Chapter 11: Fundamentals of Casting

DeGarmo's Materials and Processes in Manufacturing

11.1 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

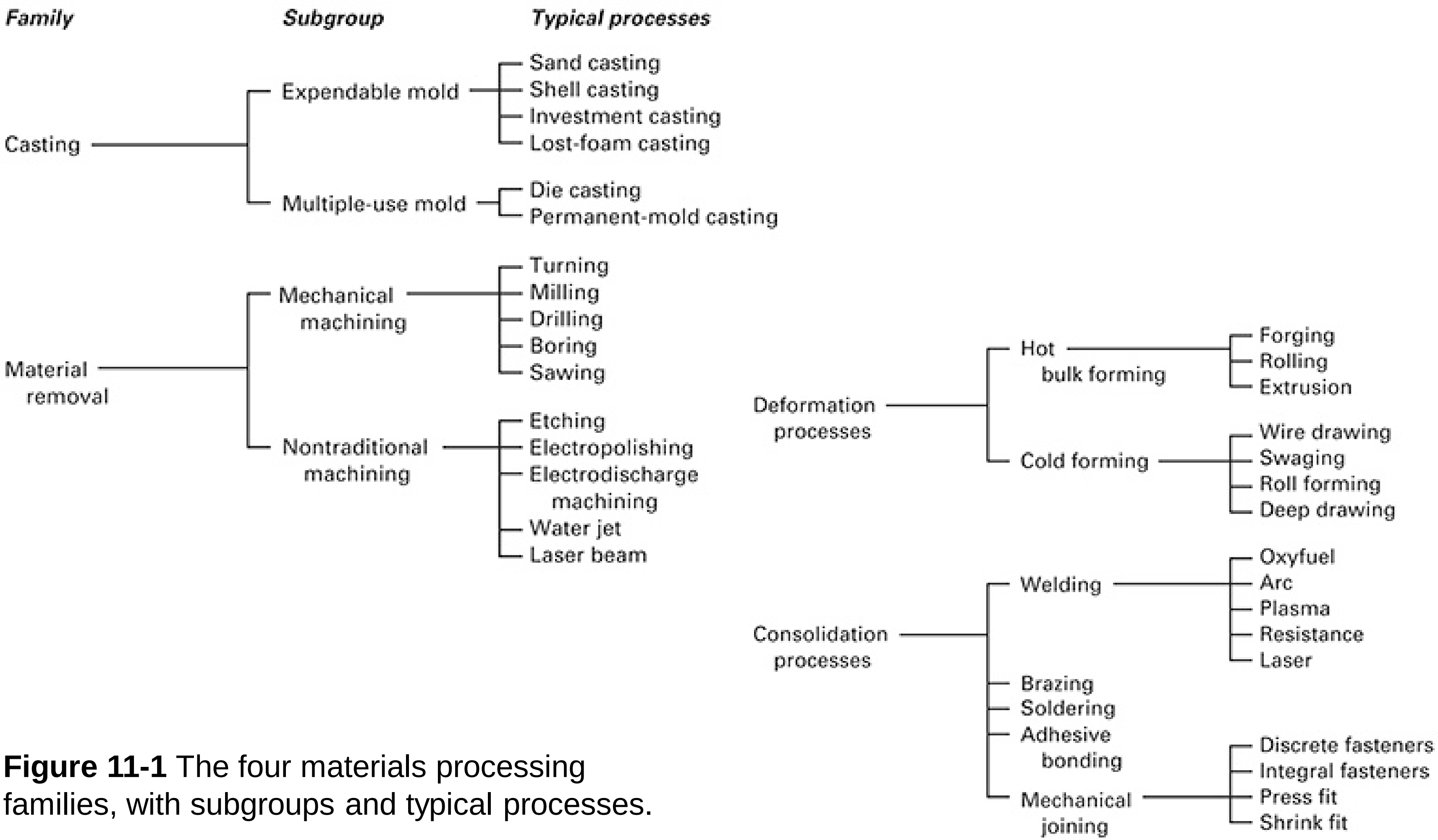


Figure 11-1 The four materials processing families, with subgroups and typical processes.

11.2 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

11.3 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

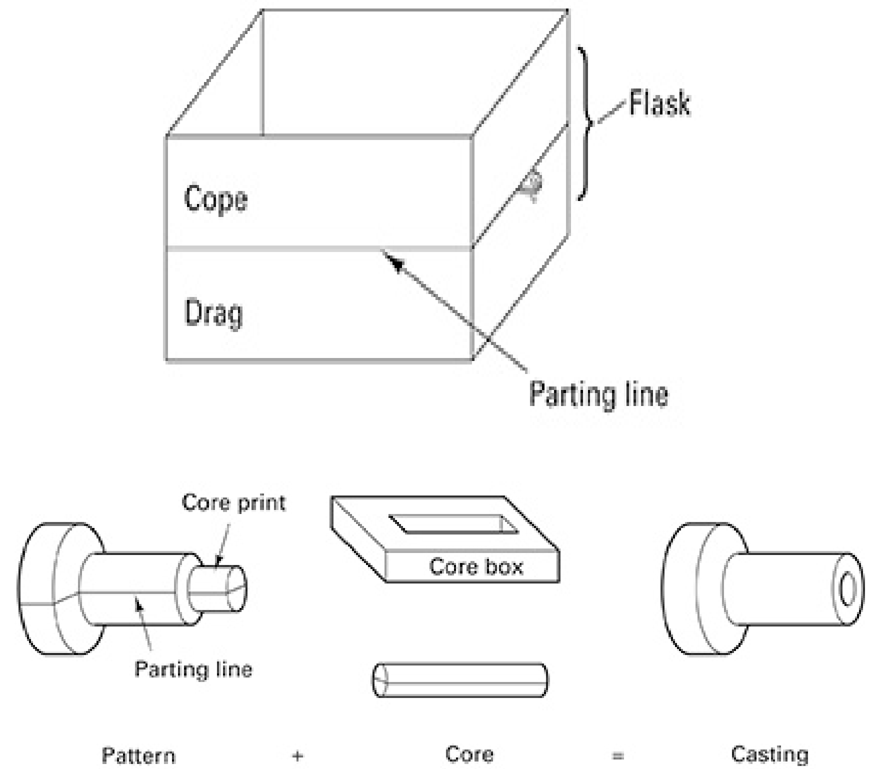


Figure 11-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

Cross Section of a Mold

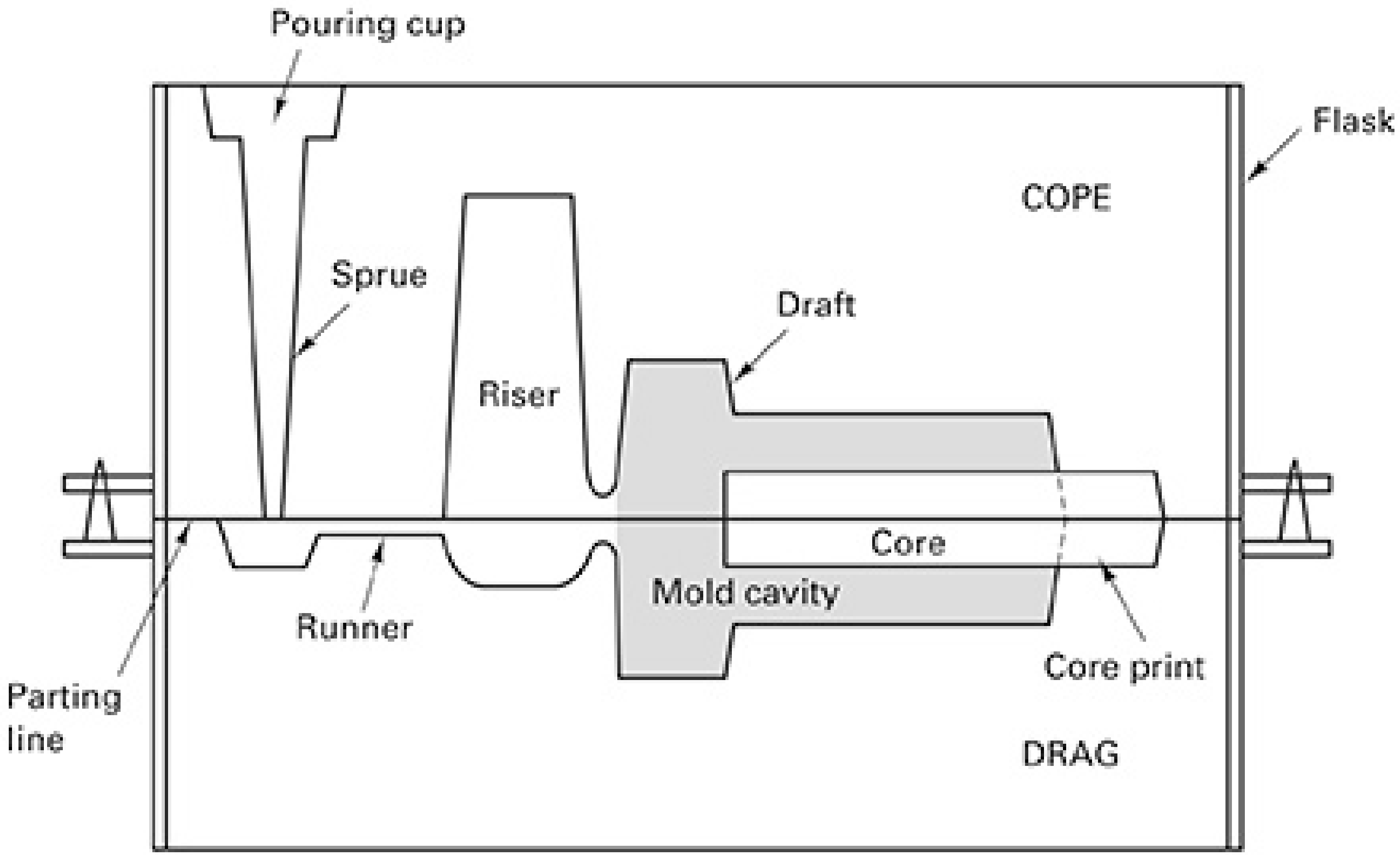


Figure 11-2

11.4 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

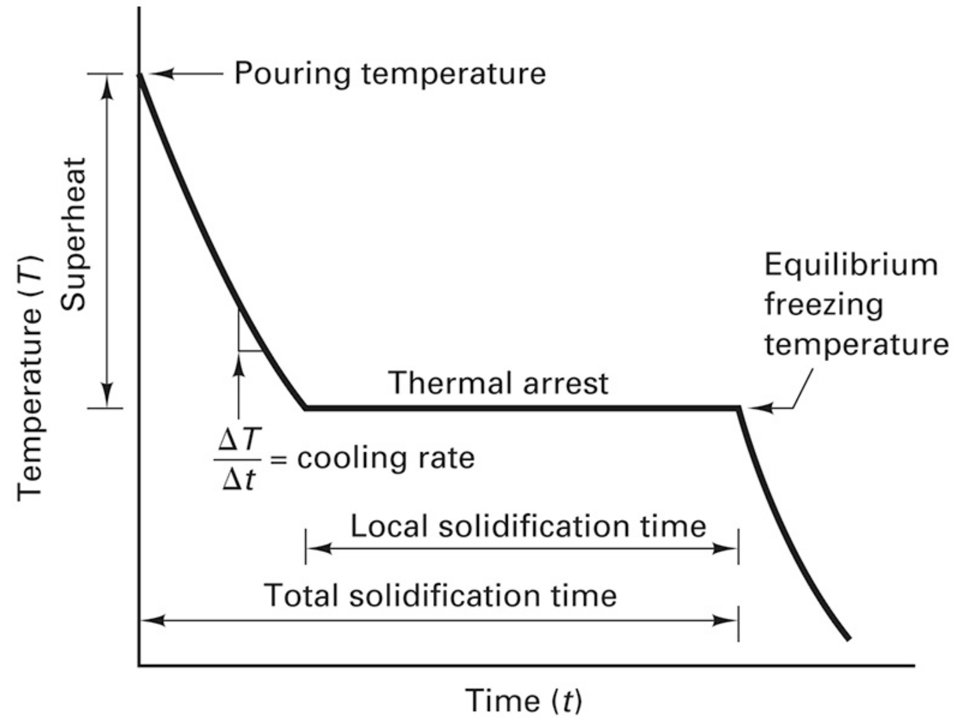


Figure 11-3 Cooling curve for a pure metal or eutectic-composition alloy (metals with a distinct freezing point), indicating major features related to solidification.

Cooling Curves

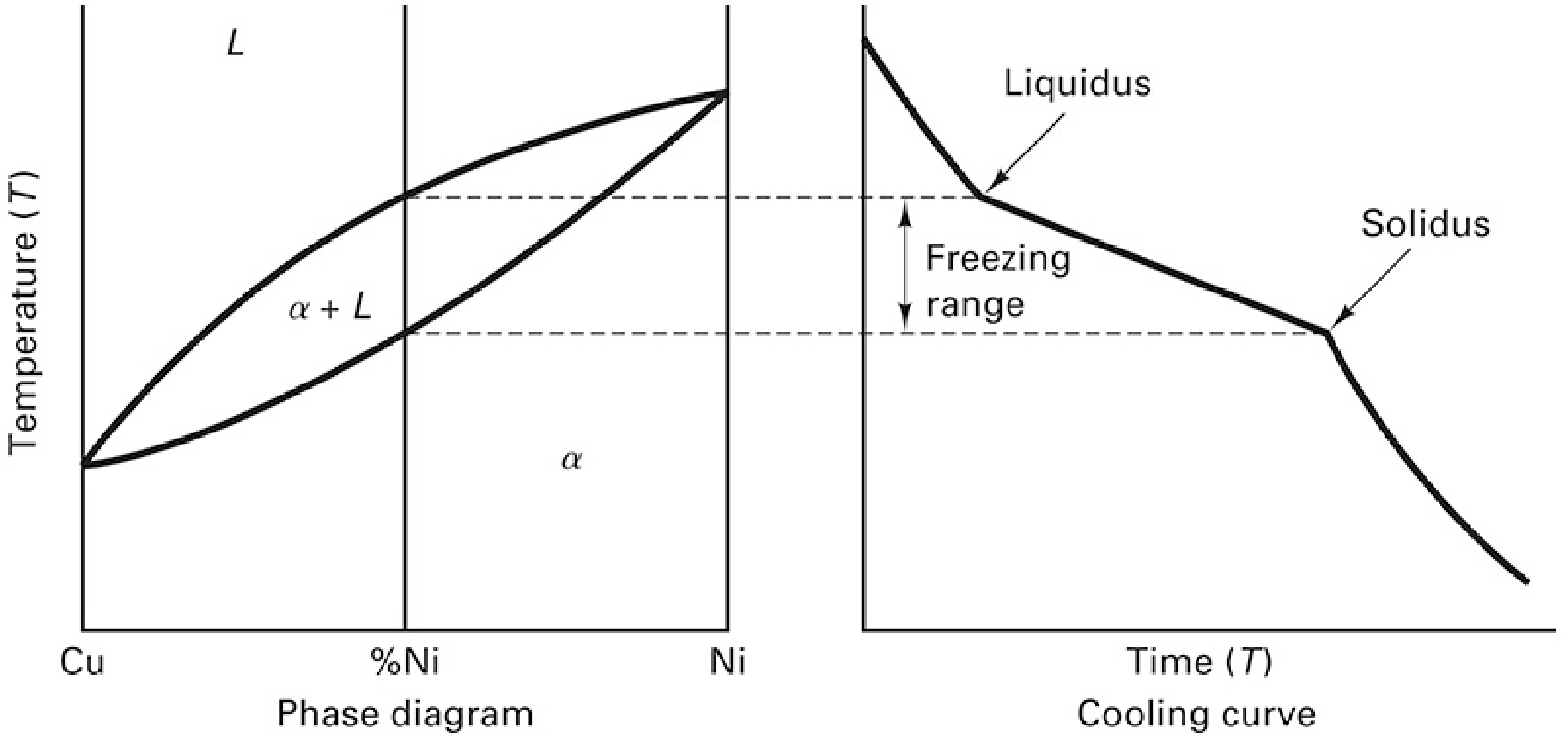


Figure 11-4 Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes indicate the onset and termination of solidification.

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

[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

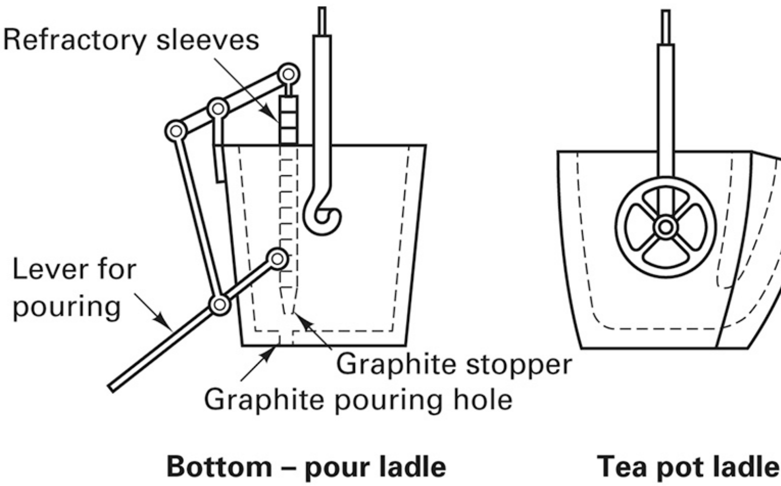
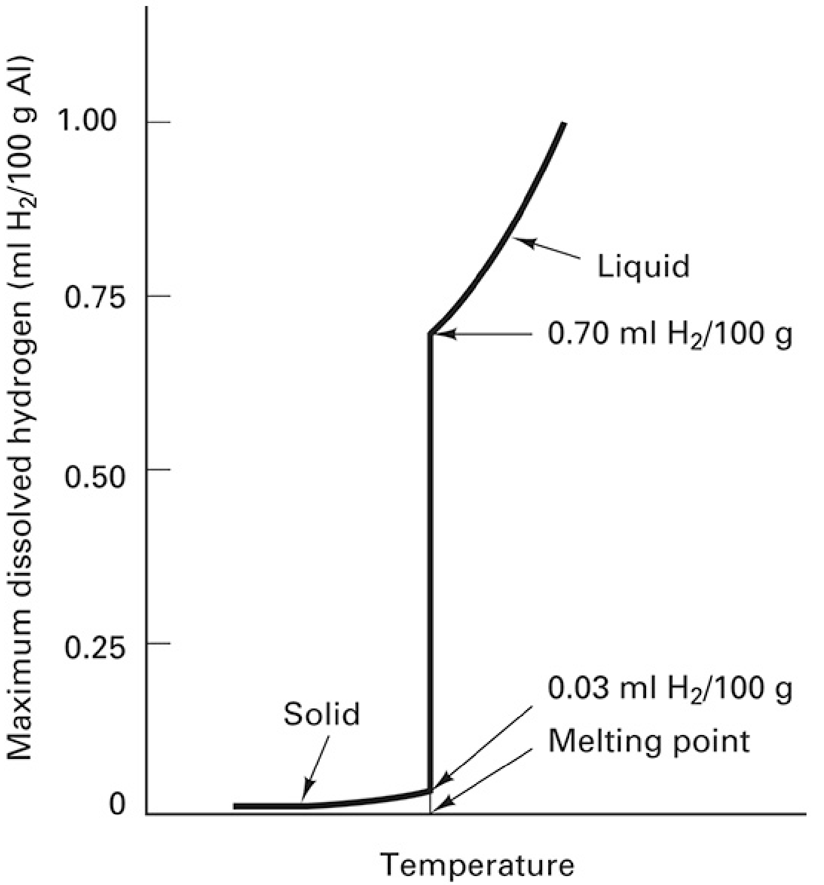


Figure 11-6 Two types of ladles used to pour castings. Note how each extracts molten material from the bottom, avoiding transfer of the impure material from the top of the molten pool.

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

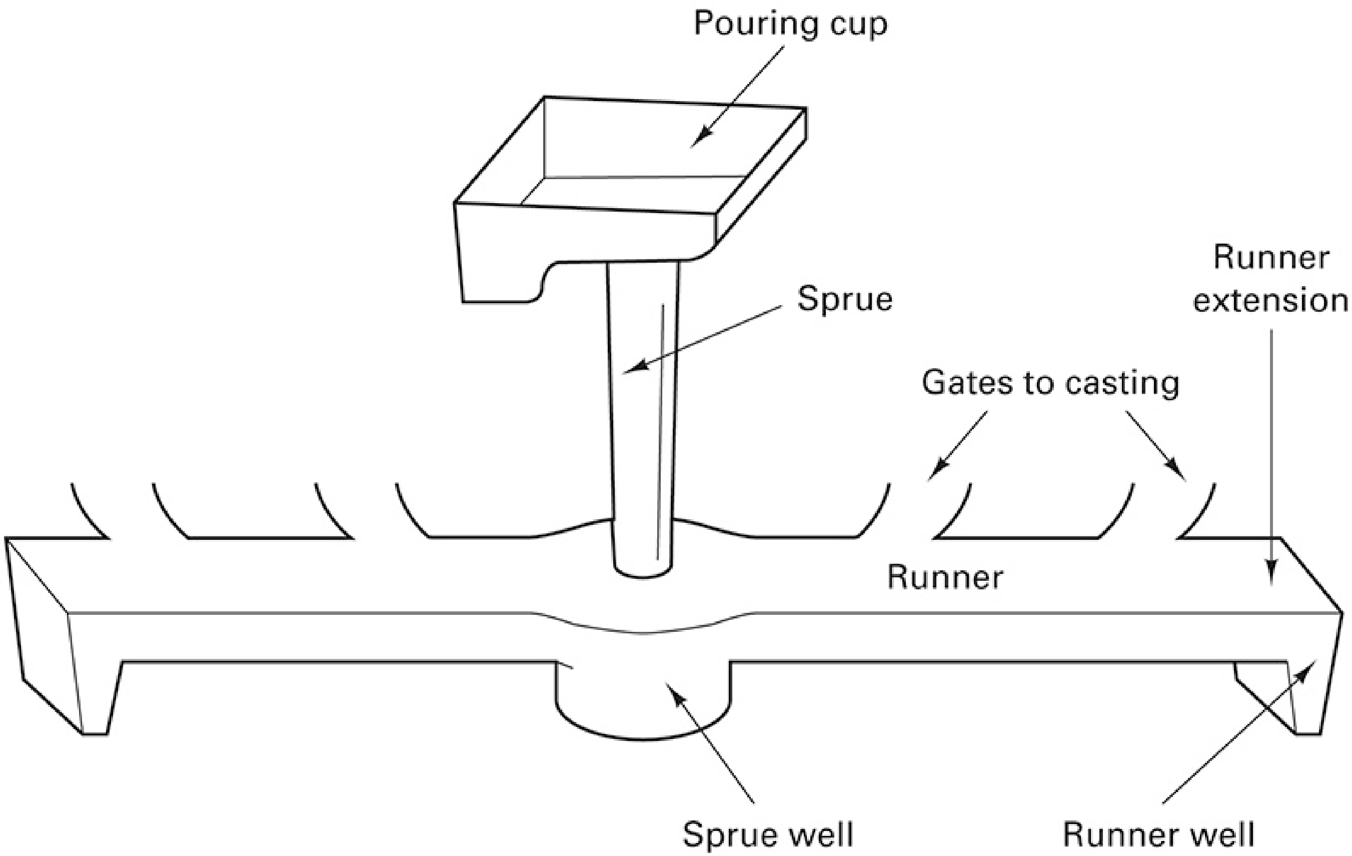


Figure 11-9 Typical gating system for a horizontal parting plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

Filters

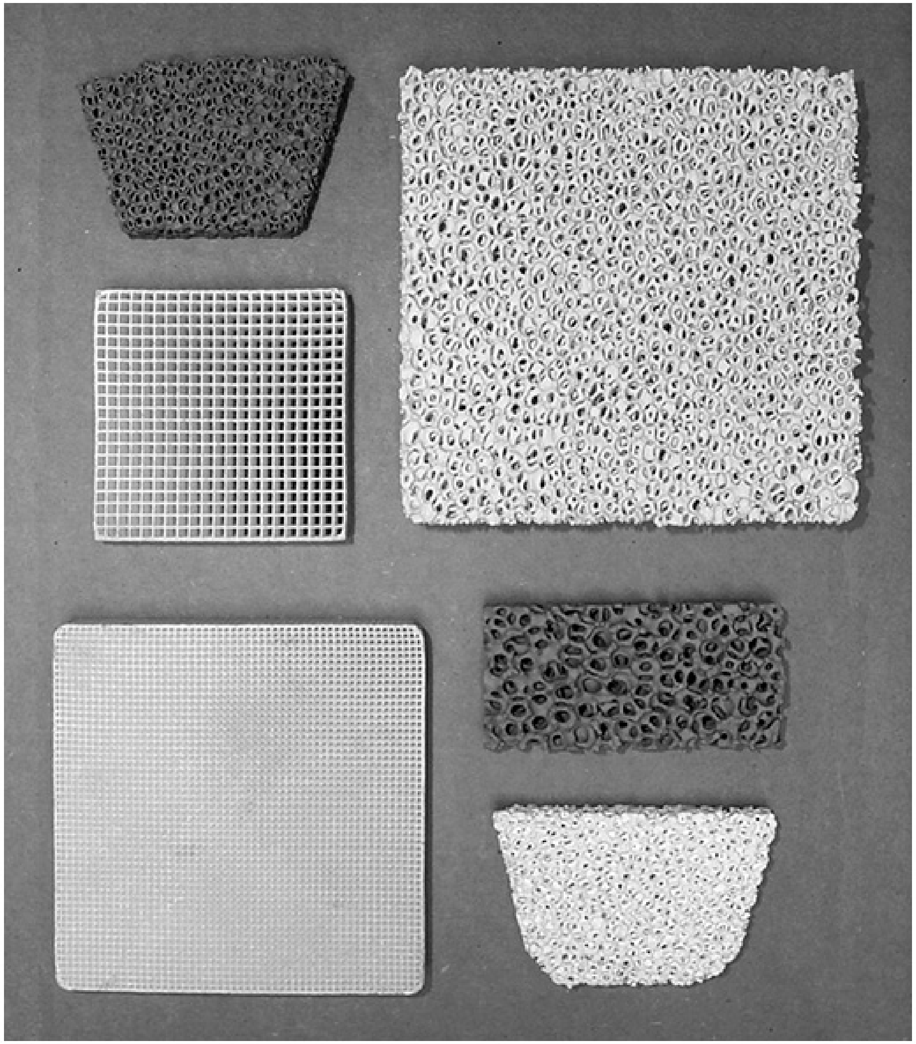


Figure 11-10 Various types of ceramic filters that may be inserted into the gating systems of metal castings.

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

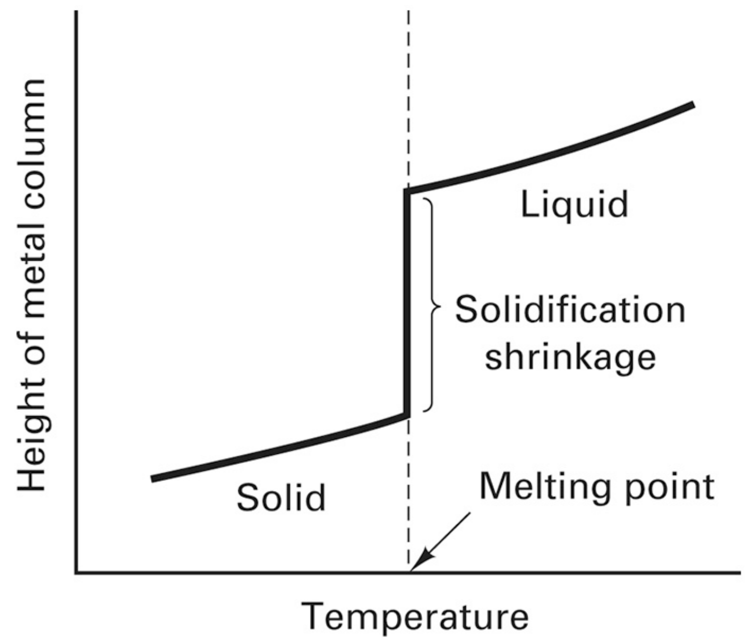


Figure 11-11 Dimensional changes experienced by a metal column as the material cools from a superheated liquid to a room-temperature solid. Note the significant shrinkage that occurs upon solidification.

