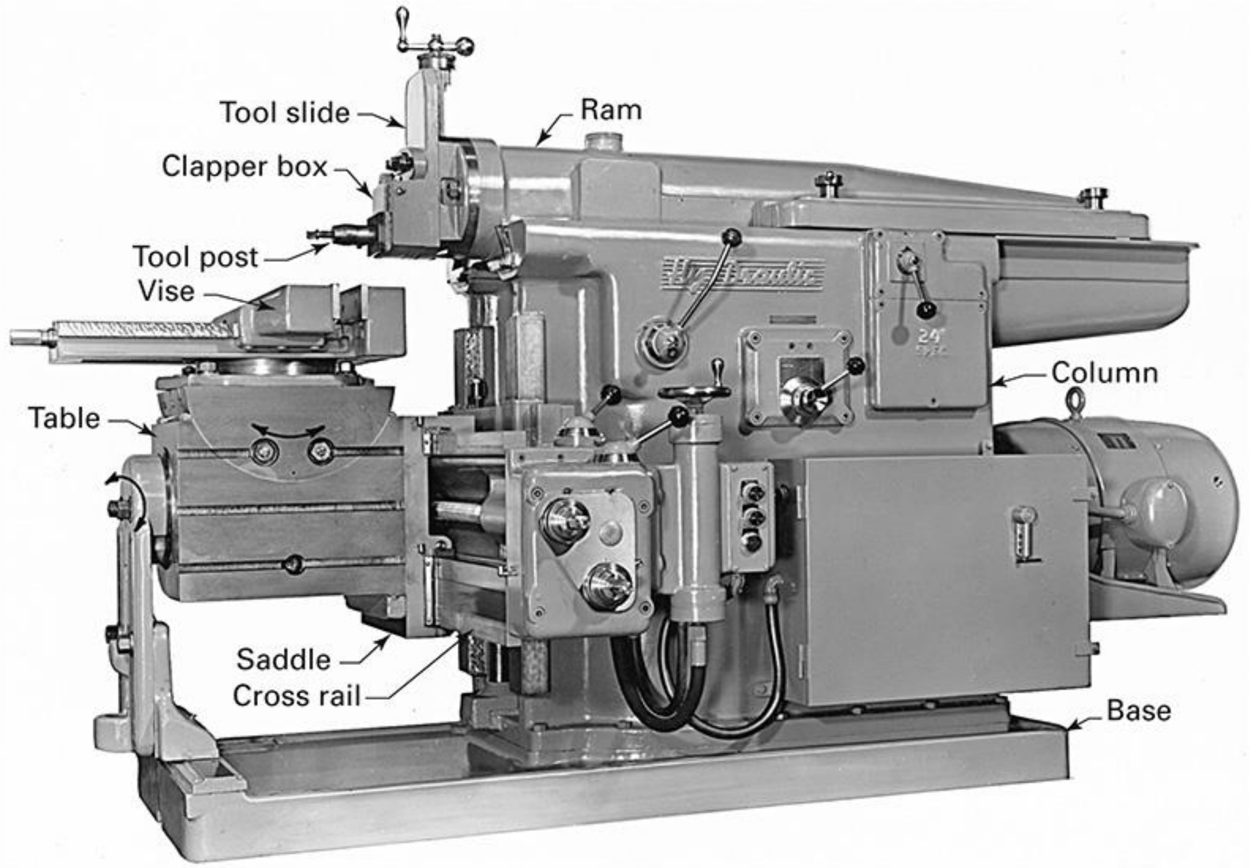
FIGURE 27-2 Types of surfaces commonly machined by shaping and planing.

Machine Tools for Shaping

- Shapers, as machine tools, are usually classified according to their general design features as follows:
  - **1.** Horizontal
    - **a.** Push-cut
    - **b.** Pull-cut or draw-cut shaper
  - **2.** Vertical
    - **a.** Regular or slotters
    - **b.** Keyseaters
  - **3.** Special
- They are also classified by their drive mechanisms: Mechanical and Hydraulic

Shaper

FIGURE 27-3 The most widely used shaper is the horizontal push-cut machine tool, shown here with no tool in the tool post.

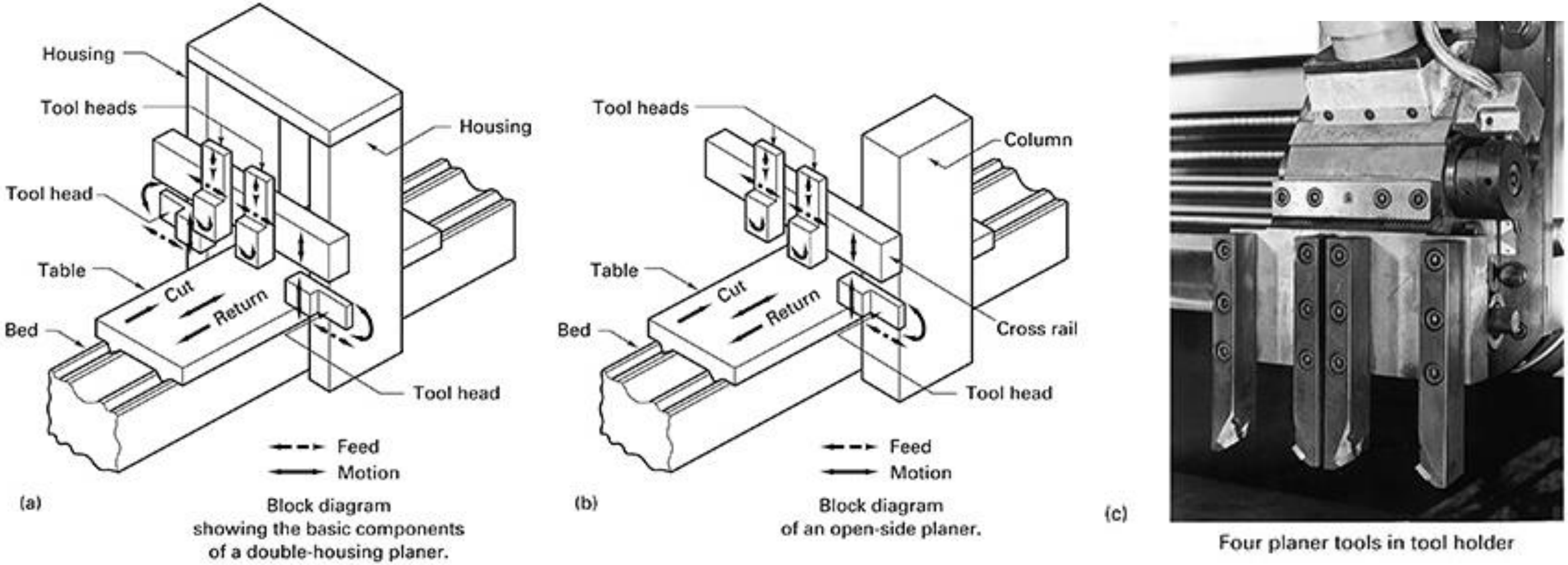


Planing Machines

- Planing is used for large workpieces too big for shapers
- Planing machines have largely been replaced by planing mills
- In planing, large workpieces and their support tables are slowly moved against the tool head.

- Can produce horizontal, vertical, and inclined surfaces
- Used for too large w.p
- Utilize a reciprocating table with slow cutting
- Can utilize several tools
- Tools can cut on both direction of table movement
- Characterized by low productivity

Schematic of a Planer



Block diagram showing the basic components of a double-housing planer.

Block diagram of an open-side planer.

Four planer tools in tool holder

FIGURE 27-4 Schematic of planers. (a) Double-housing planer with multiple tool heads (4) and a large reciprocating table; (b) single-housing or open-sided planer; (c) interchangeable multiple tool holder for use in planers. *(Photograph courtesy Gebr Boehringer GmbH.)*

27.3 Introduction to Broaching

Broaching Machine.mp4

- Broaching is where a tool, with successively increasing tooth size, is moved through the workpeice, creating the desired shape with a single pass.
- Broaching is similar to sawing, with the exception that a saw requires multiple passes, and the teeth are not increased in size along the length of the tool.
- Broaching can be used for holes of various geometry, grooves, and flat surface features.

- Most productive process
- Can produce precision-machined surfaces
- Is a single pass operation
- Used for machining holes, splines, and flat surfaces
- Utilize series of teeth, each tooth standing slightly higher than the last
- Feed /tooth = change in height of successive teeth (feed/tooth=(rise/tooth)=step
- Broach combine roughing, semifinishing, and finishing lengths
- Feed determine the chip thickness

Basic Geometry of a Broach

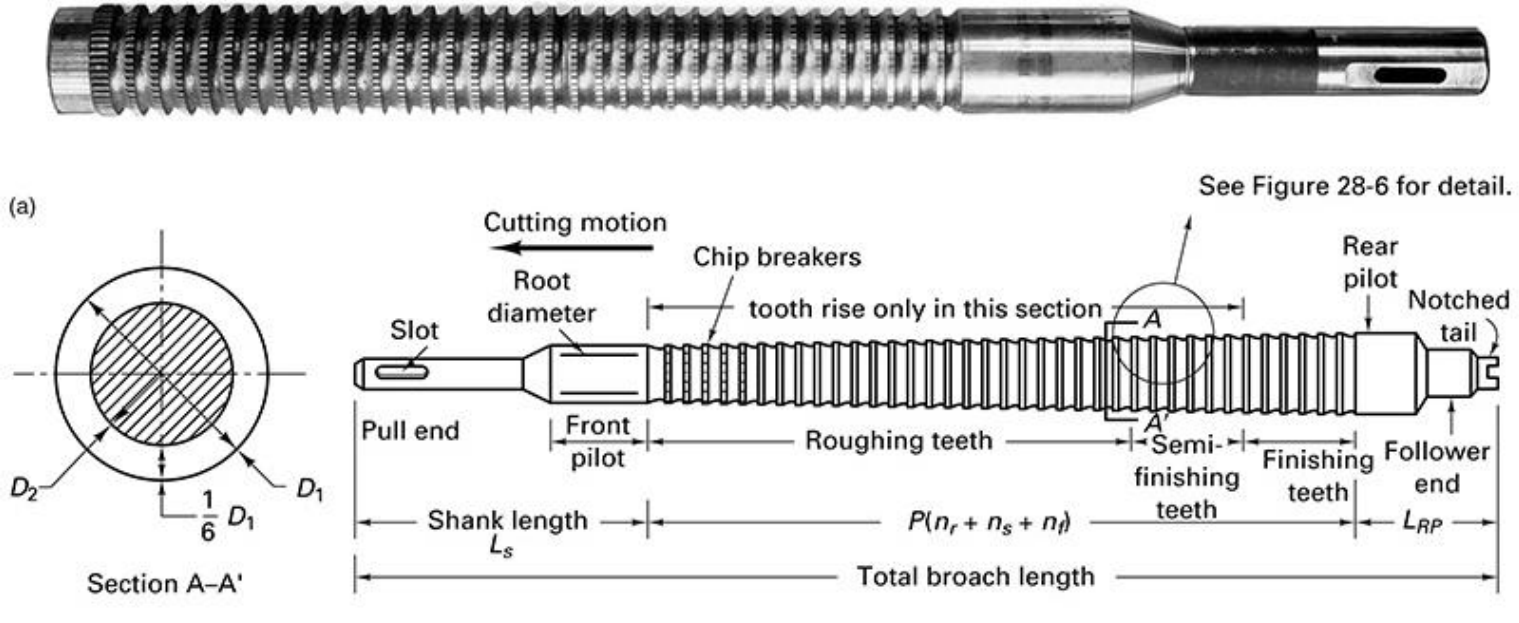


FIGURE 27-5 (a) Photo of pull broach. (b) Basic shape and nomenclature for a conventional pull (hole) broach. Section A–A shows the cross section of a tooth. P pitch; nrnumber of roughing teeth; ns number of semifinishing teeth; nf number of finishing teeth

P – pitch of teeth
D – depth of teeth (0.4P)
L – land behind cutting edge (0.25P)
R – radius of gullet (.25P)
α – hook angle or rake angle
γ – backoff angle or clearance angle
RPT – rise per tooth (chip load), t_r

Cutting Geometry of a Broach

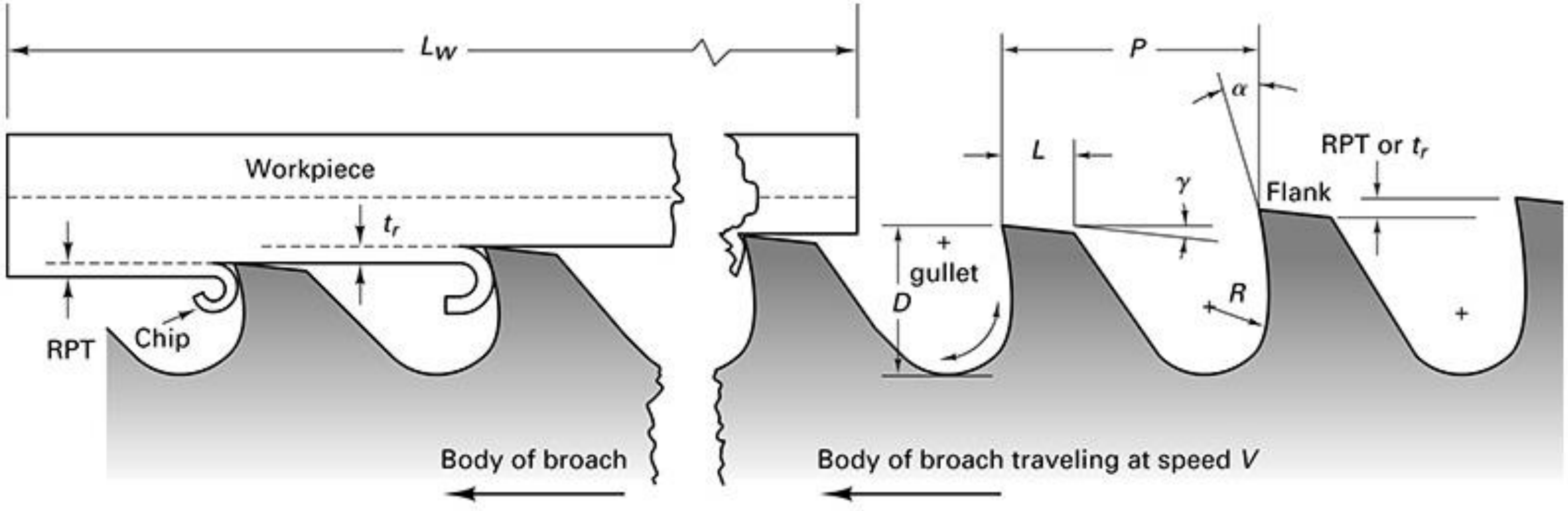


FIGURE 27-6 The feed in broaching depends on the rise per tooth *tr* (RPT). The sum of the RPT gives the depth of cut, DOC. *P* pitch of teeth; *D* depth of teeth (0.4*P*); *L* land behind cutting edge (0.25*P*); *R* radius of gullet (0.25*P*); hook angle or rake angle;   backoff angle or clearance angle.

27.4 Fundamentals of Broaching

- In broaching, the tool (or work) is translated past the work (or tool) with a single stroke of velocity *V*.
- The feed is provided by a gradual increase in height of successive teeth.
- The rise per tooth varies depending on whether the tooth is for roughing (*tr*), semifinishing (*ts*), or final sizing or finishing (*tf*).

Advantages

- Simple machining process
- Rapid method of producing a finished feature
- Used for mass production
- Complex geometries are possible using broaching
- Gives better finishing than drilling, boring, and reaming
- Rotational motion can be added to permit the broaching of splines or gun-barrel rifling
- Custom tools must be produced for each feature at $15K to $30K per tool

Disadvantages

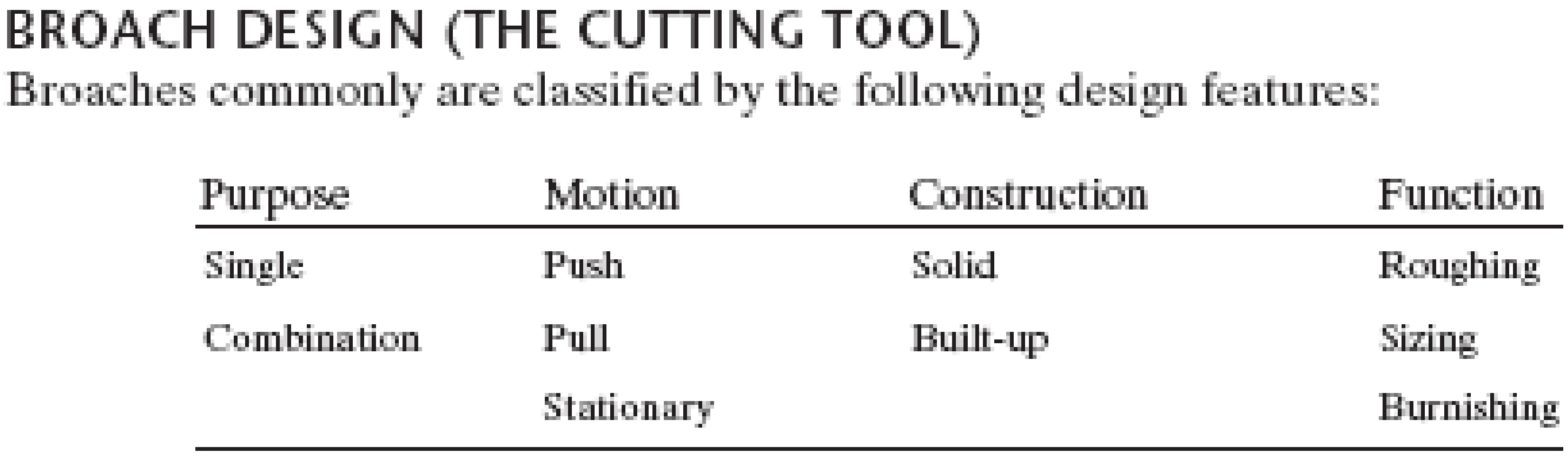
- Broaching requires that the geometry be two dimensional with a straight profile.
- Broaching requires that the tool be able to pass fully through the part.
- Broach designs require that the tool be stiff enough for the work required, small geometries are a challenge.
- When used for internal broaching a hole must exist

Broach Design

Roughing teeth: bulk of the metal is removed

Semifinishing teeth: provide surface smoothness

Finishing teeth: produce exact size (teeth are usually have the same size)

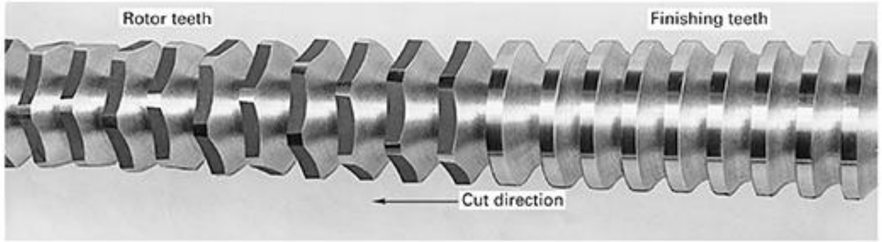


BROACH DESIGN (THE CUTTING TOOL)

Broaches commonly are classified by the following design features:

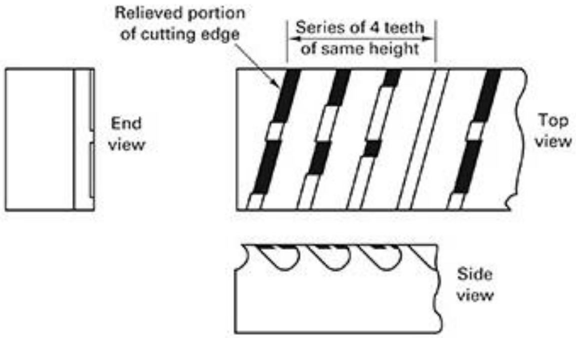
Purpose	Motion	Construction	Function
Single	Push	Solid	Roughing
Combination	Pull	Built-up	Sizing
	Stationary		Burnishing

Principle Components of a Broach

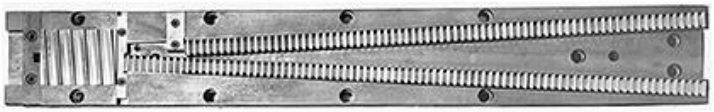


(a) Rotor- or jump-tooth broach design.

(b) Round, push-type broach with chip-breaking notches on alternate teeth except at the finishing end.



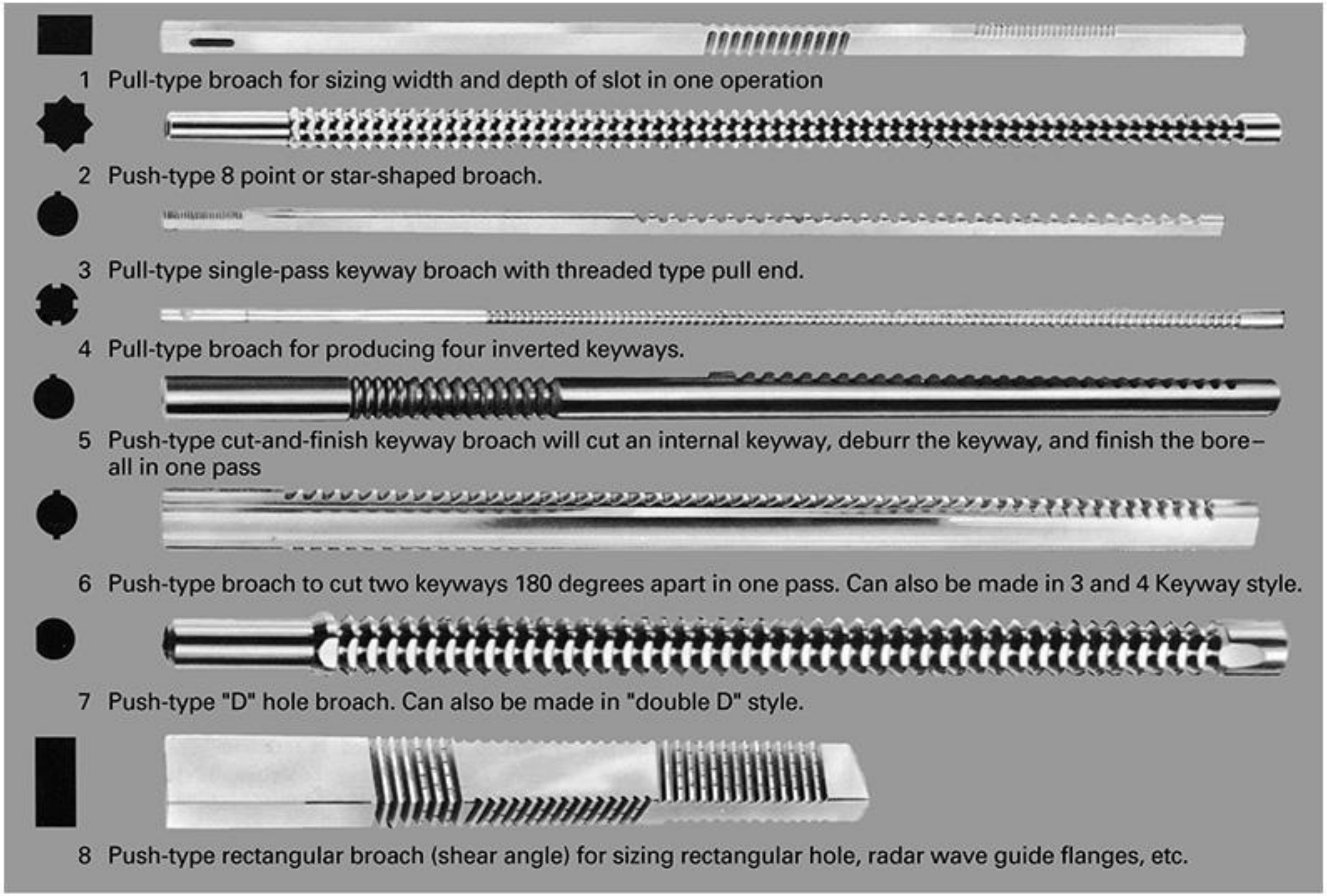
(c) Notched tooth, flat broach



(d) Progressive surface broach. *(Courtesy of Detroit Broach & Machine Company)*

FIGURE 27-7 Methods to decrease force or break up chip rings in broaches. (a) Rotor or jump tooth; (b) notched tooth, round; (c) notched tooth, flat design (overlapping teeth permit large RPTs without increasing chip load); (d) progressive tooth design for flat broach.

Broach Examples



1 Pull-type broach for sizing width and depth of slot in one operation

2 Push-type 8 point or star-shaped broach.

3 Pull-type single-pass keyway broach with threaded type pull end.

4 Pull-type broach for producing four inverted keyways.

5 Push-type cut-and-finish keyway broach will cut an internal keyway, deburr the keyway, and finish the bore–all in one pass

6 Push-type broach to cut two keyways 180 degrees apart in one pass. Can also be made in 3 and 4 Keyway style.

7 Push-type "D" hole broach. Can also be made in "double D" style.

8 Push-type rectangular broach (shear angle) for sizing rectangular hole, radar wave guide flanges, etc.

FIGURE 27-8
Examples of push- or pull-type broaches. *(Courtesy of DuMont Corporation.)*

Replaceable Broach Shells

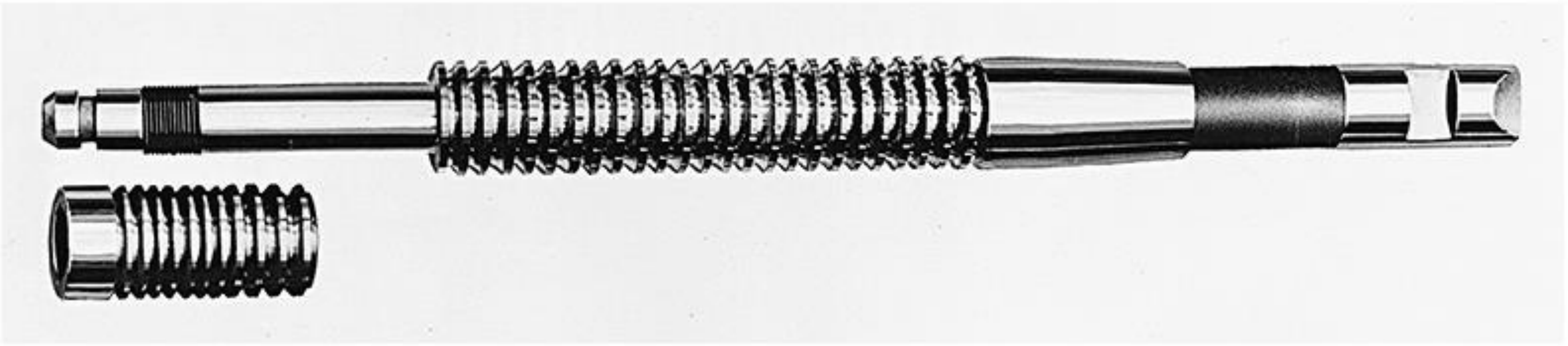


FIGURE 27-9 Shell construction for a pull broach.