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

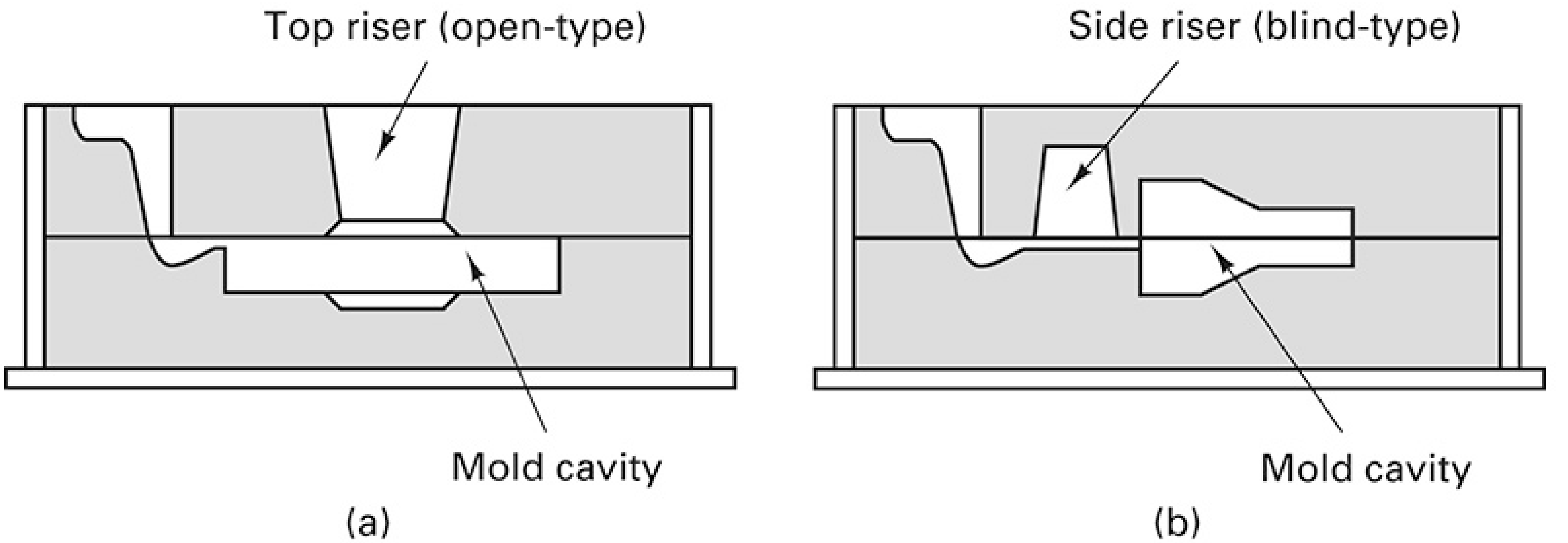


Figure 11-13 Schematic of a sand casting mold, showing a) an open-type top riser and b) a blind-type side riser. The side riser is a live riser, receiving the last hot metal to enter the mold. The top riser is a dead riser, receiving metal that has flowed through the mold cavity.

- 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

11.5 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

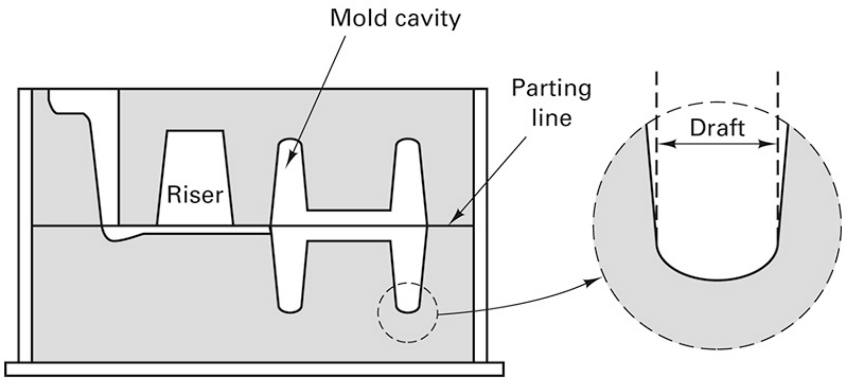


Figure 11-14 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

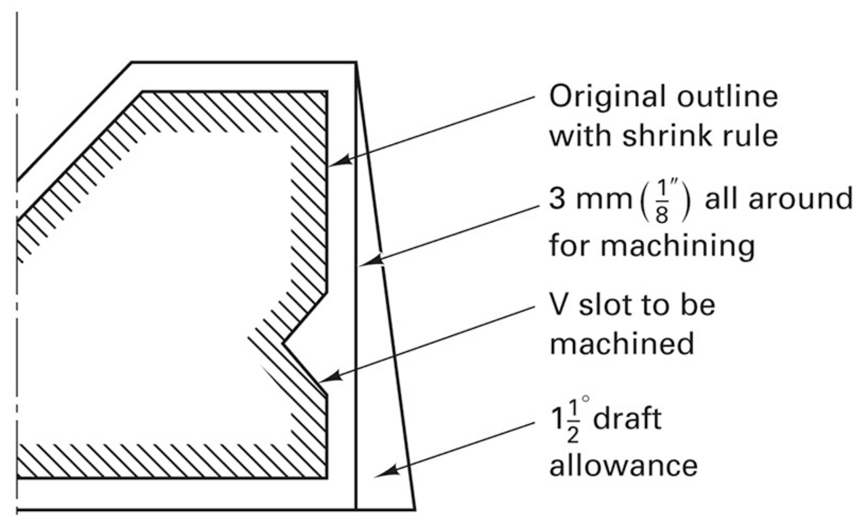


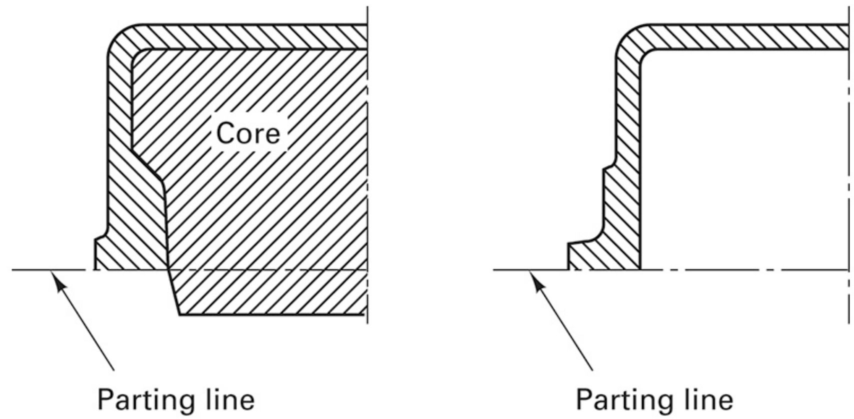
Figure 11-15 Various allowances incorporated into a casting pattern.

11.6 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.



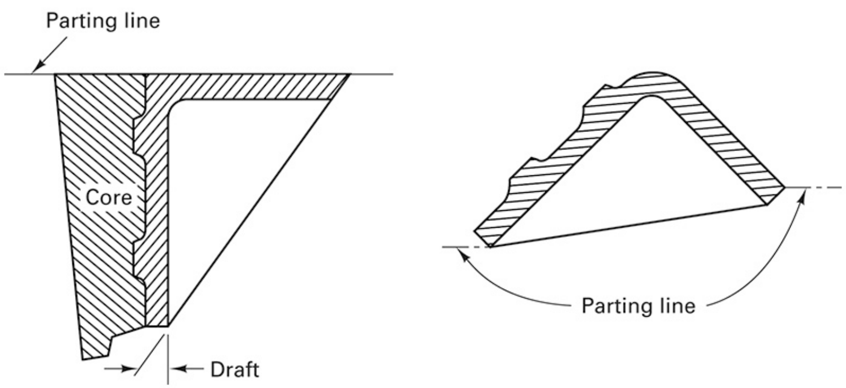


Figure 11-16 (Left) Elimination of a core by changing the location or orientation of the parting plane.

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

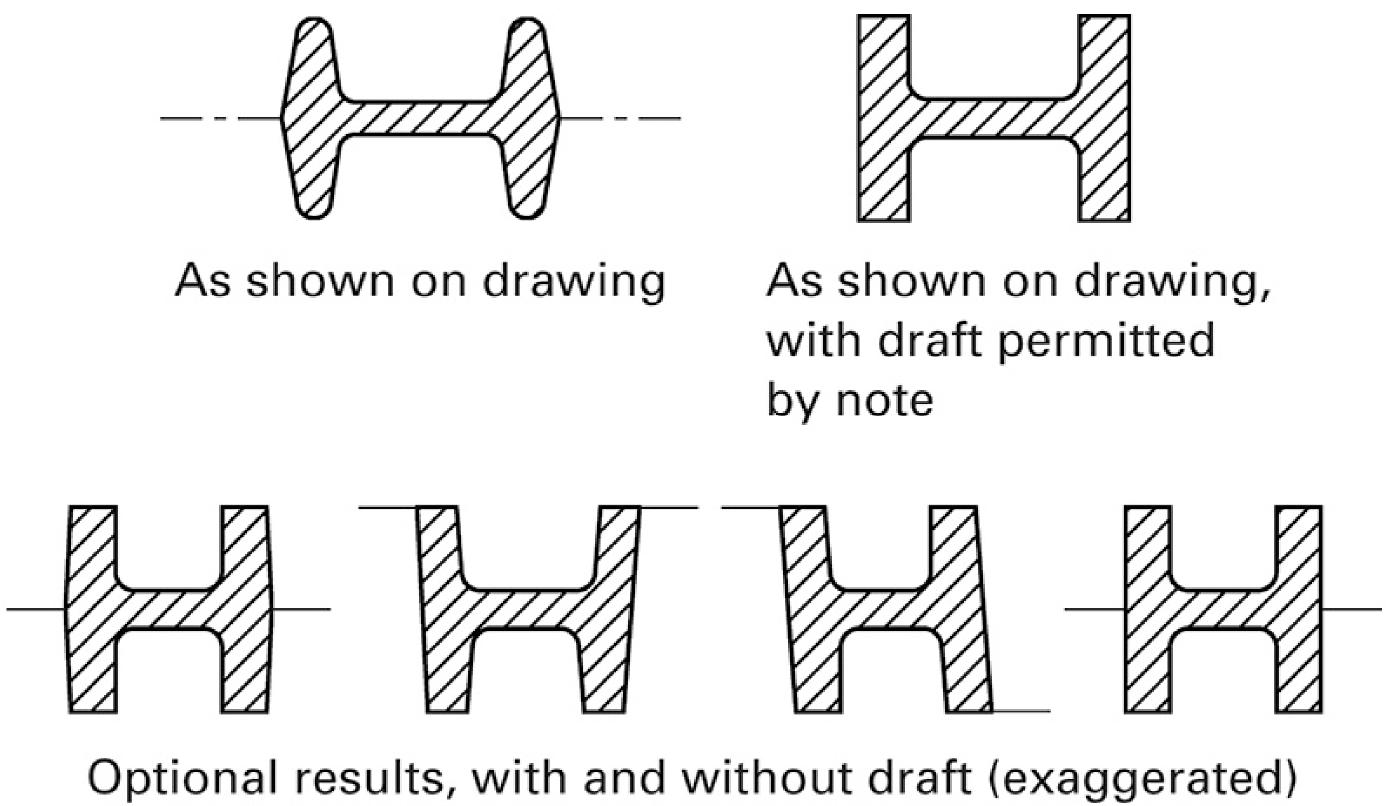


Figure 11-18 (Top left) Design where the location of the parting plane is specified by the draft. (Top right) Part with draft unspecified. (Bottom) Various options to produce the top-right part, including a no-draft design.

Section Thicknesses

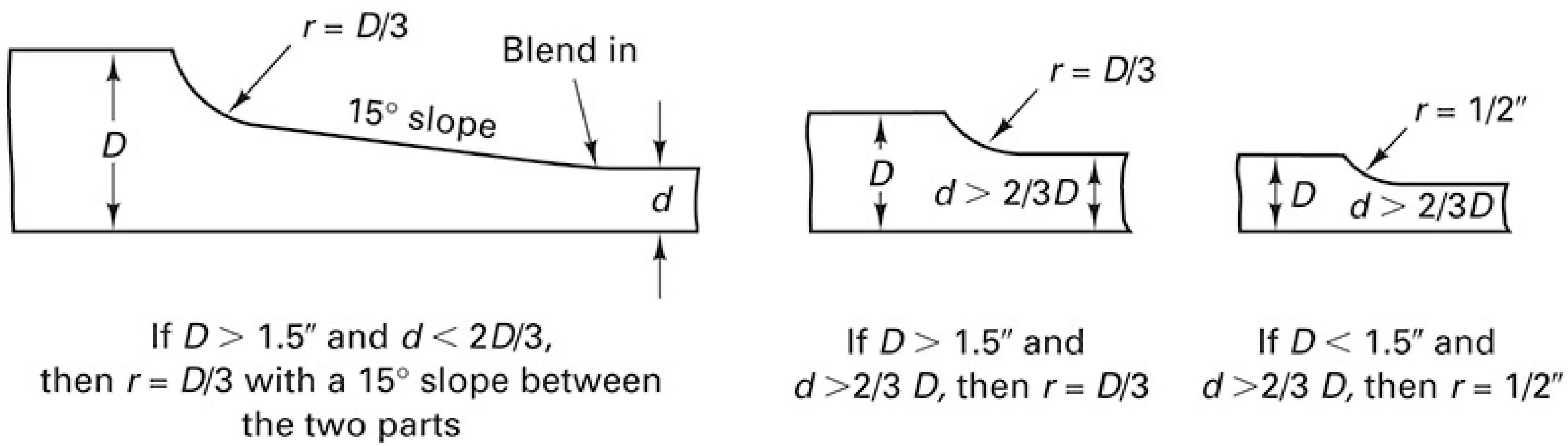


Figure 11-19 (Above) Typical guidelines for section change transitions in castings.

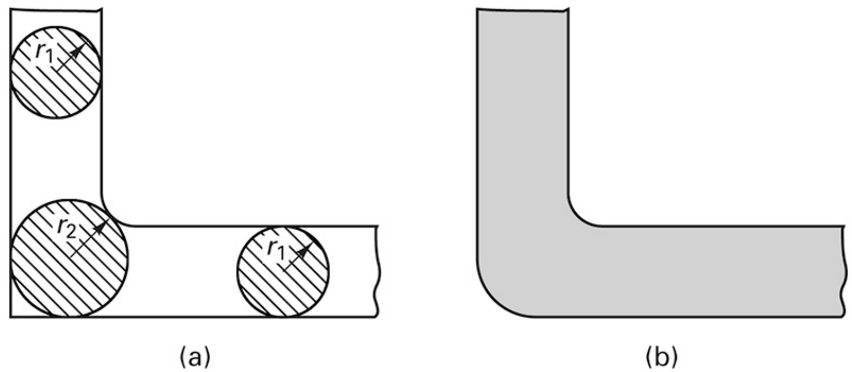


Figure 11-20 a) The "hot spot" at section r_2 is cause by intersecting sections. B) An interior fillet and exterior radius lead to more uniform thickness and more uniform cooling.

Design Modifications

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

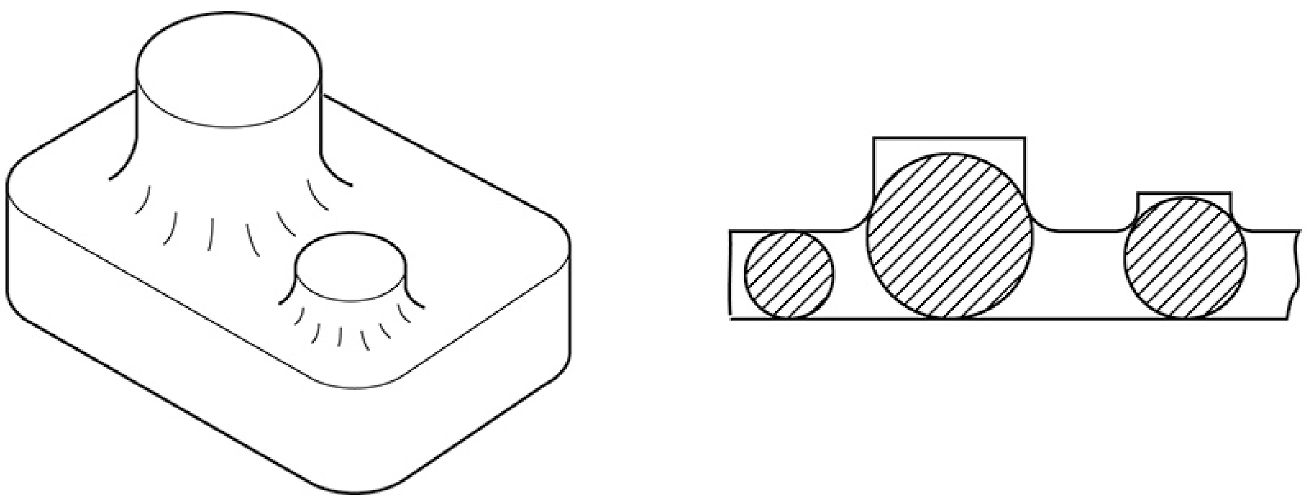


Figure 11-21 Hot spots often result from intersecting sections of various thickness.

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

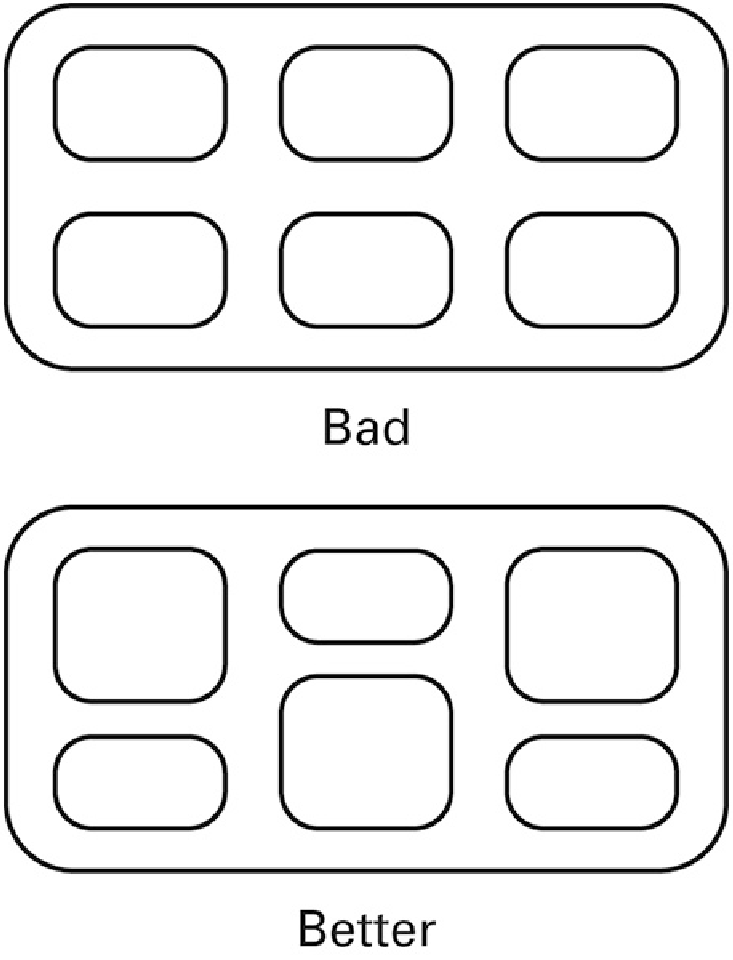


Figure 11-23 Using staggered ribs to prevent cracking during cooling.

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	—	—

11.7 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 12: Expendable-Mold Casting Process

DeGarmo's Materials and Processes in Manufacturing

12.1 Introduction

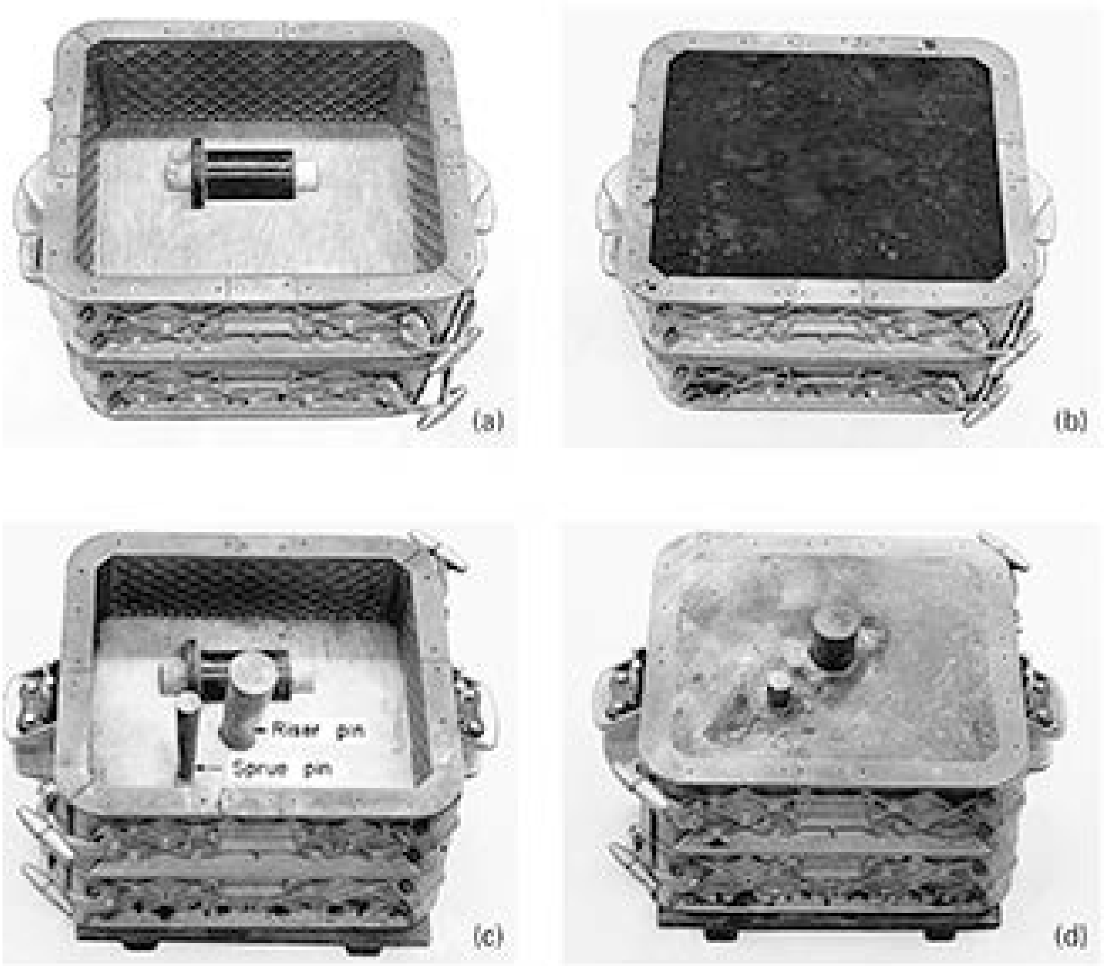
- Factors to consider for castings
  - Desired dimensional accuracy
  - Surface quality
  - Number of castings
  - Type of pattern and core box needed
  - Cost of required mold or die
  - Restrictions due to the selected material
- Three categories of molds
  - Single-use molds with multiple-use patterns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

12.2 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

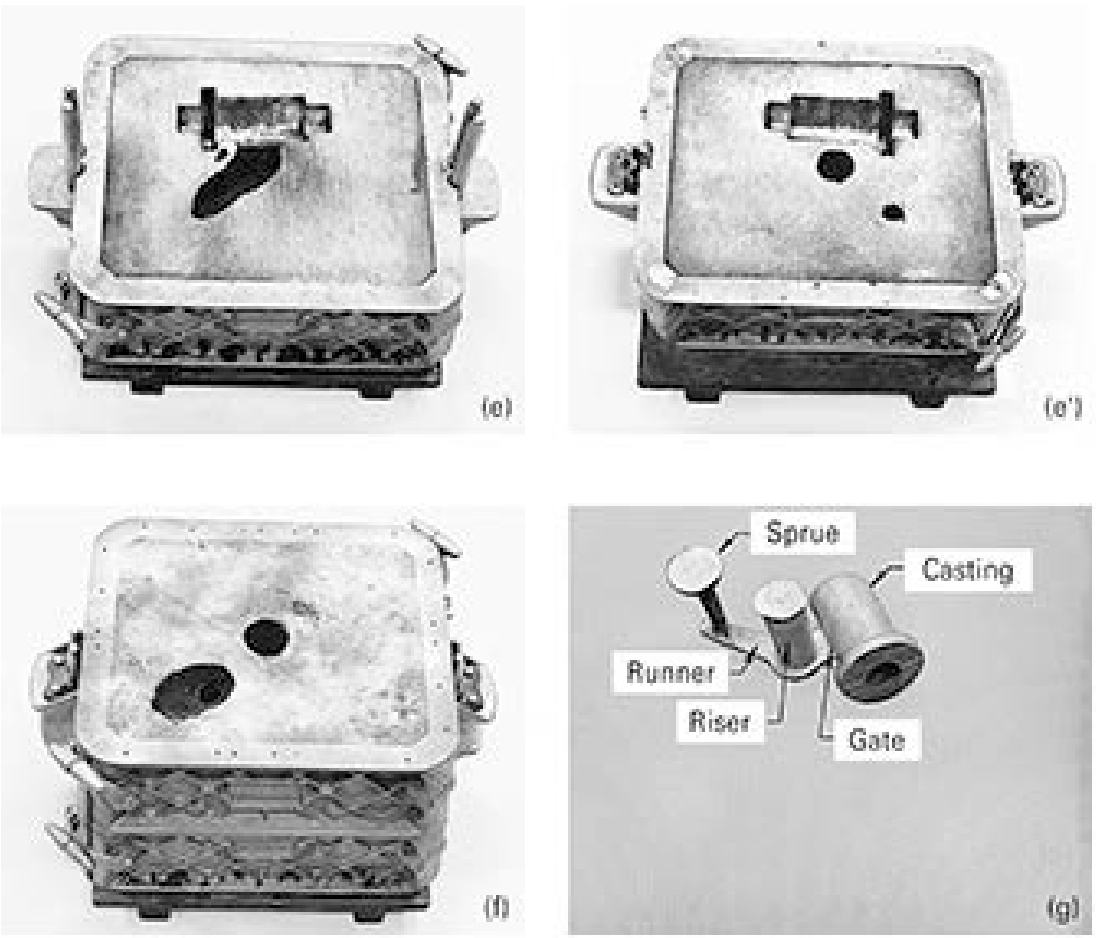


Figure 12-1 e) The mold is opened, the pattern board is drawn (removed), and the runner and gate are cut into the bottom parting surface of the sand. e') The parting surface of the upper or cope half of the mold is also shown with the pattern and pins removed. f) The mold is reassembled with the pattern 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

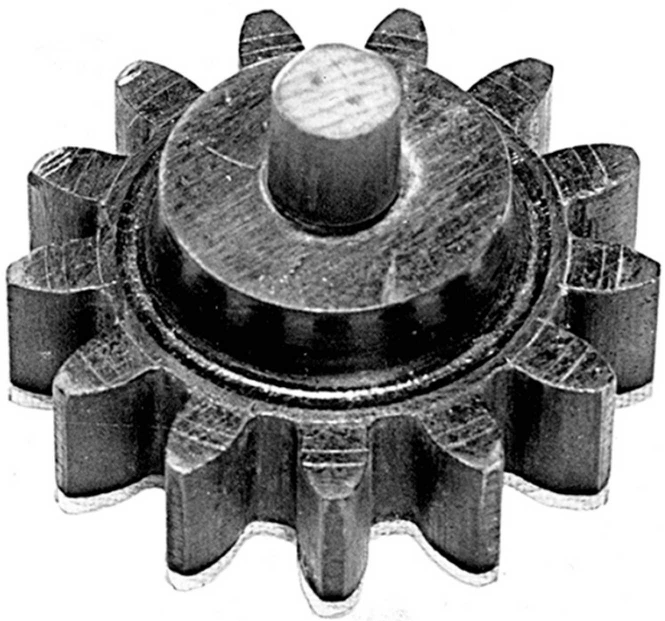
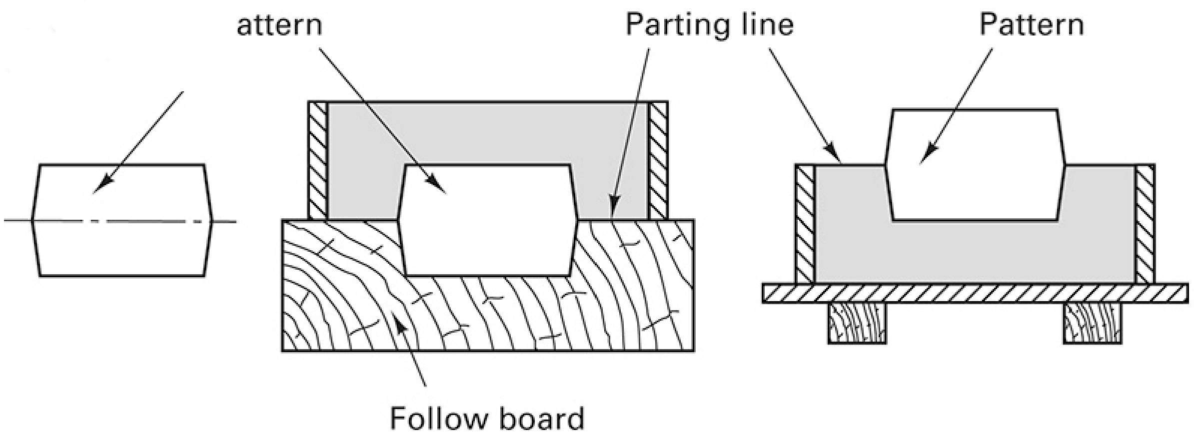


Figure 12-2 (Above) Single-piece pattern for a pinion gear.