27.5 Broaching Machines

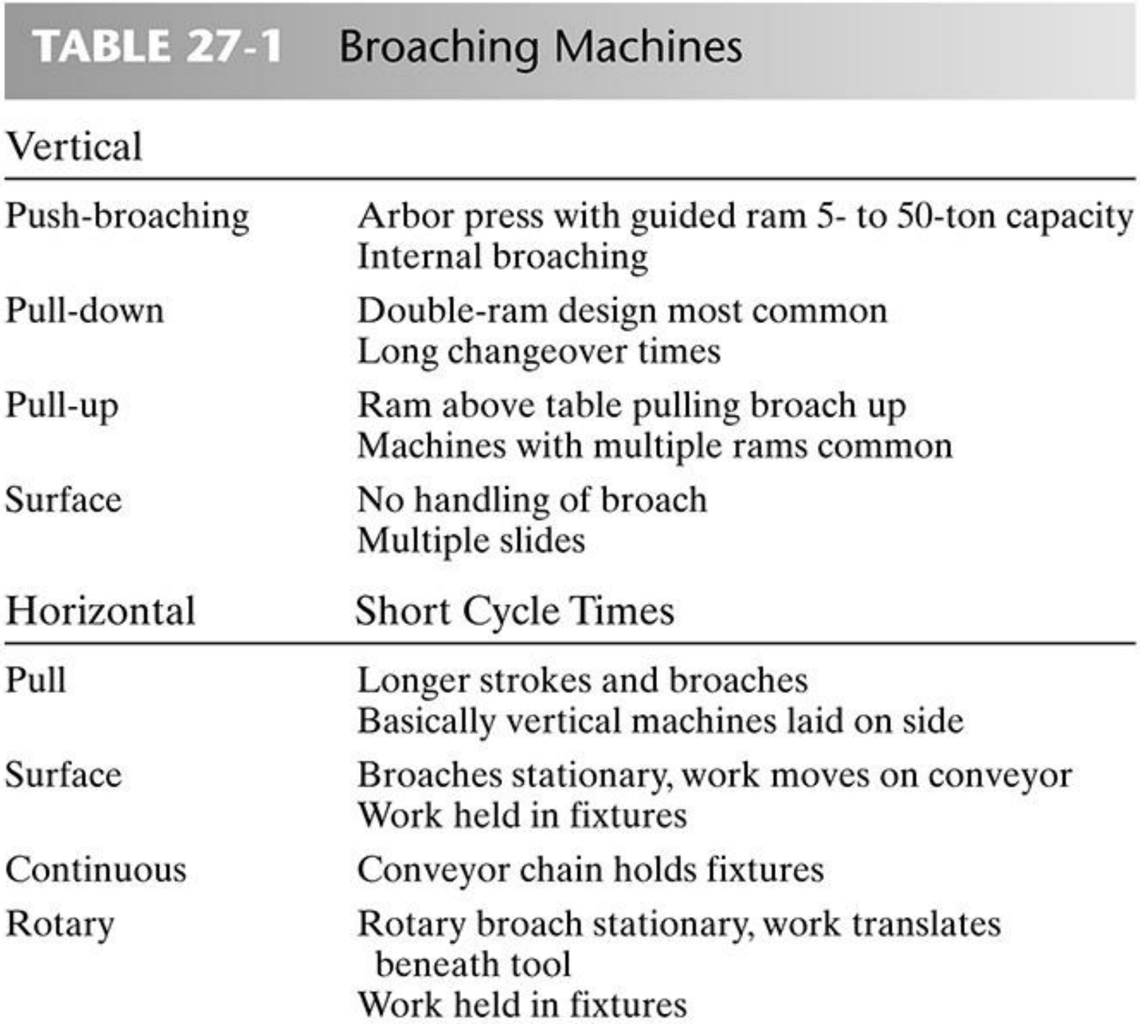


TABLE 27-1 Broaching Machines

Vertical	
Push-broaching	Arbor press with guided ram 5- to 50-ton capacity Internal broaching
Pull-down	Double-ram design most common Long changeover times
Pull-up	Ram above table pulling broach up Machines with multiple rams common
Surface	No handling of broach Multiple slides
Horizontal	**Short Cycle Times**
Pull	Longer strokes and broaches Basically vertical machines laid on side
Surface	Broaches stationary, work moves on conveyor Work held in fixtures
Continuous	Conveyor chain holds fixtures
Rotary	Rotary broach stationary, work translates beneath tool Work held in fixtures

Modular Broaching Machine

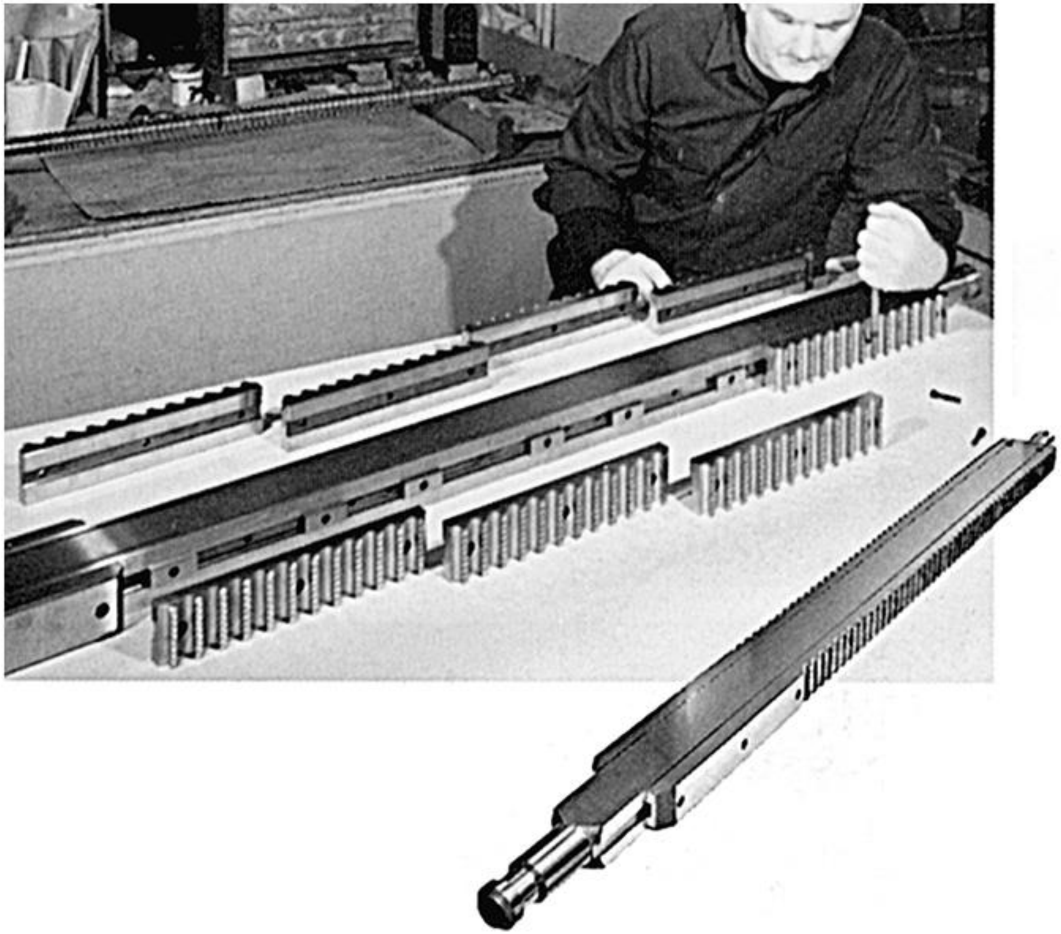
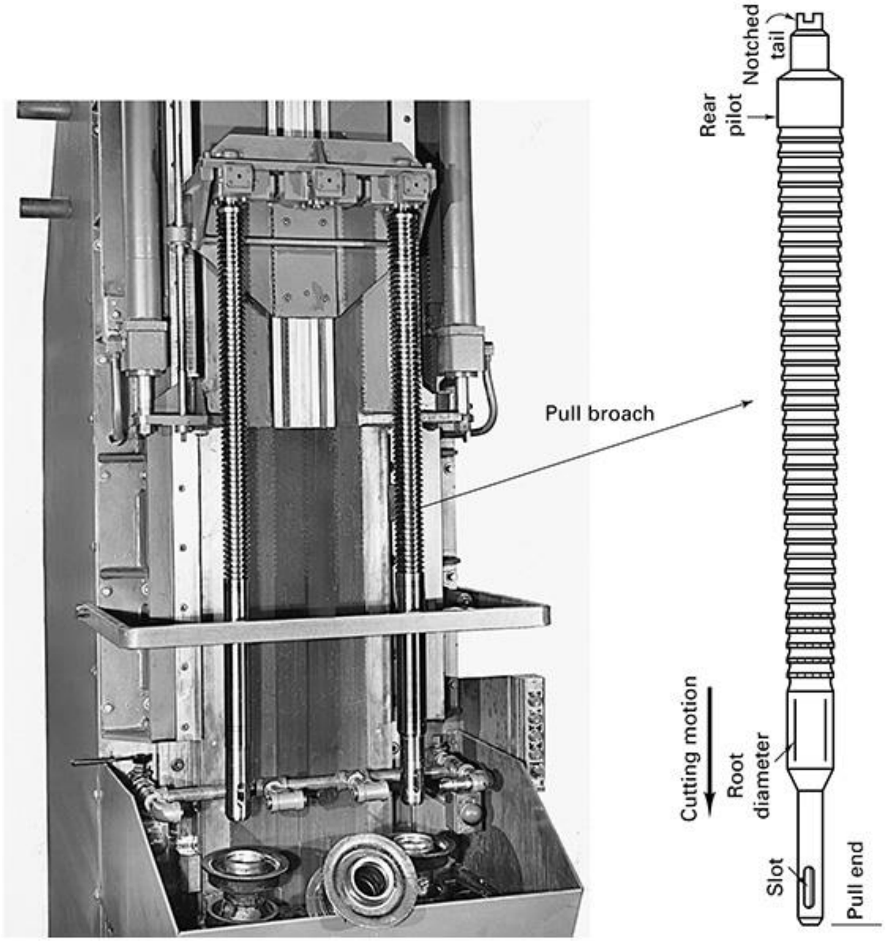


FIGURE 27-10 A modularly constructed broach is cheaper to build and can be sharpened in sections

Vertical Pulldown Broach

FIGURE 27-11 Vertical pulldown broaching machine shown with parts in position ready for the two broaches to be inserted. An extra part is shown lying at the front of the machine.



- **Continuous Surface-Broaching Machines**

In this machine the broach is stationary and the workpiece moves.

- **Rotary Broaching Machines**

The broach is stationary.

27.6 Introduction to Sawing

- Sawing is the process by which successive teeth, arranged in a narrow line, remove a small amount of material.
- Each tooth forms a chip as it passes through the material, with chips contained between the teeth
- Parts of considerable size can be severed from the workpiece with only little material removed, making this a very economical process.

Principles of a Saw Blade

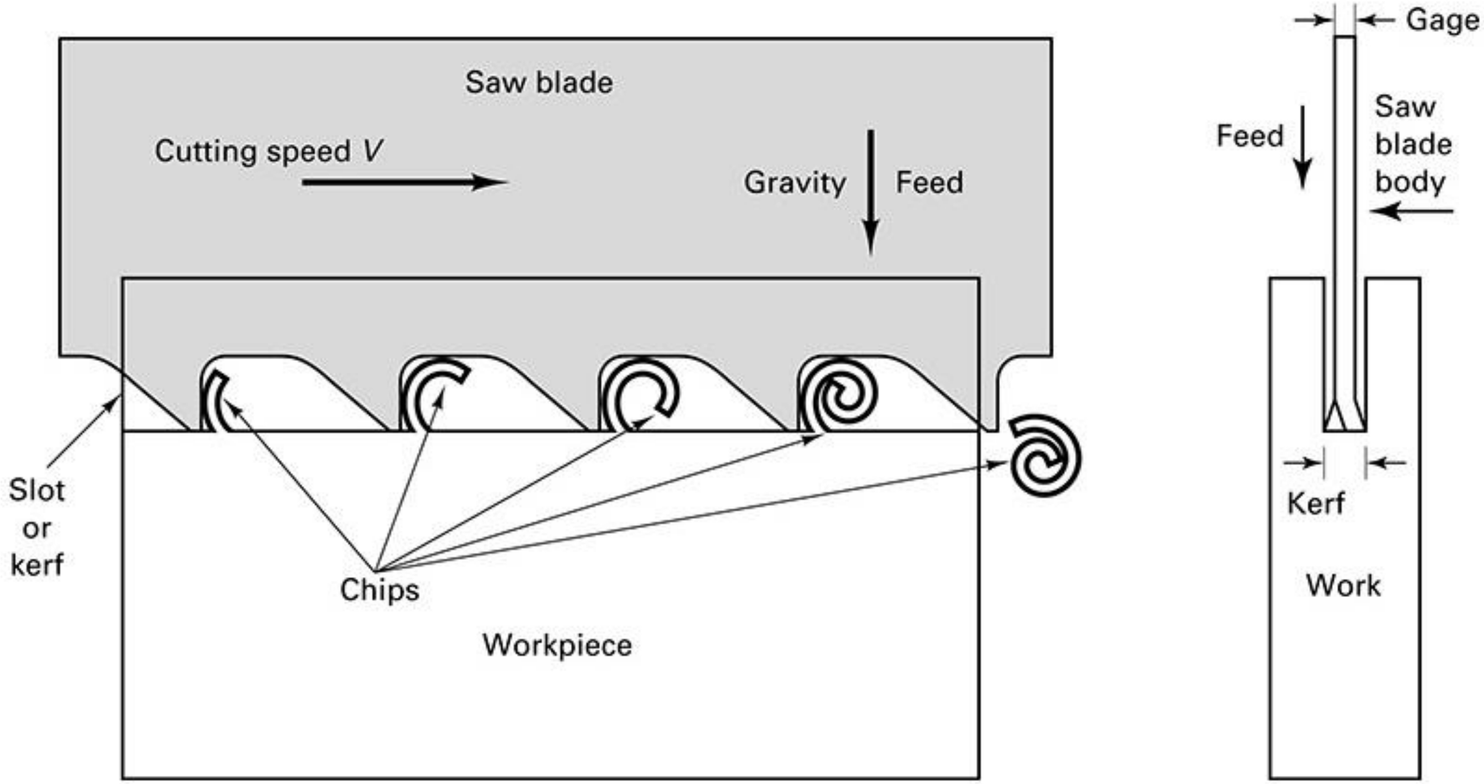
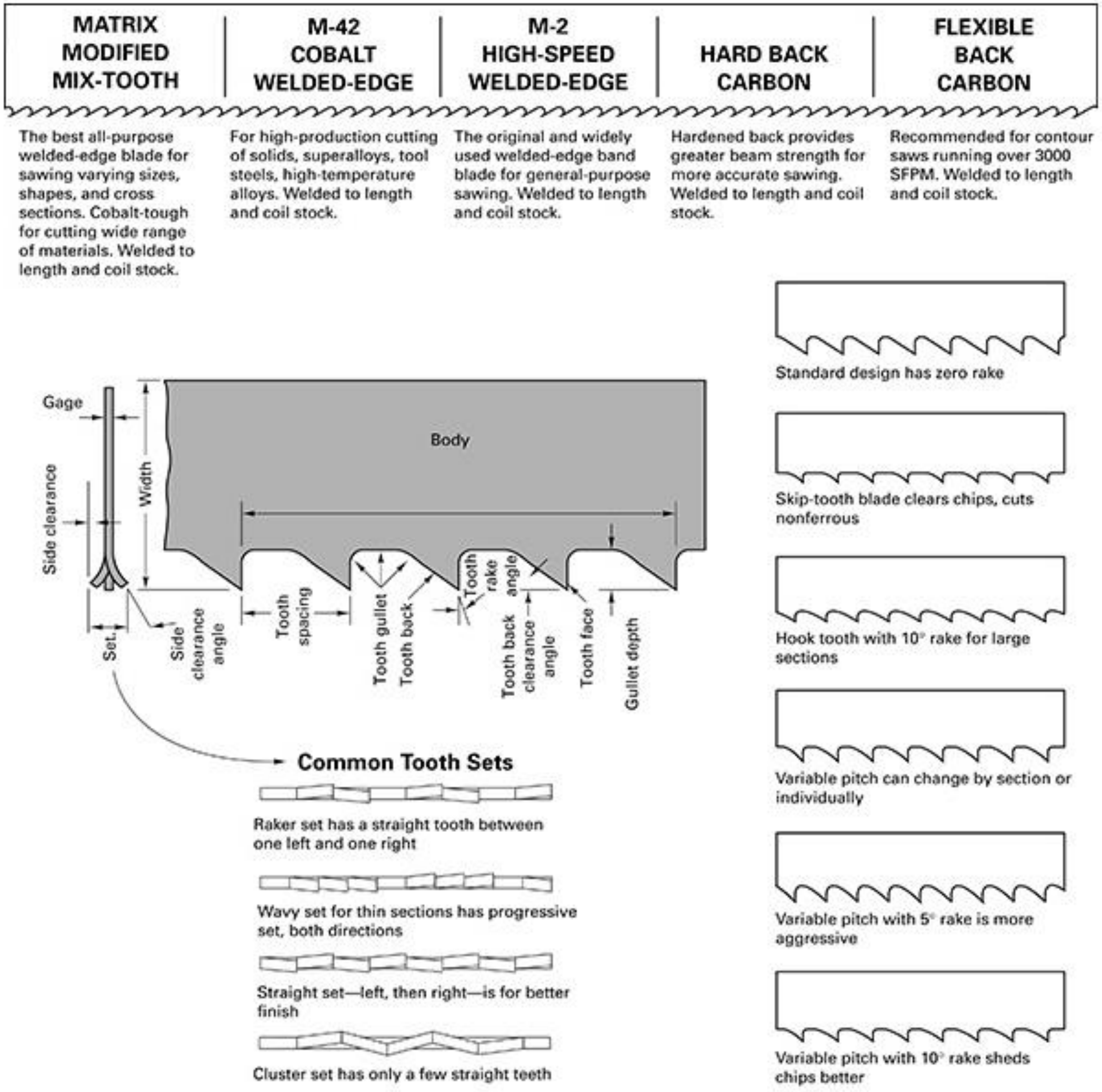


FIGURE 27-12 Formation of chips in sawing.

Types of Blades

- There are three basic types of saws
  - Hacksaws
    - A rigid straight blade with limited teeth
  - Bandsaws
    - A flexible long blade that is formed into a continuous band
  - Circular Saws
    - A rigid disk with teeth on the circumference

FIGURE 27-13 Bandsaw blade designs and nomenclature (above). Tooth set patterns (left) and tooth designs (right).



MATRIX MODIFIED MIX-TOOTH: The best all-purpose welded-edge blade for sawing varying sizes, shapes, and cross sections. Cobalt-tough for cutting wide range of materials. Welded to length and coil stock.

M-42 COBALT WELDED-EDGE: For high-production cutting of solids, superalloys, tool steels, high-temperature alloys. Welded to length and coil stock.

M-2 HIGH-SPEED WELDED-EDGE: The original and widely used welded-edge band blade for general-purpose sawing. Welded to length and coil stock.

HARD BACK CARBON: Hardened back provides greater beam strength for more accurate sawing. Welded to length and coil stock.

FLEXIBLE BACK CARBON: Recommended for contour saws running over 3000 SFPM. Welded to length and coil stock.

Raker set has a straight tooth between one left and one right

Wavy set for thin sections has progressive set, both directions

Straight set—left, then right—is for better finish

Cluster set has only a few straight teeth

Standard design has zero rake

Skip-tooth blade clears chips, cuts nonferrous

Hook tooth with 10° rake for large sections

Variable pitch can change by section or individually

Variable pitch with 5° rake is more aggressive

Variable pitch with 10° rake sheds chips better

Types of Sawing Machines

- Metal-sawing machines may be classified as follows:
  - **1.** Reciprocating saw
    - **a.** Manual hacksaw
    - **b.** Power hacksaw (Figure 27-15)
    - **c.** Abrasive disc
  - **2.** Bandsaw
    - **a.** Vertical cutoff (Figure 27-16)
    - **b.** Horizontal cutoff (Figure 27-17)
    - **c.** Combination cutoff and contour (Figure 27-18)
    - **d.** Friction
  - **3.** Circular saw (Figure 27-14)
    - **a.** Cold saw
    - **b.** Steel friction disk

Circular Saw

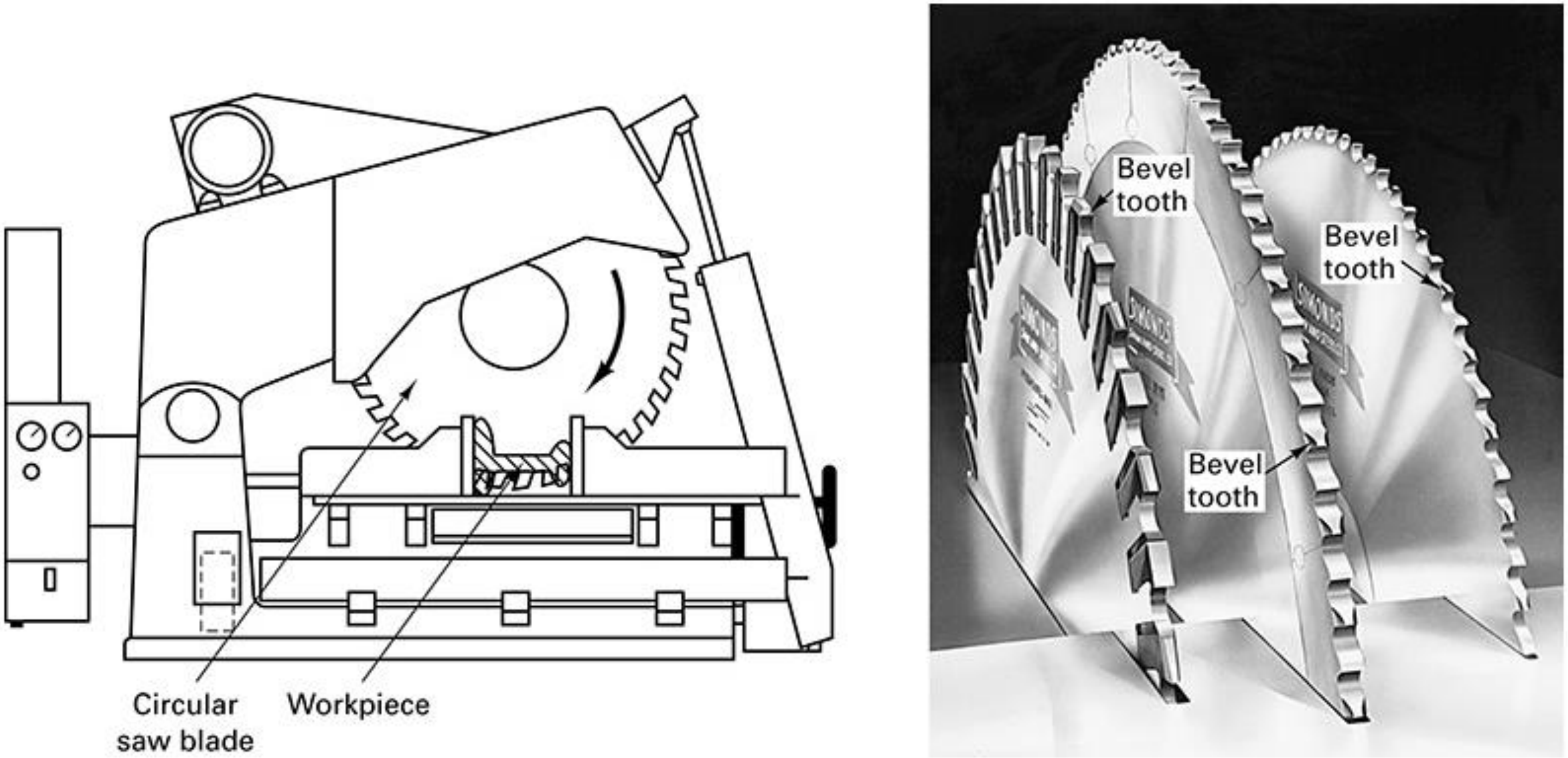


FIGURE 27-14 Circular sawing a structural shape, using (*left* to *right*) an insert tooth, a segmental tooth,and an integral-tooth circular saw blade.

Hacksaw

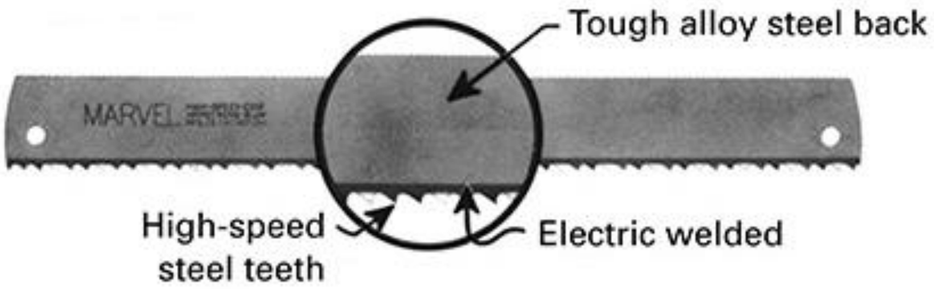
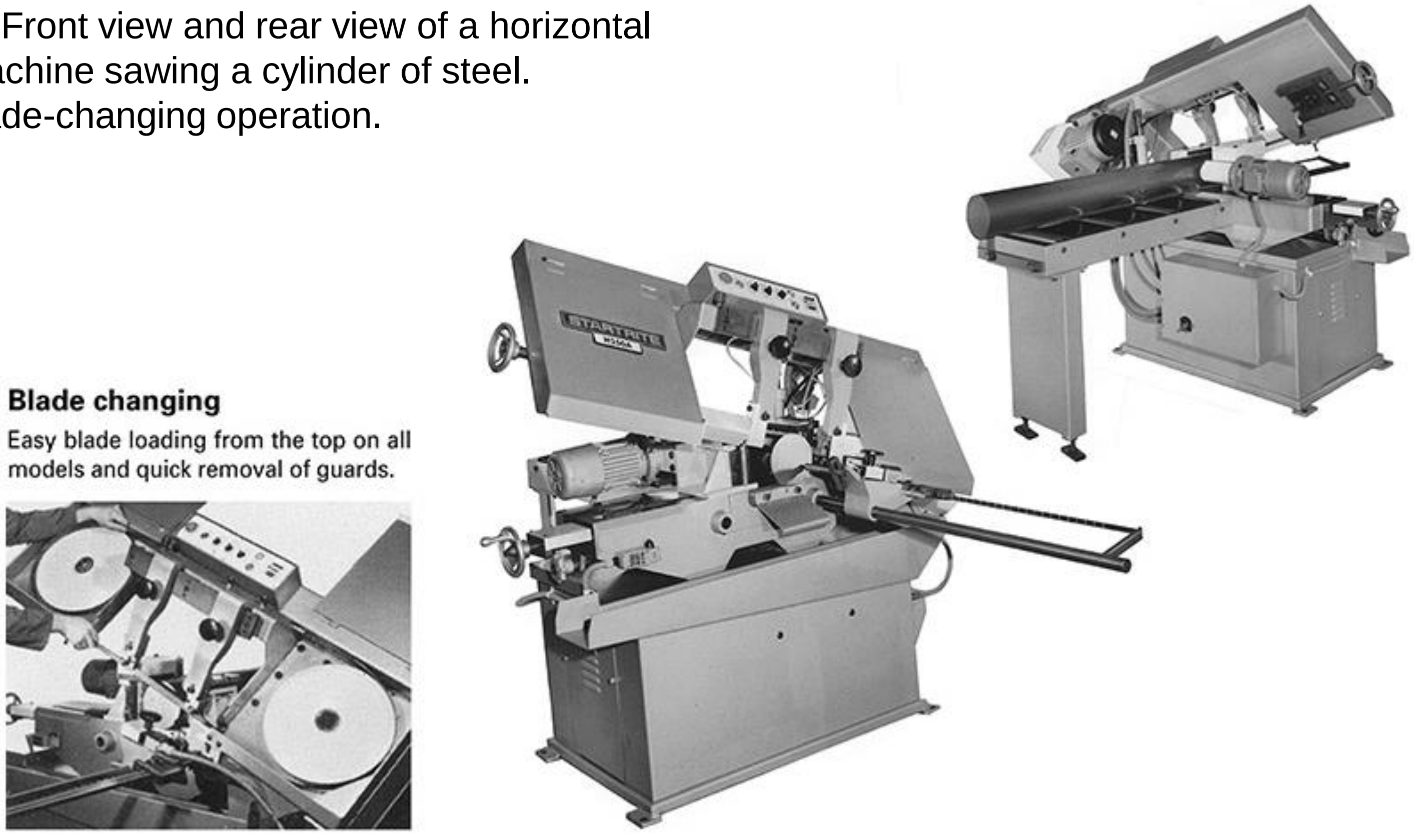


FIGURE 27-15 Power hacksaw blade (above) and hacksaw with automatic bar feeding (right) cutting two pieces of round stock.