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

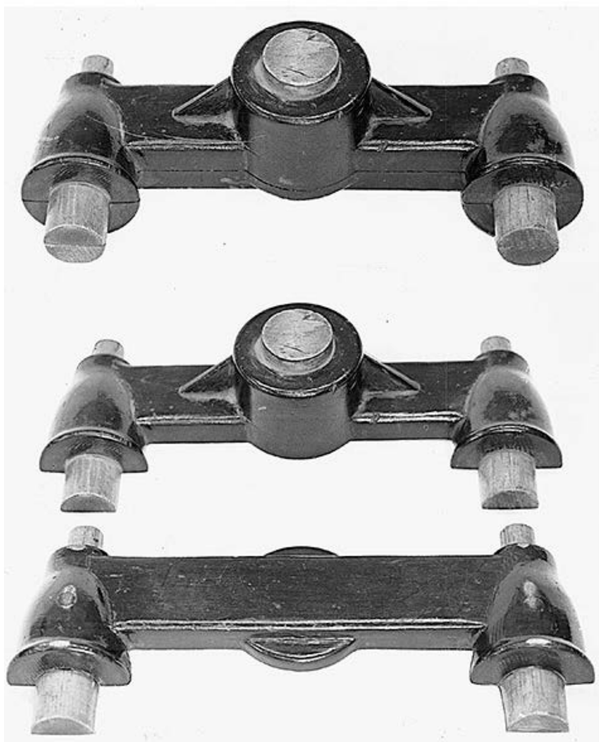


Figure 12-4 Split pattern, showing the two sections together and separated. The light-colored portions are core prints.

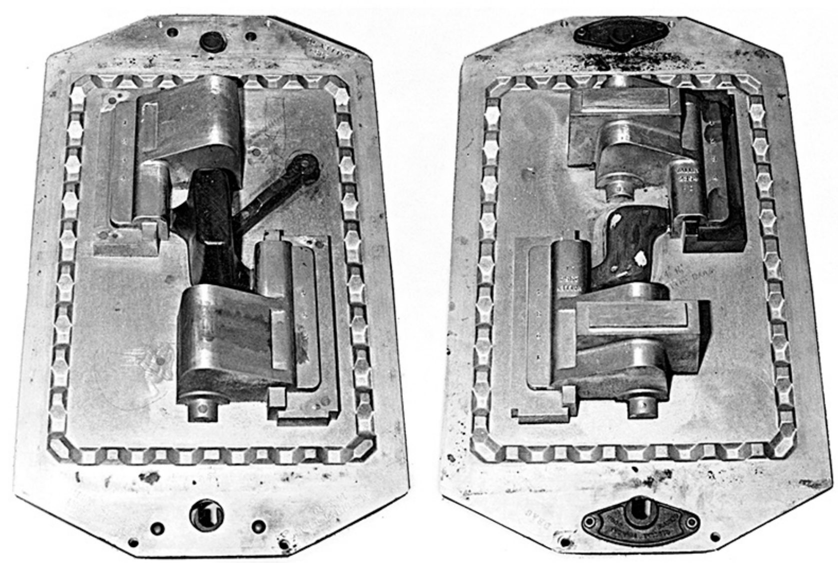


Figure 12-5 Match-plate pattern used to produce two identical parts in a single flask. (Left) Cope side; (right) drag side. (Note: The views are opposite sides of a single-pattern board.

Cope and Drag Patterns

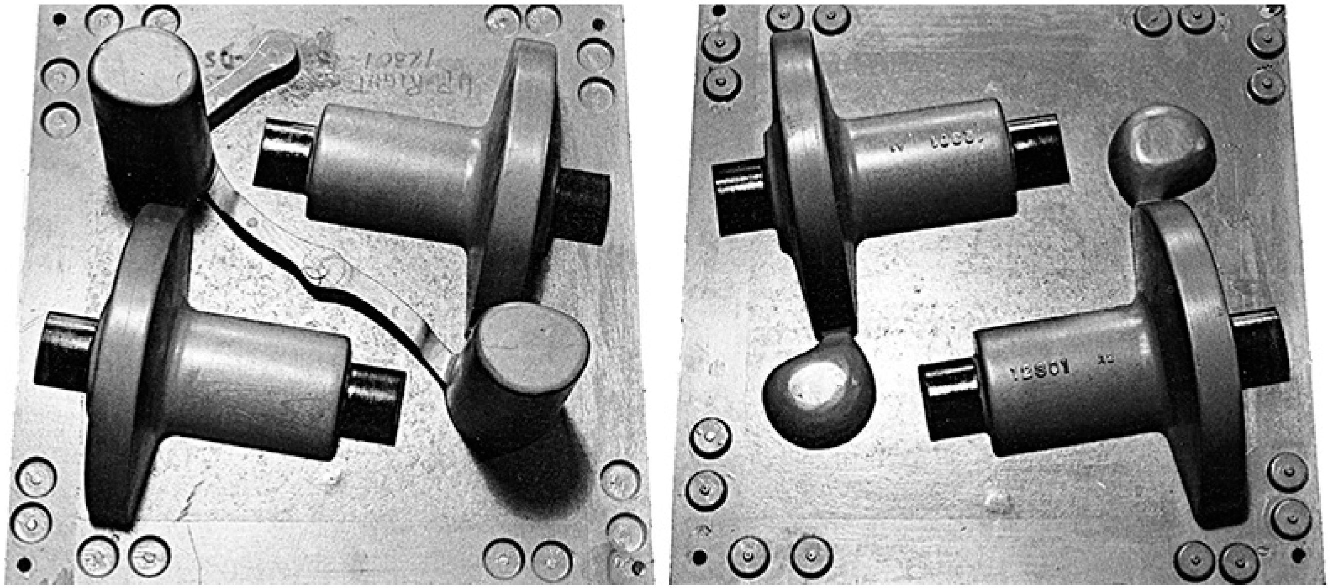


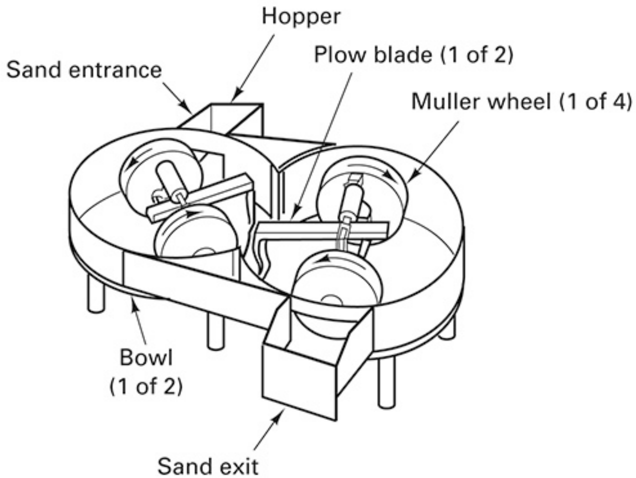
Figure 12-6 Cope-and-drag pattern for producing two heavy parts. (Left) Cope section; (right) drag section. (Note: These are two separate pattern boards.)

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



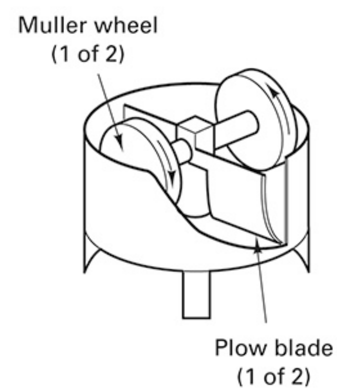


Figure 12-8 Schematic diagram of a continuous (left) and batch-type (right) sand muller. Plow blades move and loosen the sand, and the muller wheels compress and mix the components. (Courtesy of ASM International. Metals Park, OH.)

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

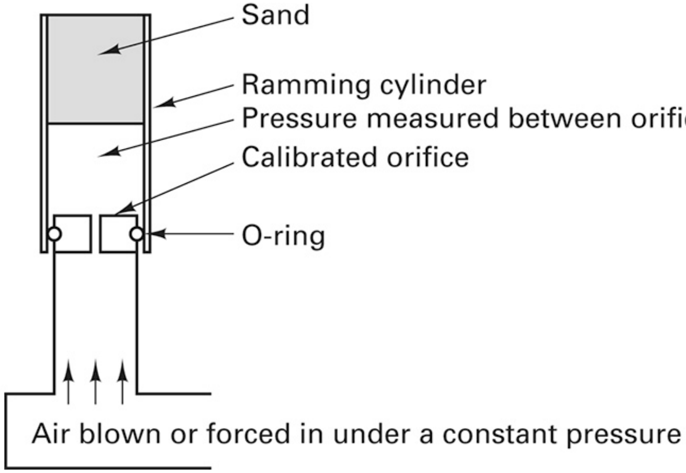
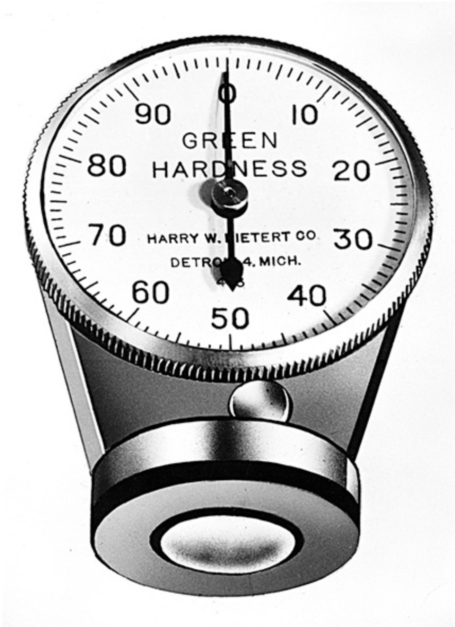


Figure 12-9 Schematic of a permeability tester in operation. A standard sample in a metal sleeve is sealed by an O-ring onto the top of the unit while air is passed through the sand. (Courtesy of Dietert Foundry Testing Equipment Inc, Detroit, MI)

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

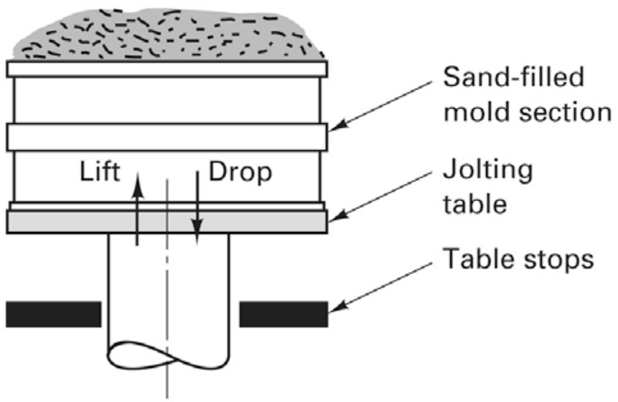


Figure 12-12 (Above) Jolting a mold section. (Note: The pattern is on the bottom, where the greatest packing is expected.)

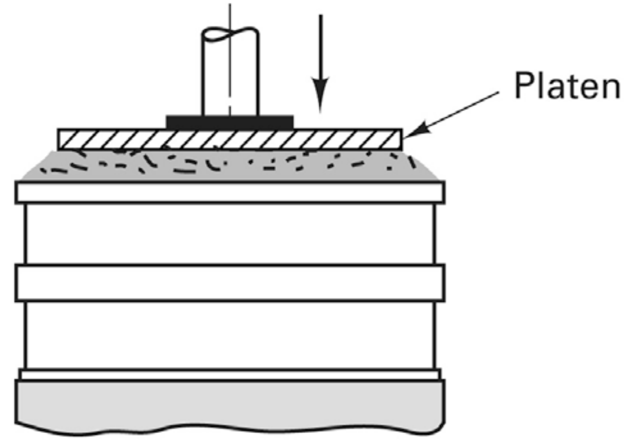


Figure 12-13 (Above) Squeezing a sand-filled mold section. While the pattern is on the bottom, the highest packing will be directly under the squeeze head.

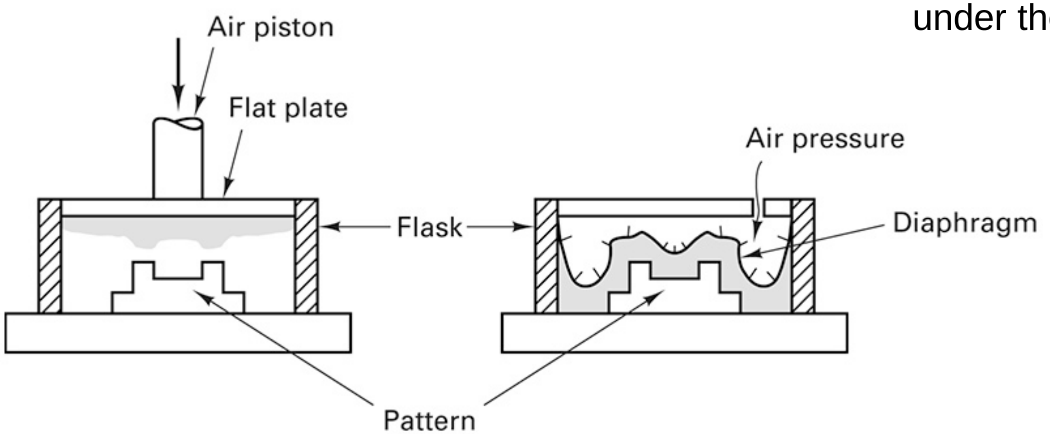


Figure 12-14 (Left) Schematic diagram showing relative sand densities obtained by flat-plate squeezing, where all areas get vertically compressed by the same amount of movement (left) and by flexible-diaphragm squeezing, where all areas flow to the same resisting pressure (right).

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

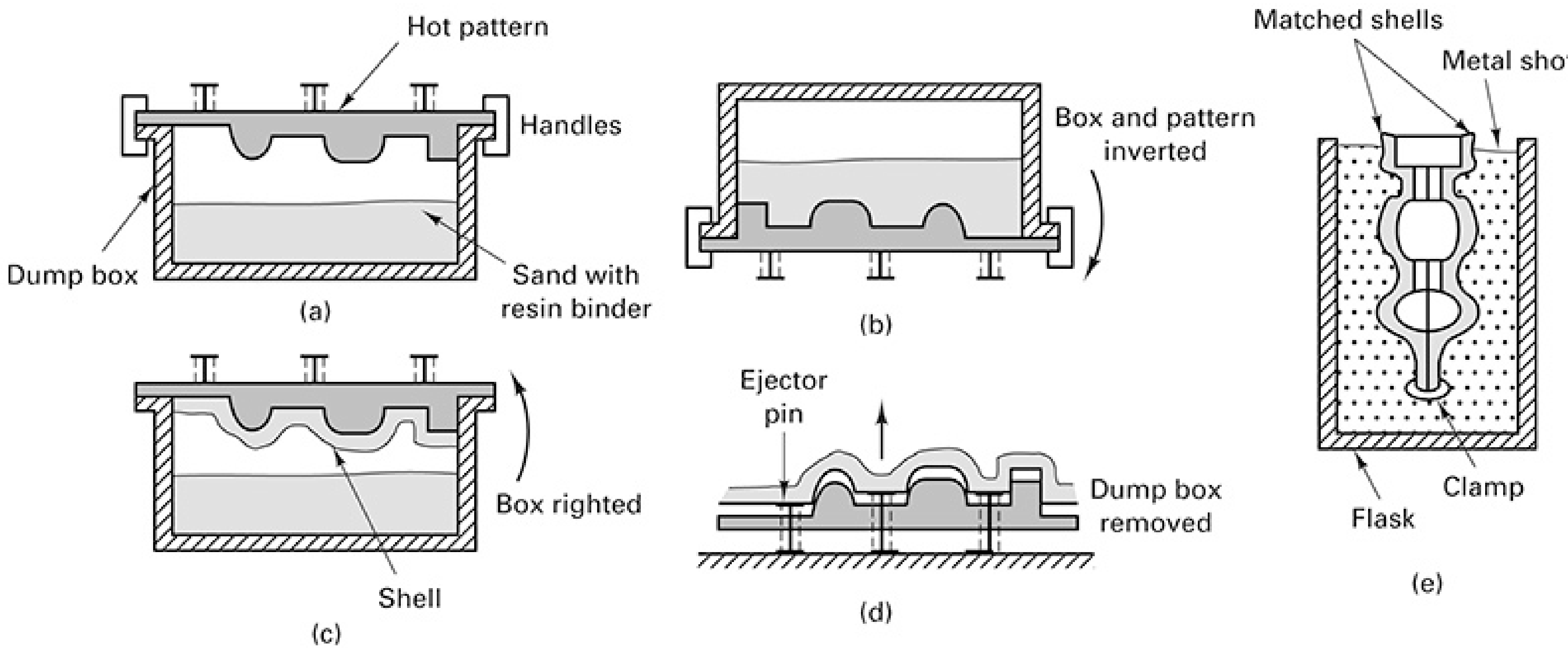


Figure 12-18 Schematic of the dump-box version of shell molding. a) A heated pattern is placed over a dump box containing granules of resin-coated sand. b) The box is inverted, and the heat forms a partially cured shell around the pattern. c) The box is righted, the top is removed, and the pattern and 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

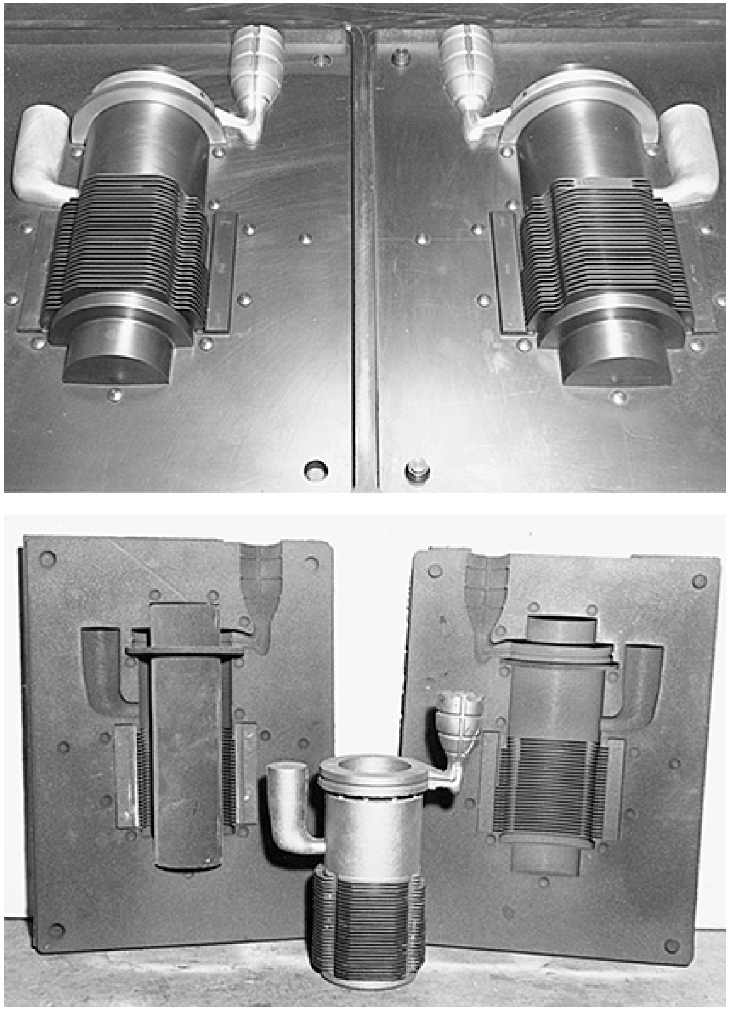


Figure 12-19 (Top) Two halves of a shell-mold pattern. (Bottom) The two shells before clamping, and the final shell-mold casting with attached pouring basin, runner, and riser. (Courtesy of Shalco Systems, Lansing, MI.)

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

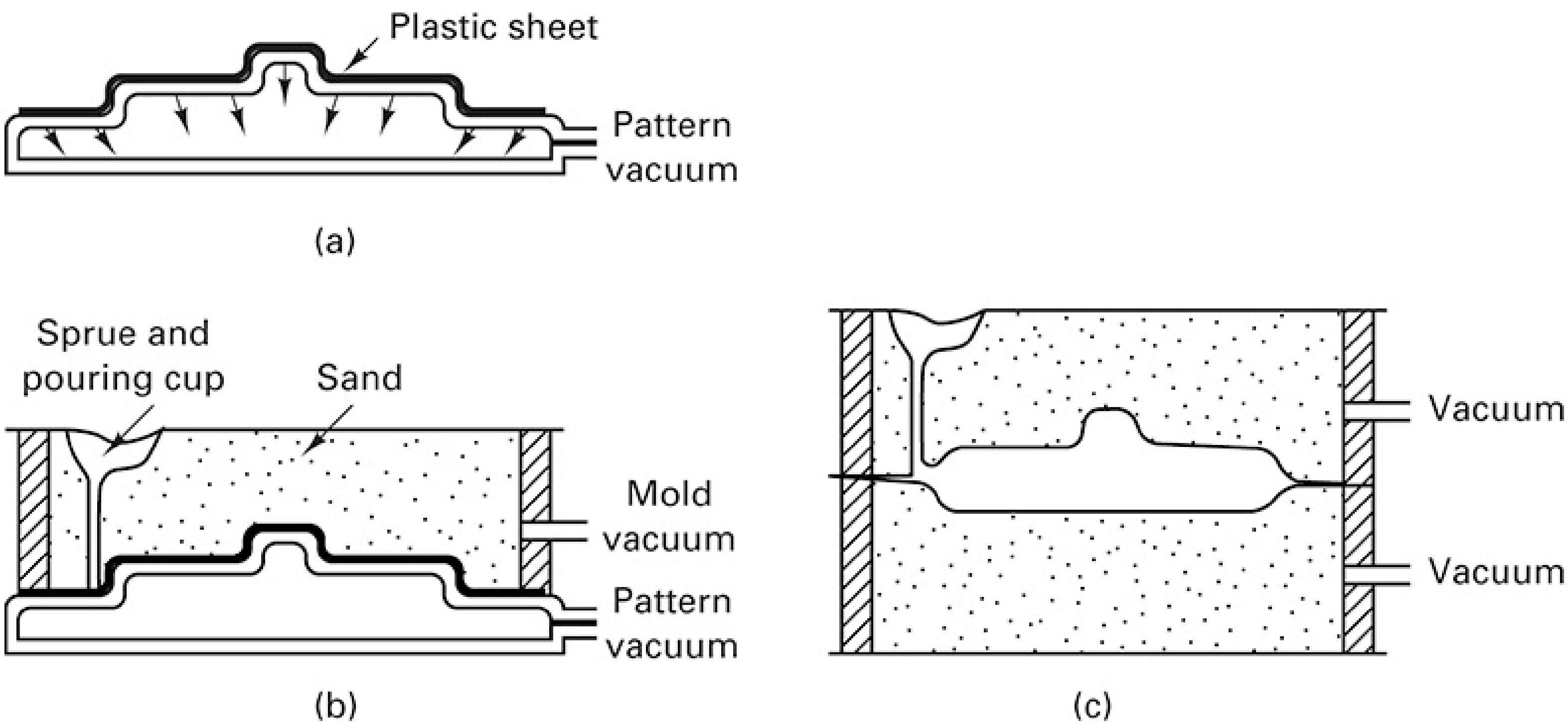


Figure 12-20 Schematic of the V-process or vacuum molding. A) A vacuum is pulled on a pattern, drawing a heated shrink-wrap plastic sheet tightly against it. b) A vacuum flask is placed over the pattern and filled with dry unbonded sand, a pouring basin and sprue are formed; the remaining sand is leveled; 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

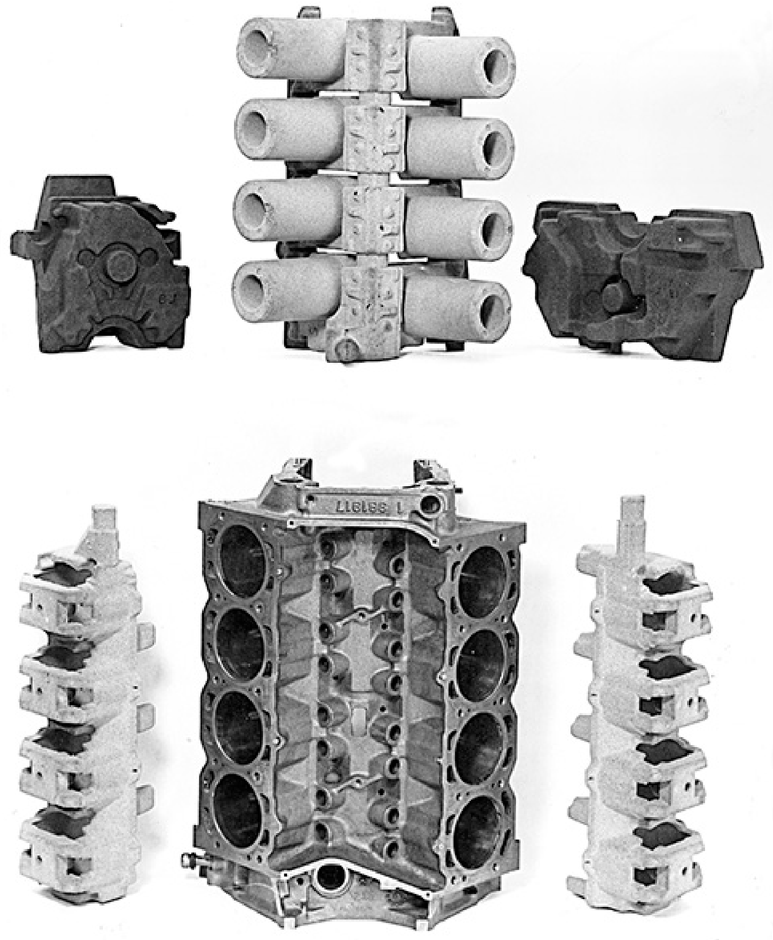
- Complex internal cavities can be produced with cores
- Cores can be used to improve casting design
- Cores may have relatively low strength
- If long cores are used, machining may need to be done afterwards
- Green sand cores are not an option for more complex shapes

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

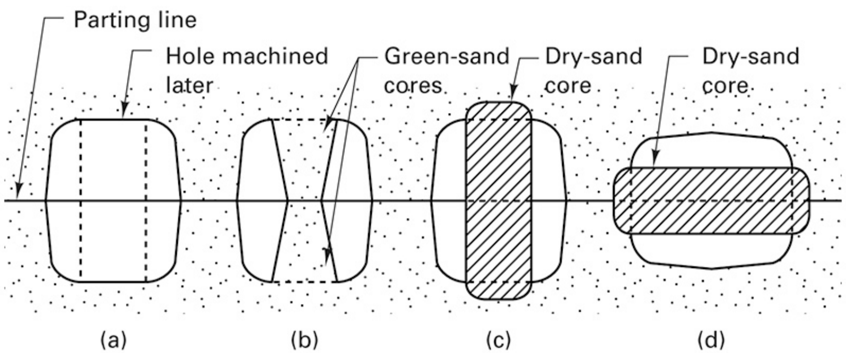


Figure 12-22 (Left) Four methods of making a hole in a cast pulley. Three involve the use of a core.