Horizontal Band Saw

FIGURE 27-16 Front view and rear view of a horizontal bandsawing machine sawing a cylinder of steel.
Inset shows blade-changing operation.



Vertical Bandsaw

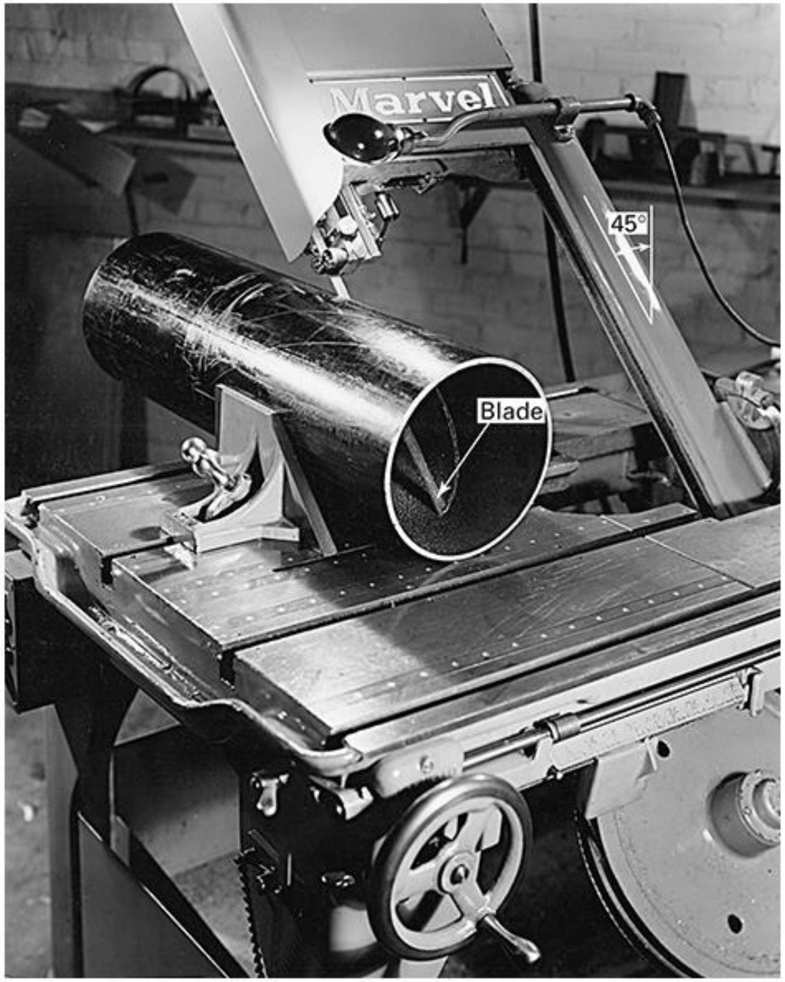


FIGURE 27-17 Vertical bandsaw cutting a piece of pipe, showing head tilted 45°.

Contour Sawing

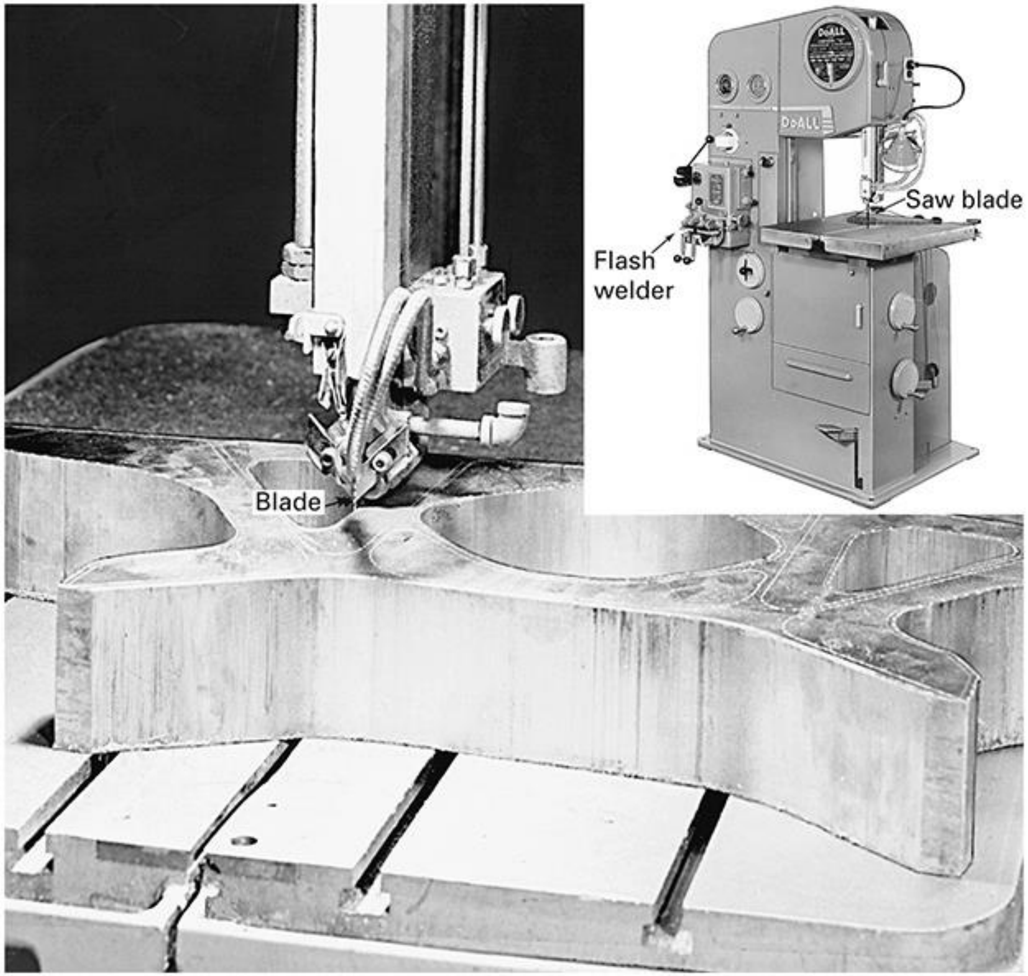


FIGURE 27-18 Contour bandsawing on vertical bandsawing machine, shown in inset.

27.7 Introduction to Filing

- The metal-removing action in filing is the same as in sawing, in that chips are removed by cutting teeth that are arranged in succession along the same plane on the surface of a tool, called a *file*.
- Files are classified according to the following:
  - **1.** The type, or *cut*, of the teeth
  - **2.** The degree of coarseness of the teeth
  - **3.** Construction
    - **a.** Single solid units for hand use or in die-filing machines
    - **b.** Band segments, for use in band-filing machines
    - **c.** Disks, for use in disk-filing machines

File Types

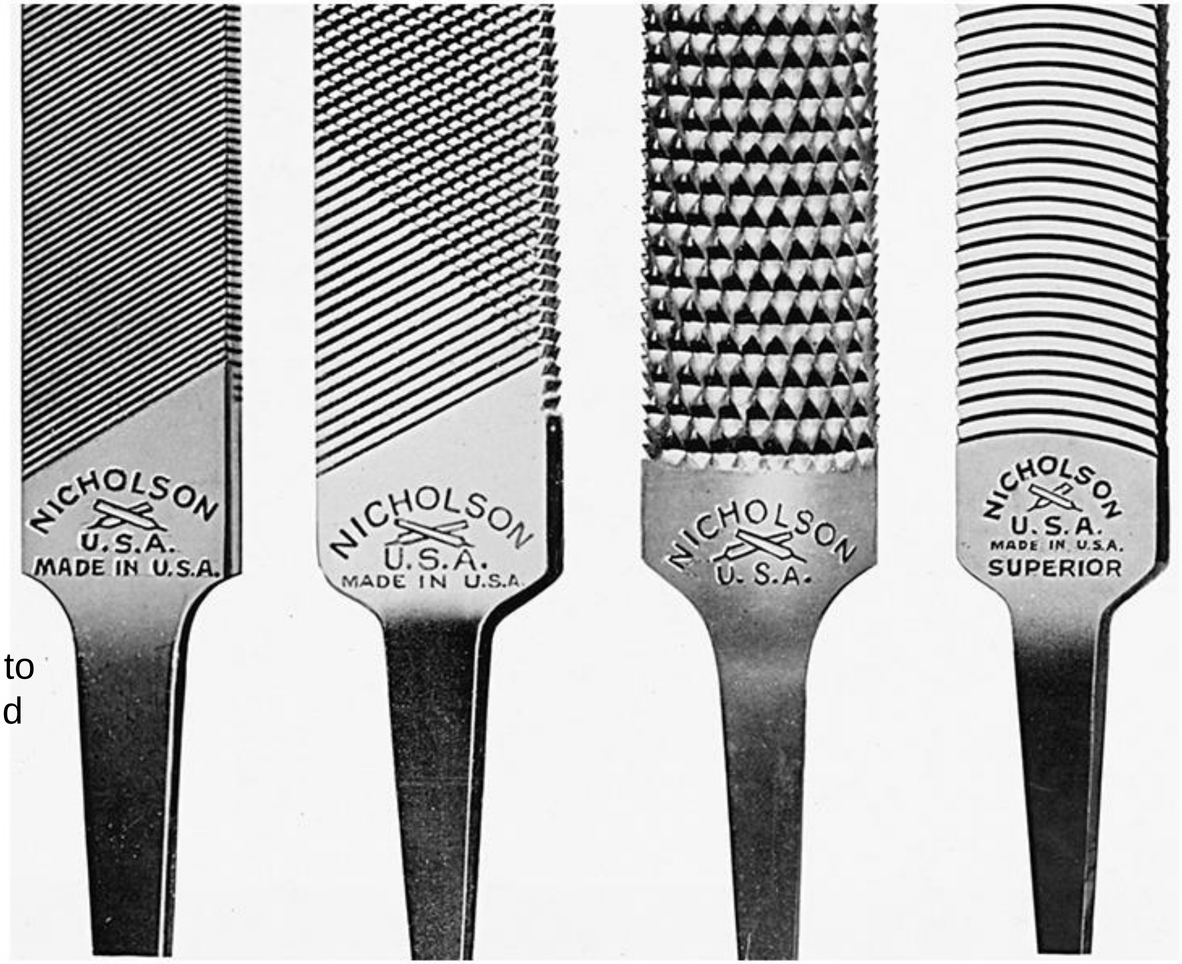
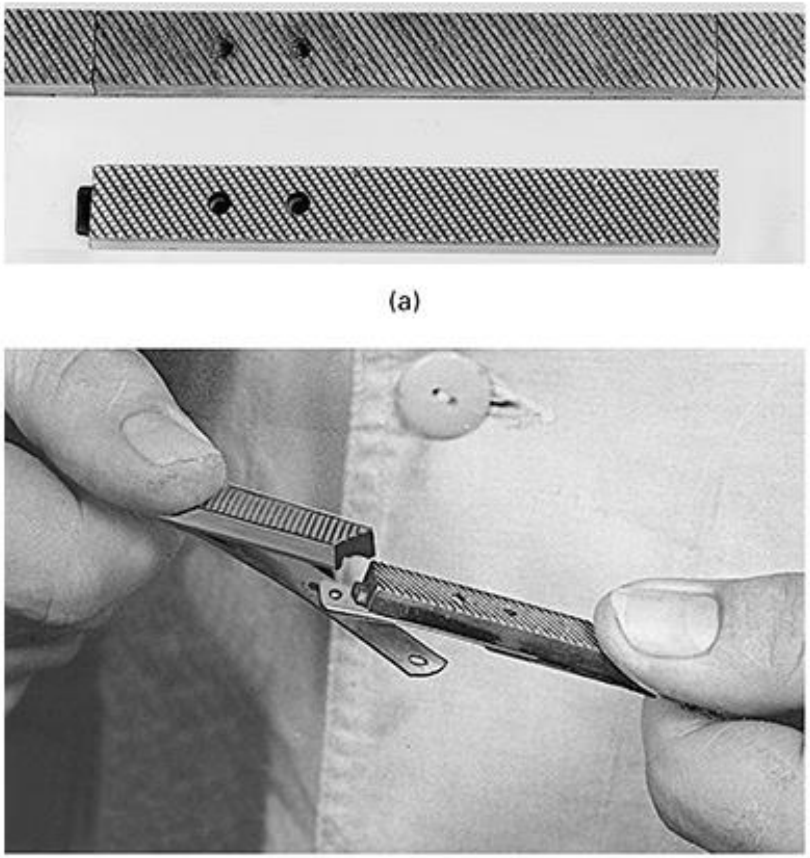


FIGURE 27-19 Four types of teeth (cuts) used in files. Left to right: Single, double, rasp, and curved (vixen). *(Courtesy of Nicholson File Company.)*

Band File Machines

FIGURE 27-20 Band file segments (a) are joined together to form a continuous band (b) which runs on a band-filing machine (c). *(Courtesy of DoALL Co.)*



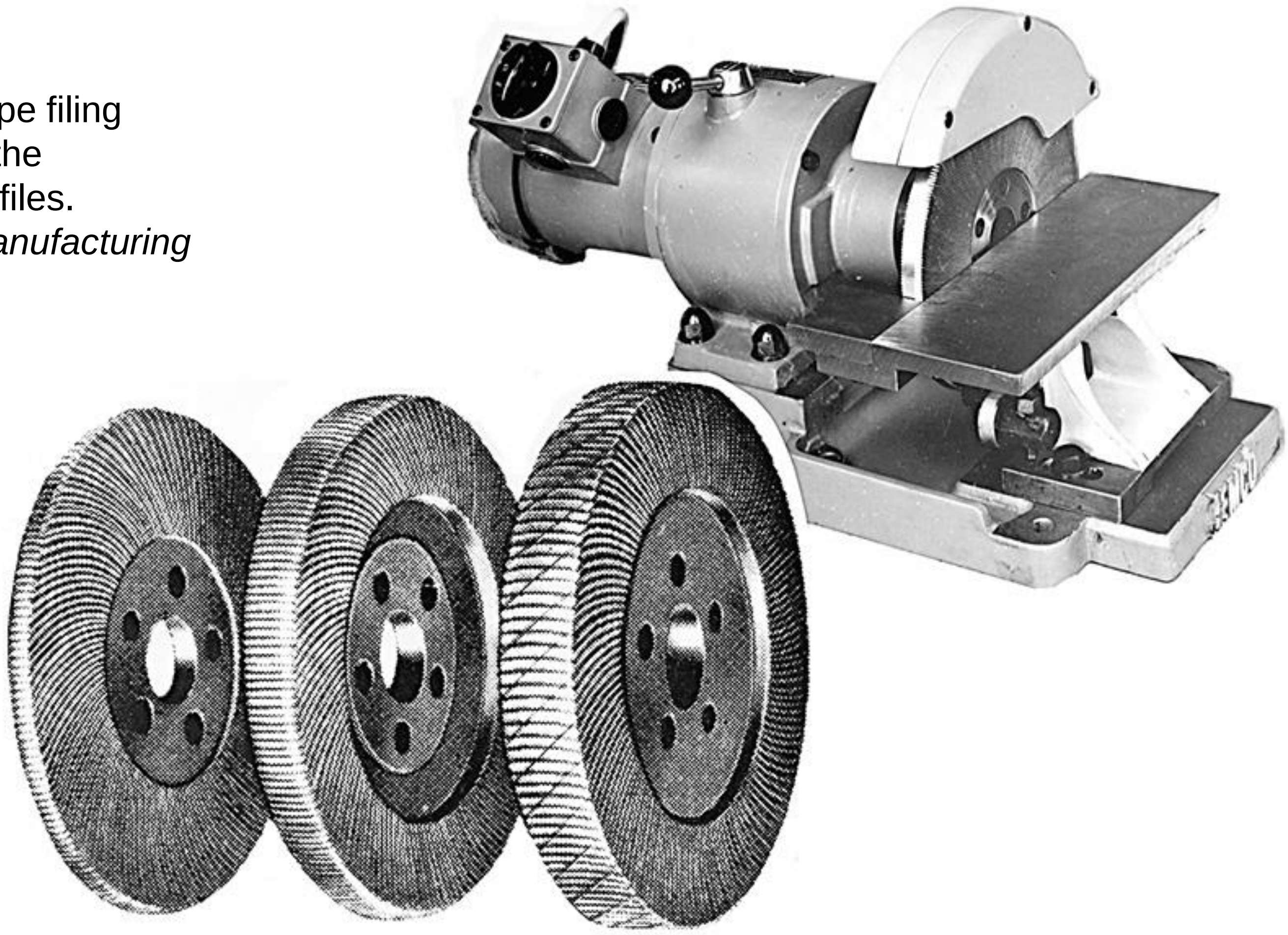
(a)

(b)

(c)

Disk File Machine

FIGURE 27-21 Disk-type filing machine and some of the available types of disk files. *(Courtesy of Jersey Manufacturing Company.)*



Chapter 27: Abrasive Machining Processes

DeGarmo’s Materials and Processes in Manufacturing

28.1 Introduction

- Abrasive machining is the process of using abrasive grit to remove material at high cutting speed and shallow depths of penetration.
- The abrasive particles may be
  - (1) free;
  - (2) mounted in resin on a belt (called *coated product*);

or, most commonly

  - (3) close packed into wheels or stones, with abrasive grits held together by bonding material (called *bonded product* or a grinding wheel).

Typical Grinding Wheel

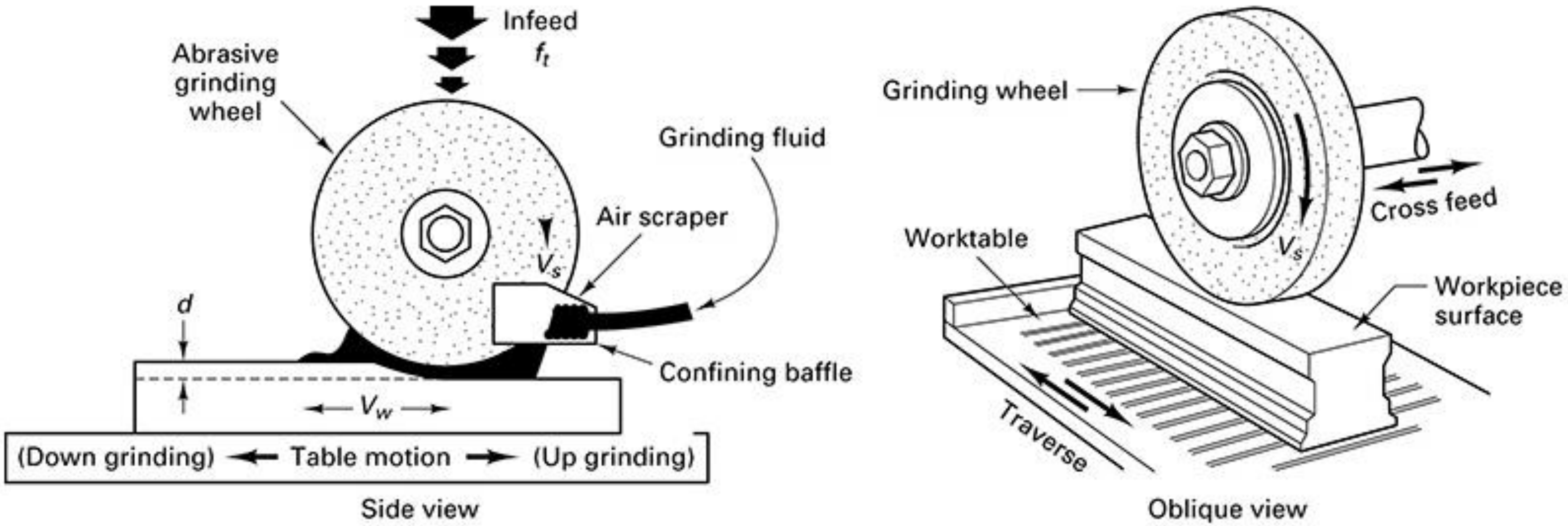


FIGURE 28-1 Schematic of surface grinding, showing infeed and cross feed motions along with cutting speeds *VS,* and workpiece velocity *VW*.

Abrasive Processes

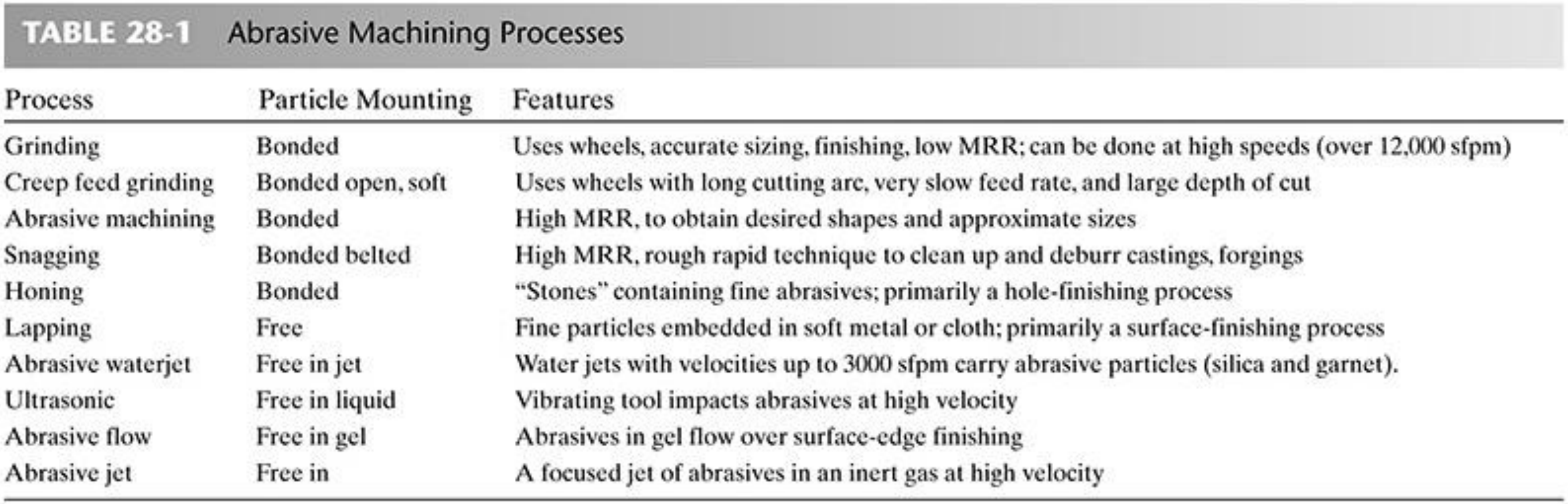


TABLE 28-1 Abrasive Machining Processes

Process	Particle Mounting	Features
Grinding	Bonded	Uses wheels, accurate sizing, finishing, low MRR; can be done at high speeds (over 12,000 sfpm)
Creep feed grinding	Bonded open, soft	Uses wheels with long cutting arc, very slow feed rate, and large depth of cut
Abrasive machining	Bonded	High MRR, to obtain desired shapes and approximate sizes
Snagging	Bonded belted	High MRR, rough rapid technique to clean up and deburr castings, forgings
Honing	Bonded	"Stones" containing fine abrasives; primarily a hole-finishing process
Lapping	Free	Fine particles embedded in soft metal or cloth; primarily a surface-finishing process
Abrasive waterjet	Free in jet	Water jets with velocities up to 3000 sfpm carry abrasive particles (silica and garnet).
Ultrasonic	Free in liquid	Vibrating tool impacts abrasives at high velocity
Abrasive flow	Free in gel	Abrasives in gel flow over surface-edge finishing
Abrasive jet	Free in	A focused jet of abrasives in an inert gas at high velocity

Grinding Parameters

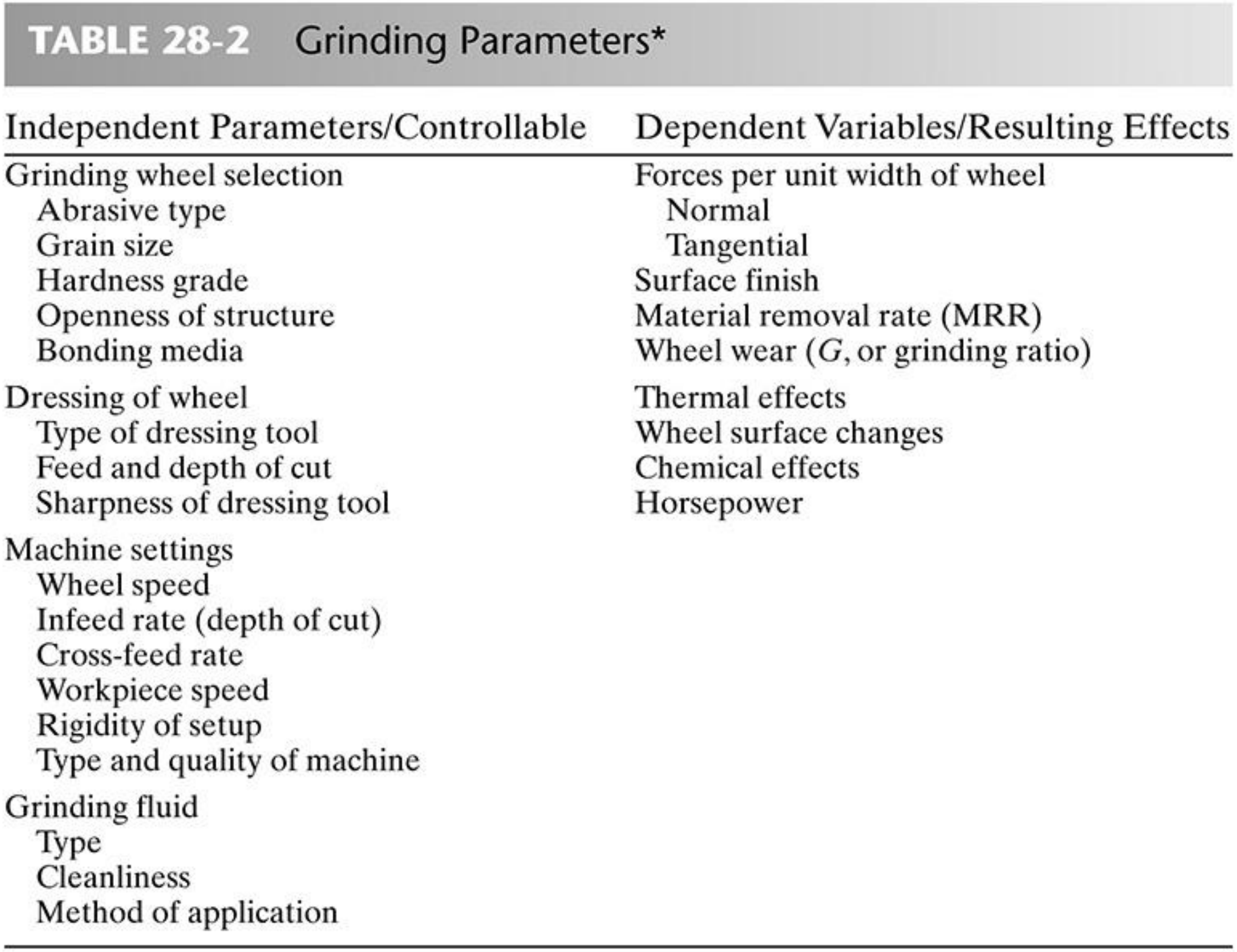


TABLE 28-2 Grinding Parameters*

Independent Parameters/Controllable	Dependent Variables/Resulting Effects
Grinding wheel selection	Forces per unit width of wheel
Abrasive type	Normal
Grain size	Tangential
Hardness grade	Surface finish
Openness of structure	Material removal rate (MRR)
Bonding media	Wheel wear (*G*, or grinding ratio)
Dressing of wheel	Thermal effects
Type of dressing tool	Wheel surface changes
Feed and depth of cut	Chemical effects
Sharpness of dressing tool	Horsepower
Machine settings	
Wheel speed	
Infeed rate (depth of cut)	
Cross-feed rate	
Workpiece speed	
Rigidity of setup	
Type and quality of machine	
Grinding fluid	
Type	
Cleanliness	
Method of application	

28.2 Abrasives

- An *abrasive* is a hard material that can cut or abrade other substances
- Natural abrasives
  - sandstone was used by ancient peoples to sharpen tools and weapons.
  - *Emery*, a mixture of alumina (Al2O3) and magnetite (Fe3O4), is another natural abrasive still in use today
  - *Corundum* (natural Al2O3) and diamonds are other naturally occurring abrasive materials.
  - Today, the only natural abrasives that have commercial importance are quartz SiO2, sand, garnets, and diamonds.