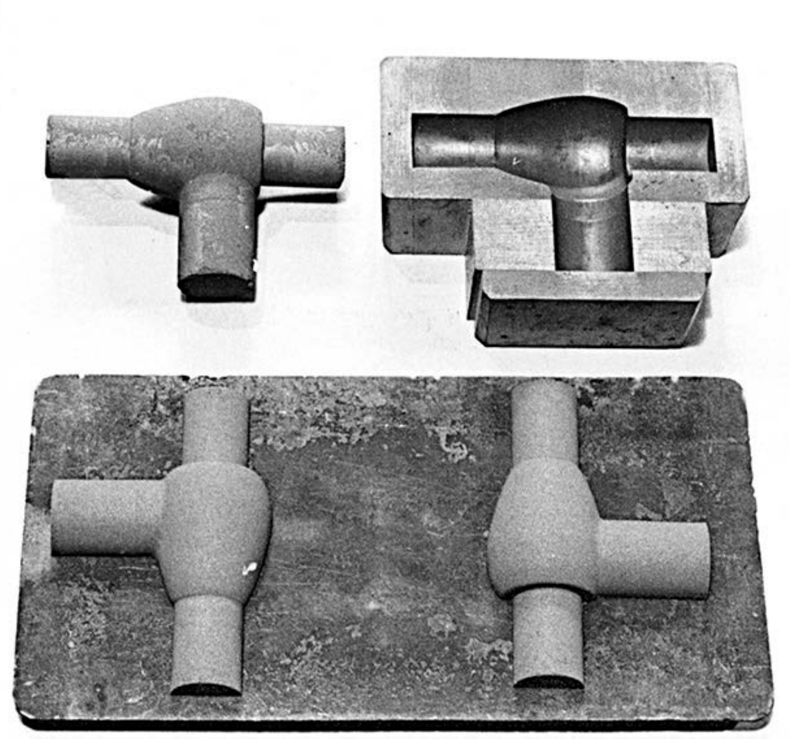


Figure 12-23 (Right) Upper Right; A dump-type core box; (bottom) core halves for baking; and (upper left) a completed core made by gluing two opposing halves together.

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

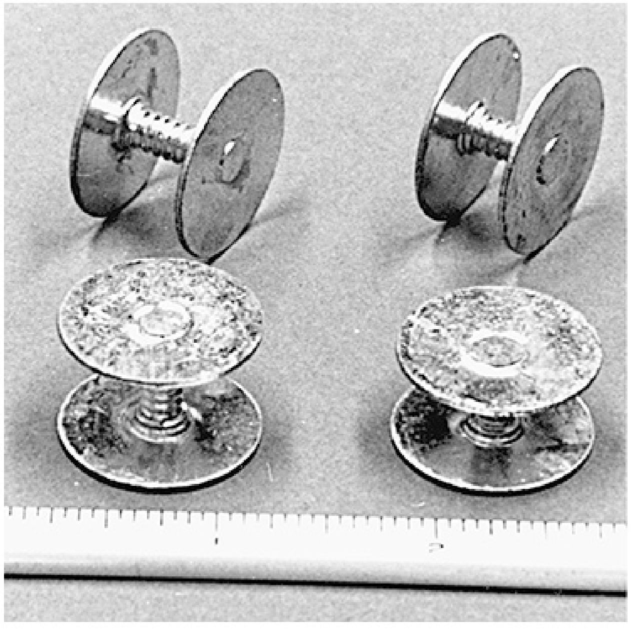
Casting Core Characteristics

- 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



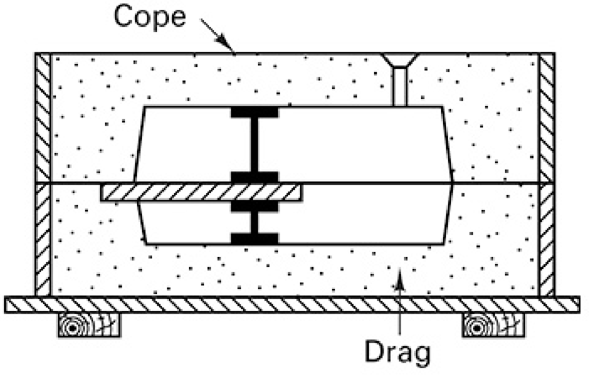
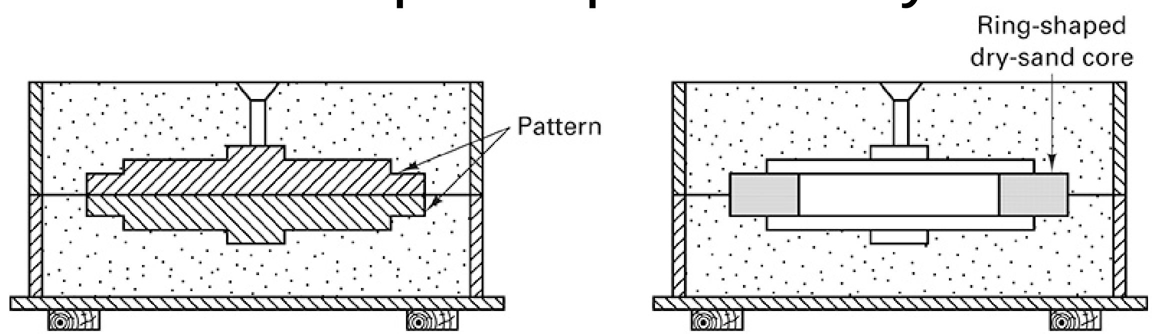


Figure 12-24 (Left) Typical chaplets. (Right) Method of supporting a core by use of chaplets (relative size of the chaplets is exaggerated).

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.



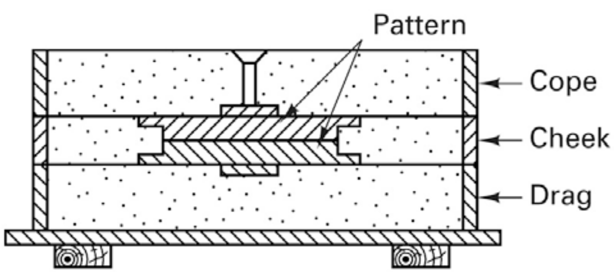


Figure 12-25 (Left) Method of making a reentrant angle or inset section by using a three-piece flask.

12.4 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.

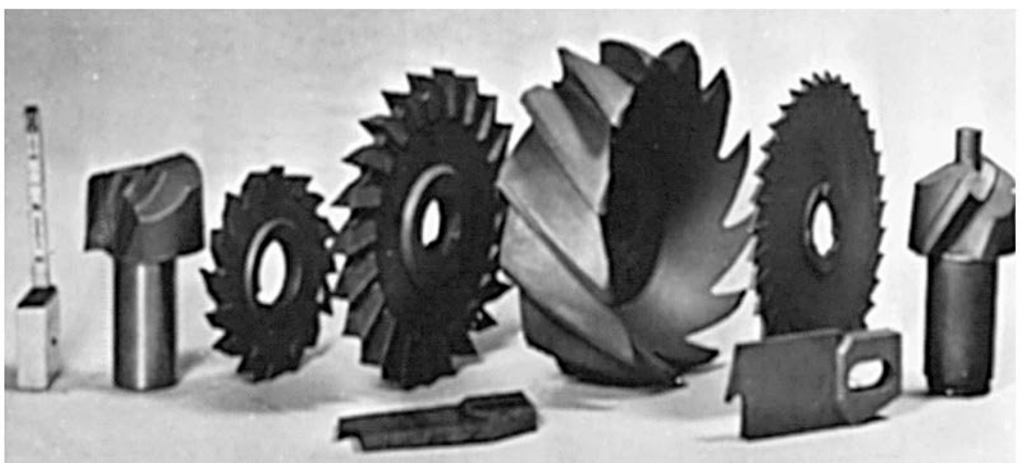


Figure 12-27 Group of intricate cutters produced by ceramic mold casting. (Courtesy of Avnet Shaw Division of Avnet, Inc., Phoenix, AZ)

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

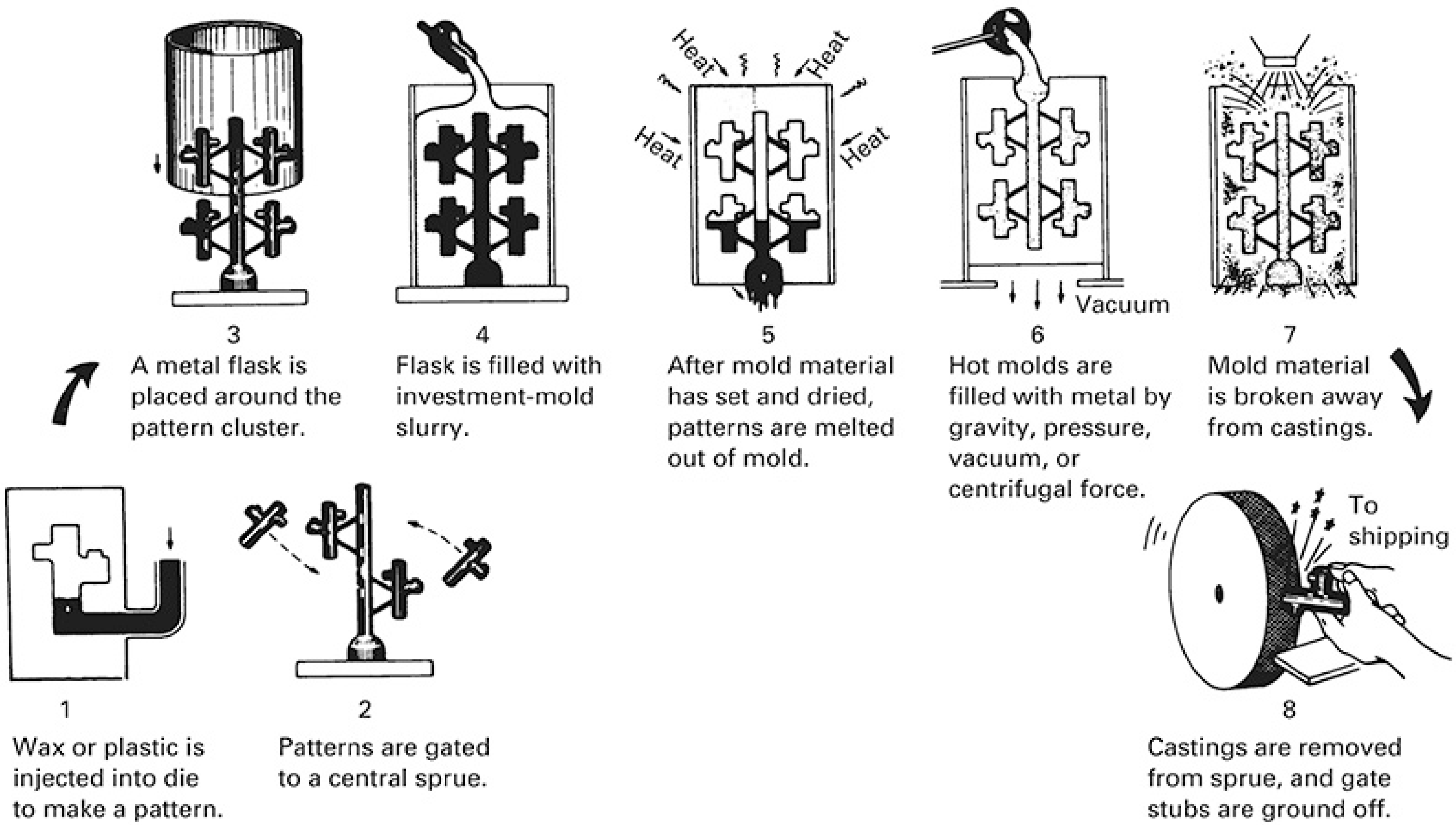


Figure 12-28 Investment-casting steps for the flask-cast method. (Courtesy of Investment Casting Institute, Dallas, TX.)

Investment Casting

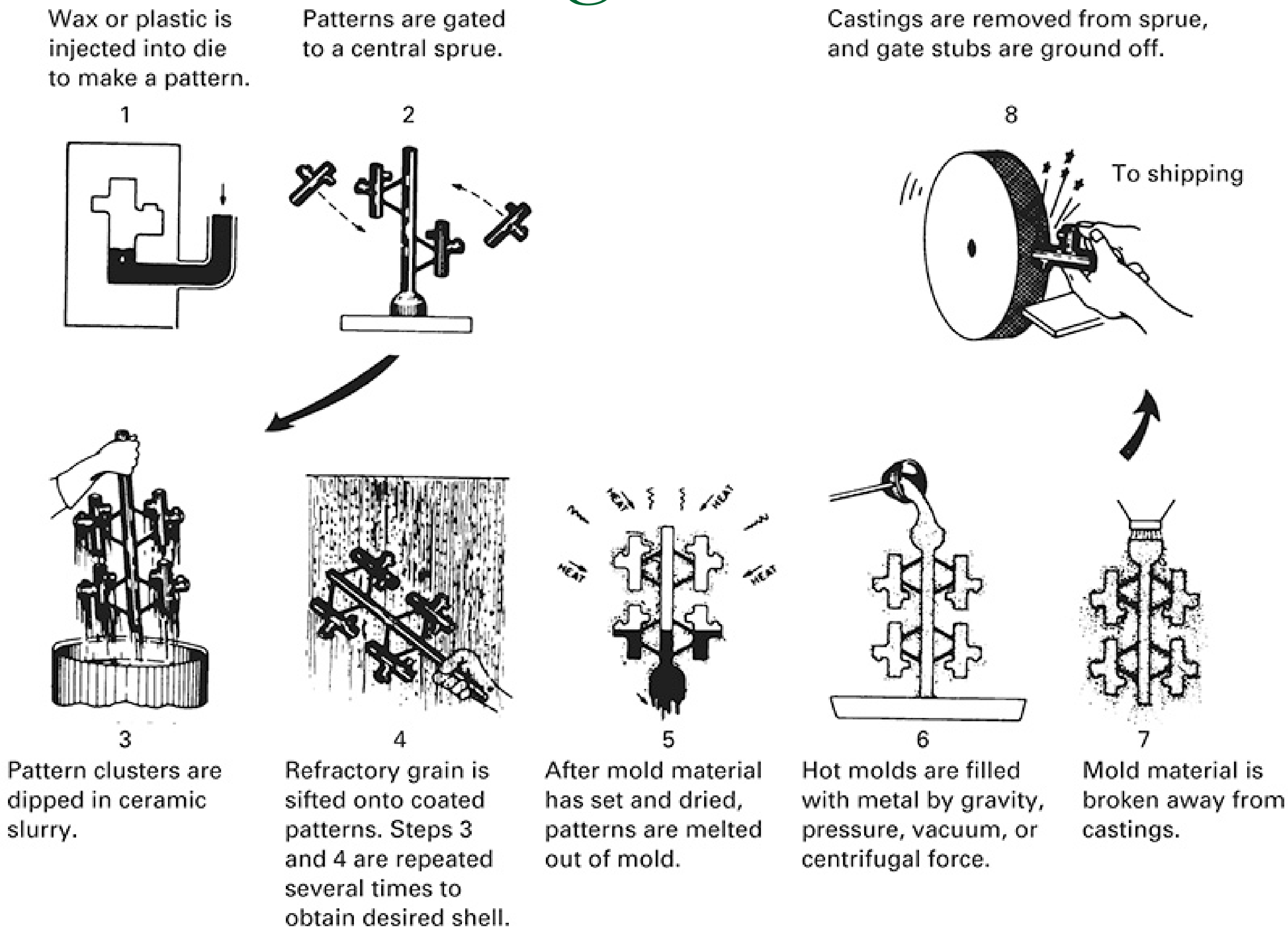


Figure 12-29 Investment-casting steps for the shell-casting procedure. (Courtesy of Investment Casting Institute, Dallas, TX.)

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

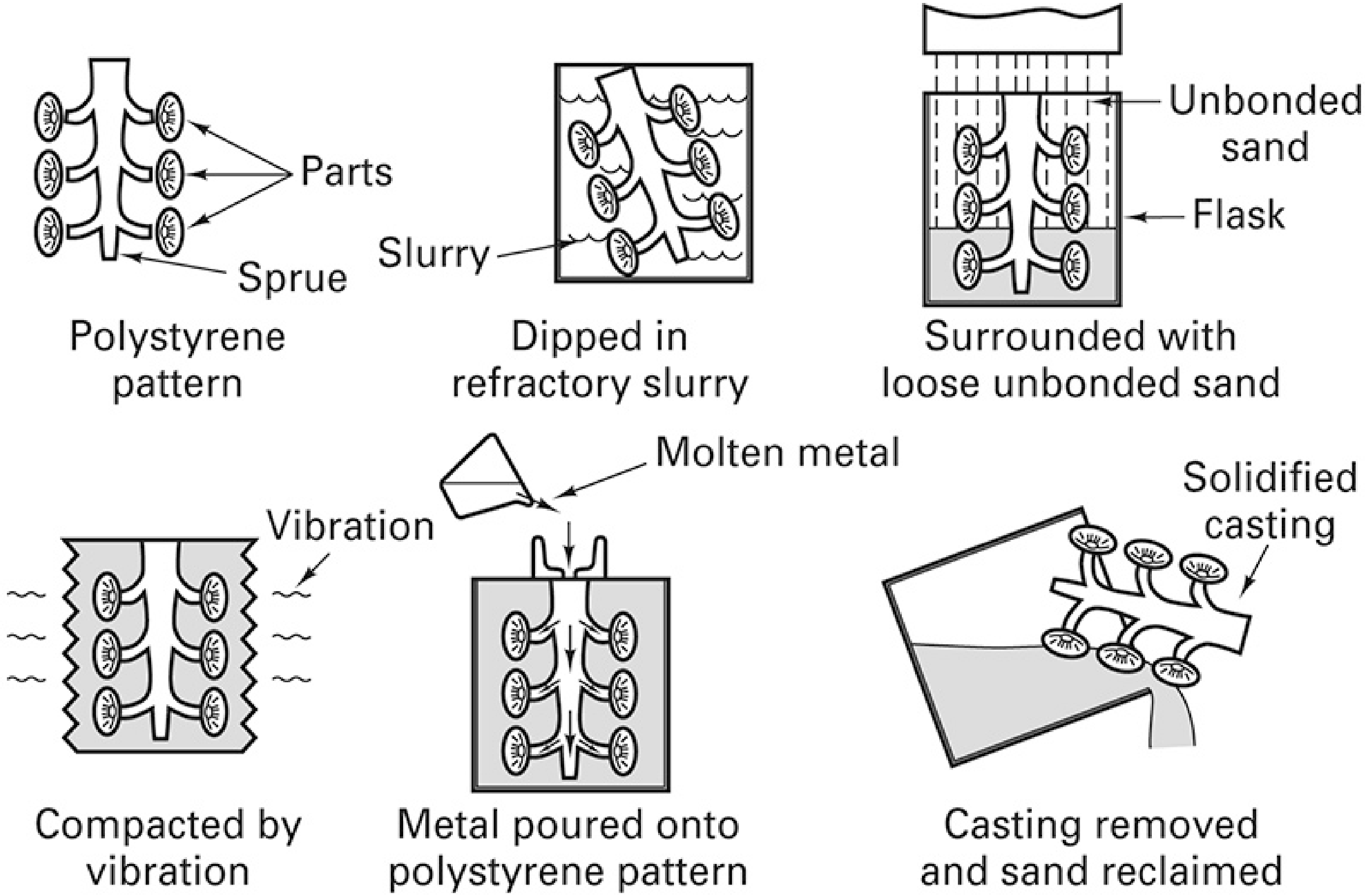


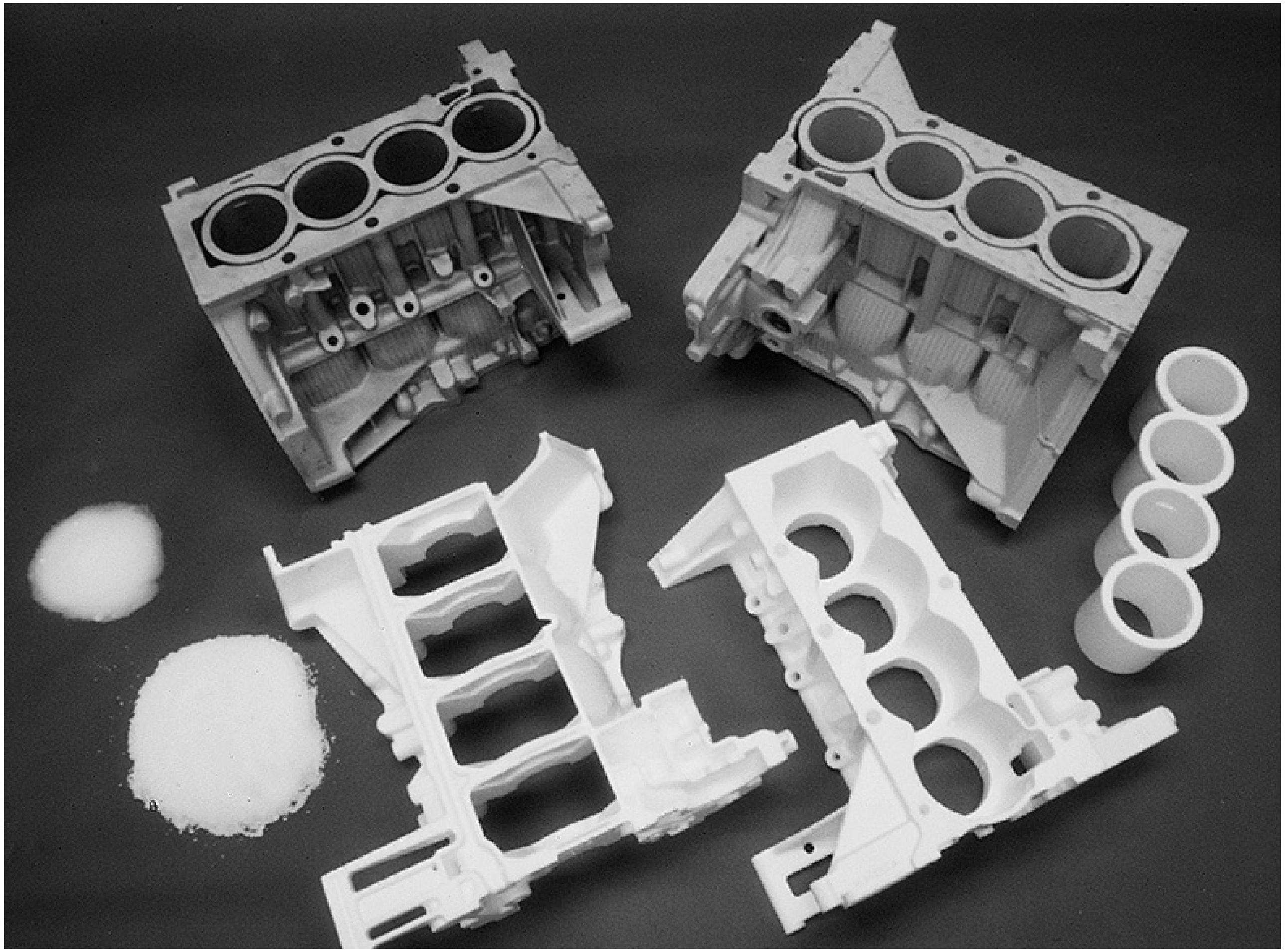
Figure 12-32 Schematic of the lost-foam casting process. In this process, the polystyrene pattern is dipped in a ceramic slurry, and the coated pattern is then surrounded with loose, unbonded sand.

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.

12.6 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

12.7 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 13: 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

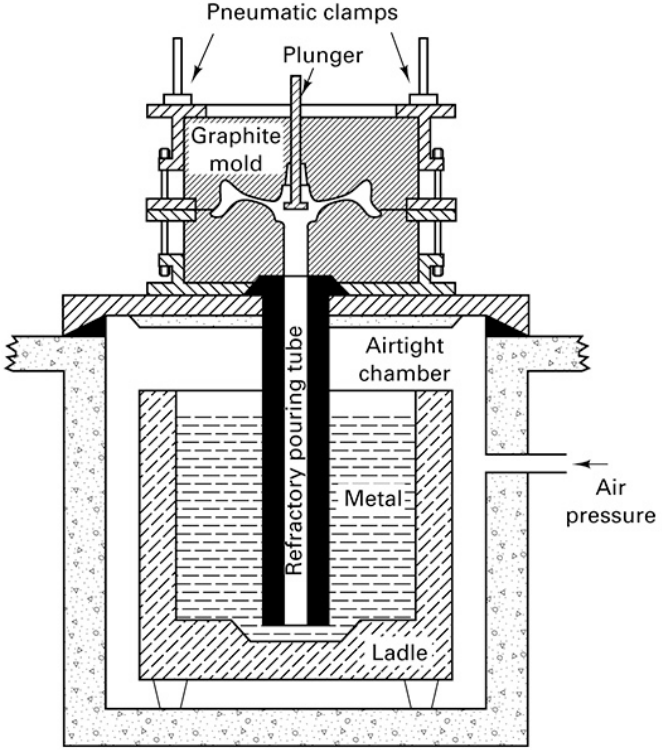


Figure 13-2 Schematic of the low-pressure permanent-mold process. (Courtesy of Amsted Industries, Chicago, IL.)

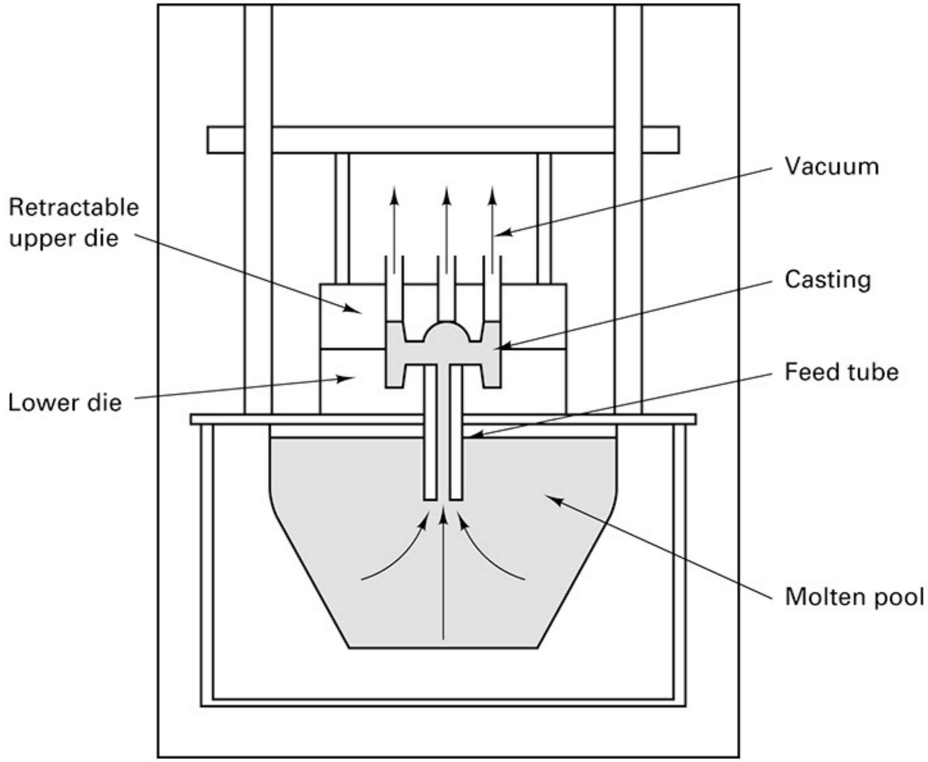


Figure 13-3 Schematic illustration of vacuum permanent-mold casting. Note the similarities to the low-pressure process.

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

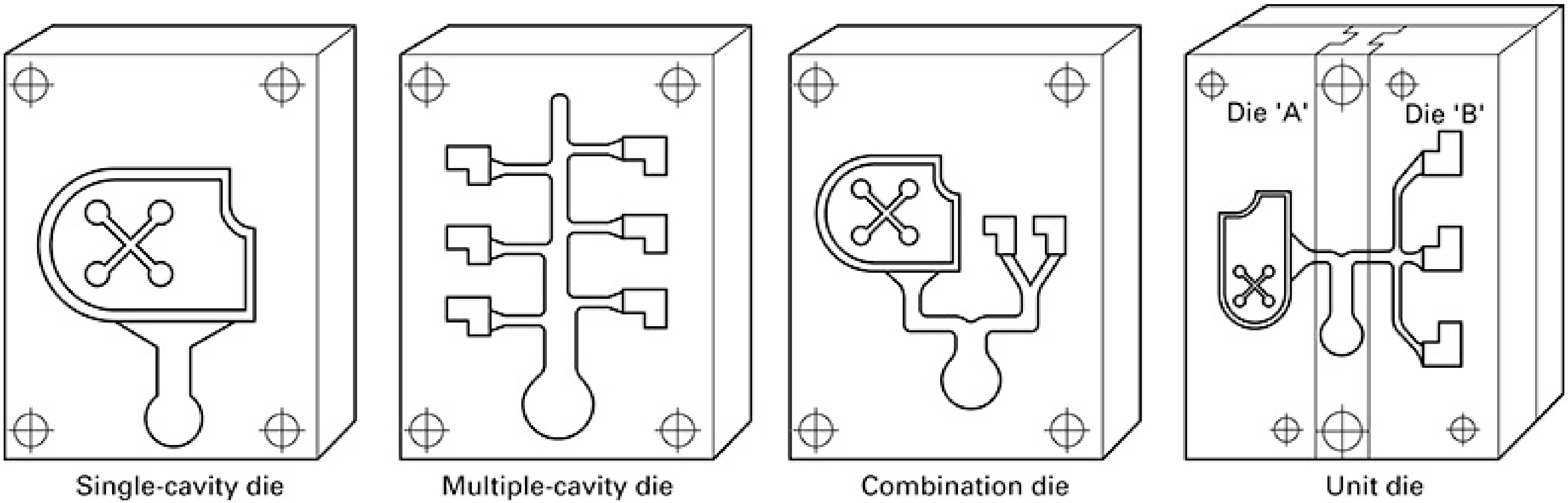


Figure 13-4 Various types of die-casting dies. (Courtesy of American Die Casting Institute, Inc., Des Plaines, IL.)

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.).

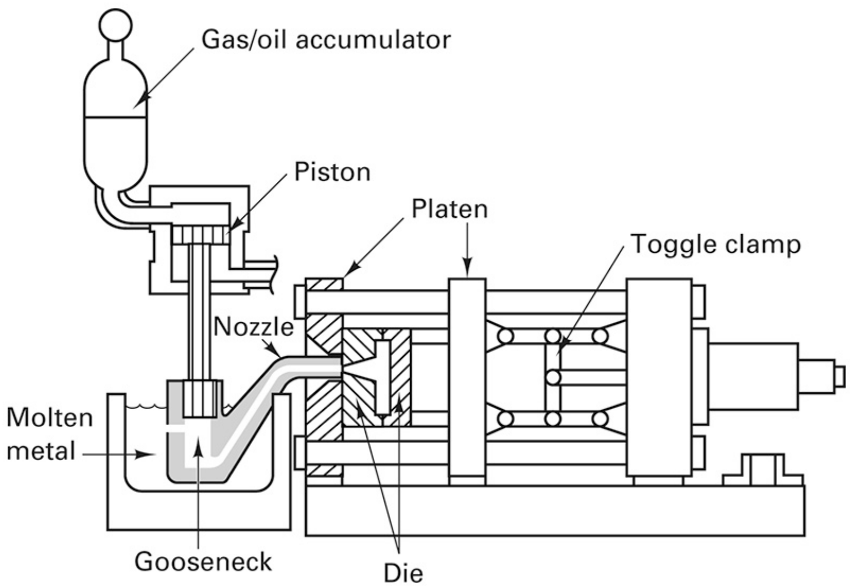
Typical tolerances: Varies with metal being cast; typically 0.1mm for the first 2.5 cm (0.005 in. for the first inch) and 0.02 mm for each additional centimeter (0.002 in. for each additional inch).

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.)



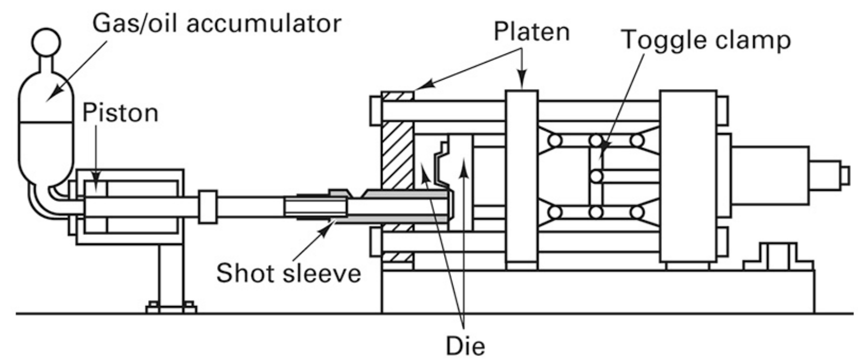


Figure 13-6 (Above) Principal components of a cold-chamber die-casting machine. (Adapted from Metals Handbook, 9th ed., Vol 15, p. 287, ASM International, Metals Park, OH.)

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

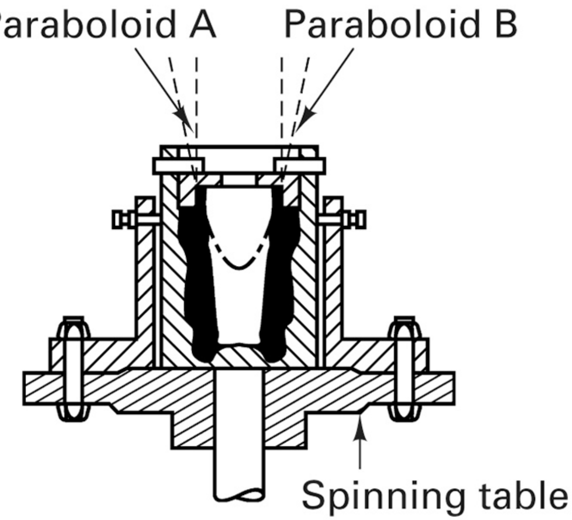


Figure 13-9 (Above) Vertical centrifugal casting, showing the effect of rotational speed on the shape of the inner surface. Parabaloid A results from fast spinning whereas slower spinning will produce parabaloid B.

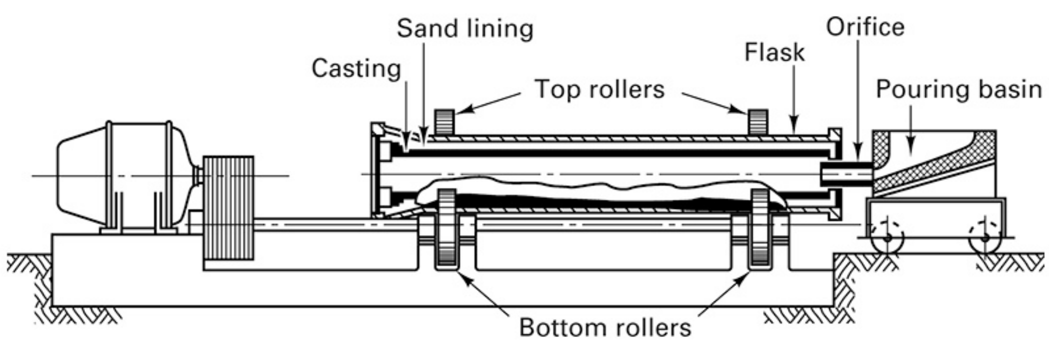


Figure 13-8 (Left) Schematic representation of a horizontal centrifugal casting machine. (Courtesy of American Cast Iron Pipe Company, Birmingham, AL.)

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.

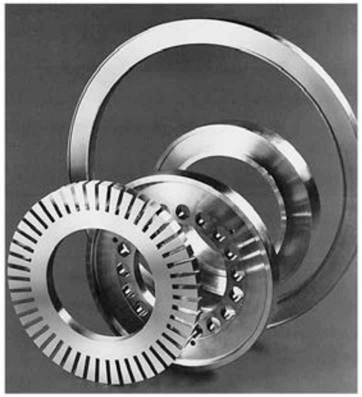
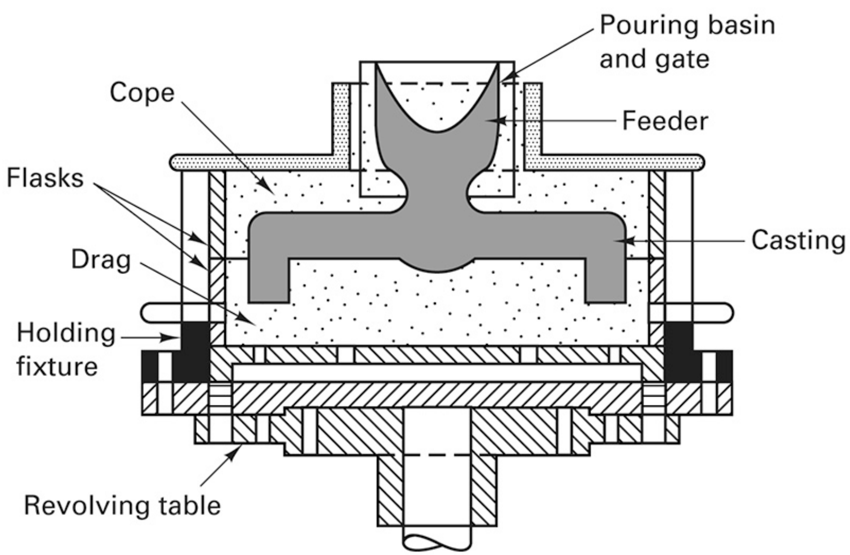


Figure 13-10 Electrical products (collector rings, slip rings, and rotor end rings) that have been centrifugally cast from aluminum and copper. (Courtesy of The Electric Materials Company, North East, PA.)

Centrifuging

Figure 13-11 Schematic of a semicentrifugal casting process.



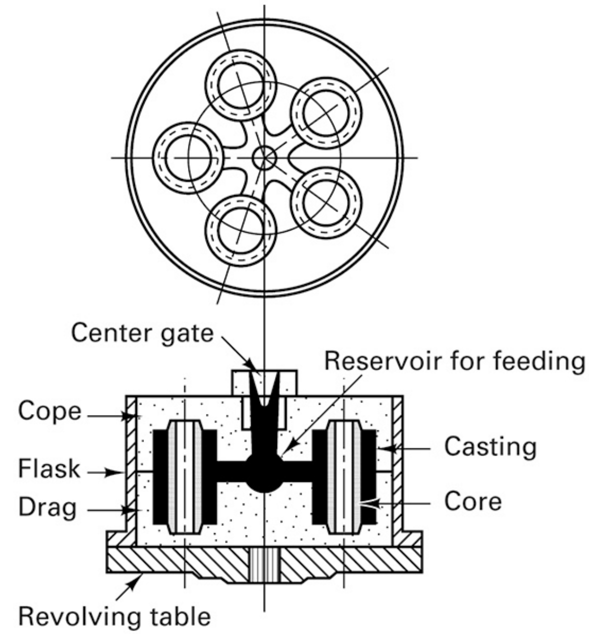


Figure 13-12 (Above) Schematic of a centrifuging process. Metal is poured into the central pouring sprue and spun into the various mold cavities. (Courtesy of American Cast Iron Pipe Company, Birmingham, AL.)

13.6 Continuous Casting

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

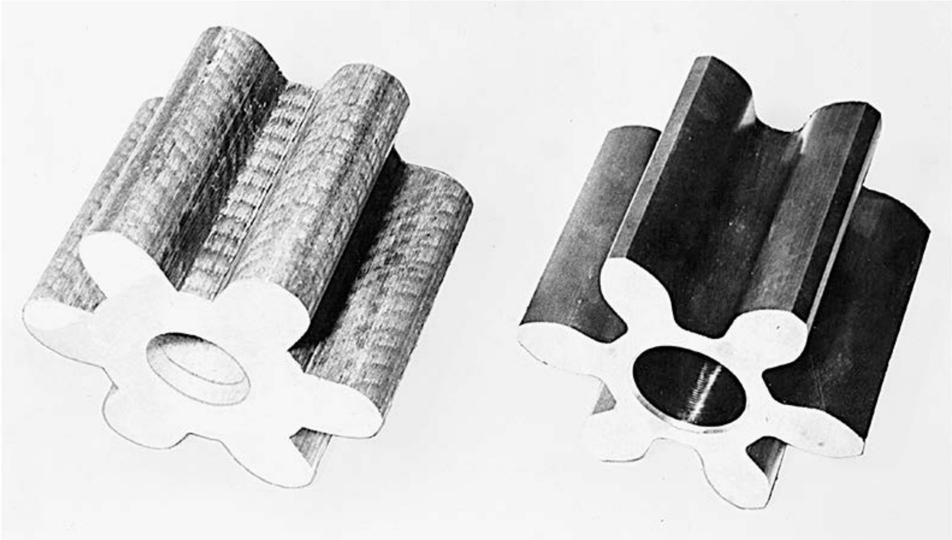


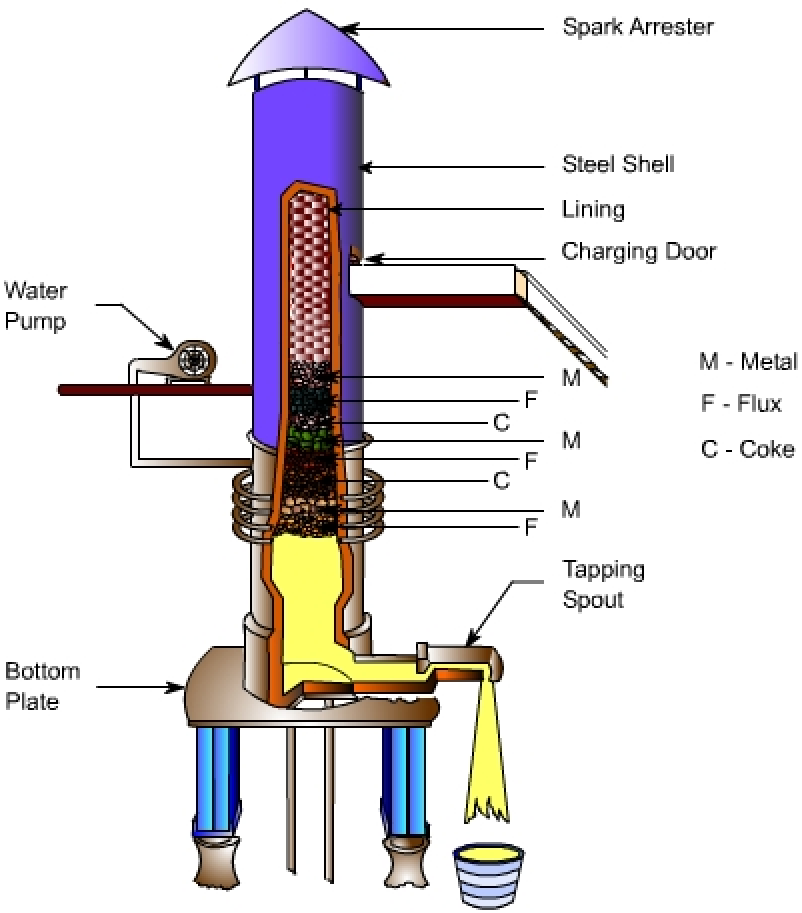
Figure 13-13 Gear produced by continuous casting. (Left) As-cast material; (right) after machining. (Courtesy of ASARCO, Tucson, AZ.)

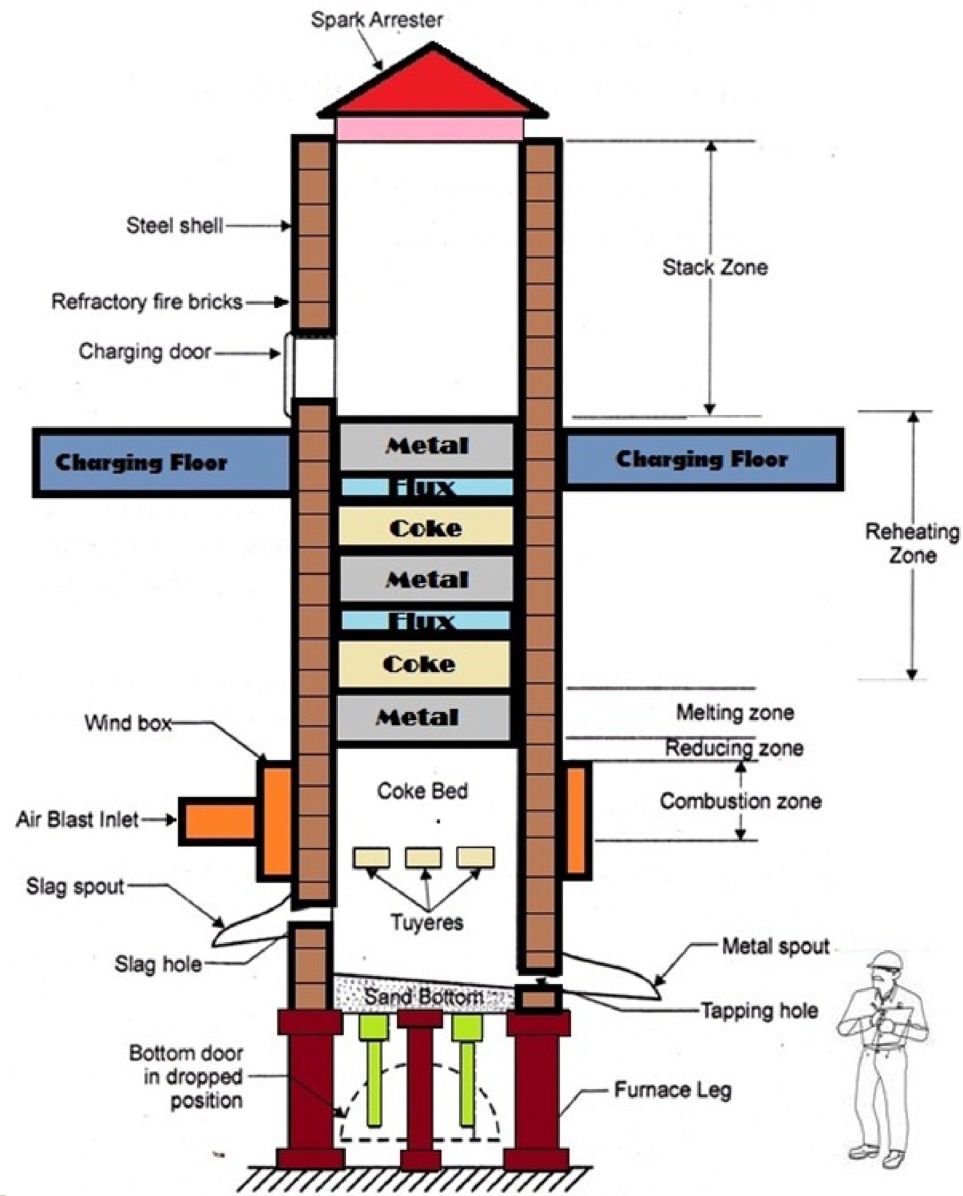
13.7 Melting

- 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

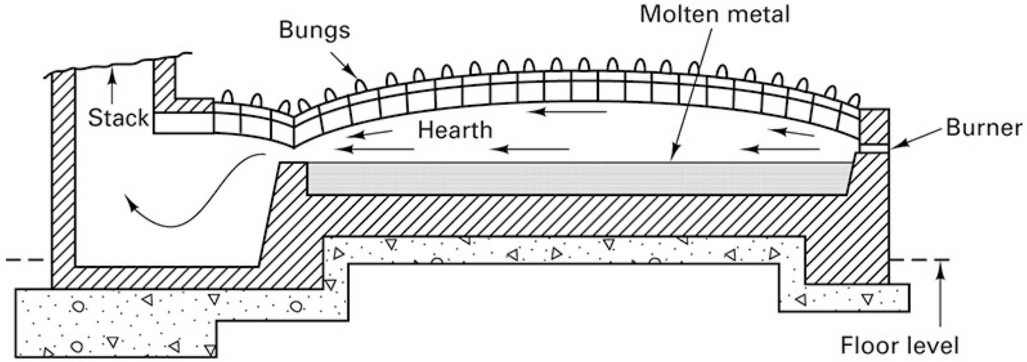


Figure 13-14 Cross section of a direct fuel-fired furnace. Hot combustion gases pass across the surface of a molten metal pool.

Arc Furnaces

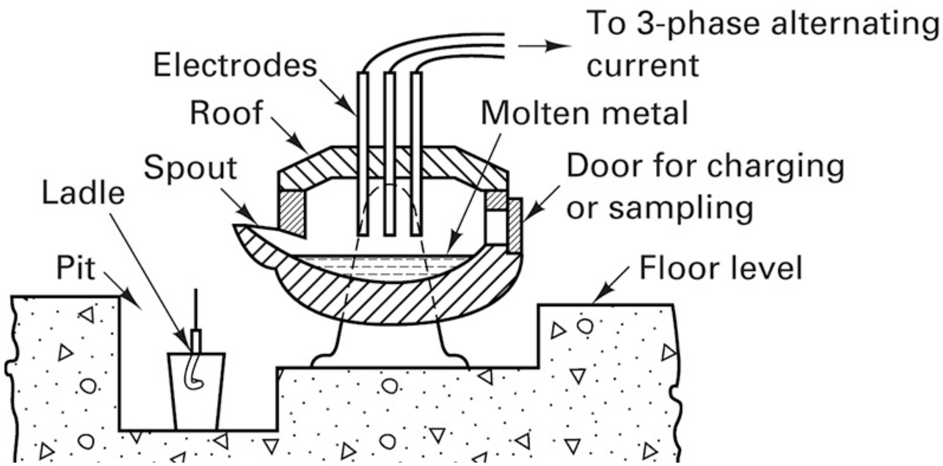


Figure 13-15 Schematic diagram of a three-phase electric-arc furnace.

- 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

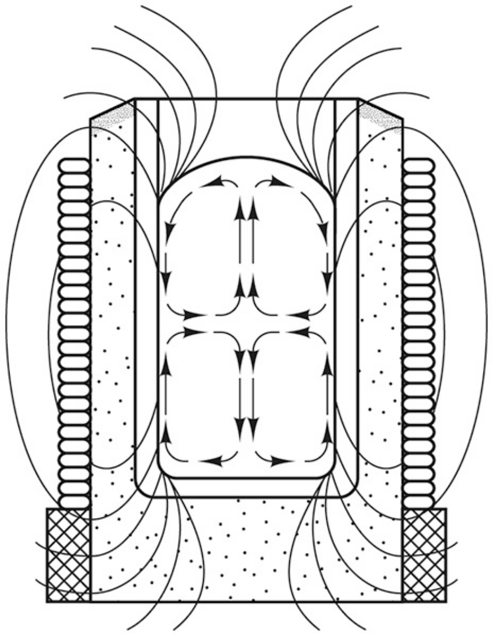
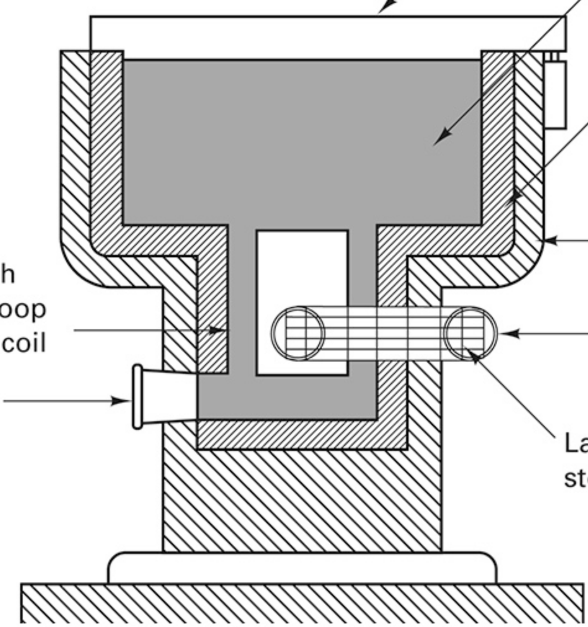


Figure 13-17 (Above) Schematic showing the basic principle of a coreless induction furnace.