- Properties:
- Hardness: ability to resist penetration
- Attrition: wear action of the grits resulting in dulled edges(grit flattering and wheel glazing)
- Friability: fracture of the grits and is the opposite to toughness

- *Artificial* abrasives date from 1891, when *silicon carbide* (SiC) was first produced.
- Other artifical abrasives used today include:
    - *Aluminum oxide* (Al2O3) is the most widely used artificial abrasive.
    - *Diamonds* are the hardest of all materials. Those that are used for abrasives are either natural, off-color stones that are not suitable for gems, or small, synthetic stones that are produced specifically for abrasive purposes.
    - *Cubic boron nitride* (CBN) is extremely hard. It is the second-hardest substance created by nature or manufactured and is often referred to, along with diamonds, as a superabrasive.

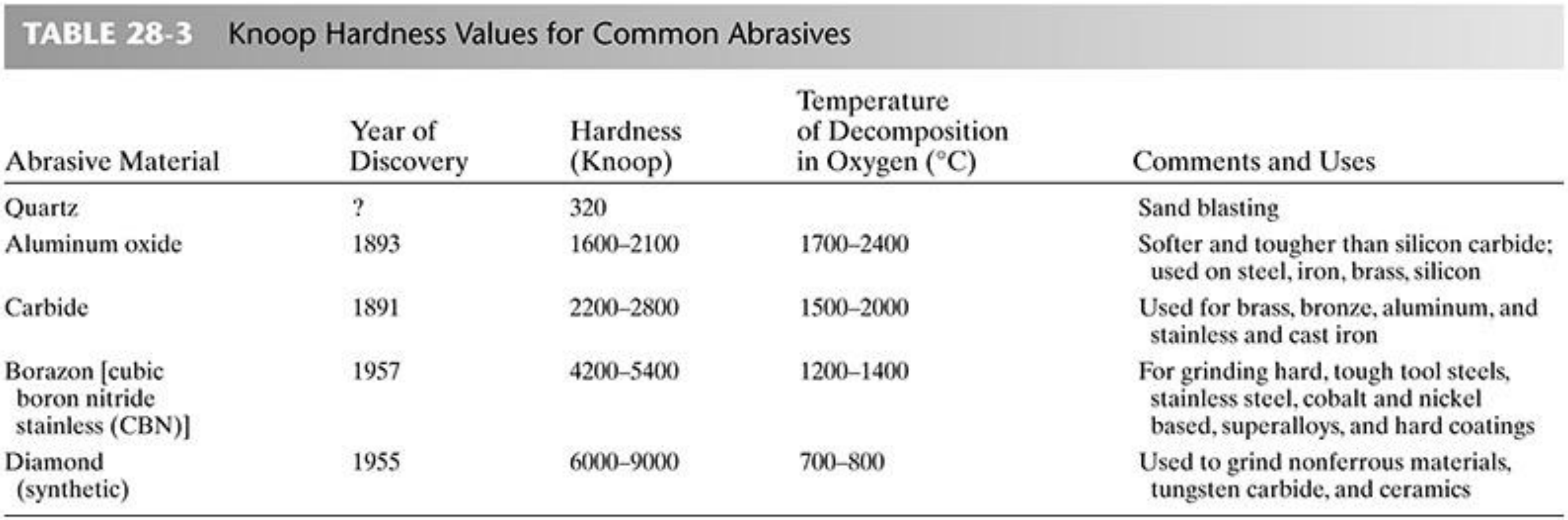


TABLE 28-3 Knoop Hardness Values for Common Abrasives

Abrasive Material	Year of Discovery	Hardness (Knoop)	Temperature of Decomposition in Oxygen (°C)	Comments and Uses
Quartz	?	320		Sand blasting
Aluminum oxide	1893	1600–2100	1700–2400	Softer and tougher than silicon carbide; used on steel, iron, brass, silicon
Carbide	1891	2200–2800	1500–2000	Used for brass, bronze, aluminum, and stainless and cast iron
Borazon [cubic boron nitride stainless (CBN)]	1957	4200–5400	1200–1400	For grinding hard, tough tool steels, stainless steel, cobalt and nickel based, superalloys, and hard coatings
Diamond (synthetic)	1955	6000–9000	700–800	Used to grind nonferrous materials, tungsten carbide, and ceramics

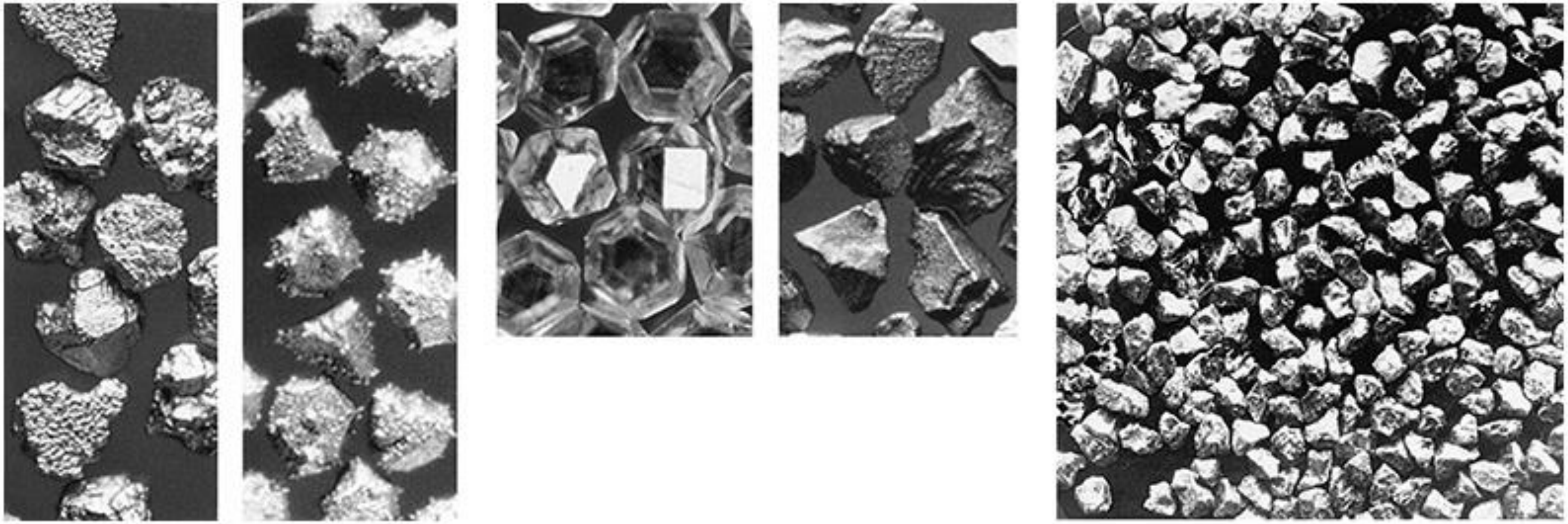


FIGURE 28-2 Loose abrasive grains at high magnification, showing their irregular, sharp cutting edges. *(Courtesy of Norton Company.)*

Sizing of Abrasives

- Abrasives are sized to control material removal rate and resultant surface finish.
- A screen size number refers to the number of openings per square inch at a give wire size.
- Grit numbers have been converted to millimeter in micrometer sizes for more standardization.
- Regardless of grain size only 2-5% of a individual grain is exposed due to bonding

Sizing Screens

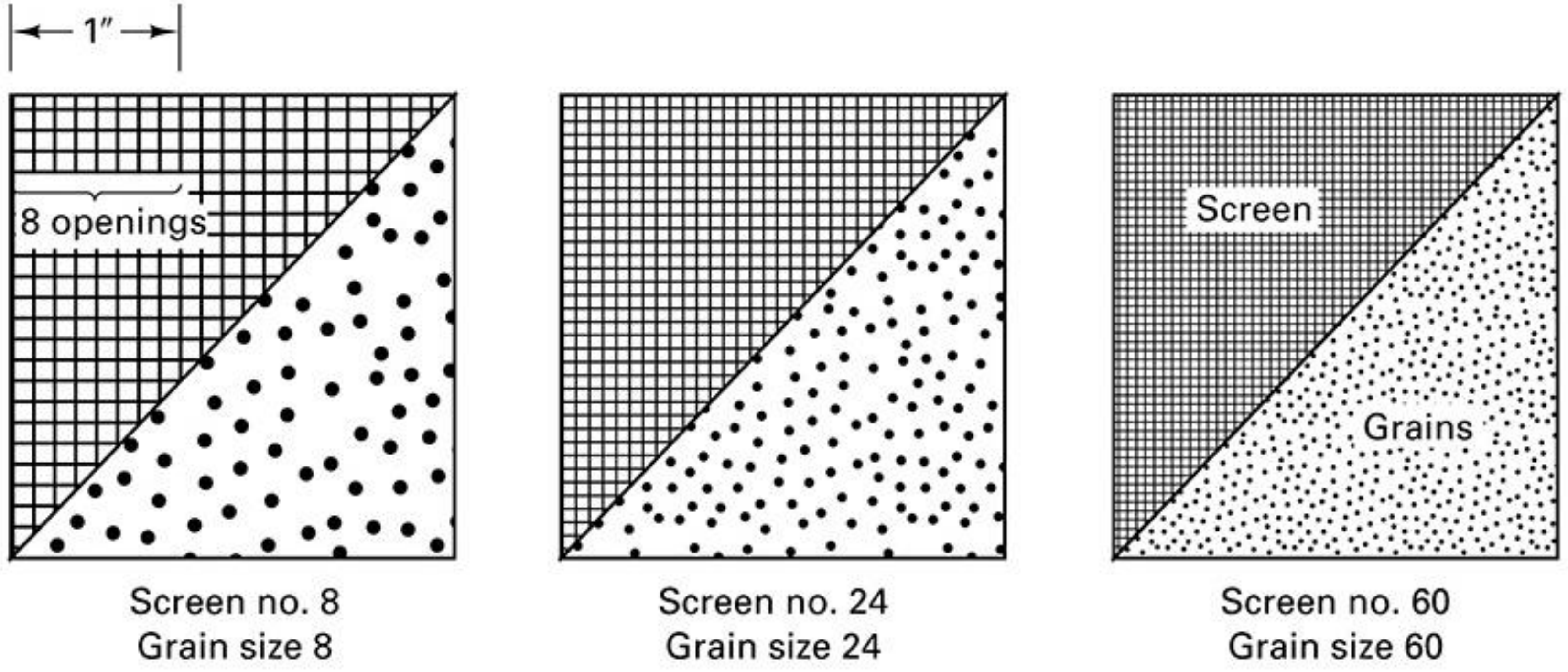


FIGURE 28-3 Typical screens for sifting abrasives into sizes. The larger the screen number (of opening per linear inch), the smaller the grain size. *(Courtesy of Carborundum Company.)*

Surface Finish versus Grit Size

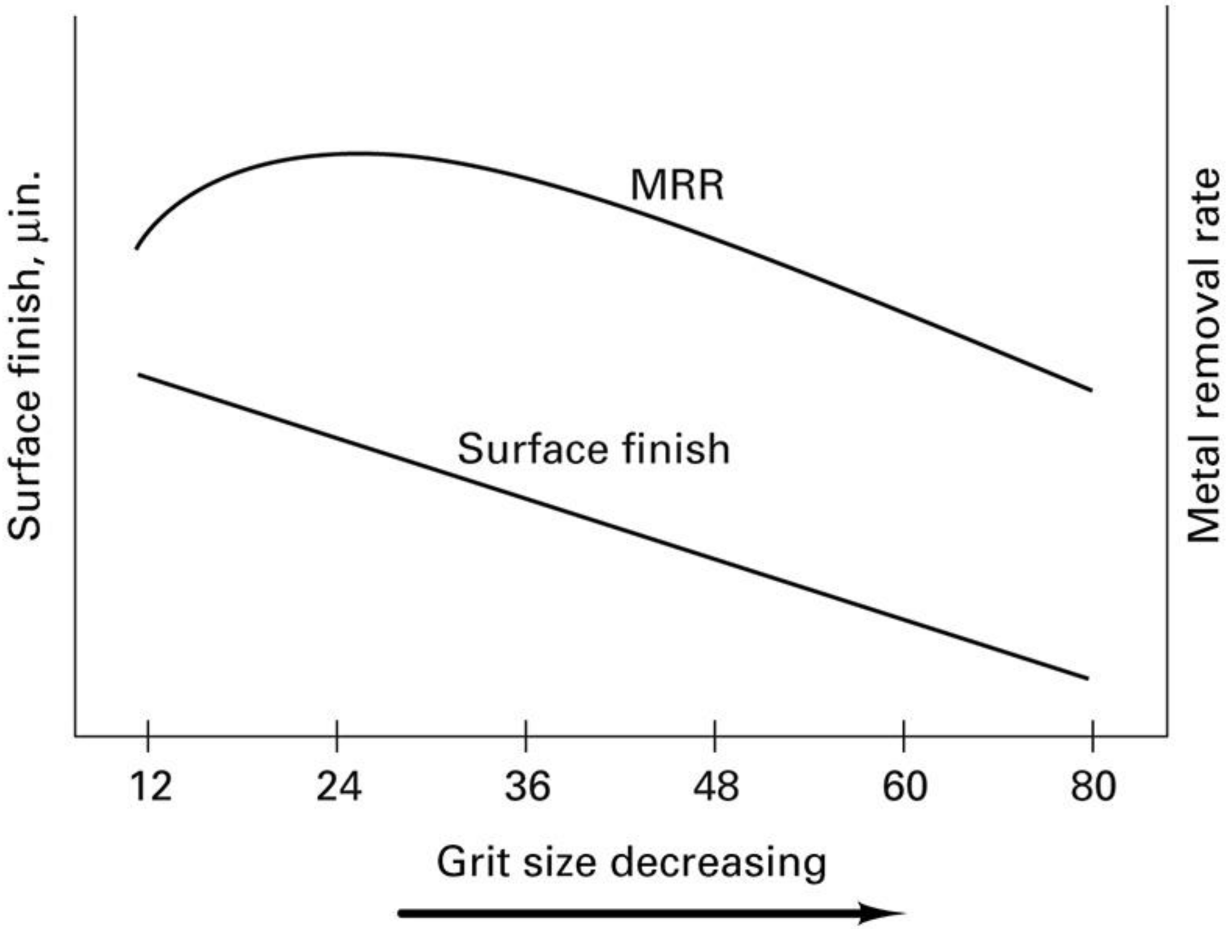


FIGURE 28-4 MRR and surface finish versus grit size.

Grit Geometry

- Abrasive grains are not uniform in shape and are randomly distributed across the surface.
- Not all grains cut at the optimum angle but due to distribution, the grinding surface is designed to the average distribution.
- Chips either cut, plow or rub on the surface.
- Grit density determines the chip loading.
- As grit material abrade, fracture, or are dislodged, new grit material is exposed, creating a continuous removal rate.

Rake Angle

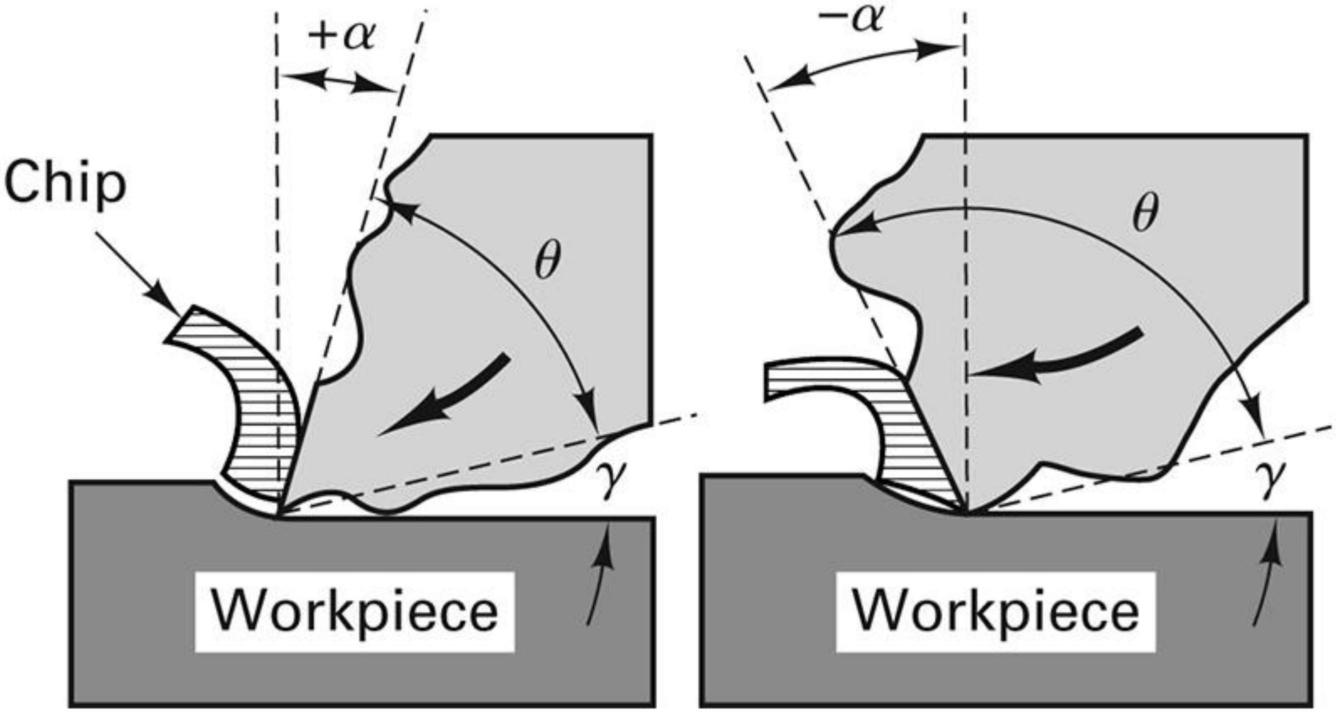


FIGURE 28-5 The rake angle of abrasive particles can be positive, zero, or negative.

Grit Distribution

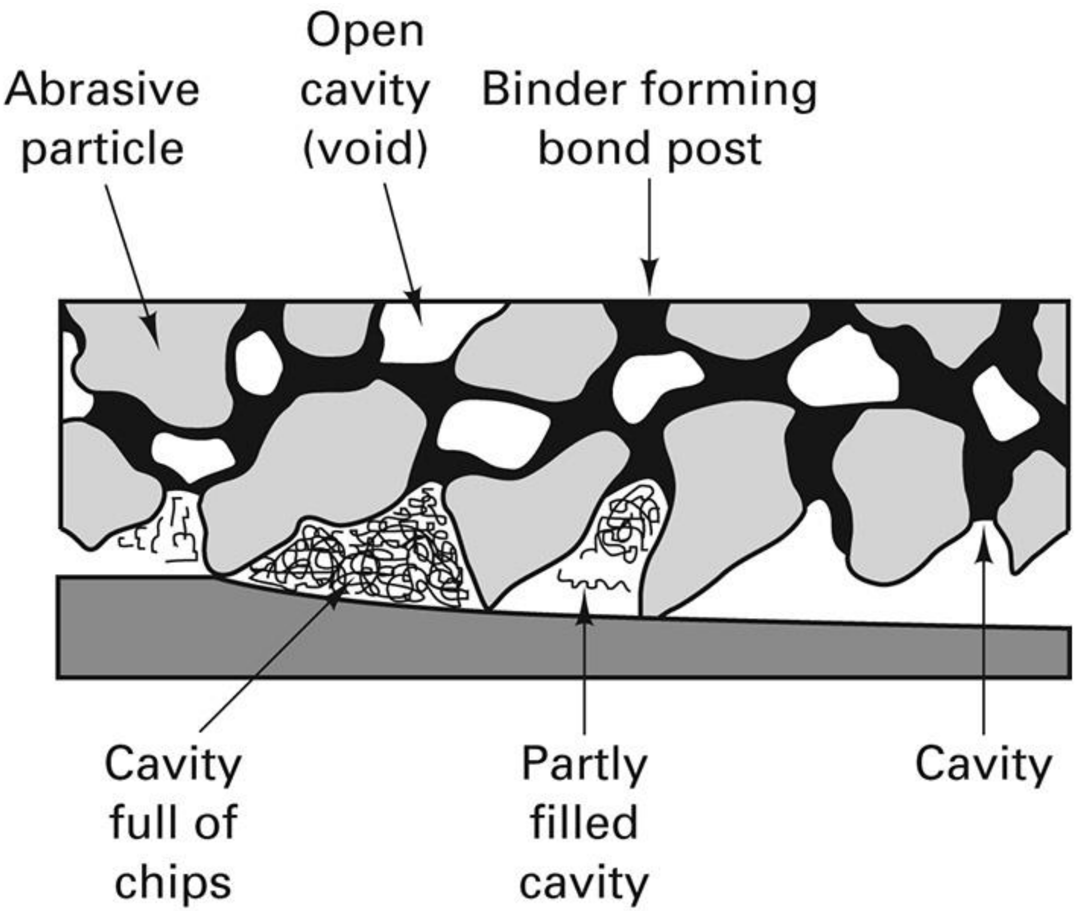


FIGURE 28-6 The cavities or voids between the grains must be large enough to hold all the chips during the cut.

Grit Orientation

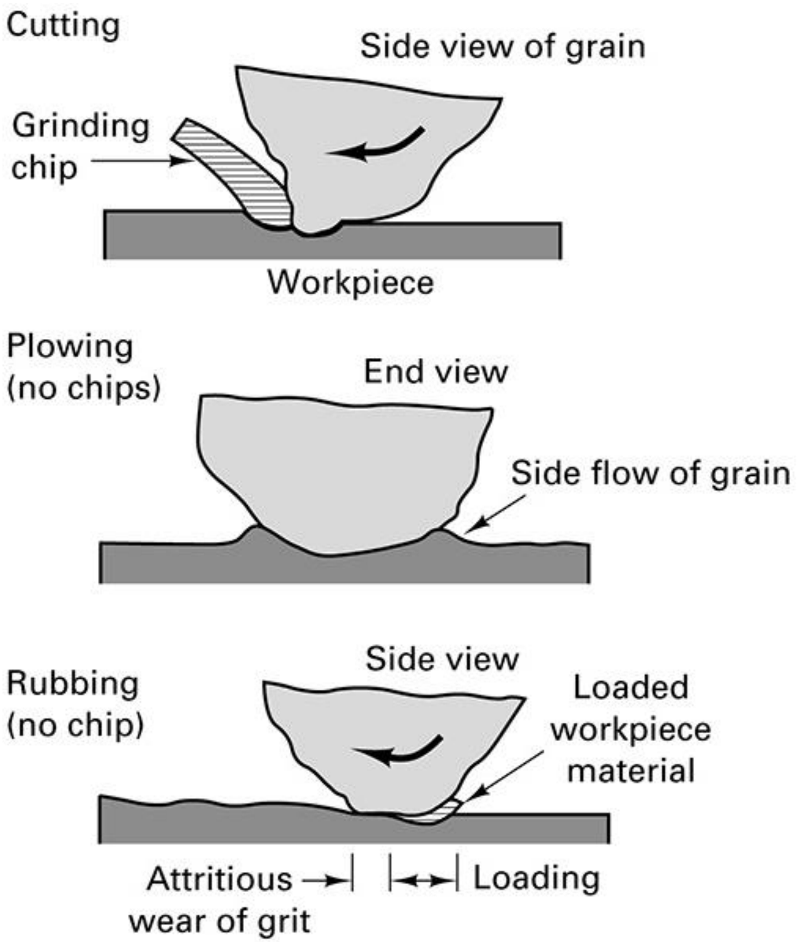


FIGURE 28-7 The grits interact with the surface in three ways: cutting, plowing, and rubbing.

Plowing

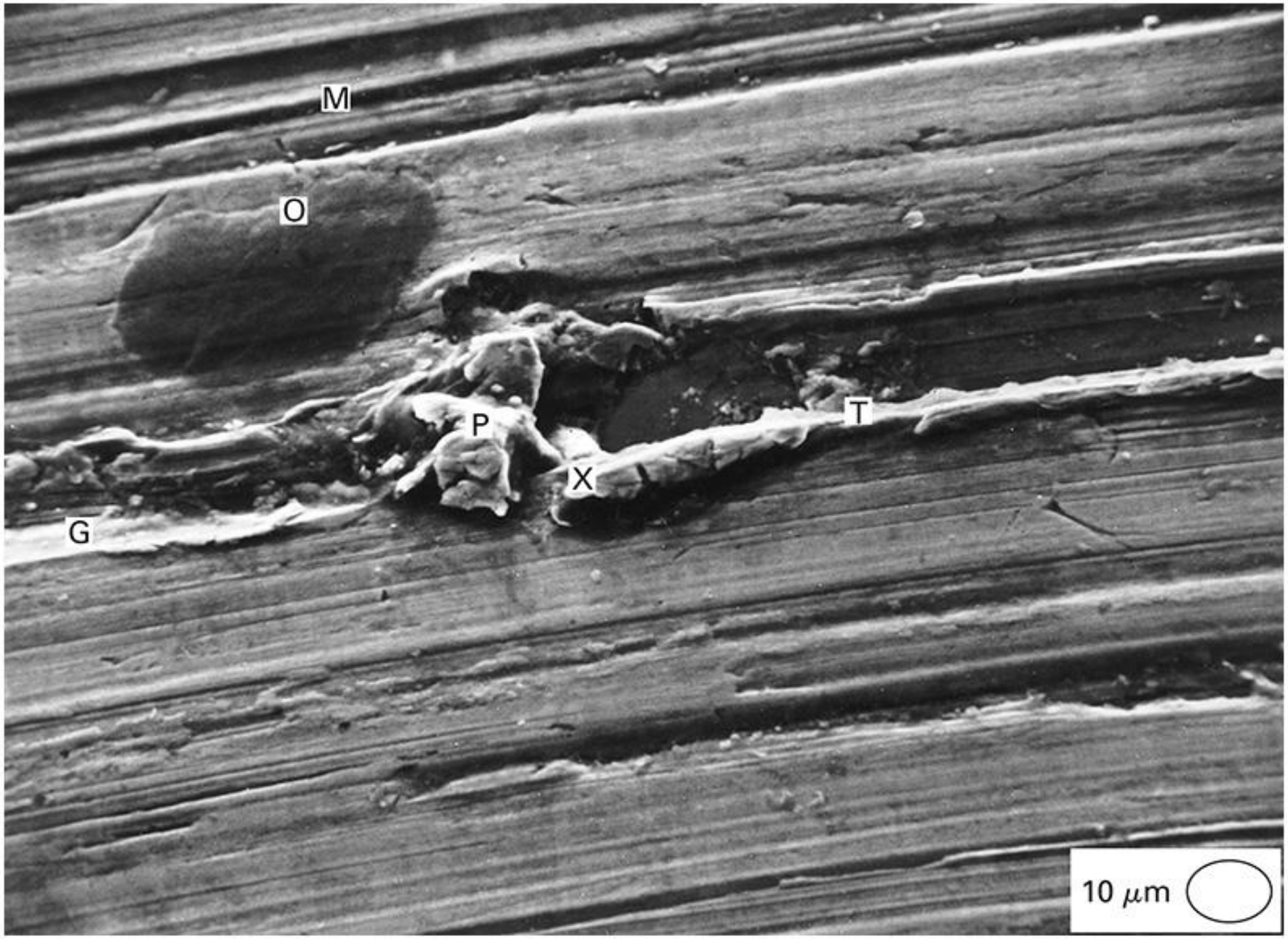


FIGURE 28-8 SEM micrograph of a ground steel surface showing a plowed track (T) in the middle and a machined track (M) above. The grit fractured, leaving a portion of the grit in the surface (X), a prow formation (P), and a groove (G) where the fractured portion was pushed farther across the surface. The area marked (O) is an oil deposit.

Grinding Chips

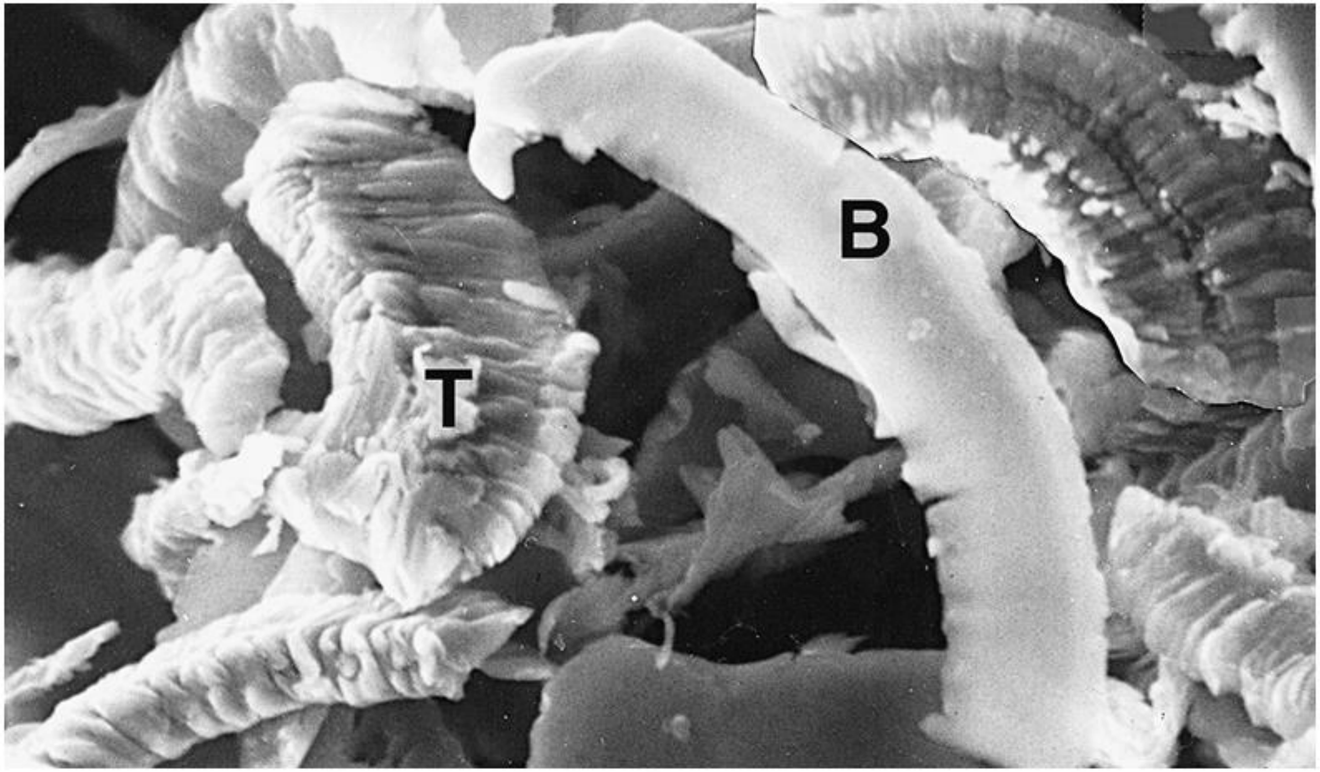


FIGURE 28-9 SEM micrograph of stainless steel chips from a grinding process. The tops (T) of the chips have the typical shearfront-lamella structure while the bottoms (B) are smooth where they slide over the grit 4800.

28.3 Grinding Wheel Structure and Grade

- Grinding is where the abrasive is bonded into a wheel, and is the most common abrasive method.
- The grade of a wheel is a function of the rate of fracture of the abrasive from the surface.

Depends on: 1) strength of bonding material

- 2) amount of bonding agent
- Grains are held together by “posts” which are classified as hard or soft.
- A wheel is graded as hard if the dislodging force is high and soft if the abrasive dislodging force is small

G Ratio

- The G ratio is defined as the ratio of workpiece material removed to grinding wheel material removed. Ratios of 20:1 to 80:1 are common.
- Wheel performance is influenced by:
  - **1.** The mean force required to dislodge a grain from the surface (the grade of the wheel)
  - **2.** The cavity size and distribution of the porosity (the structure)
  - **3.** The mean spacing of active grains in the wheel surface (grain size and structure)
  - **4.** The properties of the grain (hardness, attrition, and friability)
  - **5.** The geometry of the cutting edges of the grains (rake angles and cutting-edge radius compared to depth of cut)
  - **6.** The process parameters (speeds, feeds, cutting fluids) and type of grinding (surface, or cylindrical)

Wheel Structure: spacing of particles

- Dense structure: Close packed grains
- Open structure: larger chip cavity and fewer cutting edges

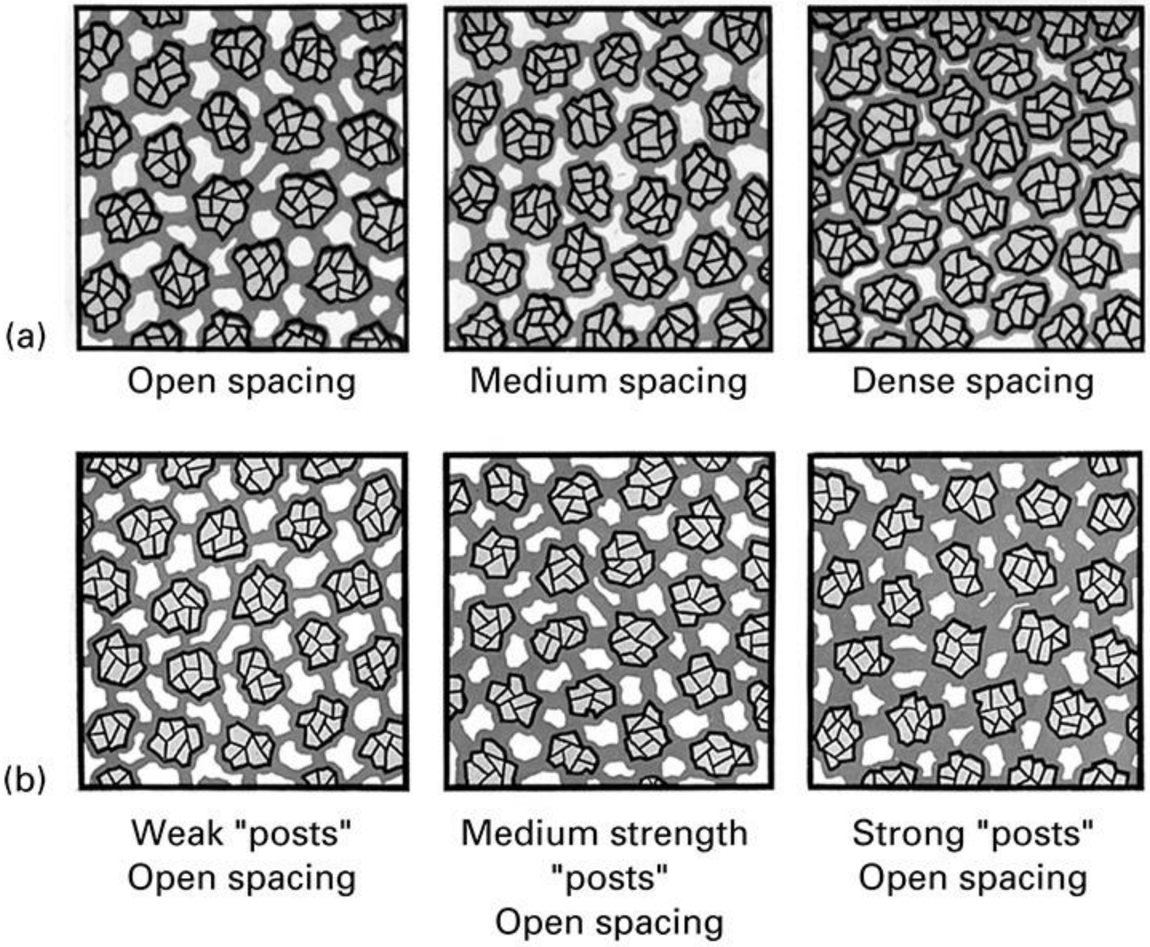


FIGURE 28-10 Meaning of terms *structure* and *grade* for grinding wheels. (a) The structure of a grinding wheel depends on the spacing of the grits. (b) The grade of a grinding wheel depends on the amount of bonding agent (posts) holding abrasive grains in the wheel.

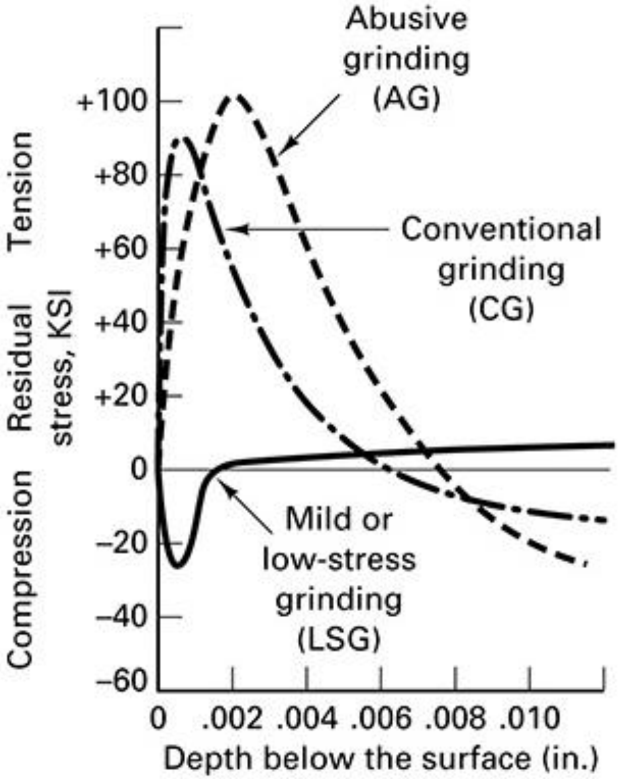
Bonding Materials

- Bonding materials in common use are the following:
  - **1.** *Vitrified bonds* are composed of clays and other ceramic substances.
  - **2.** *Resinoid*, or phenolic resins are used.
  - **3.** *Silicate* wheels use silicate of soda (waterglass) as the bond material.
  - **4.** *Shellac-bonded* wheels are made by mixing the abrasive grains with shellac in a heated mixture
  - **5.** *Rubber* bonding is used to produce wheels that can operate at high speeds but must have a considerable degree of flexibility.
  - **6.** *Superabrasive* wheels are either electroplated or a thin segmented drum of vitrified CBN surrounds on a steel core.

Grinding Force

- Very rapid material rates, similar in speed to milling, is called abrasive machining.
- Abrasive machining can produce high localized stress and heat within the material resulting in abusive grinding
- Figure 28-11 shows the stress differences between abusive, conventional and low stress grinding.

Wheel Stress Distribution



Grinding conditions

	Abusive AG	Conventional CG	Low-stress LSG
Wheel	A46MV	A46KV	A46HV or A60IV
Wheel speed ft/min	6,000–18,000	4,500–6,500	2500–3000
Down feed in./pass	.002–.004	.001–.003	.0002–.005
Cross feed in./pass	.040–.060	.040–.060	.040–.060
Table speed ft/min	40–100	40–100	40–100
Fluid	Dry	Sol oil (1:20)	Sulfurized oil

FIGURE 28-11 Typical residual stress distributions produced by surface grinding with different grinding conditions for abusive, conventional, and low-stress grinding. Material is 4340 steel. *(From M. Field and W. P. Kosher, "Surface Integrity in Grinding," in* New Developments in Grinding, *Carnegie-Mellon University Press, Pittsburgh, 1972, p. 666.)*

Grinding Wheel Truing and Dressing

- Grinding wheels lose their geomtry with use, truing restores the original shape.
- Truing grinds a small amount of material to expose new grinding media, and new cutting edges on worn glazed grains.
- As grinding wheels are used then tend to become loaded with lodged metal chips in the cavities.
- Dressing is used to remove the lodged metal chips.

Truing Methods

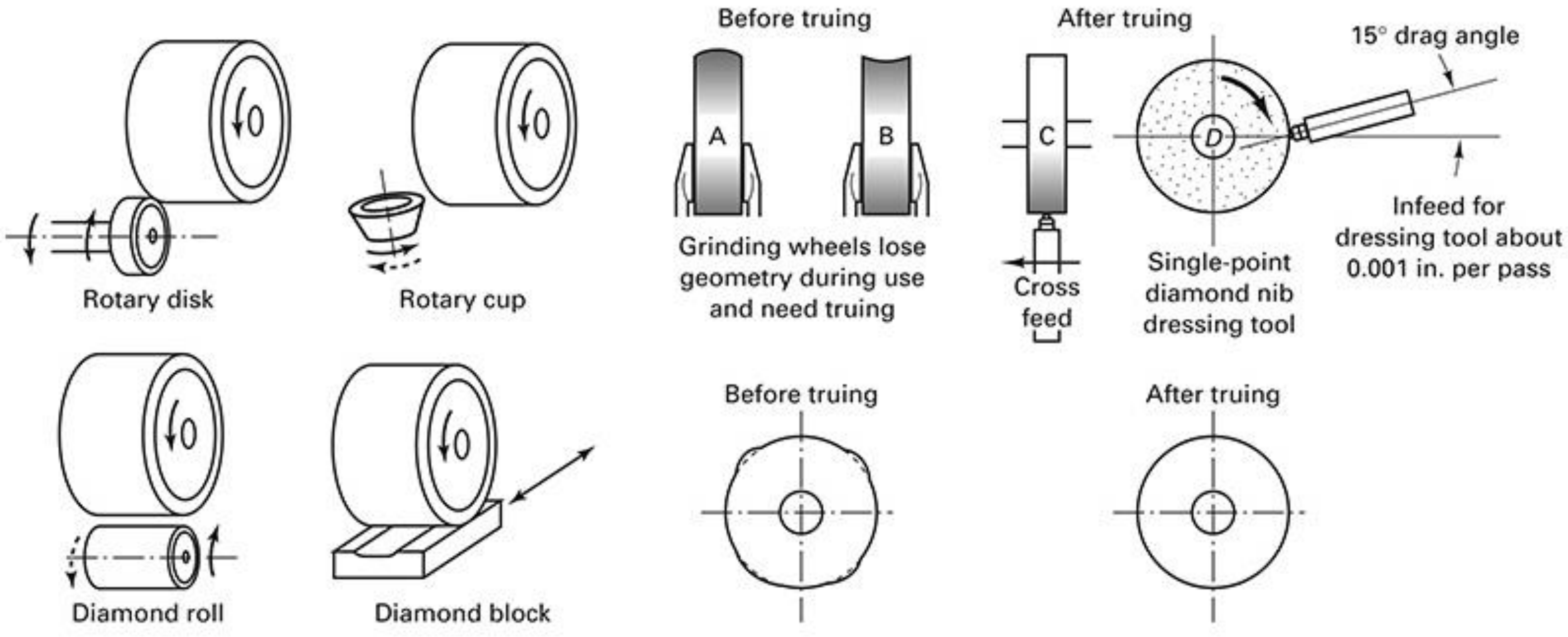


FIGURE 28-12 Truing methods for restoring grinding geometry include nibs, rolls, disks, cups, and blocks.

Dressing

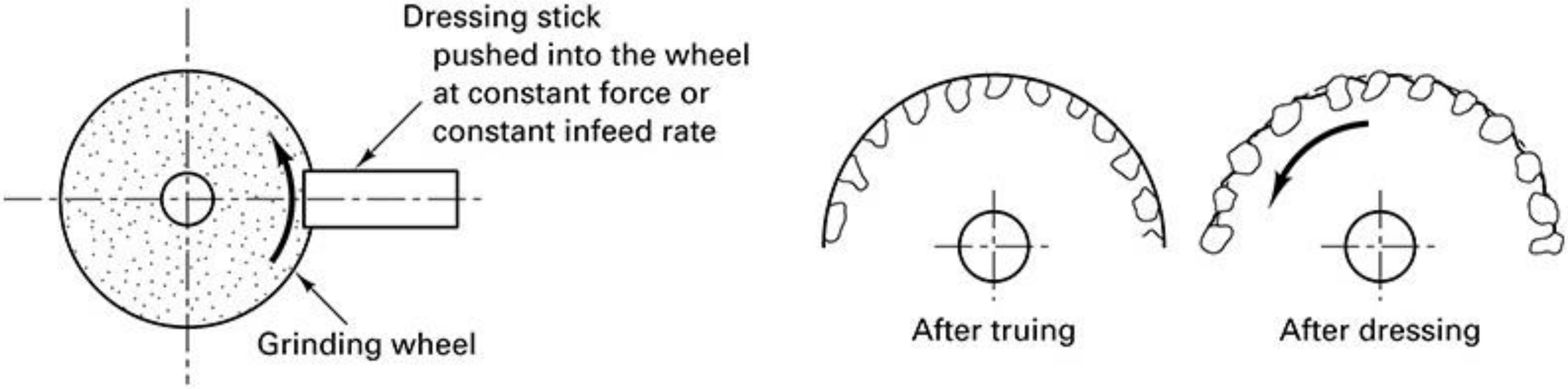
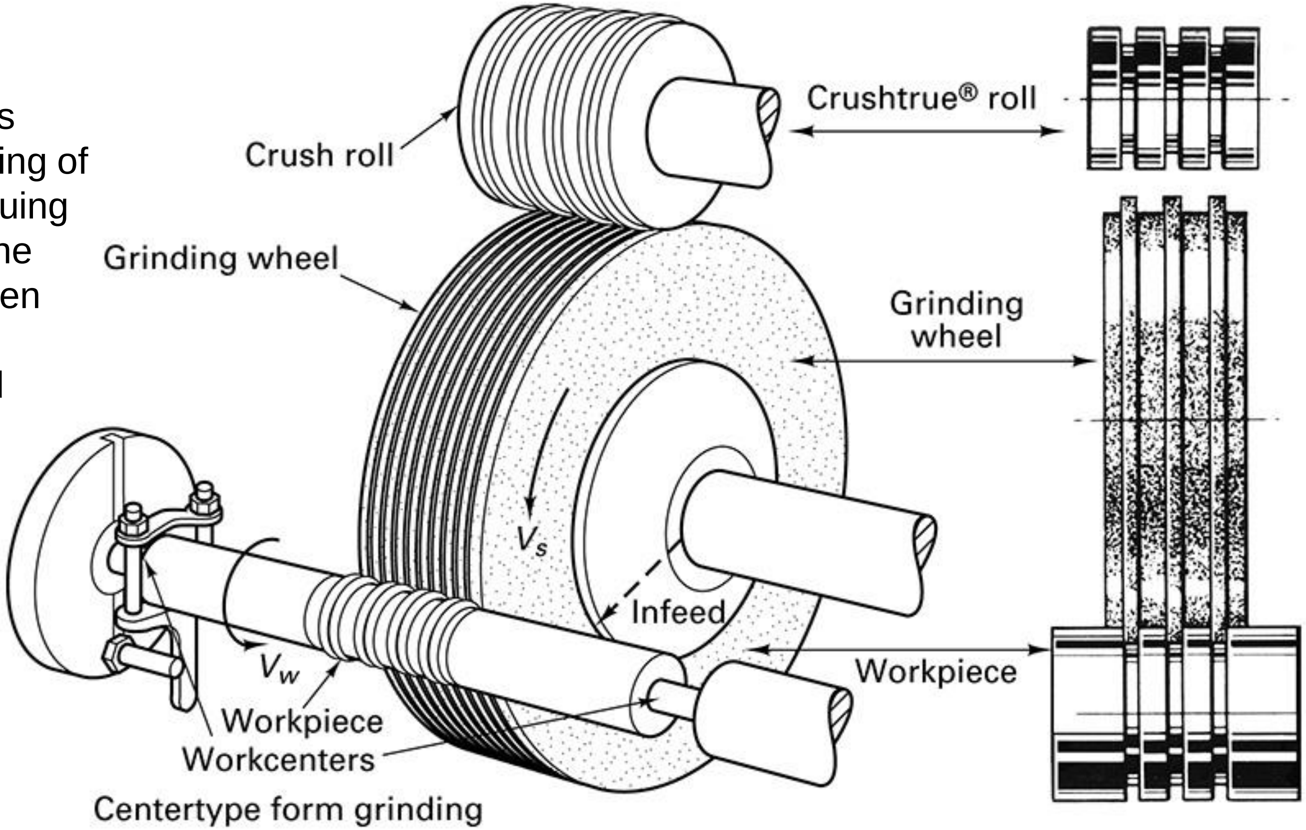


FIGURE 28-13 Schematic arrangement of stick dressing versus truing.

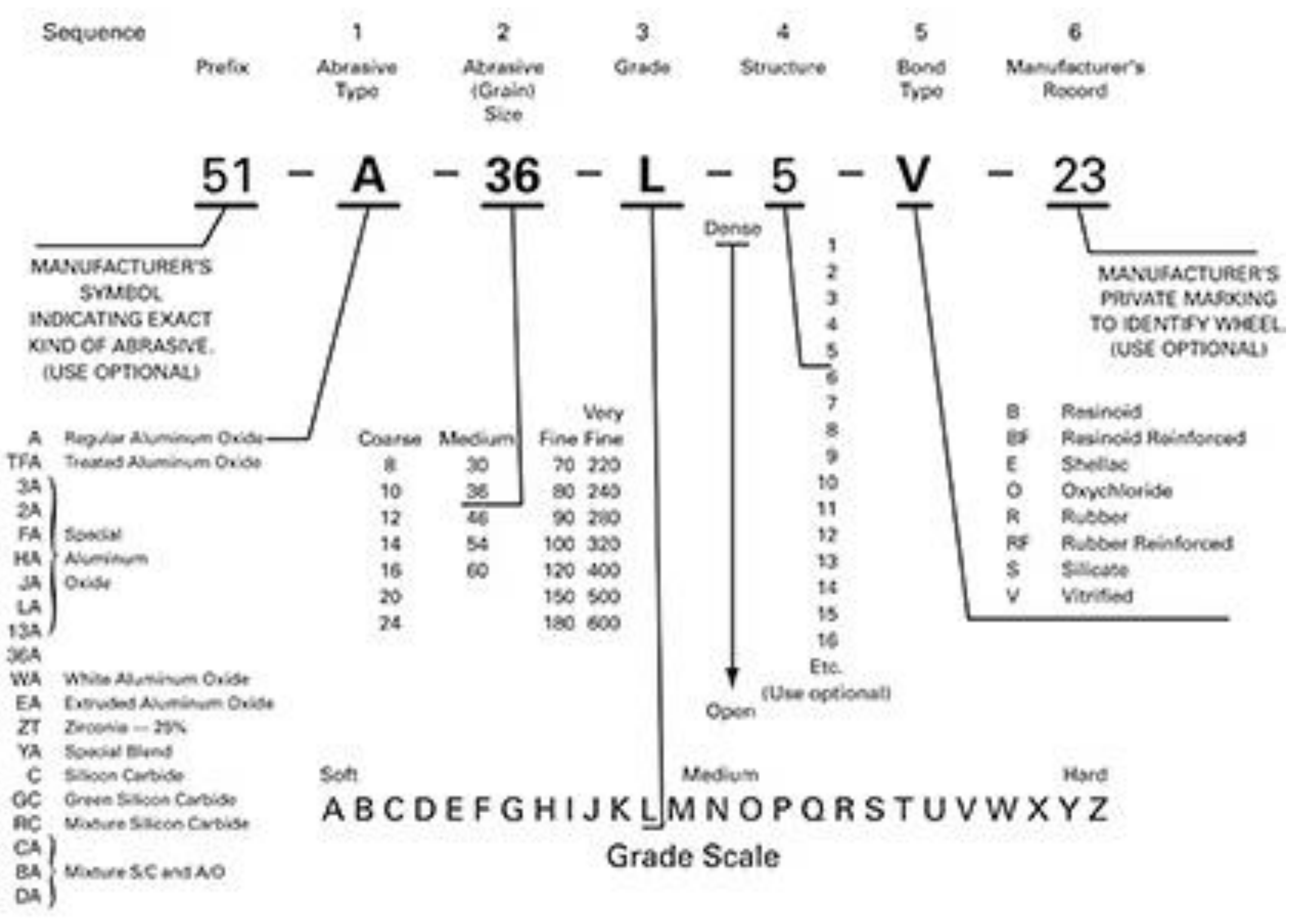
Crush Dressing

FIGURE 28-14 Continuous crush roll dressing and truing of a grinding wheel (form—truing and dressing throughout the process rather than between cycles) doing plunge cut grinding on a cylinder held between centers.



28.4 Grinding Wheel Identification

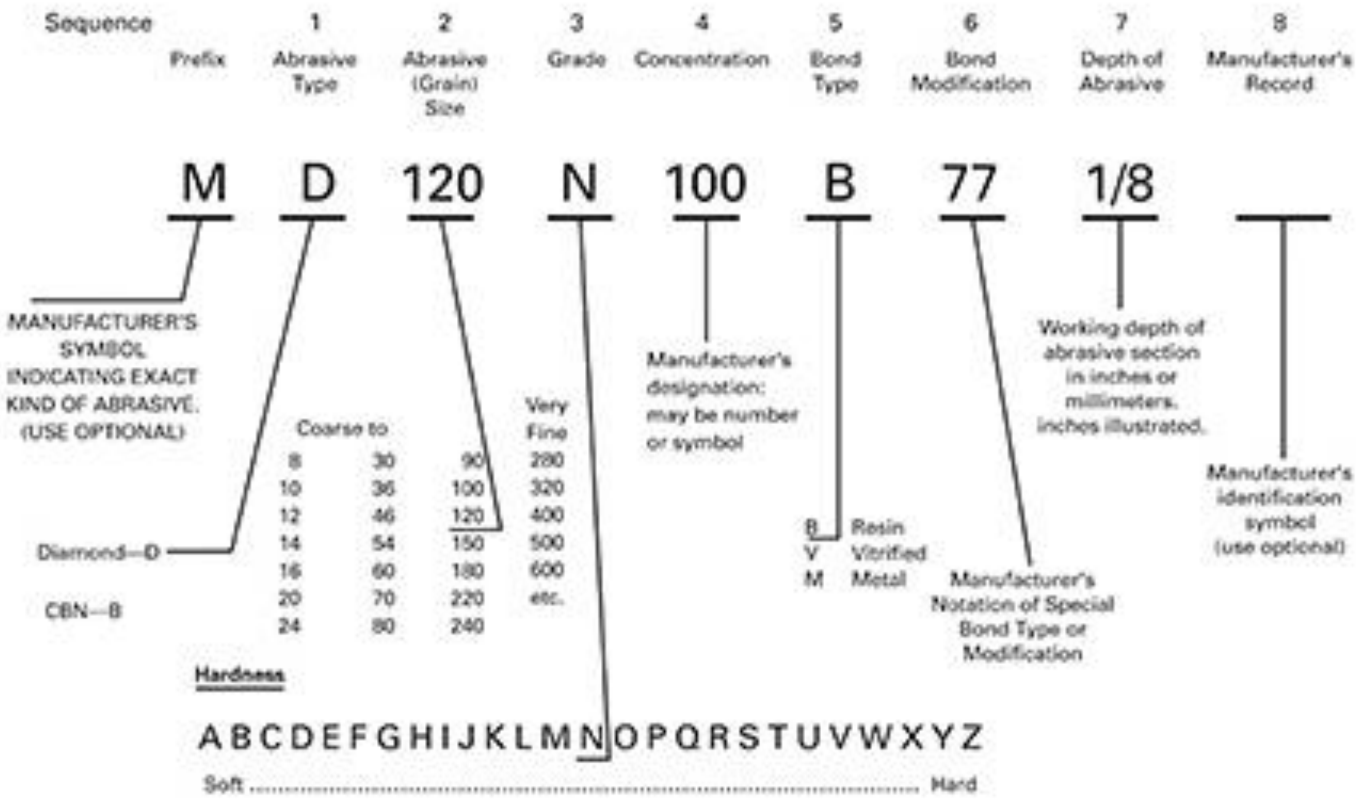
FIGURE 28-15 Standard marking systems for grinding wheels (ANSI standard B74. 13-1977).