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

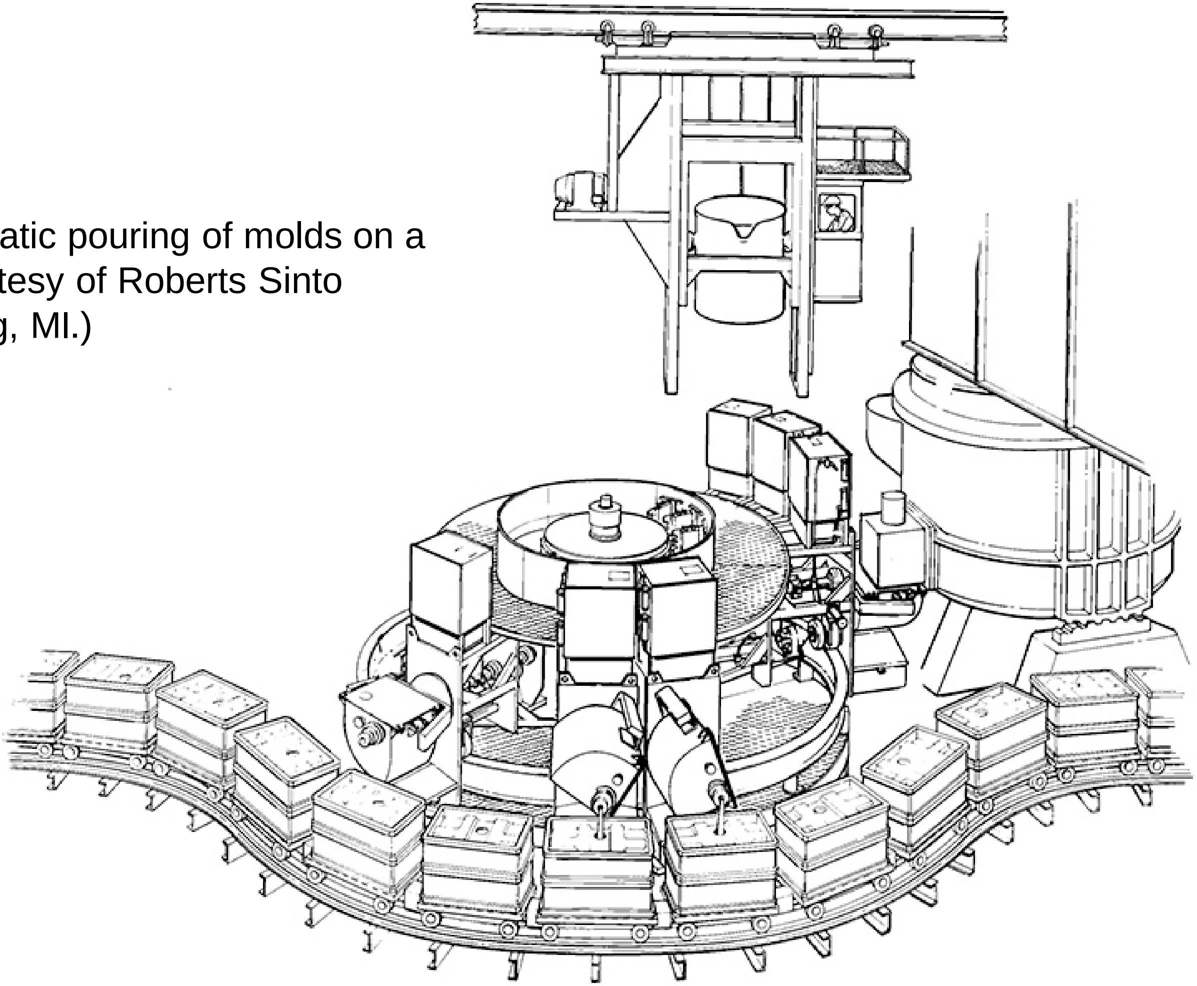


Figure 13-19 Automatic pouring of molds on a conveyor line. (Courtesy of Roberts Sinto Corporation, Lansing, MI.)

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)

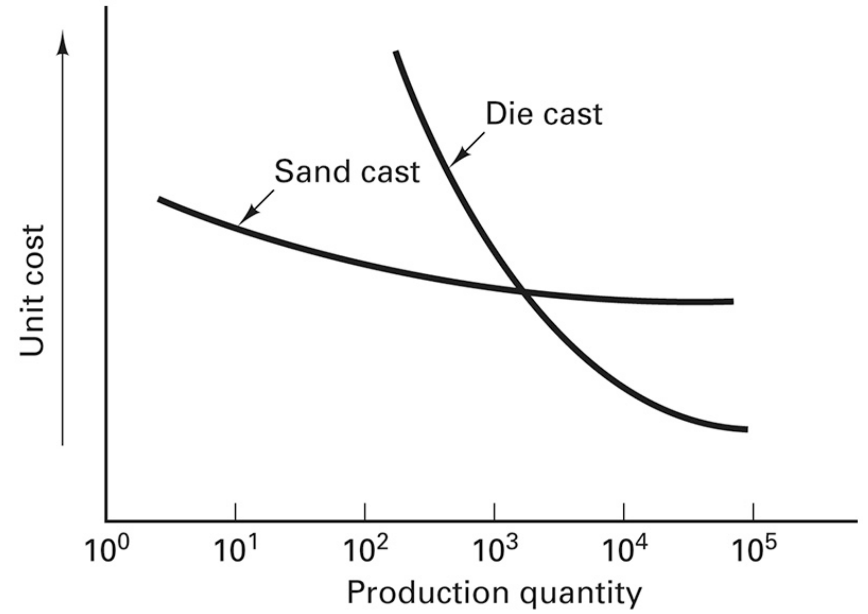


Figure 13-20 Typical unit cost of castings comparing sand casting and die casting. Note how the large cost of a die-casting die diminishes as it is spread over a larger quantity of parts.

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 15: Fundamentals of Metal Forming

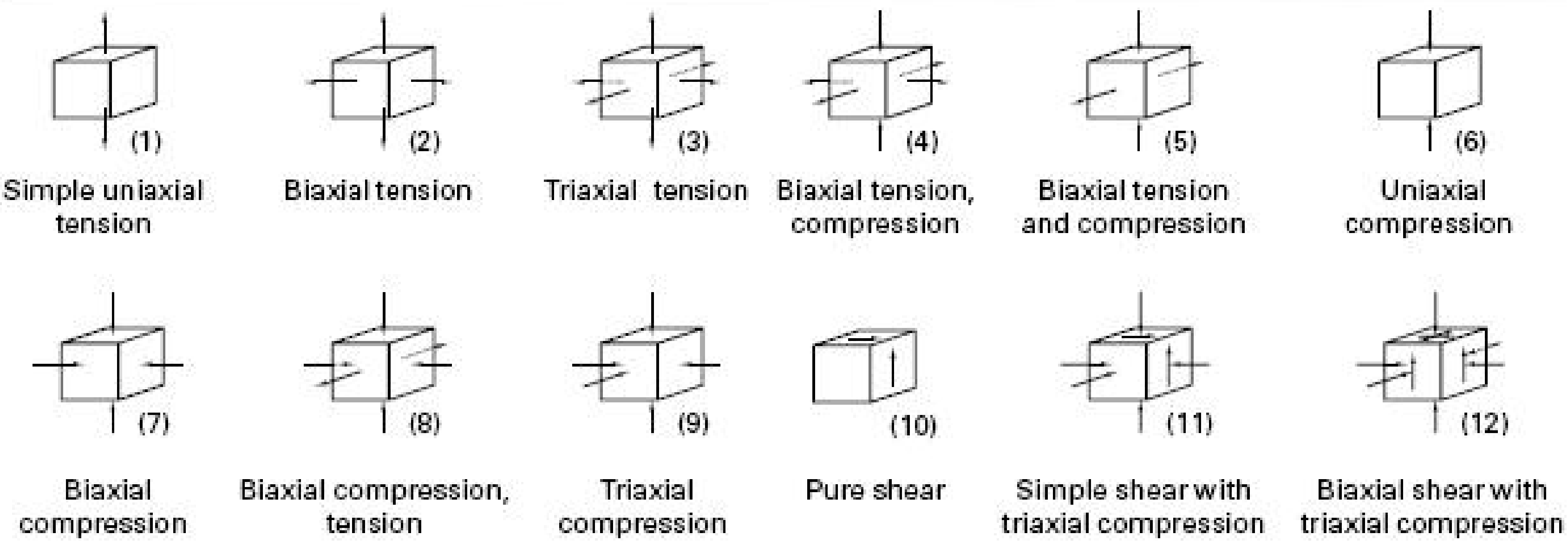
DeGarmo's Materials and Processes in Manufacturing

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

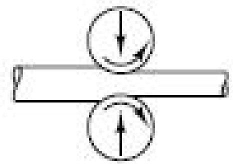
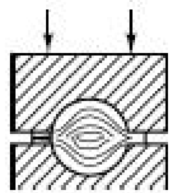
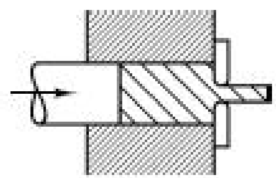
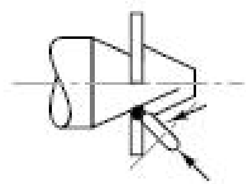


15.2 Forming Processes: Independent Variables

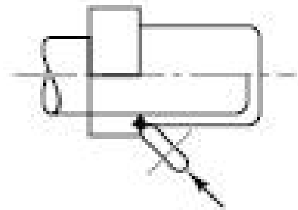
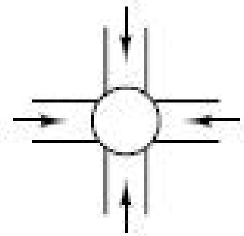
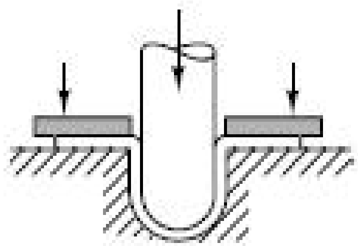
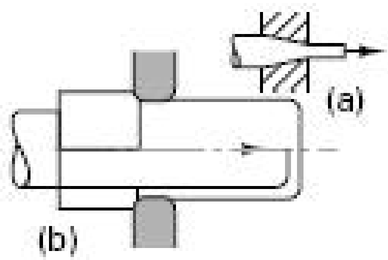
- Forming processes consist of independent and dependent variables
- Independent variables are the aspects of the processes that the engineer or operator has direct control
  - Starting material
  - Starting geometry of the workpiece
  - Tool or die geometry
  - Lubrication
  - Starting temperature
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

Forming Operations

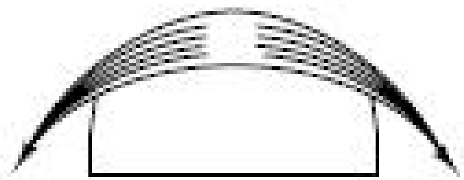
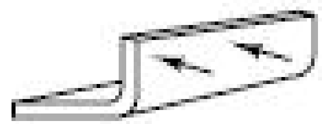
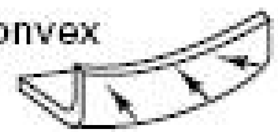
TABLE 15-2 Classification of Some Forming Operations

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

Forming Operations

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

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

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

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

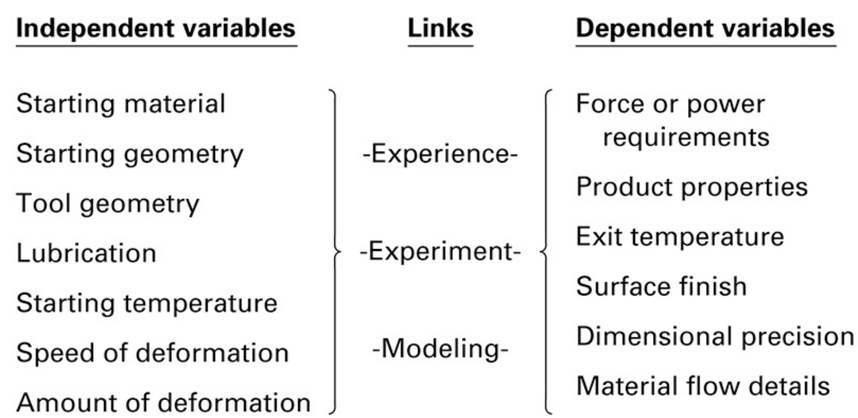


Figure 15-1 Schematic representation of a metalforming system showing independent variables, dependent variables, and the various means of linking the two.

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

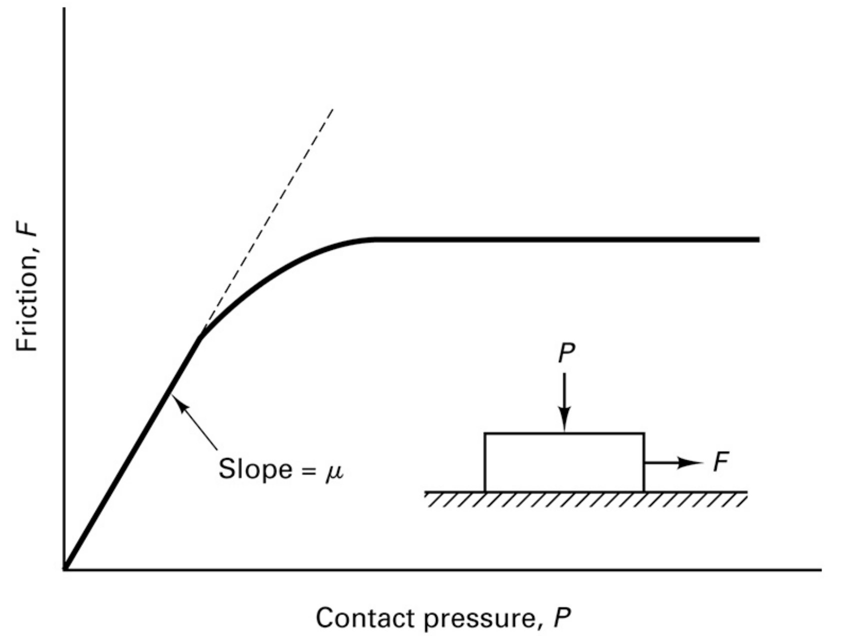


Figure 15-2 The effect of contact pressure on the frictional resistance between two surfaces.

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

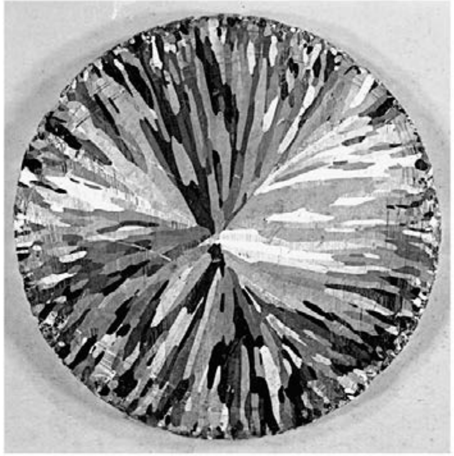
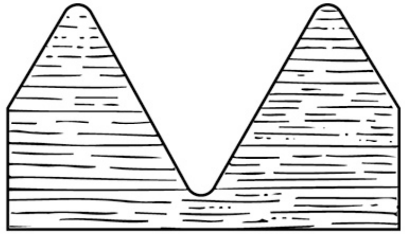


Figure 15-3 Cross section of a 4-in.-diameter case copper bar polished and etched to show the as-cast grain structure.

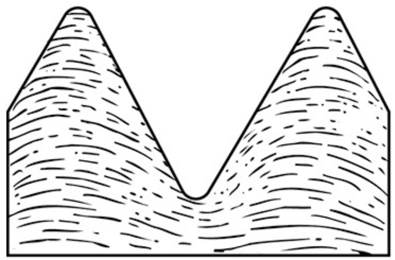
Figure 15-4 Flow structure of a hot-forged gear blank. Note how flow is parallel to all critical surfaces. (*Courtesy of Bethlehem Steel Corporation, Bethlehem, PA.)*

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



(a)



(b)

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

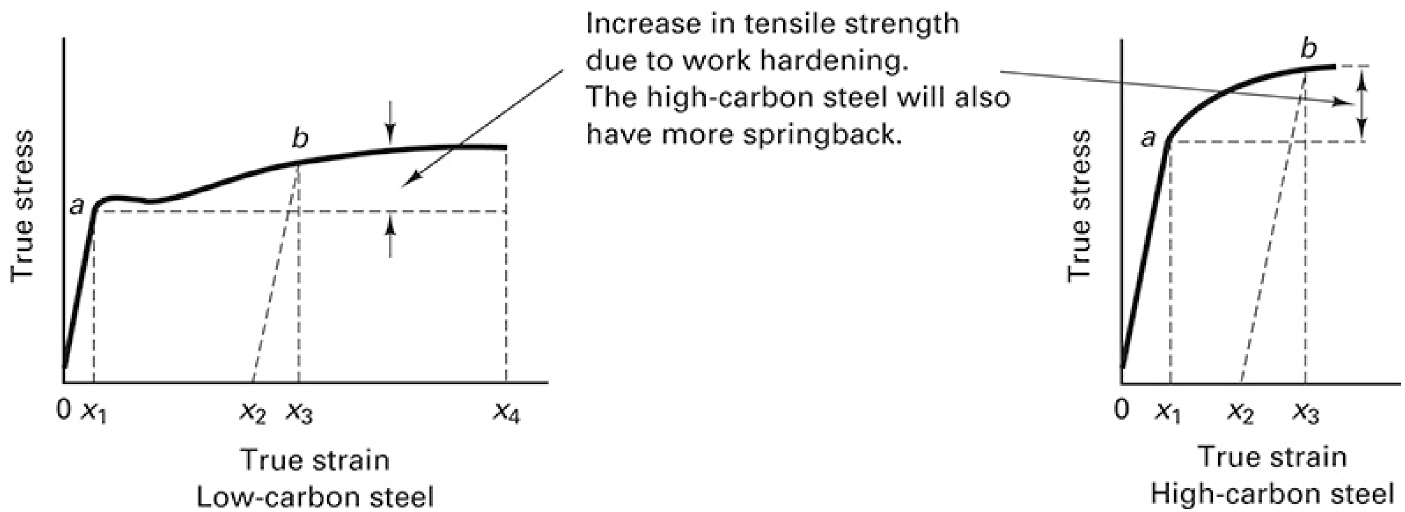
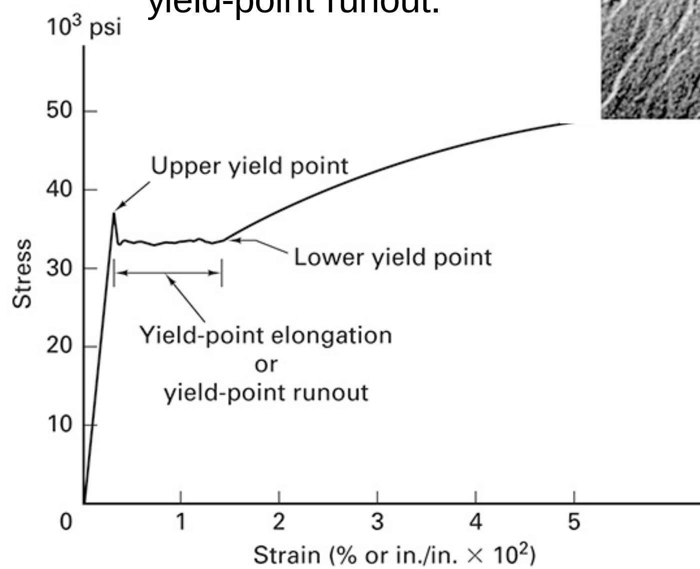


Figure 15-6 Use of true stress-true strain diagram to assess the suitability of two metals for cold working.

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

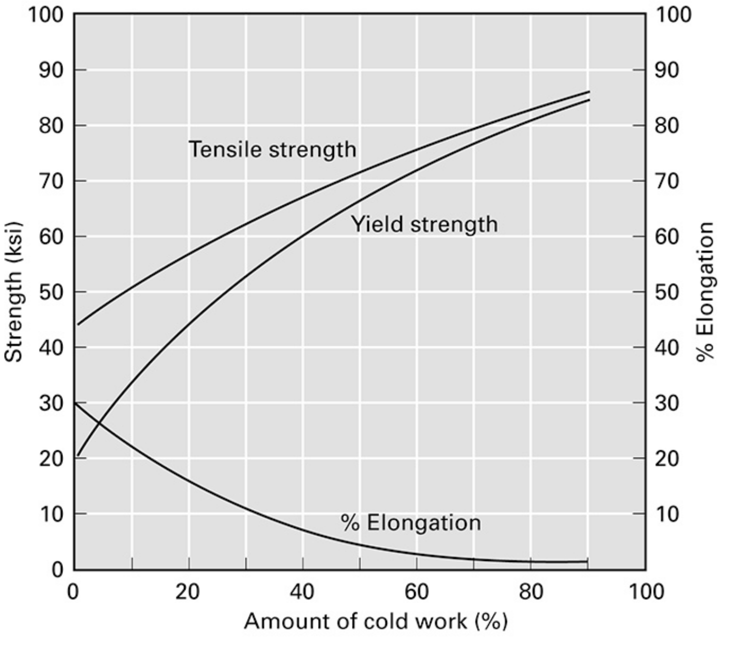


Figure 15-8 Mechanical properties of pure copper as a function of the amount of cold work (expressed in percent).

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

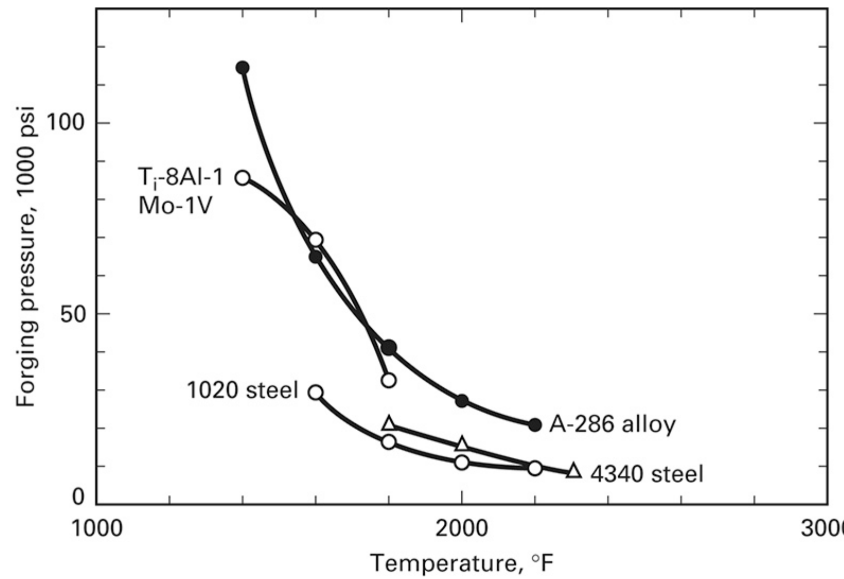


Figure 15-9 Yield strength of various materials (as indicated by pressure required to forge a standard specimen) as a function of temperature. Materials with steep curves may require isothermal forming. (*From "A Study of Forging Variables," ML-TDR-64-95, March 1964; courtesy of Battelle Columbus Laboratories,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

Chapter 16:
Bulk Forming Processes

DeGarmo’s Materials and Processes in Manufacturing

16.1 Introduction

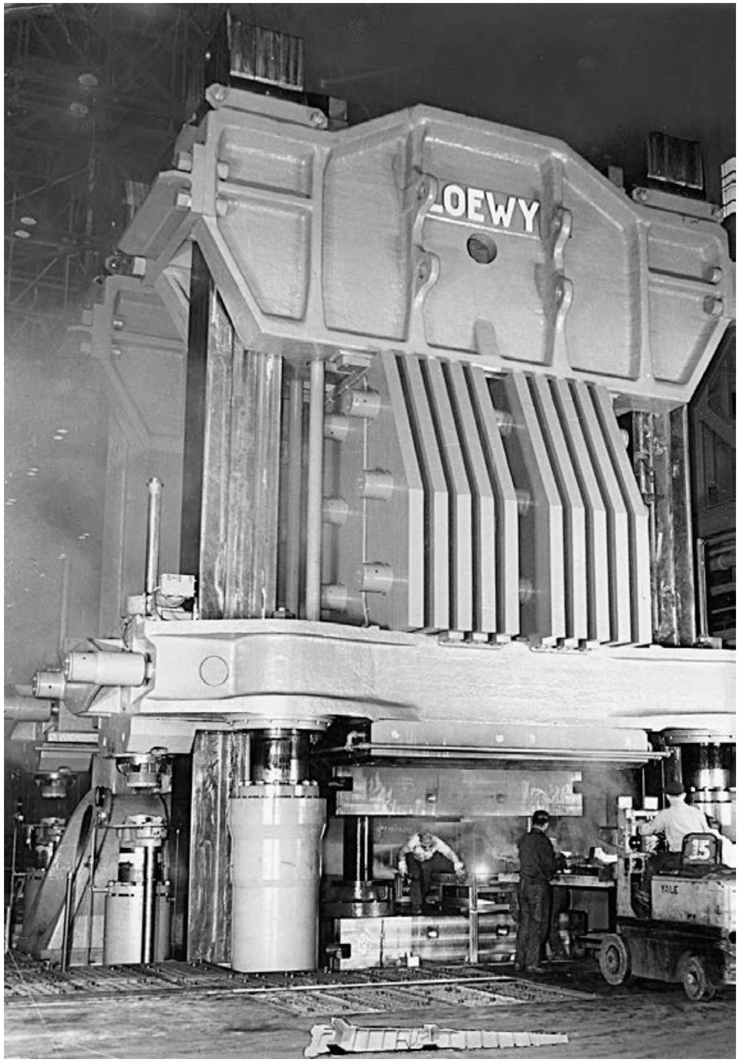
- Metal has been shaped by deformation processes for several thousand years
- Forging, rolling, and wire drawing were performed in the Middle Ages
- The Industrial Revolution allowed these processes to be done at a higher level
- Recently, many processes have begun to be automated

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

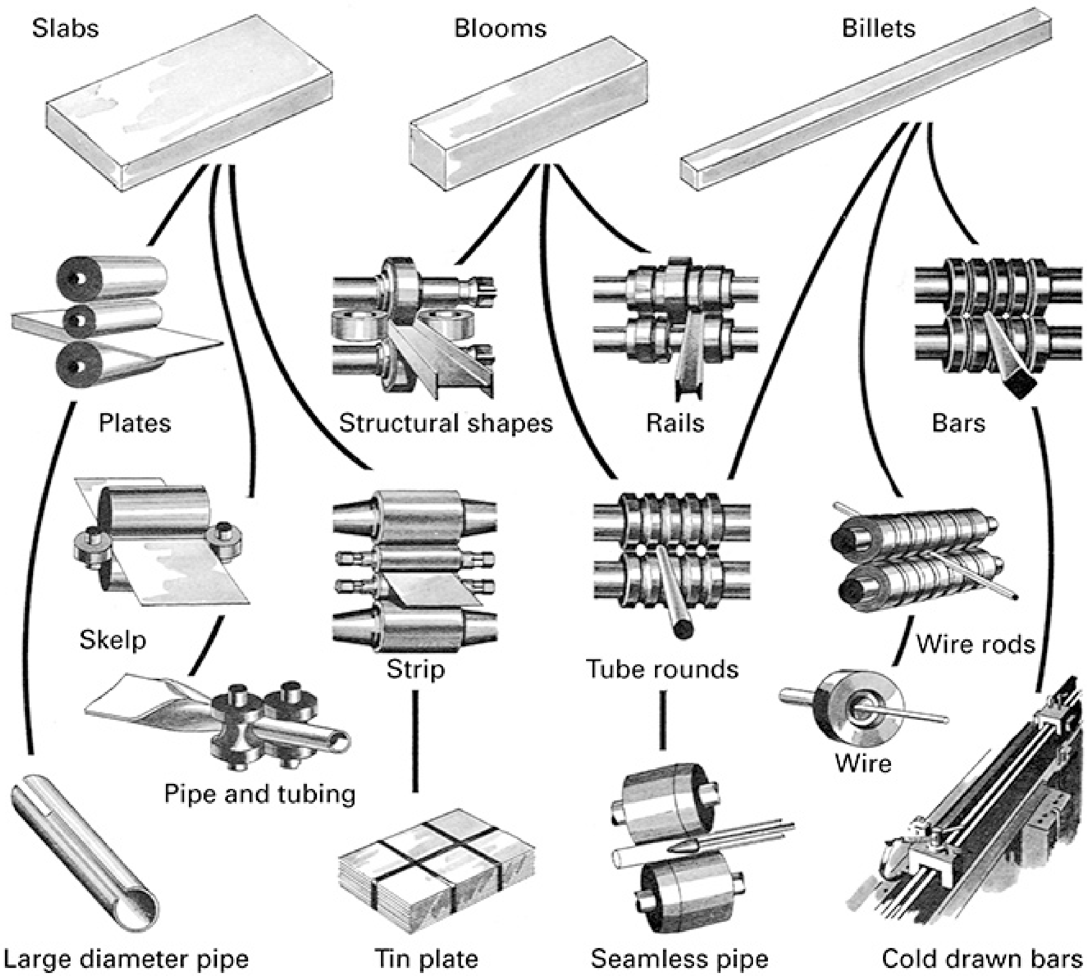
- Rolling operations reduce the thickness or change the cross section of a material through compressive forces
- Often the first process that is used to convert material into a finished wrought product
- Thick stock can be rolled into blooms, billets, or slabs