Standard bonded-abrasive wheel-marching system (ANSI *Standard* B74.13-1977)

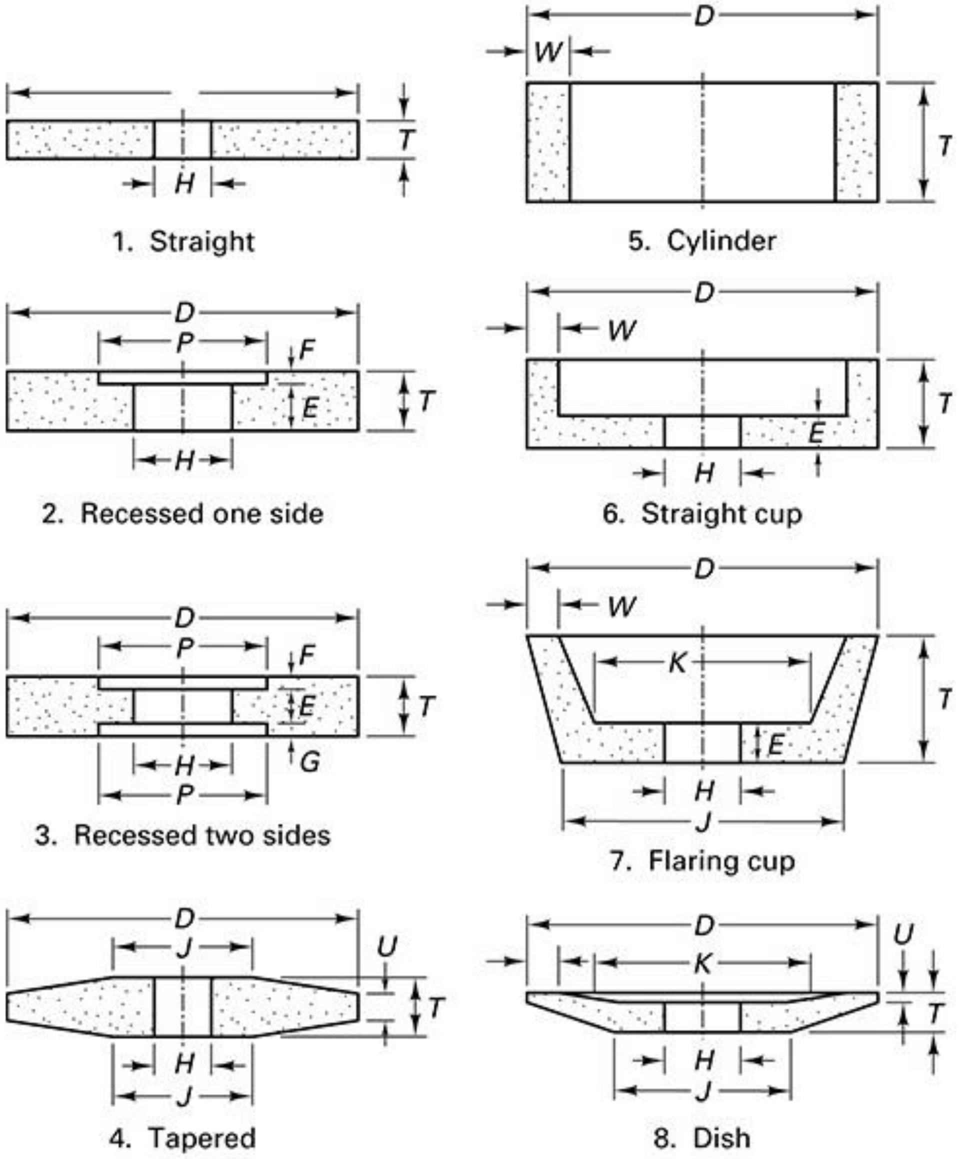
Grinding Wheel Identification

FIGURE 28-15 Standard marking systems for grinding wheels (ANSI standard B74. 13-1977).



Wheel-marking system for diamond and cubic boron nitride wheels (ANSI Standard B74.13-1977).

Wheel Shapes



1. Straight
5. Cylinder
2. Recessed one side
6. Straight cup
3. Recessed two sides
7. Flaring cup
4. Tapered
8. Dish

FIGURE 28-16 Standard grinding wheel shapes commonly used. *(Courtesy of Carborundum Company.)*

Standard Faces

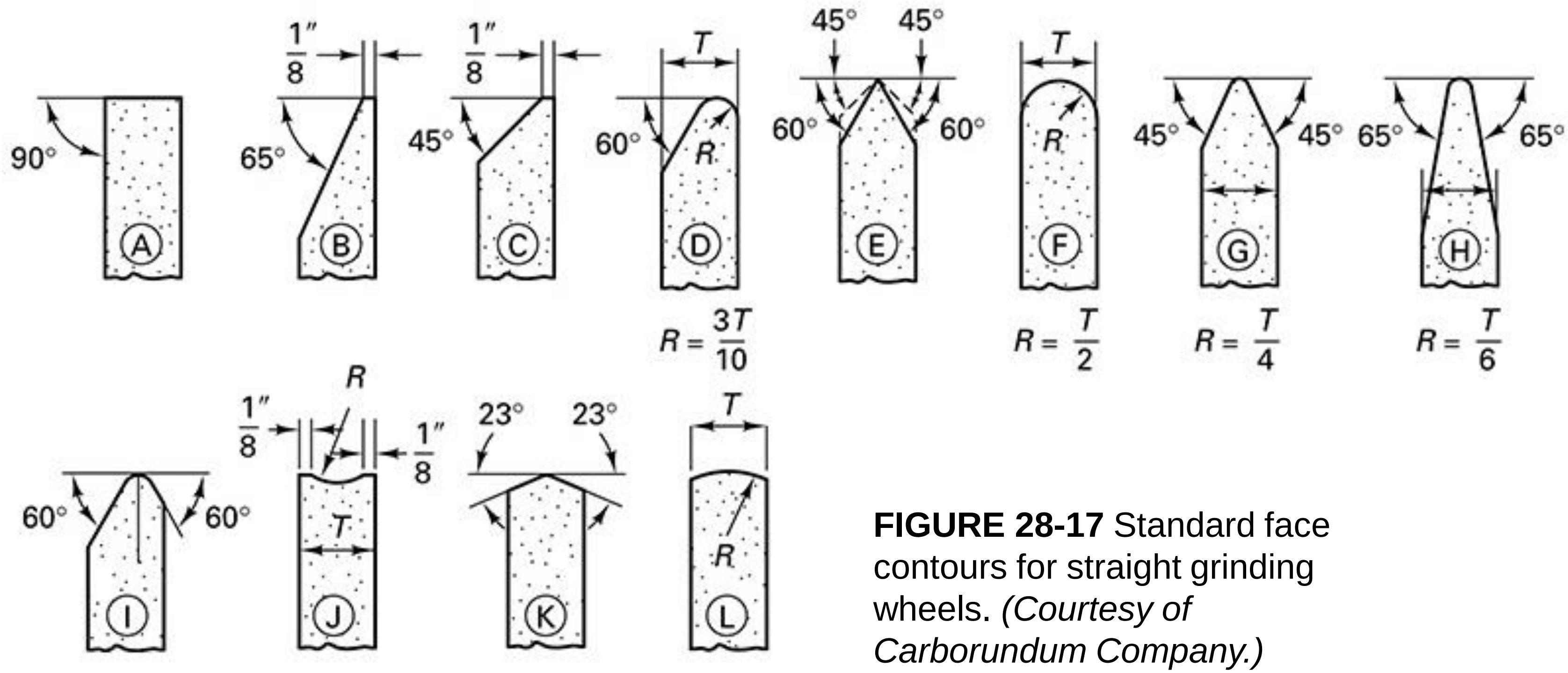


FIGURE 28-17 Standard face contours for straight grinding wheels. *(Courtesy of Carborundum Company.)*

Grinding Operations

- The major use categories are the following:
  - **1.** *Cutting off*: for slicing and slotting parts; use thin wheel, organic bond
  - **2.** *Cylindrical between centers*: grinding outside diameters of cylindrical workpieces
  - **3.** *Cylindrical, centerless*: grinding outside diameters with work rotated by regulating wheel
  - **4.** *Internal cylindrical*: grinding bores and large holes
  - **5.** *Snagging*:removing large amounts of metal without regard to surface finish or tolerances
  - **6.** *Surface grinding*: grinding flat workpieces
  - **7.** *Tool grinding*: for grinding cutting edges on tools such as drills, milling cutters, taps, reamers, and single-point high-speed-steel tools
  - **8.** *Offhand grinding*: work or the grinding tool is handheld

Operational Parameters

- Grinding Wheel Balance
    - Wheel balance in needed to ensure that vibration will not cause the wheel to break
    - Truing will often return a wheel to balance
- Grinding Safety
    - Wheel accident the result of wheel being turn at too high of rpm
    - Abuse of wheels, such as dropping cause wheel weakness
    - Improver use, such a grinding on the side
    - Improper use of eye sheilds
- Use of Cutting Fluids
    - Fluids wash away chips
    - Cool the workpiece

Coolant Delivery

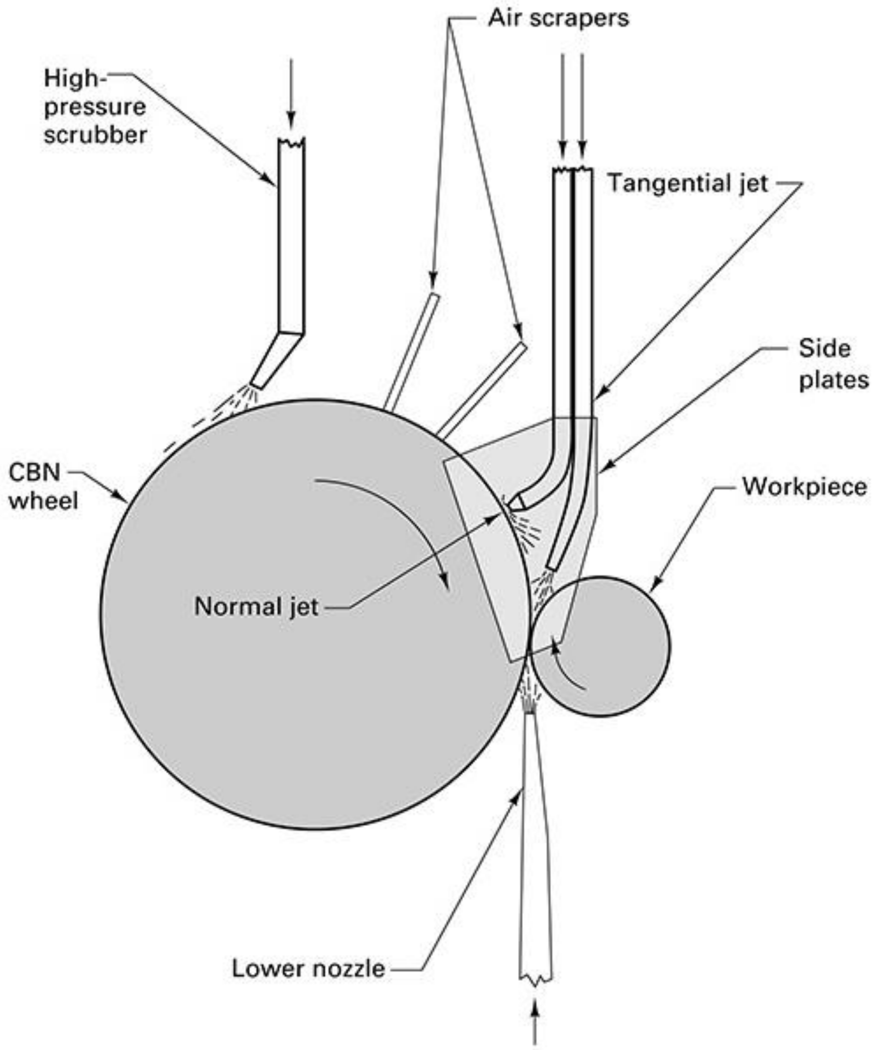


FIGURE 28-18 Coolant delivery system for optimum CBN grinding. (*Source: "Production Grinding with CBN," M. P. Hitchiner, CBN Grinding Systems Manager, Universal Beck, Romulus, MI,* Machining Technology, *Vol. 2, No. 2, 1991.)* improper

28.5 Grinding Machines

- Grinding Machines are classified according to the surface they produce.
    - Table 28-4 list the types of grinding machines
- Grinding is done in three ways
    - Infeed – moving the wheel across the surface
    - Plunge-cut – the material is rotates as the wheel moves radially into the surface.
    - Creep Feed Grinding – the material is feed past the wheel.

Types of Grinding Machines

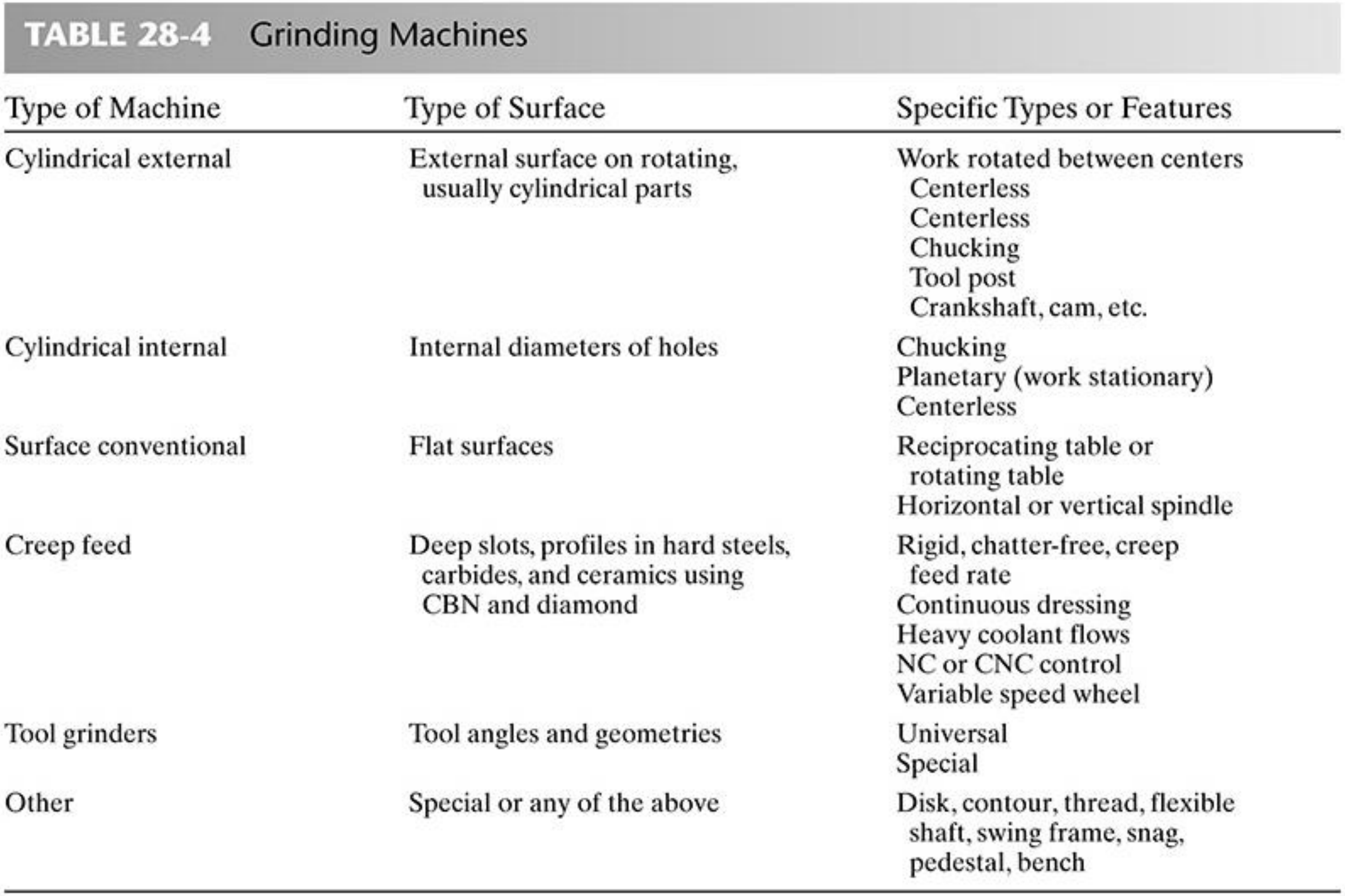


TABLE 28-4 Grinding Machines

Type of Machine	Type of Surface	Specific Types or Features
Cylindrical external	External surface on rotating, usually cylindrical parts	Work rotated between centers Centerless Centerless Chucking Tool post Crankshaft, cam, etc.
Cylindrical internal	Internal diameters of holes	Chucking Planetary (work stationary) Centerless
Surface conventional	Flat surfaces	Reciprocating table or rotating table Horizontal or vertical spindle
Creep feed	Deep slots, profiles in hard steels, carbides, and ceramics using CBN and diamond	Rigid, chatter-free, creep feed rate Continuous dressing Heavy coolant flows NC or CNC control Variable speed wheel
Tool grinders	Tool angles and geometries	Universal Special
Other	Special or any of the above	Disk, contour, thread, flexible shaft, swing frame, snag, pedestal, bench

Horizontal Spindle

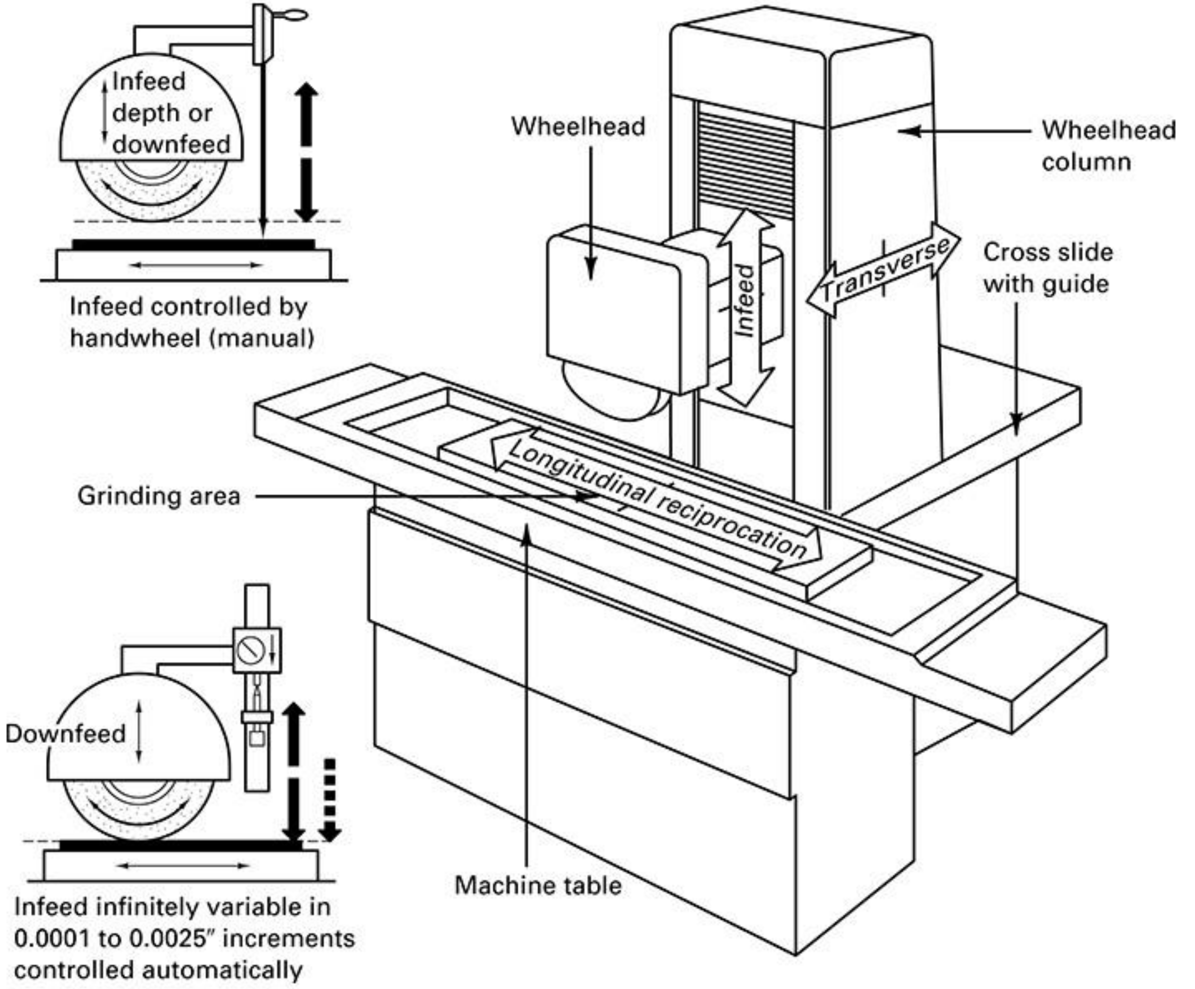
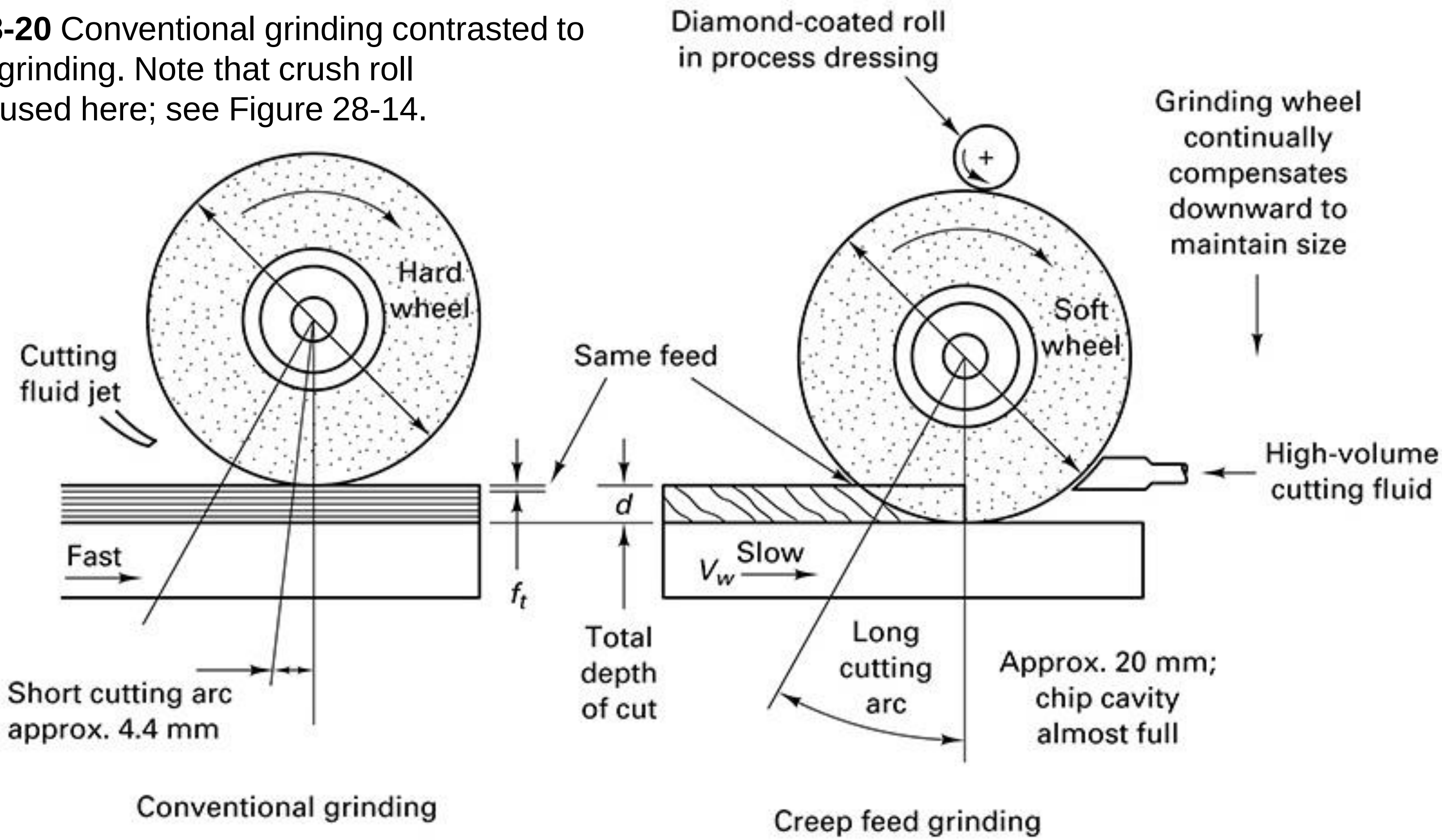


FIGURE 28-19
Horizontal spindle surface grinder, with insets showing movements of wheelhead.

Conventional Grinding

FIGURE 28-20 Conventional grinding contrasted to creep feed grinding. Note that crush roll dressing is used here; see Figure 28-14.



Grinding Comparison

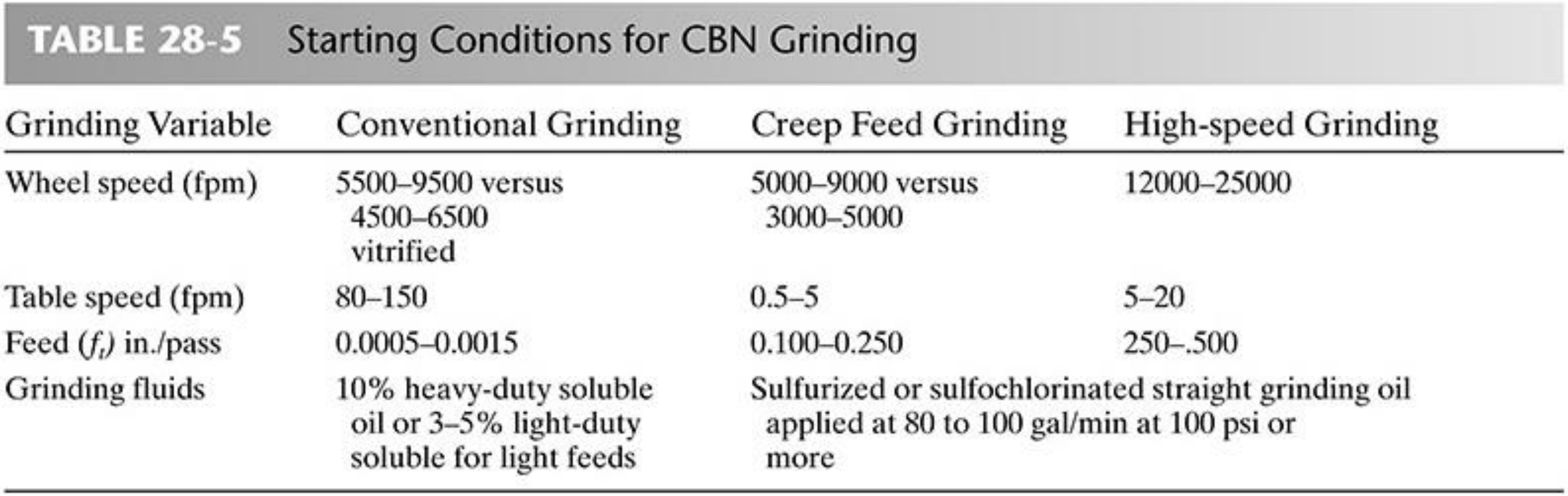


TABLE 28-5 Starting Conditions for CBN Grinding

Grinding Variable	Conventional Grinding	Creep Feed Grinding	High-speed Grinding
Wheel speed (fpm)	5500–9500 versus 4500–6500 vitrified	5000–9000 versus 3000–5000	12000–25000
Table speed (fpm)	80–150	0.5–5	5–20
Feed (f_t) in./pass	0.0005–0.0015	0.100–0.250	250–.500
Grinding fluids	10% heavy-duty soluble oil or 3–5% light-duty soluble for light feeds	Sulfurized or sulfochlorinated straight grinding oil applied at 80 to 100 gal/min at 100 psi or more	

Cylindrical Grinding

- Cylindrical grinding is used to produce external cylindrical surfaces
- In cylindrical grinding the workpiece is mounted and rotated on a longitudinal axis, the grinding wheel rotate in the same axis, but in opposite directions.
- With long workpieces, the workpiece typically is moved relative to the wheel.
- With smaller high production parts, a chuck-type external grinder is used, and the wheel moves relative to the workpiece.

Center Grinding

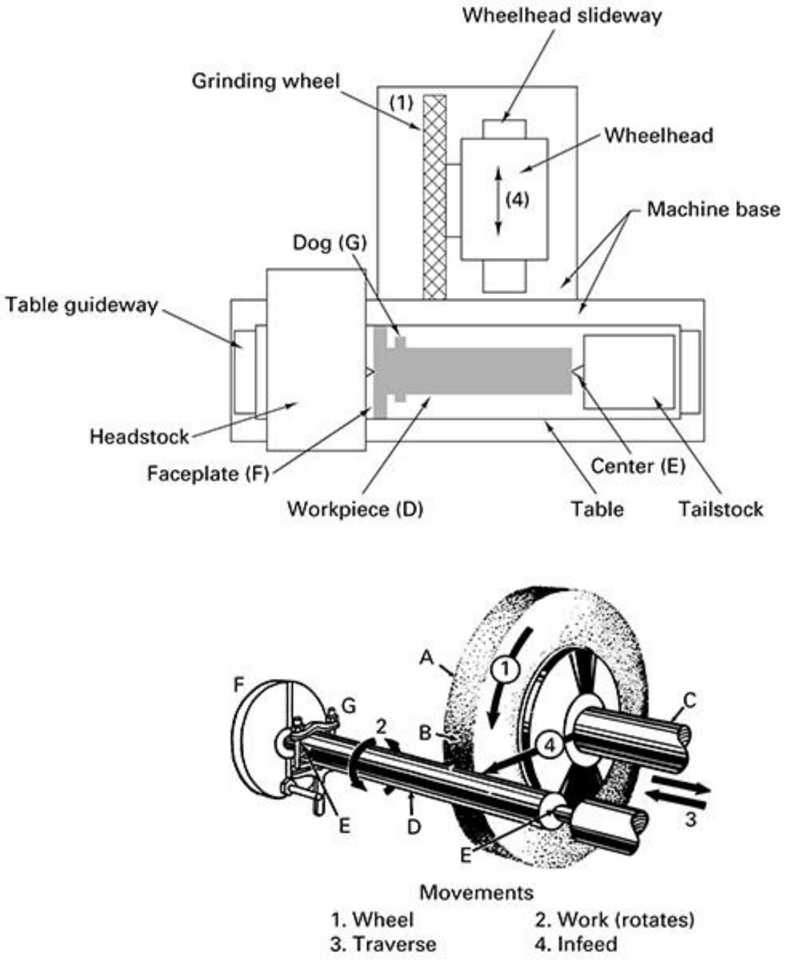


FIGURE 28-21 Cylindrical grinding between centers.

Centerless Grinding

- In centerless grinding the workpiece can be ground internally or externally without requiring the material to be mounted in a center or chuck.
- The workpiece rests between two wheels, one providing the grinding and the other providing regulation of the grinding speed.

Centerless Grinding

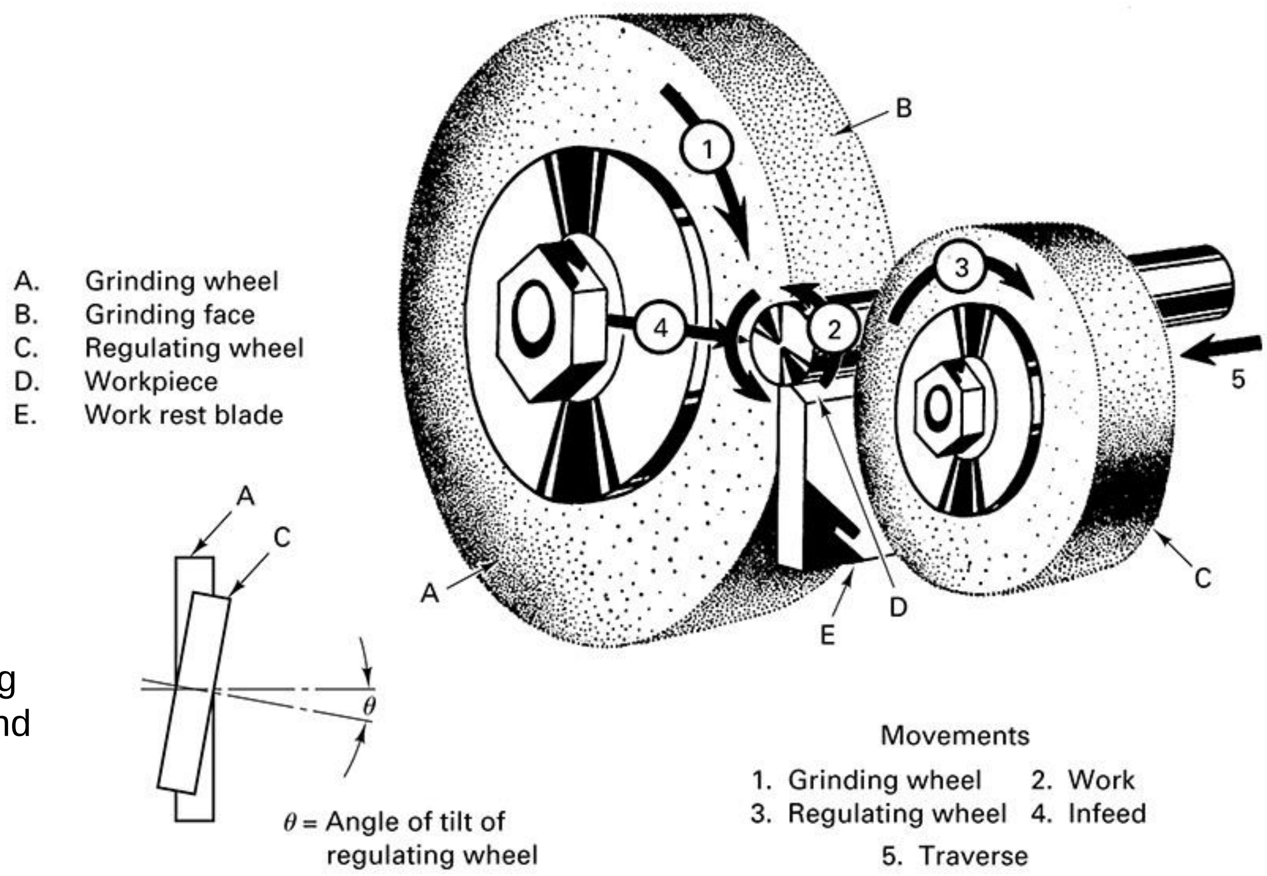


FIGURE 28-22 Centerless grinding showing the relationship among the grinding wheel, the regulating wheel, and the workpiece in centerless method. *(Courtesy of Carborundum Company.)*

Advantages of Centerless Grinding

- Centerless grinding has several important advantages:
    - **1.** It is very rapid; infeed centerless grinding is almost continuous.
    - **2.** Very little skill is required of the operator.
    - **3.** It can often be made automatic (single-cycle automatic).
    - **4.** Where the cutting occurs, the work is fully supported by the work rest and the regulating wheel.This permits heavy cuts to be made.
    - **5.** Because there is no distortion of the workpiece, accurate size control is easily achieved.
    - **6.** Large grinding wheels can be used, thereby minimizing wheel wear.

Disadvantages of Centerless Grinding

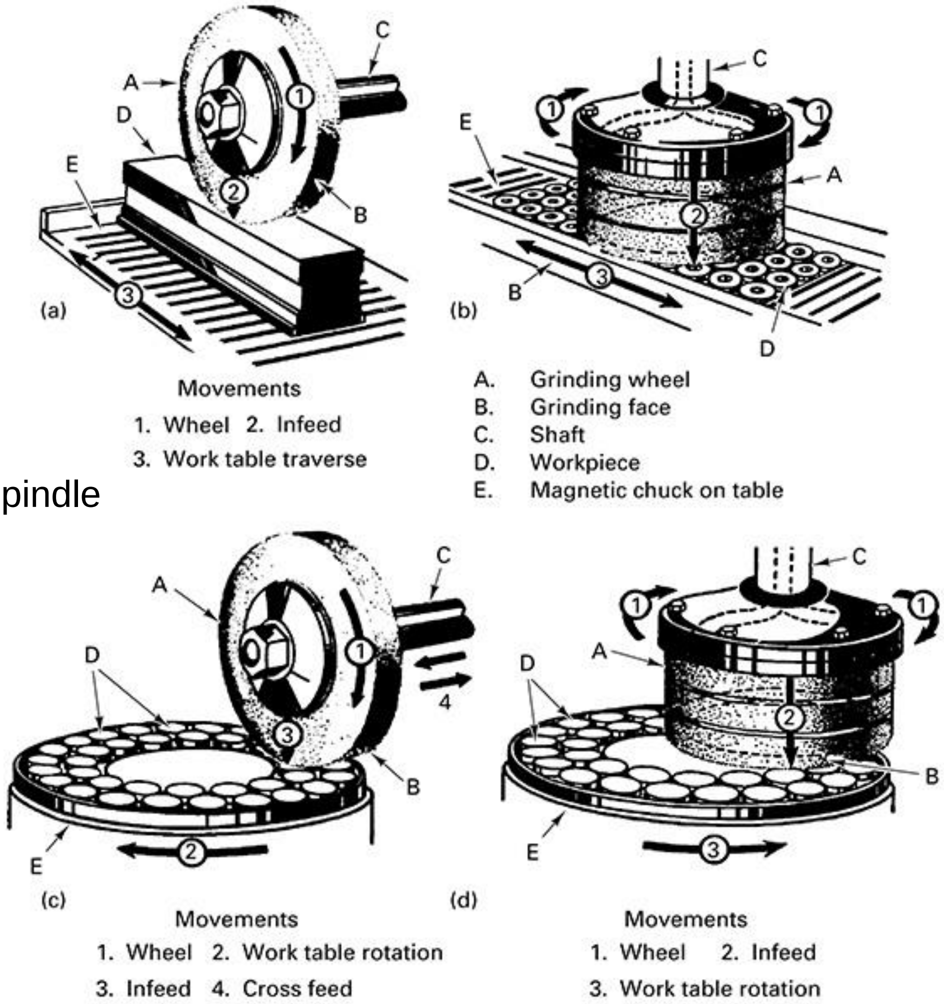
- The major disadvantages are as follows:
  - **1.** Special machines are required that can do no other type of work.
  - **2.** The work must be round—no flats, such as keyways, can be present.
  - **3.** Its use on work having more than one diameter or on curved parts is limited.
  - **4.** In grinding tubes, there is no guarantee that the OD and Internal Diameter (ID) are concentric.

Surface Grinding

- Surface Grinding Machines are used to produce flat surfaces. The four basic types are:
  - **1.** Horizontal spindle and reciprocating table
  - **2.** Vertical spindle and reciprocating table
  - **3.** Horizontal spindle and rotary table
  - **4.** Vertical spindle and rotary table

Surface Grinding Machines

FIGURE 28-23 Surface B grinding: (a) horizontal surface grinding and reciprocating table; (b) vertical spindle with reciprocating table; (c) and (d) both horizontal- and verticalspindle machines can have rotary tables. *(Courtesy of Carborundum Company.)*



Tool Grinding

- Mills cutters, reams, and single point tools require sophisticated grinding provided by a tool grinder that differs from a universal cylindrical center-type grinder by:
  - **1.** The headstock is not motorized.
  - **2.** The headstock can be swiveled about a horizontal as well as a vertical axis.
  - **3.** The wheelhead can be raised and lowered and can be swiveled through at 360° rotation about a vertical axis.
  - **4.** All table motions are manual. No power feeds being provided.

Tool Grinding Machine

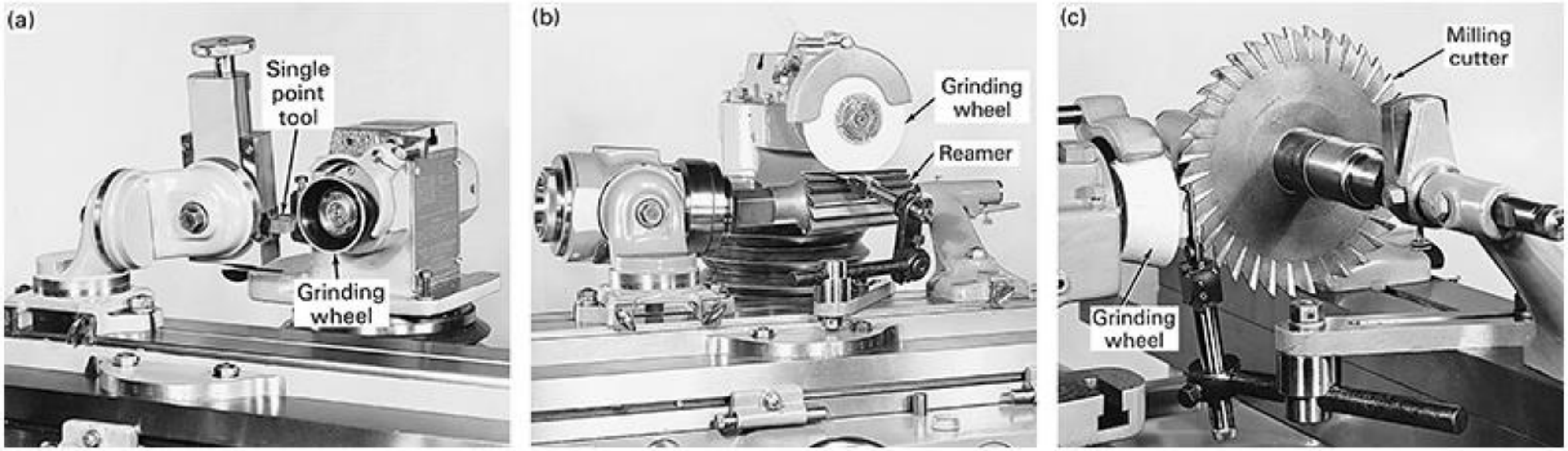


FIGURE 28-24 Three typical setups for grinding single- and multiple-edge tools on a universal tool and cutter grinder. (a) Singlepoint tool is held in a device that permits all possible angles to be ground. (b) Edges of a large hand reamer are being ground. (c) Milling cutter is sharpened with a cupped grinding wheel.

Other Grinding Tools

- Mounted Wheels and Points are small tools used in finishing work.
  - Typically mounted on portable high speed chucks
  - RPM’s to 100,000 depending upon diamter
- Coated Abrasives
  - Come in disk, sheets, rolls, belts, etc.
  - Consist of abrasives glued to a cloth or paper backing
  - Designed to be easily replaced when dull or the loaded

Mounted Wheels and Points for High Speed Hand Tools

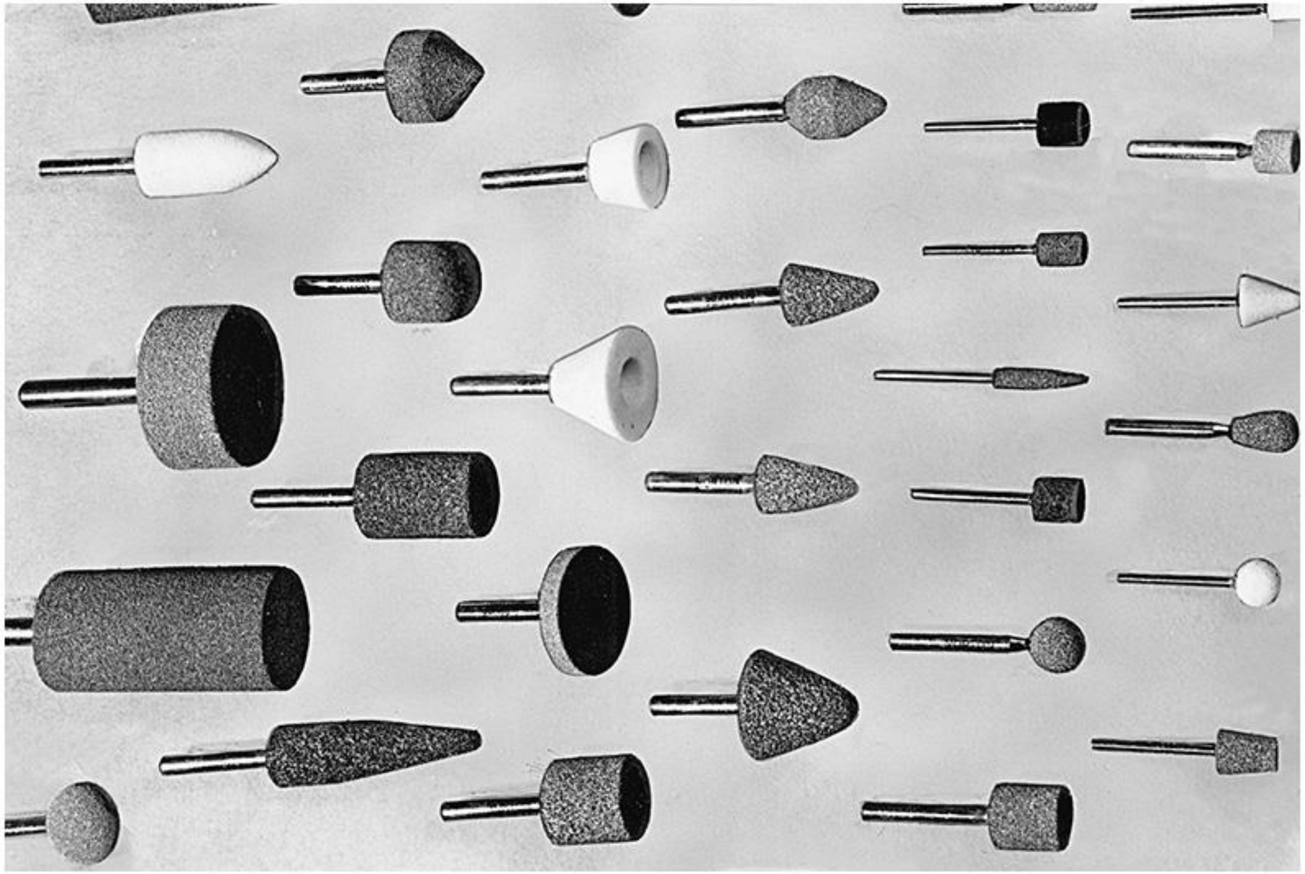
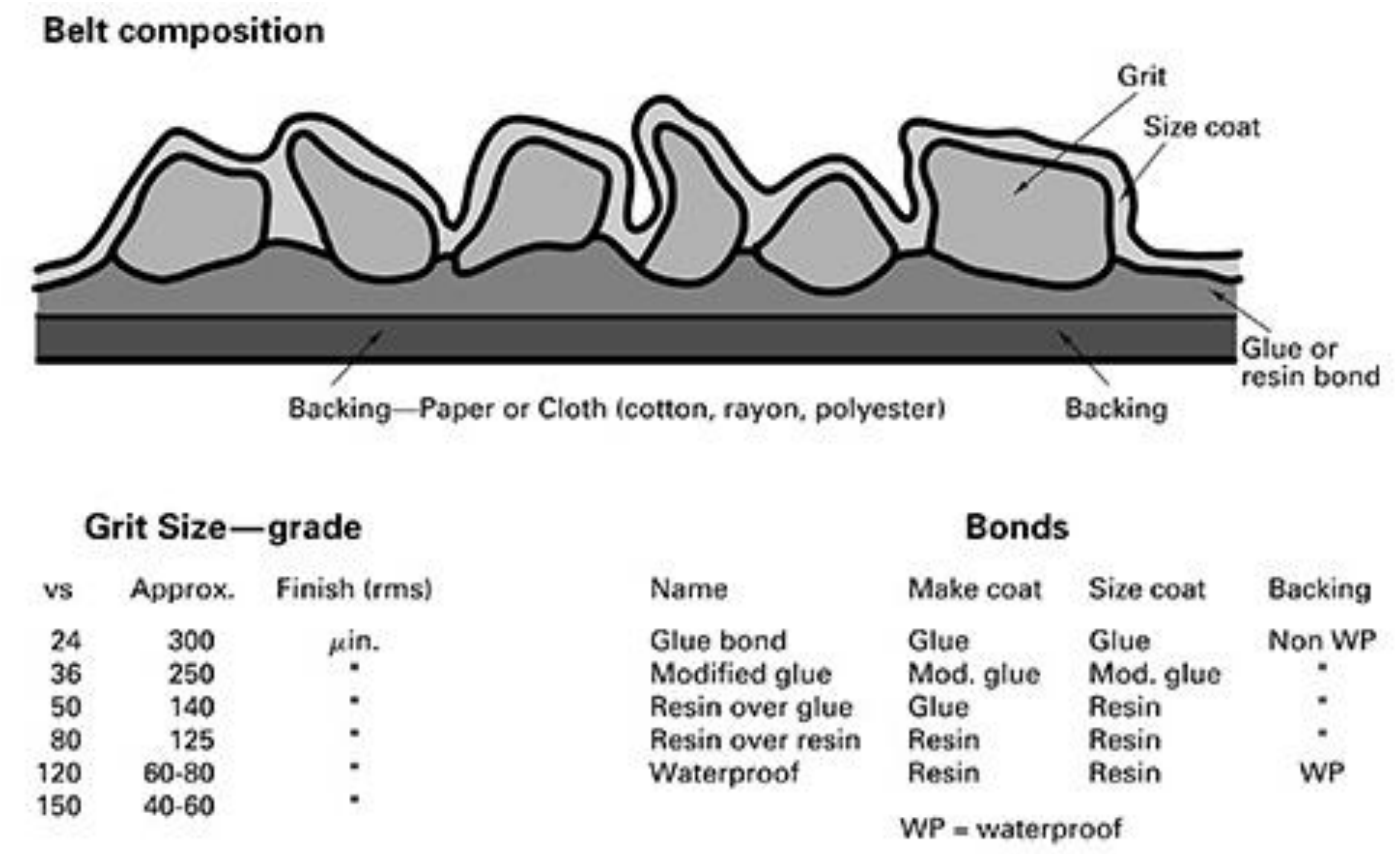


FIGURE 28-25 Examples of mounted abrasive wheels and points. *(Courtesy of Norton Company.)*

Coated Abrasives



Grit Size—grade

vs	Approx.	Finish (rms)
24	300	µin.
36	250	"
50	140	"
80	125	"
120	60-80	"
150	40-60	"

Bonds

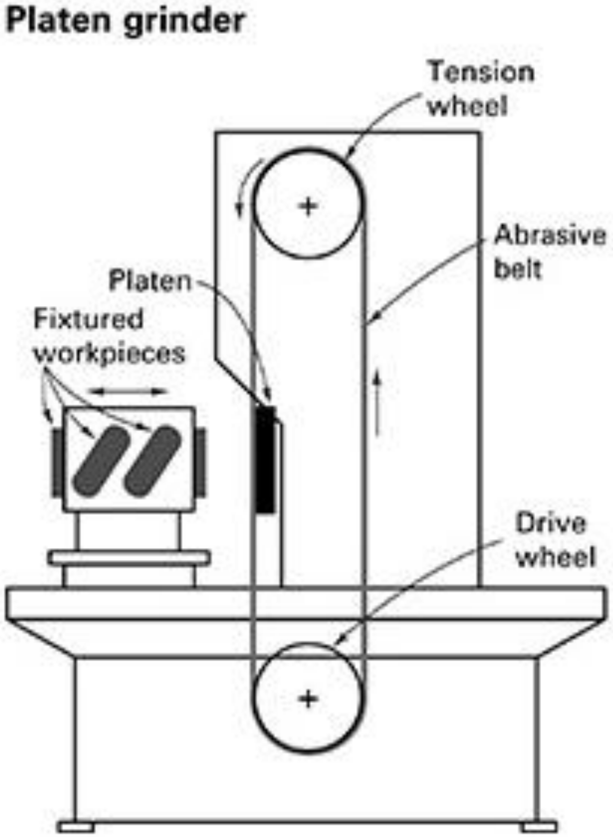
Name	Make coat	Size coat	Backing
Glue bond	Glue	Glue	Non WP
Modified glue	Mod. glue	Mod. glue	"
Resin over glue	Glue	Resin	"
Resin over resin	Resin	Resin	"
Waterproof	Resin	Resin	WP

WP = waterproof

FIGURE 28-26 Belt composition for coated abrasives (top).

Coated Abrasive Machines

FIGURE 28-26 Platen grinder and examples of belts and disks for abrasive machining.

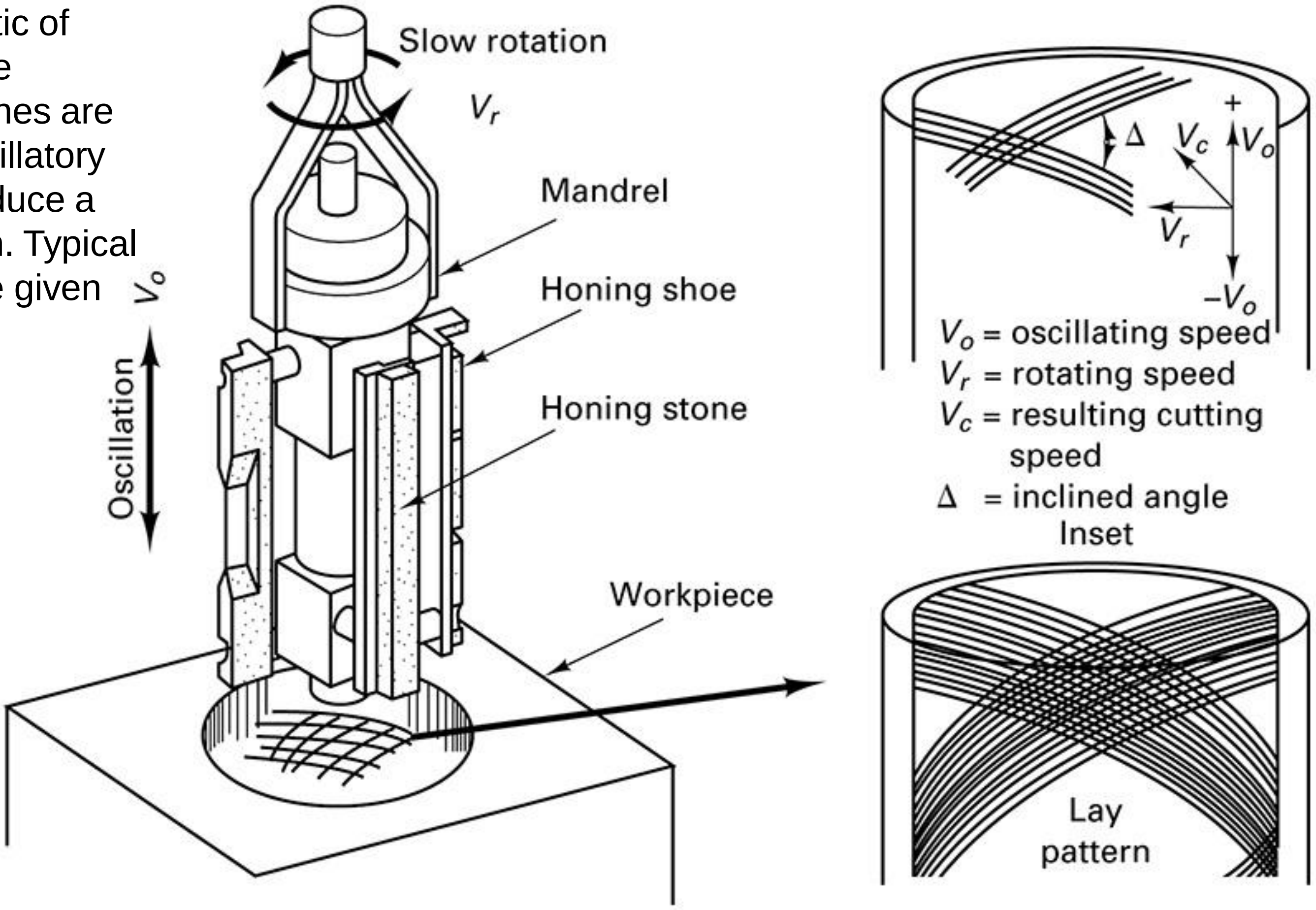


28.6 Honing

- Honing is used to produce is used to remove small amounts of material to produce an exacting size and surface finish.
- Most common application is to produce precise surface finish in engine cylinder walls and hydraulic cylinder fabrication
- Rotation and axial oscillation is used to produce the desired surface throughout the entire length of the hole.
- Honing is done with cutting fluids and honing stones, special grinding stones with 80-600 grit with the addition of additives to modify the cutting

Cylindrical Honing

FIGURE 28-27 Schematic of honing head showing the manner in which the stones are held. The rotary and oscillatory motions combine to produce a crosshatched lay pattern. Typical values for *Vc* and *Ps* are given below.