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

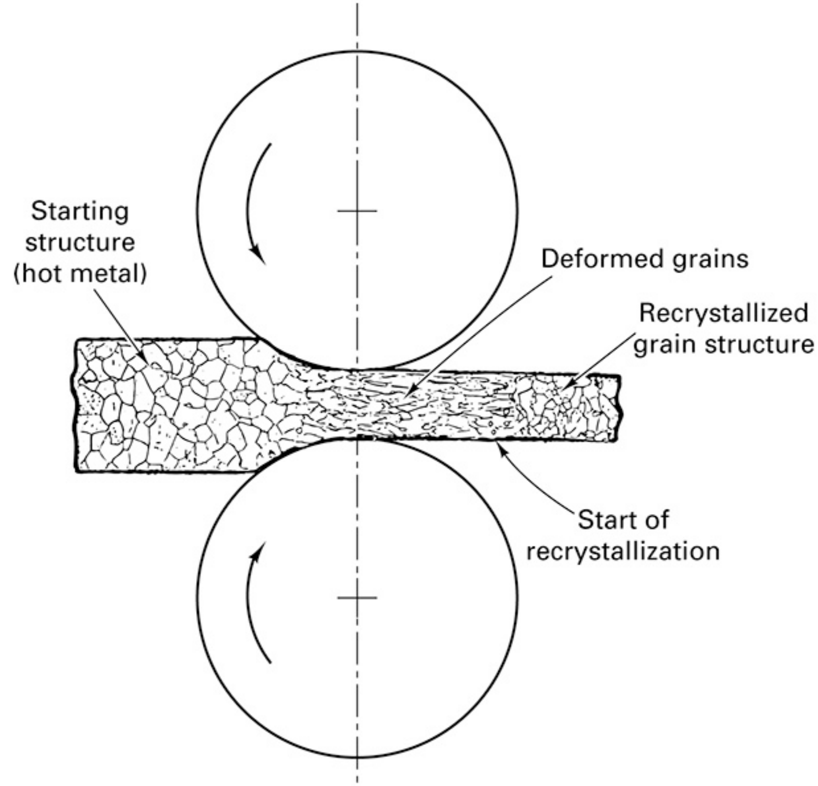


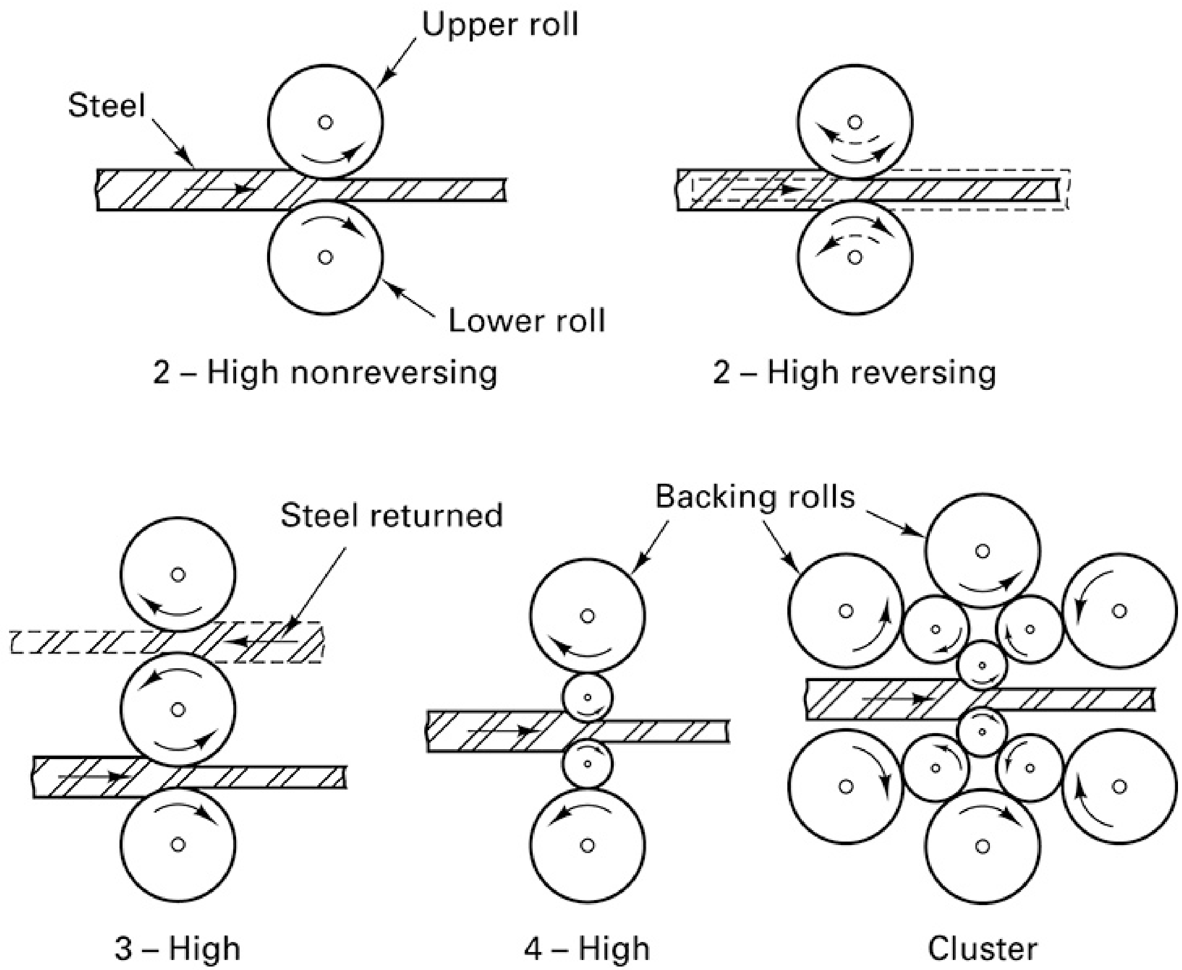
Figure 16-2 Schematic representation of the hot-rolling process, showing the deformation and recrystallization of the metal being rolled.

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

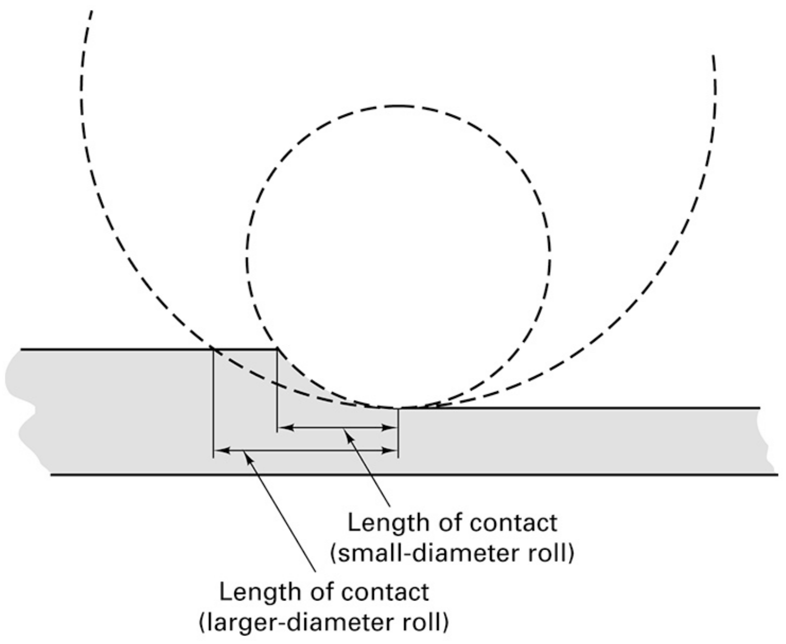
Figure 16-3 Various roll configurations used in rolling operations.



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

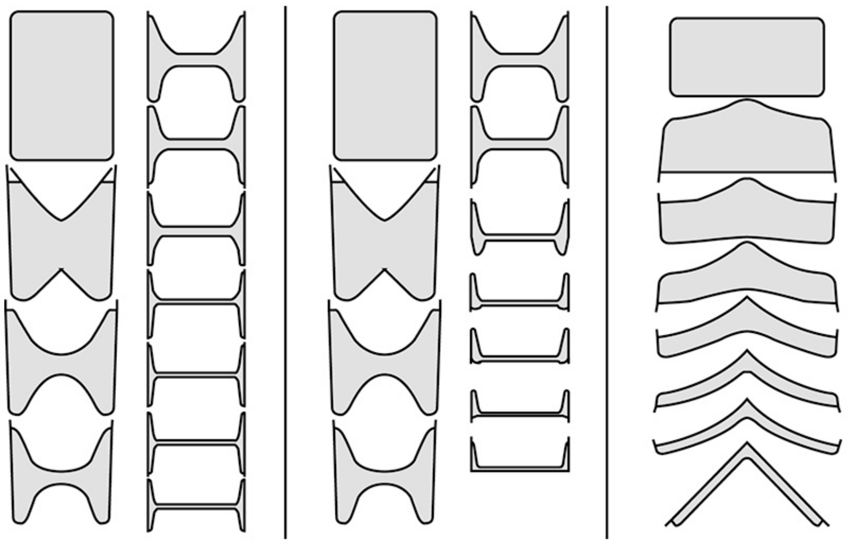


Figure 16-5 Typical roll-pass sequences used in producing structural shapes.

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

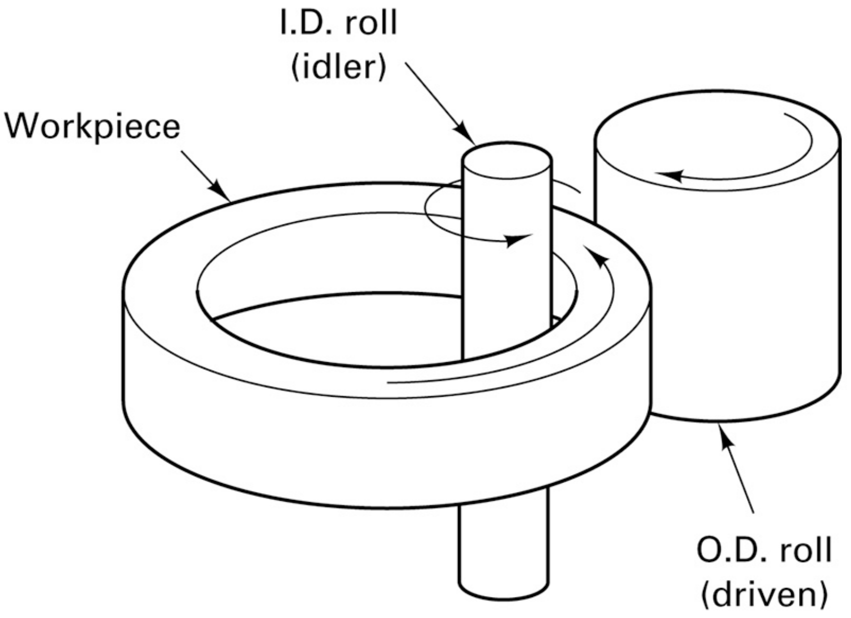
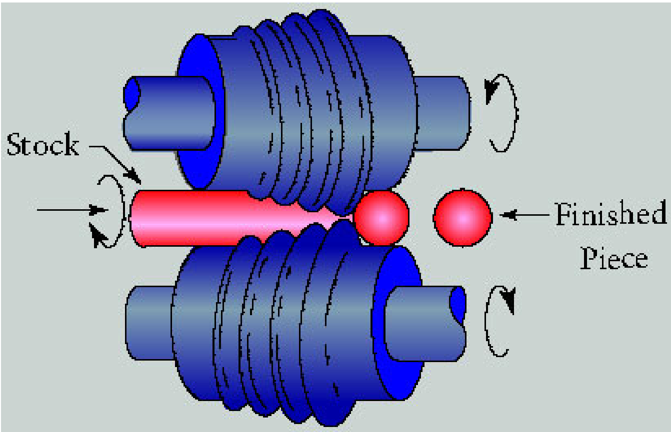


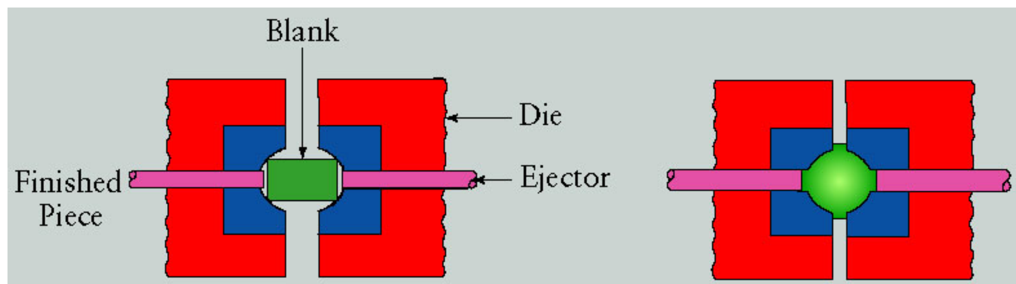
Figure 16-6 Schematic of horizontal ring rolling operation. As the thickness of the ring is reduced, its diameter will increase.

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

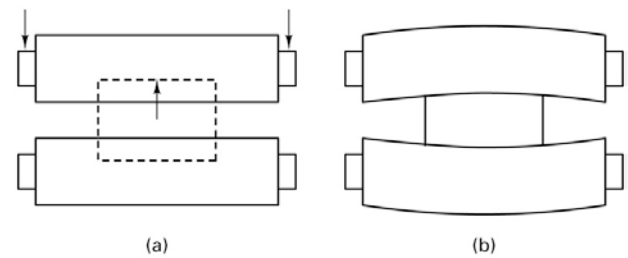


Figure 16-7 (above) (a) Loading on a rolling mill roll. The top roll is pressed upward in the center while being supported on the ends. (b) The elastic response to the three-point bending.

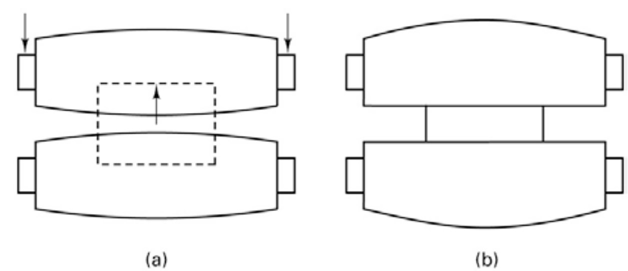


Figure 16-8 Use of a “crowned” roll to compensate for roll flexure. When the roll flexes in three-point bending, the crowned roll flexes into flatness.

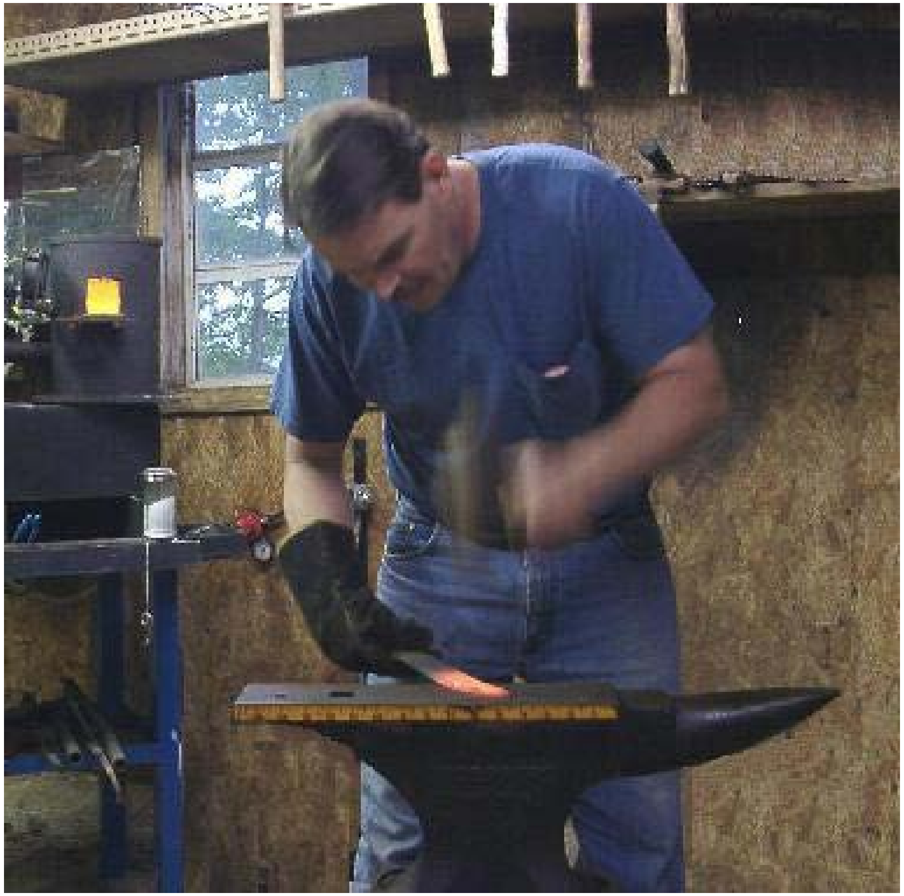
Thermomechanical Processing and Controlled Rolling

- 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

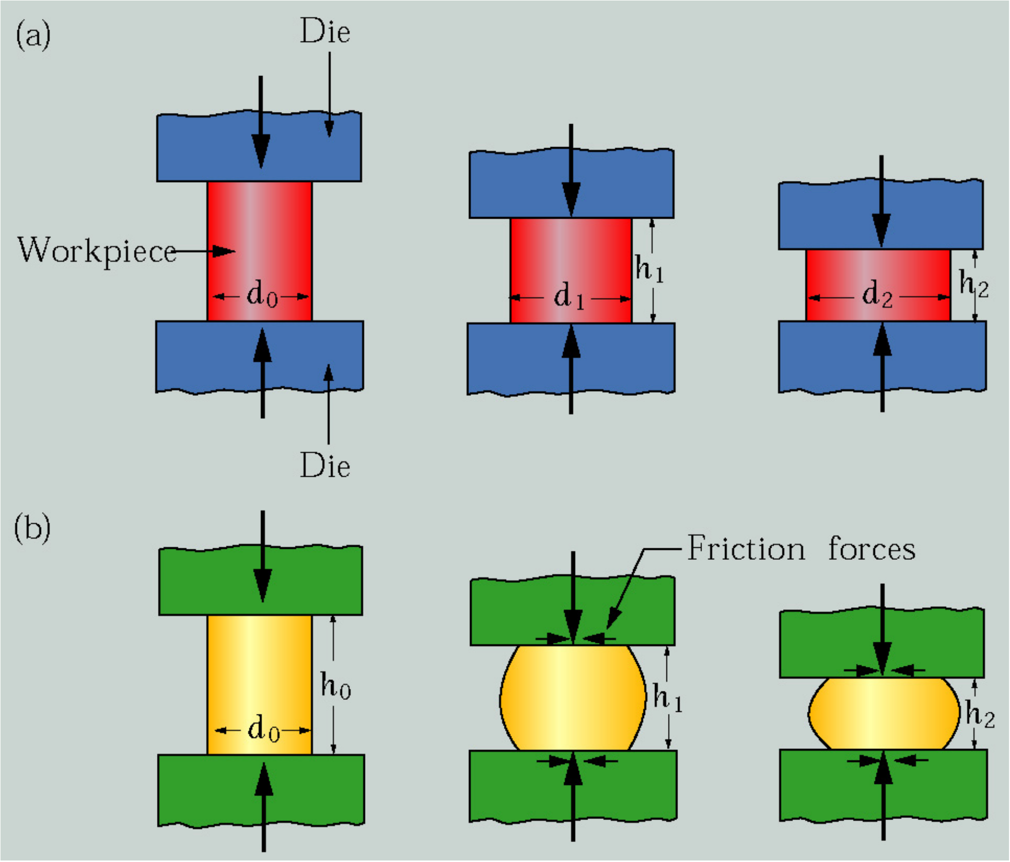
Traditional Forging



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

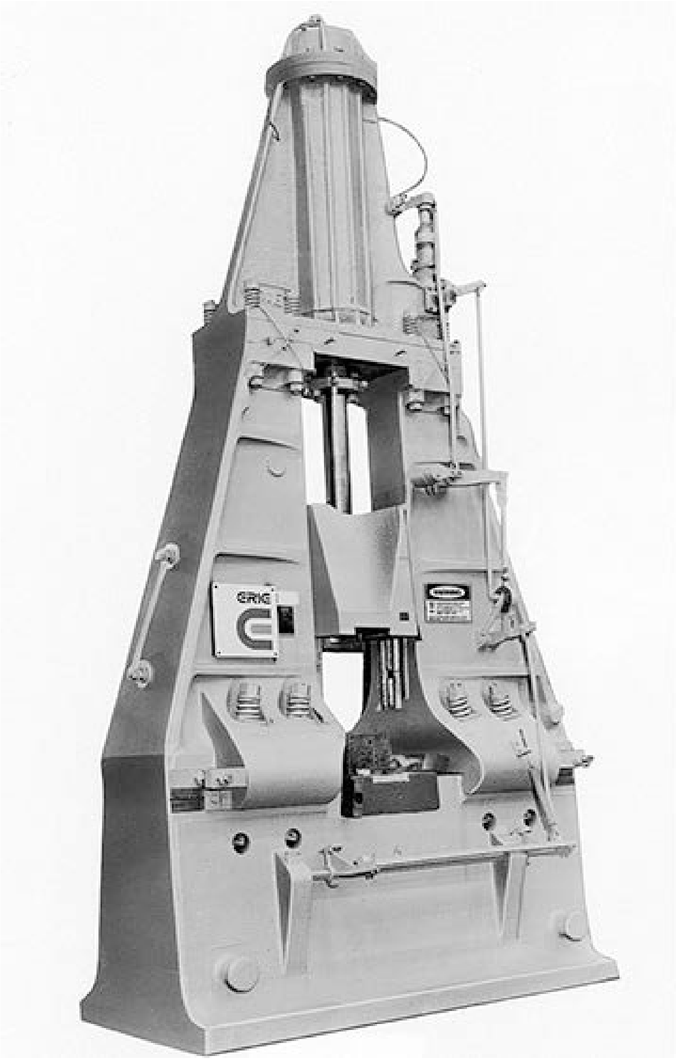
Open Die Forging: Upsetting-ideal



(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



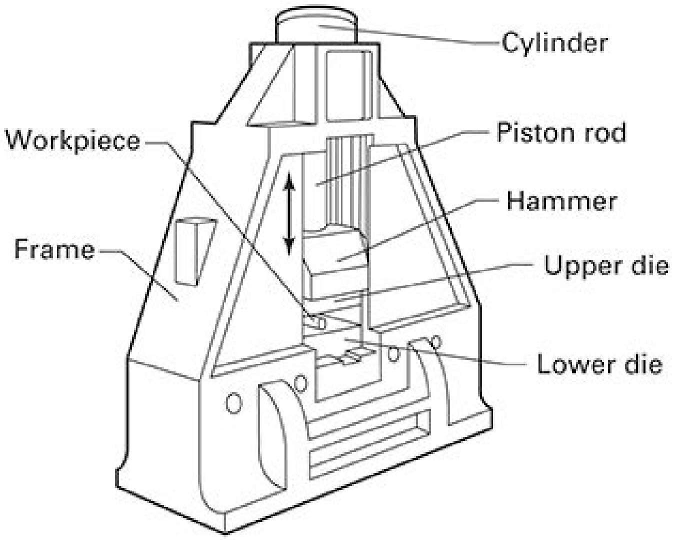


Figure 16-9 (Left) Double-frame drop hammer. (*Courtesy of Erie Press Systems, Erie, PA*.) (Right) Schematic diagram of a forging hammer.