28.7 Superfinishing

- *Superfinishing* is a variation of honing that is typically used on flat surfaces. The process is:
  - **1.** Very light, controlled pressure, 10 to 40 psi
  - **2.** Rapid (over 400 cycles per minute), short strokes—less than 1/4 in.
  - **3.** Stroke paths controlled so that a single grit never traverses the same path twice
  - **4.** Copious amounts of low-viscosity lubricant-coolant flooded over the work surface

Superfinishing

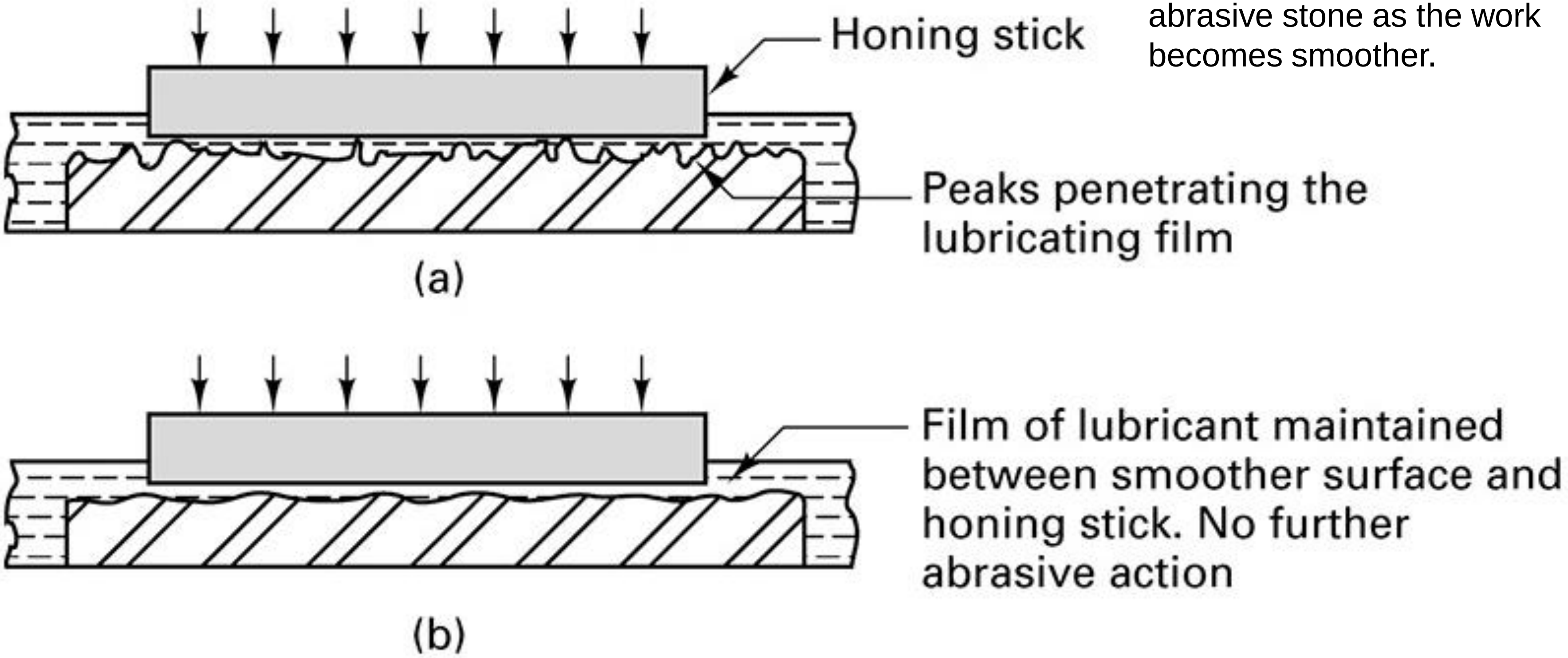


FIGURE 28-28 In superfinishing and honing, a film of lubricant is established between the work and the abrasive stone as the work becomes smoother.

Lapping

- Lapping is the process where the abrasive media is charged (embedded) into a softer media called lap
- Lap material range from various types of cloth, or soft metal such as copper.
- The embedded particles do the cutting not the lap
- The abrasive is carried away by the lapping oil, or coolant, and needs frequent replacement.
- Lapping removes material very slowly and is typically used to remove machining and grinding marks, producing a polished surface.

28.8 Free Abrasives

- There are various forms of free abrasive machining
  - Ultrasonic
    - Abrasives are mixed in a slurry, ultrasonic transducers provide the mechanical agitation to remove the material
  - Waterjet cutting (WJC)
    - Water at 60,000 psi and 3000 ft/s erode the material
  - Abrasive Waterjet Cutting (AWC)
    - Abrasives are added to a Waterjet to improve the efficiency
  - Abrasive Jet Cutting (AJC)
    - Abrasives are mixed in a high velocity air stream at 1000 ft/s

Ultrasonic Machining

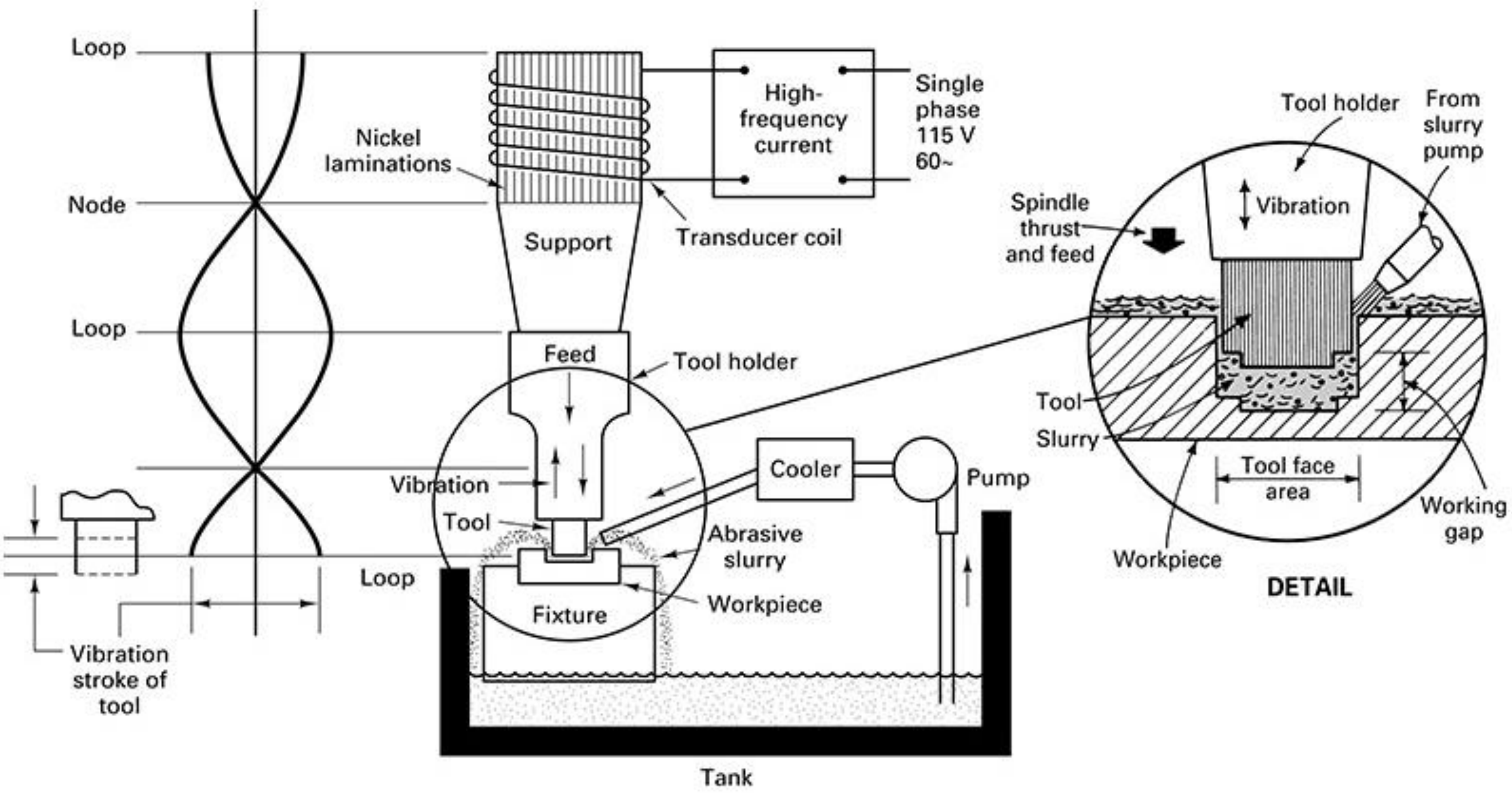


FIGURE 28-29 Sinking a hole in a workpiece with an ultrasonically vibrating tool driving an abrasive slurry.

Water Jet Machining

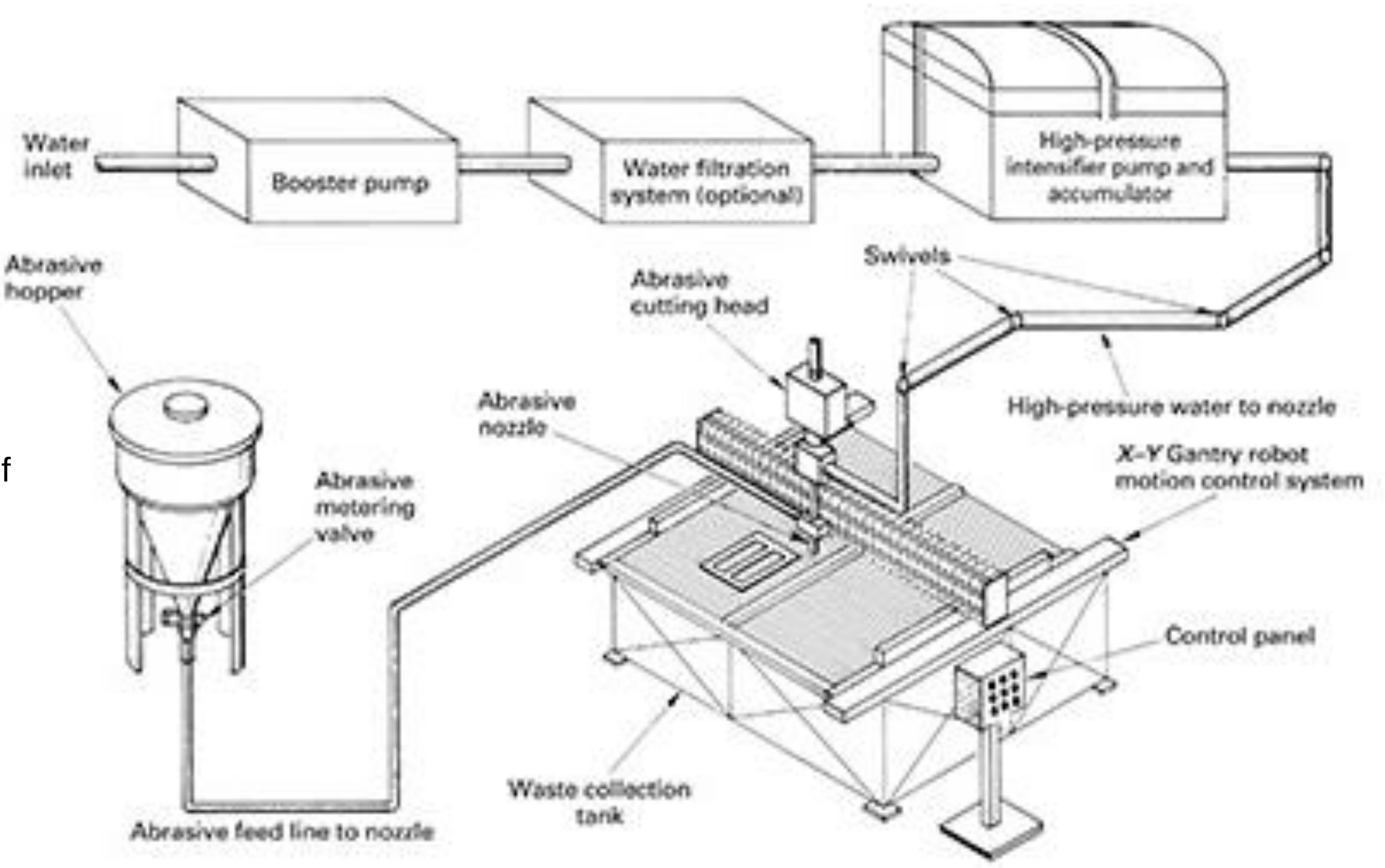
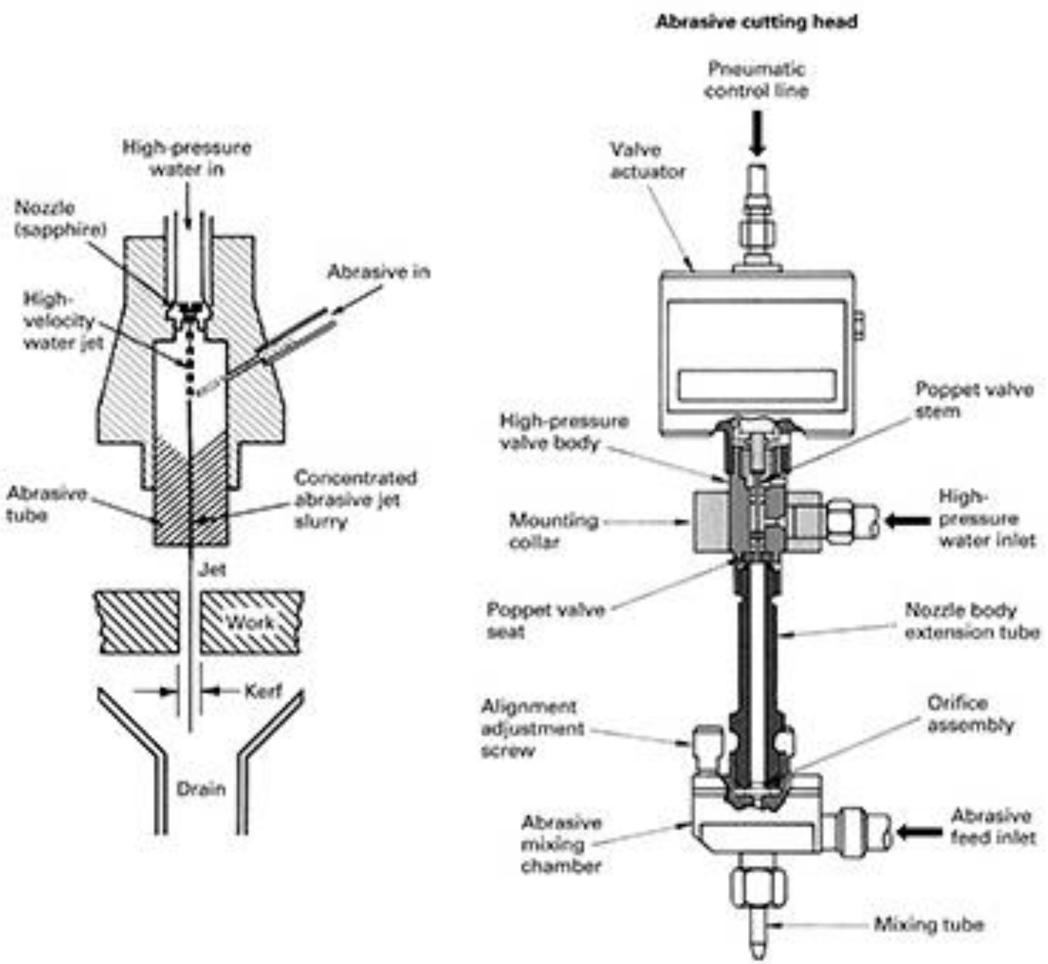


FIGURE 28-30
Schematic diagram of hydrodynamic jet machining.
The intensifier elevates the fluid to the desired nozzle pressure while the accumulator smoothes out the pulses in the fluid jet.

Water Jet Cutting Head

FIGURE 28-30 Schematic of an abrasive waterjet machining nozzle is shown on the right.



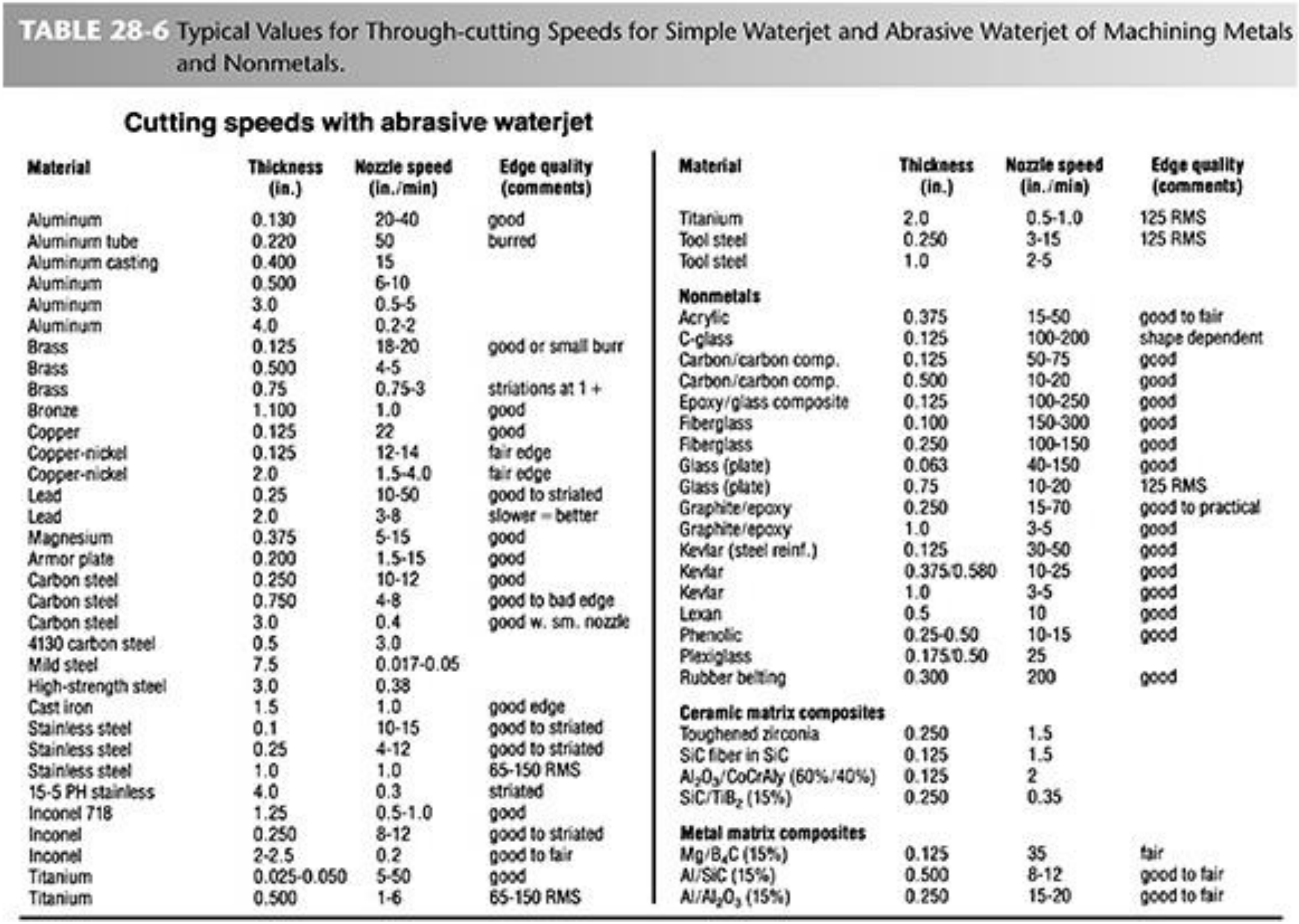


TABLE 28-6 Typical Values for Through-cutting Speeds for Simple Waterjet and Abrasive Waterjet of Machining Metals and Nonmetals.

Cutting speeds with abrasive waterjet

Material	Thickness (in.)	Nozzle speed (in./min)	Edge quality (comments)
Aluminum	0.130	20-40	good
Aluminum tube	0.220	50	burred
Aluminum casting	0.400	15	
Aluminum	0.500	6-10	
Aluminum	3.0	0.5-5	
Aluminum	4.0	0.2-2	
Brass	0.125	18-20	good or small burr
Brass	0.500	4-5	
Brass	0.75	0.75-3	striations at 1 +
Bronze	1.100	1.0	good
Copper	0.125	22	good
Copper-nickel	0.125	12-14	fair edge
Copper-nickel	2.0	1.5-4.0	fair edge
Lead	0.25	10-50	good to striated
Lead	2.0	3-8	slower = better
Magnesium	0.375	5-15	good
Armor plate	0.200	1.5-15	good
Carbon steel	0.250	10-12	good
Carbon steel	0.750	4-8	good to bad edge
Carbon steel	3.0	0.4	good w. sm. nozzle
4130 carbon steel	0.5	3.0	
Mild steel	7.5	0.017-0.05	
High-strength steel	3.0	0.38	
Cast iron	1.5	1.0	good edge
Stainless steel	0.1	10-15	good to striated
Stainless steel	0.25	4-12	good to striated
Stainless steel	1.0	1.0	65-150 RMS
15-5 PH stainless	4.0	0.3	striated
Inconel 718	1.25	0.5-1.0	good
Inconel	0.250	8-12	good to striated
Inconel	2-2.5	0.2	good to fair
Titanium	0.025-0.050	5-50	good
Titanium	0.500	1-6	65-150 RMS
Titanium	2.0	0.5-1.0	125 RMS
Tool steel	0.250	3-15	125 RMS
Tool steel	1.0	2-5	
Nonmetals			
Acrylic	0.375	15-50	good to fair
C-glass	0.125	100-200	shape dependent
Carbon/carbon comp.	0.125	50-75	good
Carbon/carbon comp.	0.500	10-20	good
Epoxy/glass composite	0.125	100-250	good
Fiberglass	0.100	150-300	good
Fiberglass	0.250	100-150	good
Glass (plate)	0.063	40-150	good
Glass (plate)	0.75	10-20	125 RMS
Graphite/epoxy	0.250	15-70	good to practical
Graphite/epoxy	1.0	3-5	good
Kevlar (steel reinf.)	0.125	30-50	good
Kevlar	0.375/0.580	10-25	good
Kevlar	1.0	3-5	good
Lexan	0.5	10	good
Phenolic	0.25-0.50	10-15	good
Plexiglass	0.175/0.50	25	
Rubber belting	0.300	200	good
Ceramic matrix composites			
Toughened zirconia	0.250	1.5	
SiC fiber in SiC	0.125	1.5	
Al_2O_3/CoCrAly (60%/40%)	0.125	2	
SiC/TiB_2 (15%)	0.250	0.35	
Metal matrix composites			
Mg/B_4C (15%)	0.125	35	fair
Al/SiC (15%)	0.500	8-12	good to fair
Al/Al_2O_3 (15%)	0.250	15-20	good to fair

Cutting Speeds for a Waterjet

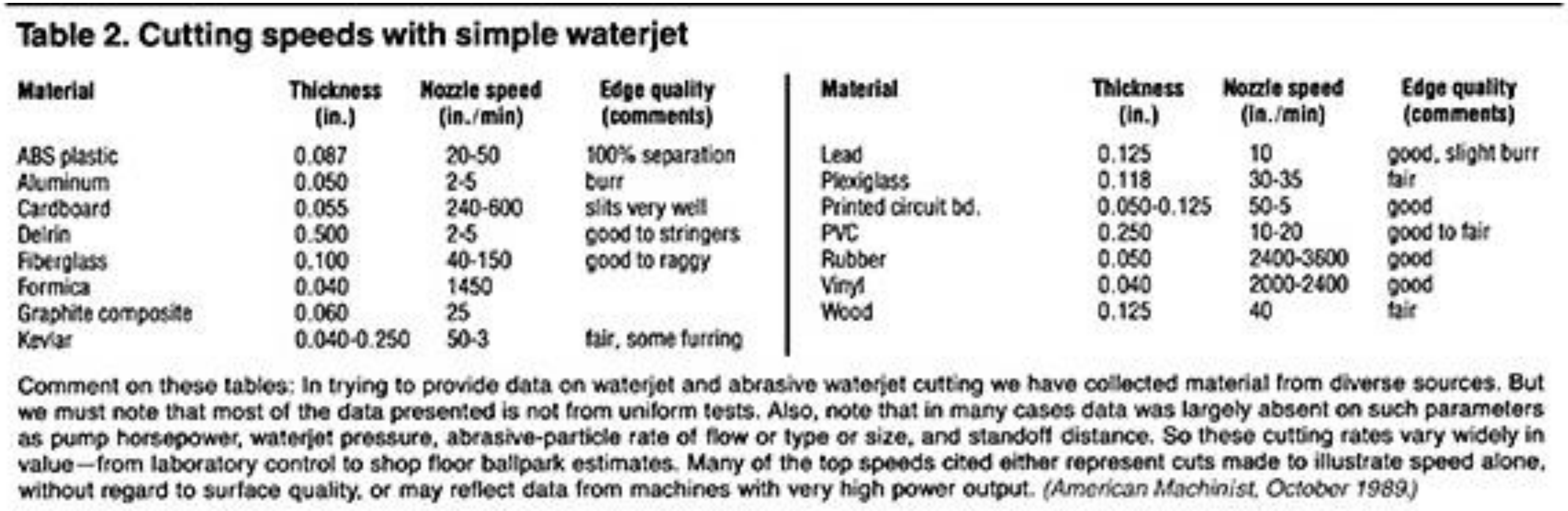


Table 2. Cutting speeds with simple waterjet

Material	Thickness (in.)	Nozzle speed (in./min)	Edge quality (comments)
ABS plastic	0.087	20-50	100% separation
Aluminum	0.050	2-5	burr
Cardboard	0.055	240-600	slits very well
Delrin	0.500	2-5	good to stringers
Fiberglass	0.100	40-150	good to raggy
Formica	0.040	1450	
Graphite composite	0.060	25	
Kevlar	0.040-0.250	50-3	fair, some furring
Lead	0.125	10	good, slight burr
Plexiglass	0.118	30-35	fair
Printed circuit bd.	0.050-0.125	50-5	good
PVC	0.250	10-20	good to fair
Rubber	0.050	2400-3600	good
Vinyl	0.040	2000-2400	good
Wood	0.125	40	fair

Comment on these tables: In trying to provide data on waterjet and abrasive waterjet cutting we have collected material from diverse sources. But we must note that most of the data presented is not from uniform tests. Also, note that in many cases data was largely absent on such parameters as pump horsepower, waterjet pressure, abrasive-particle rate of flow or type or size, and standoff distance. So these cutting rates vary widely in value—from laboratory control to shop floor ballpark estimates. Many of the top speeds cited either represent cuts made to illustrate speed alone, without regard to surface quality, or may reflect data from machines with very high power output. *(American Machinist, October 1989.)*