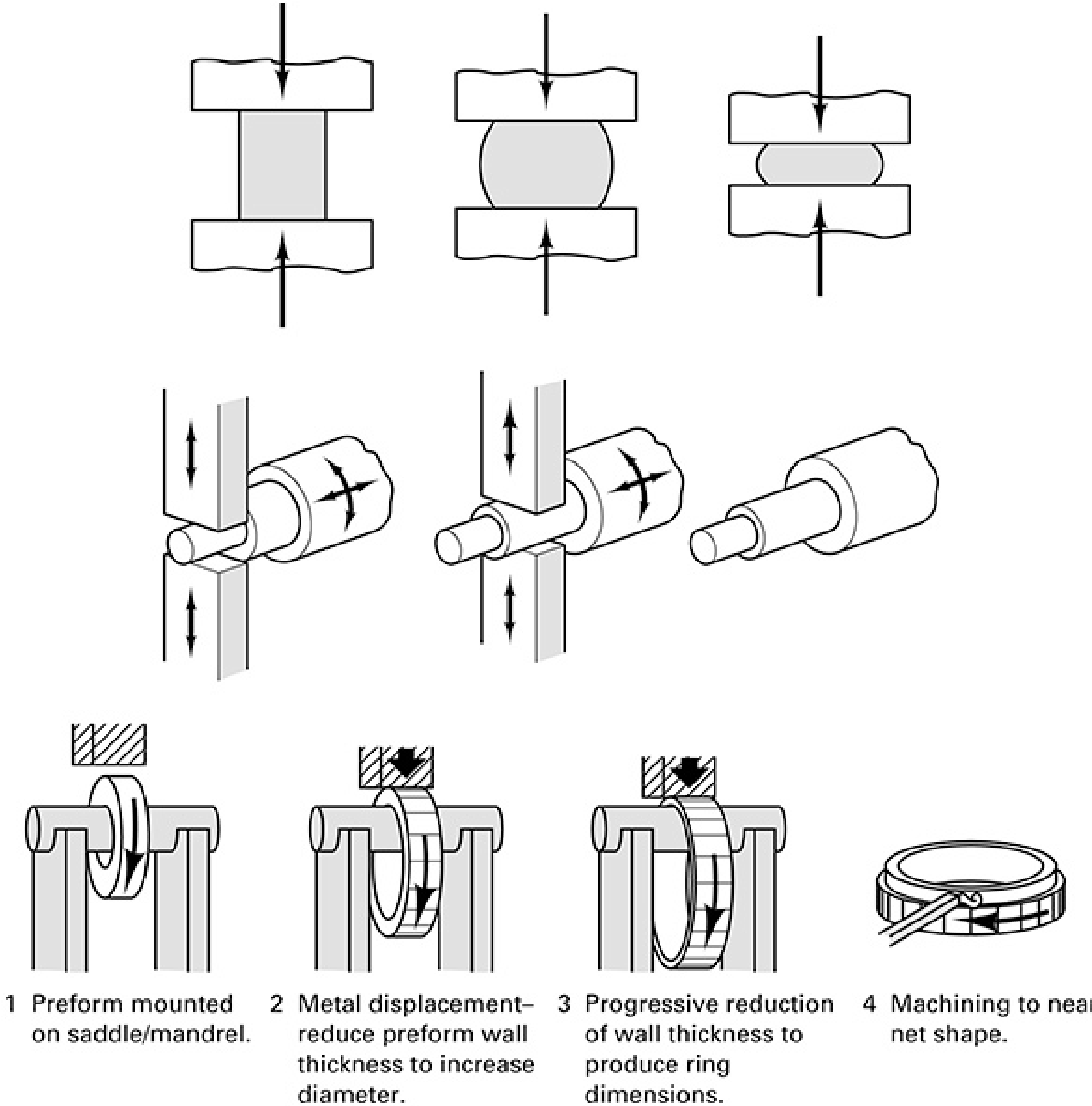
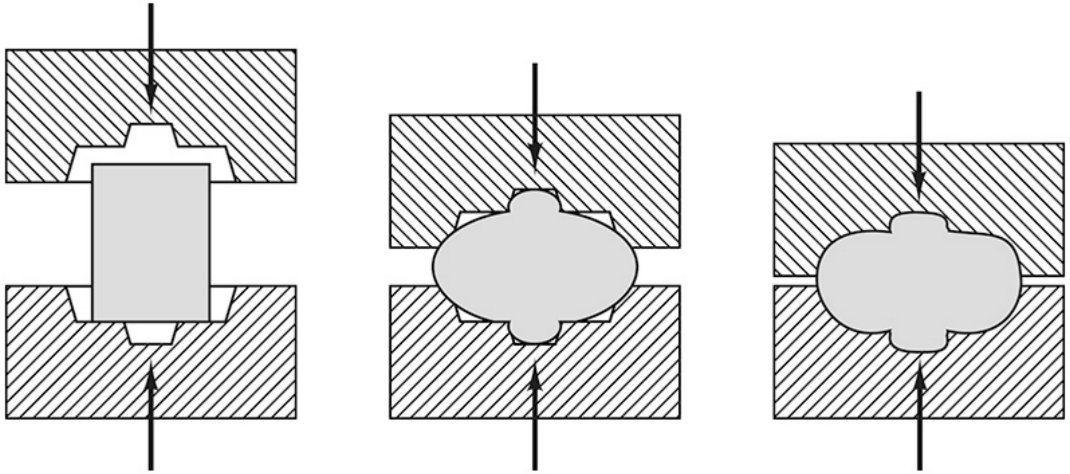


Figure 16-10 (Top) Illustration of the unrestrained flow of material in open-die forging. Note the barrel shape that forms due to friction between the die and material. (Middle) Open-die forging of a multidiameter shaft. (Bottom) Forging of a seamless ring by the open-die method. (Courtesy of Forging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

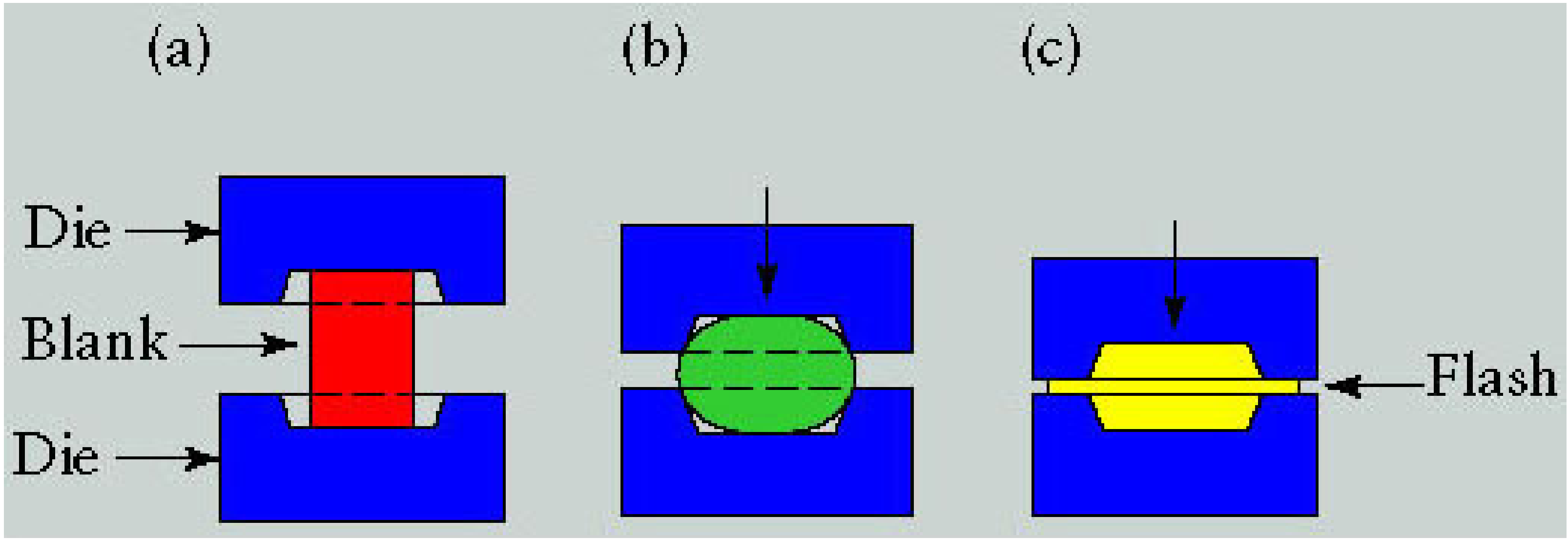
Impression-Die Hammer Forging

- 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.



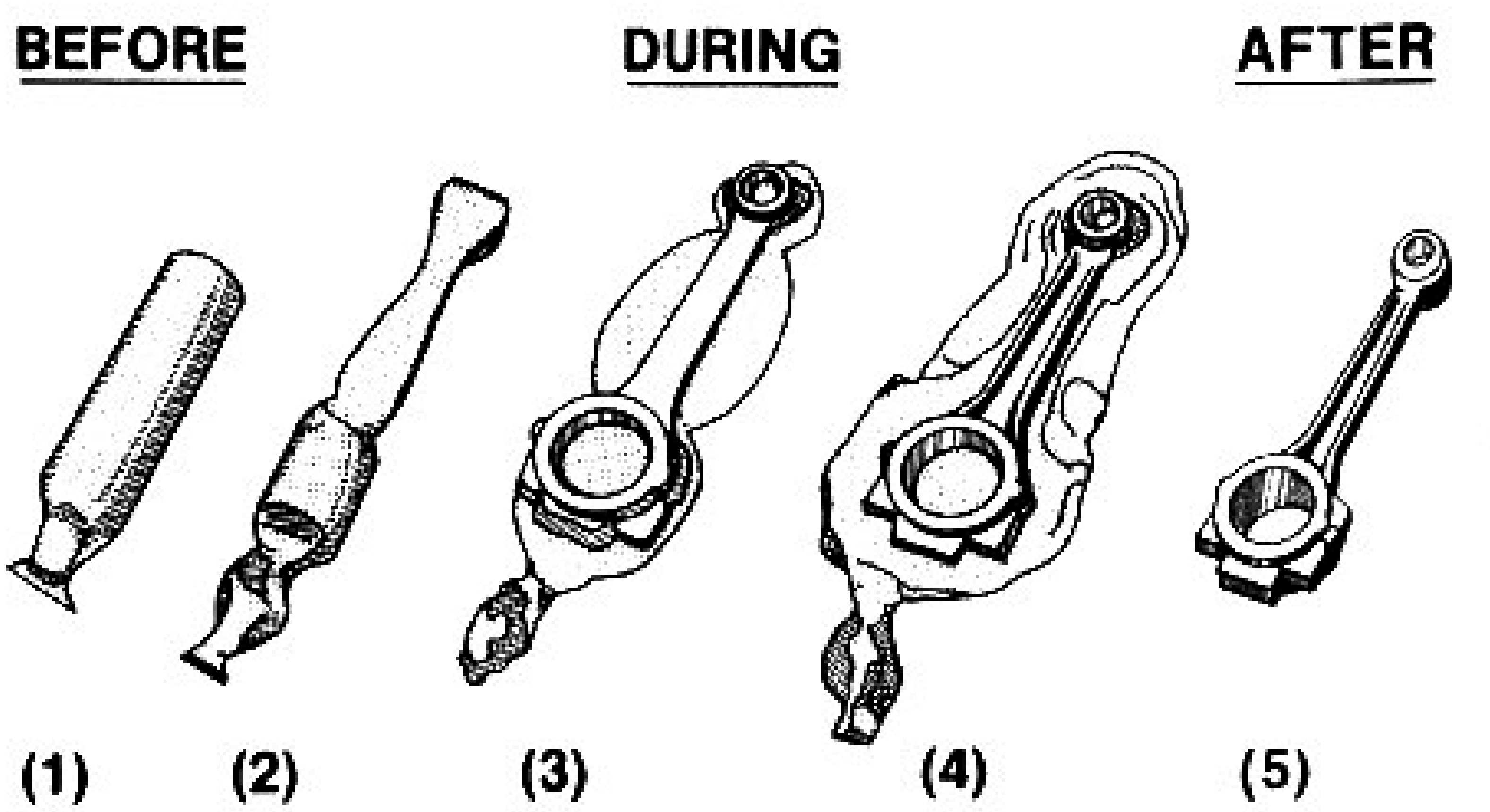
Impression Die Forging



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

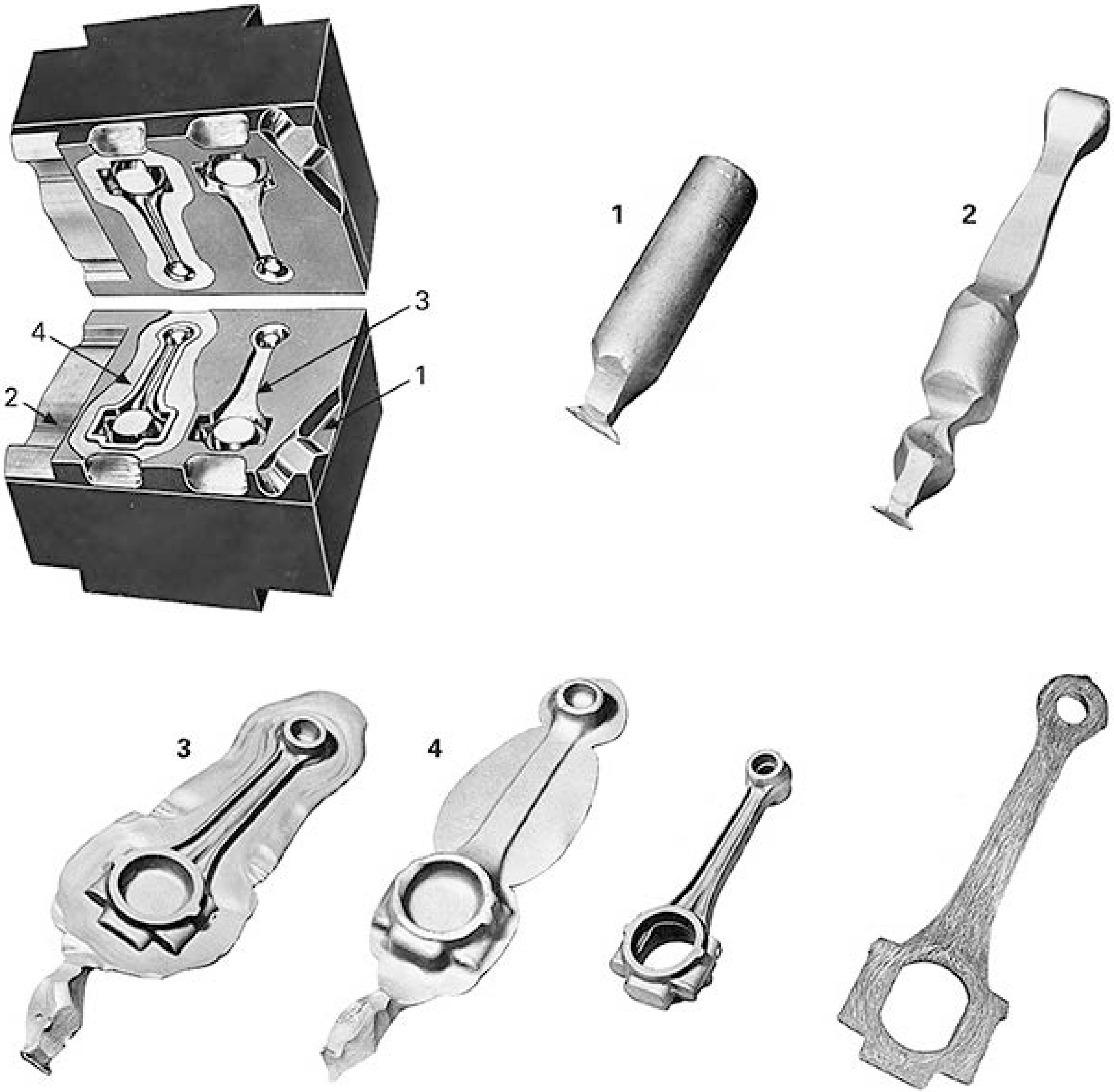


Figure 16-12
Impression drop-forging dies and the product resulting from each impression. The flash is trimmed from the finished connecting rod in a separate trimming die. The sectional view shows the grain flow resulting from the forging process. (*Courtesy of Forging Industry Association, Cleveland,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

Alternatives to Hammer and Anvil Arrangement

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

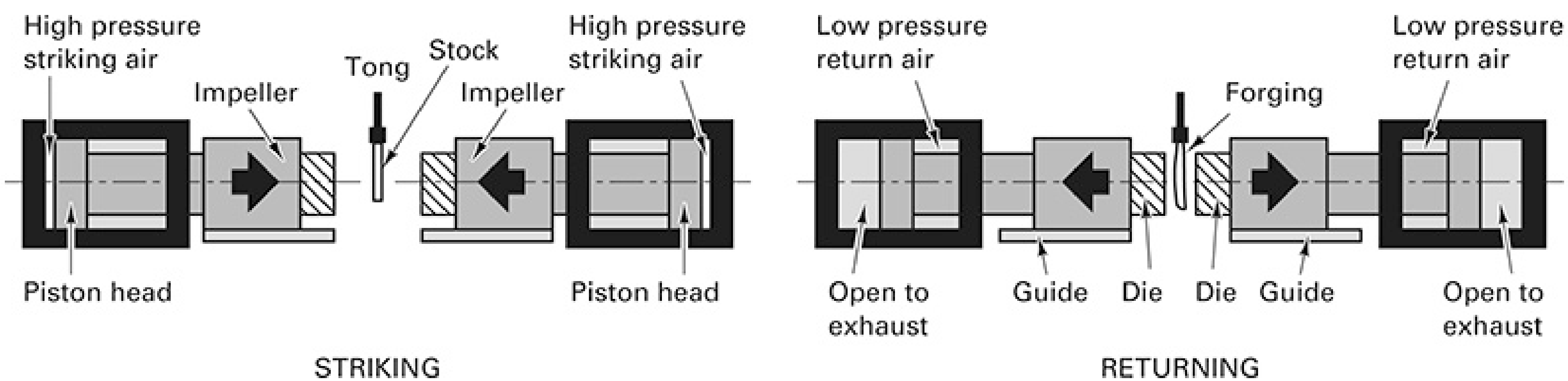


Figure 16-13 Schematic diagram of an impactor in the striking and returning modes. (*Courtesy of Chambersburg Engineering Company, Chambersburg, PA*)

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

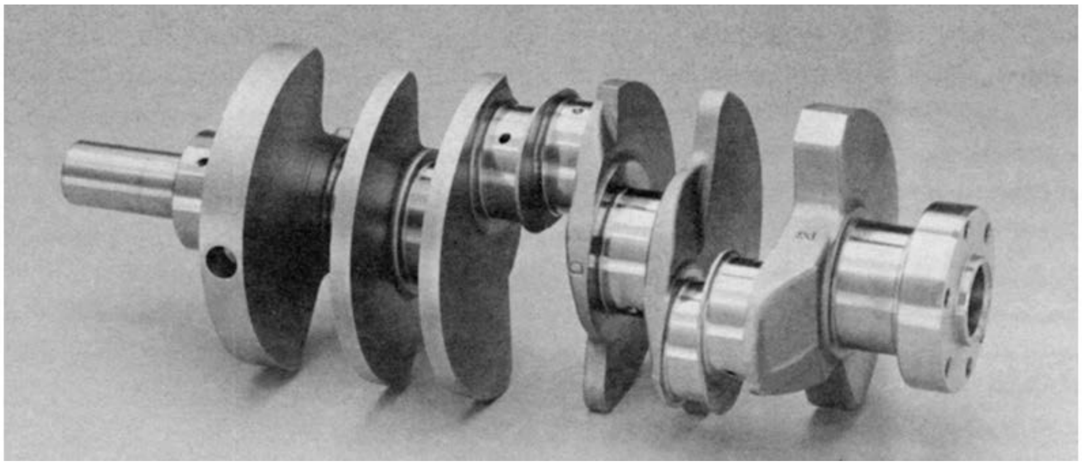


Figure 16-15 A forged-and-machined automobile engine crankshaft that has been formed from microalloyed steel. Performance is superior to cranks of cast ductile iron.

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

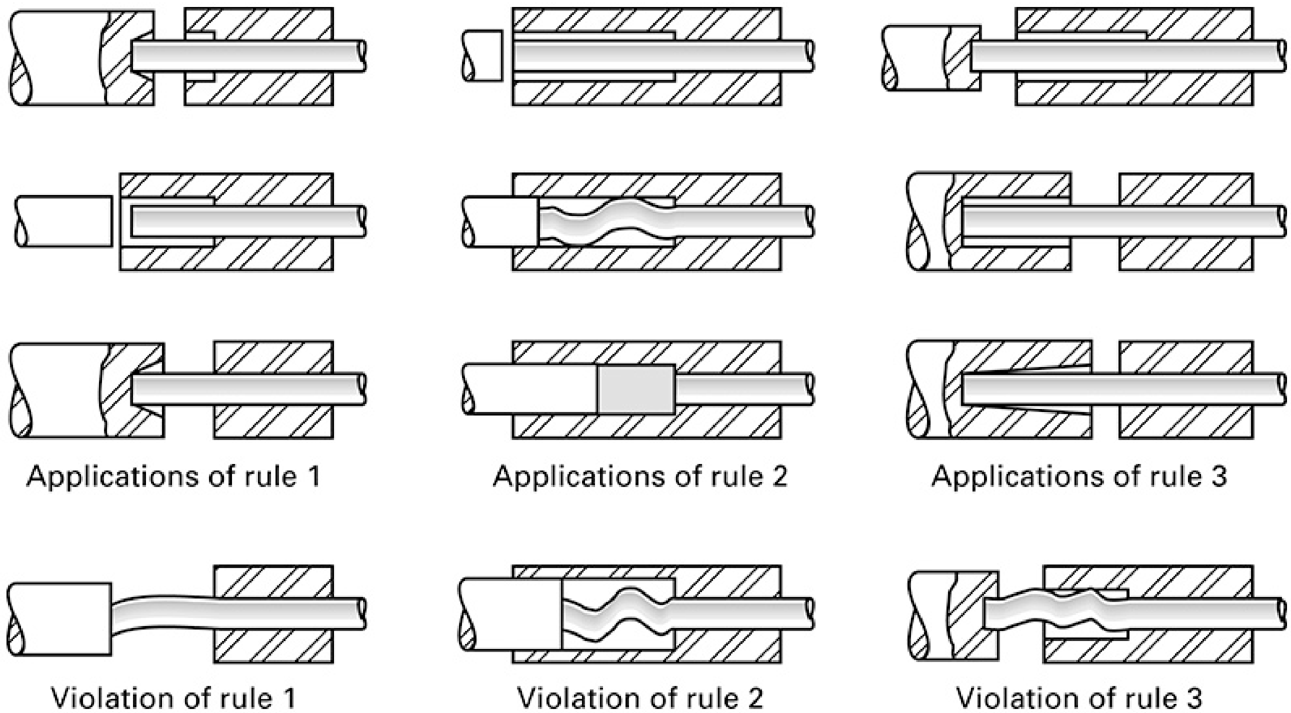
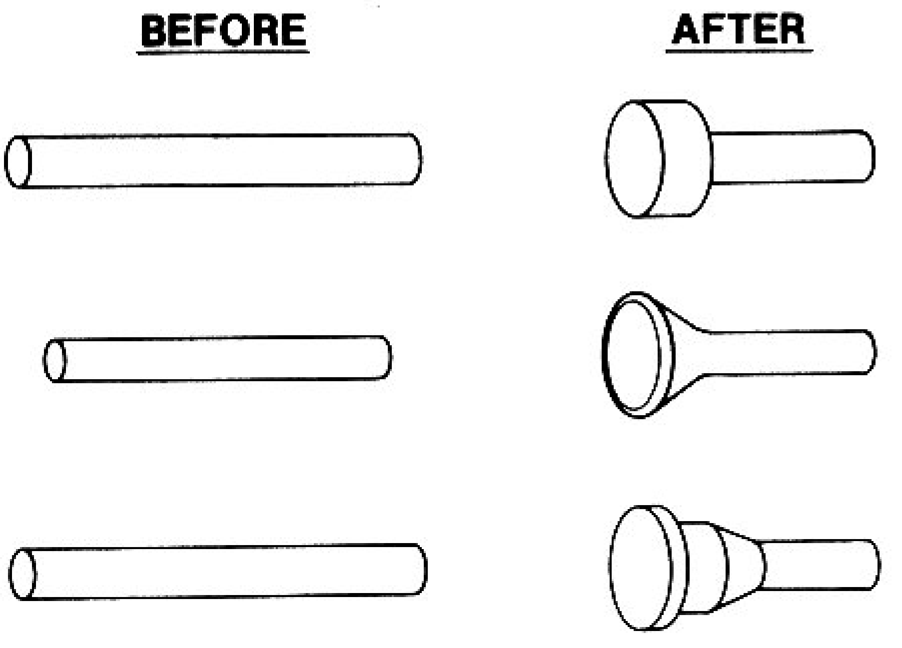
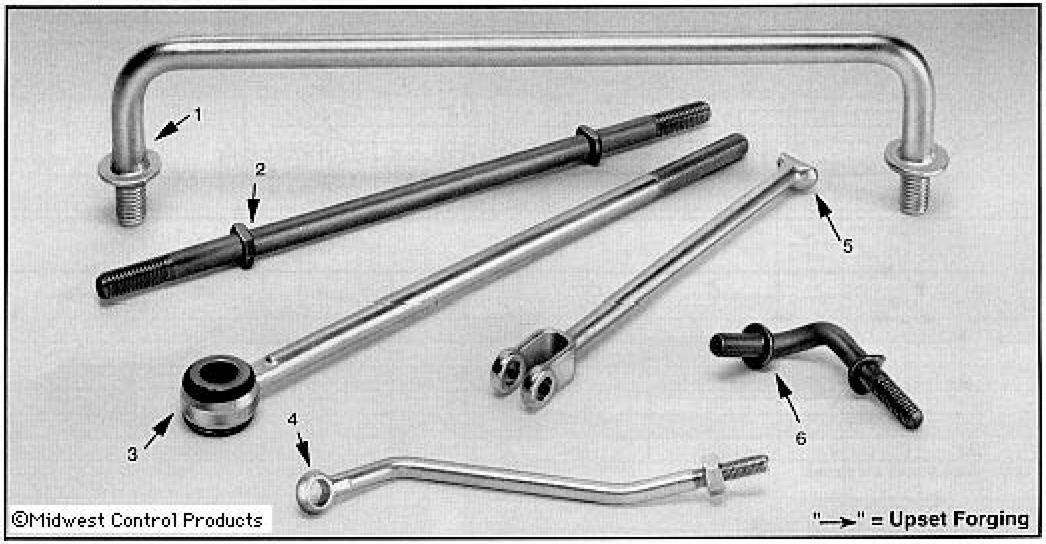


Figure 16-17 Schematics illustrating the rules governing upset forging. (*Courtesy of National Machinery Company, Tiffin, OH.)*

Upsetting



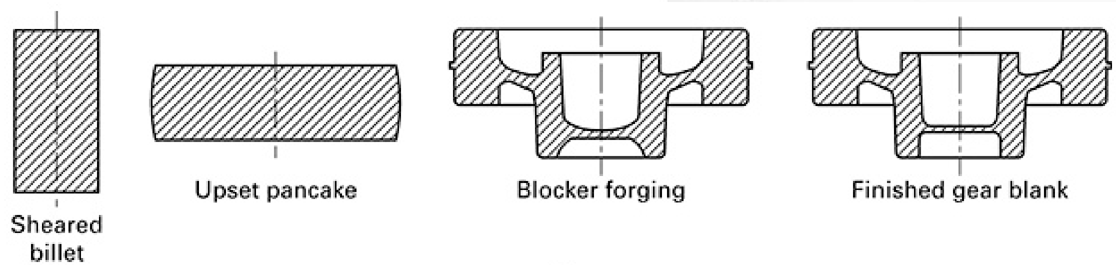
Upsetting Examples



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



(a)

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

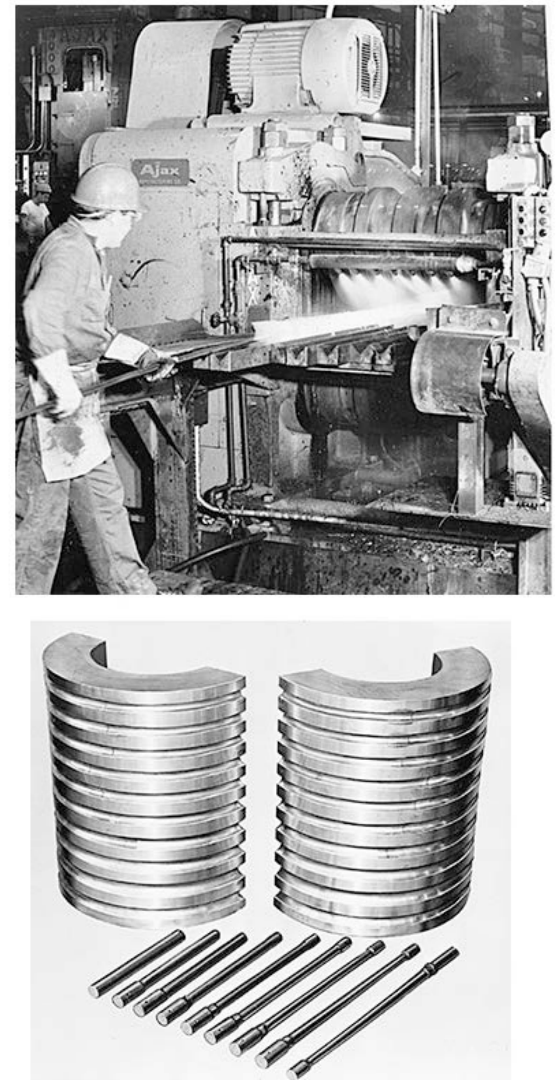
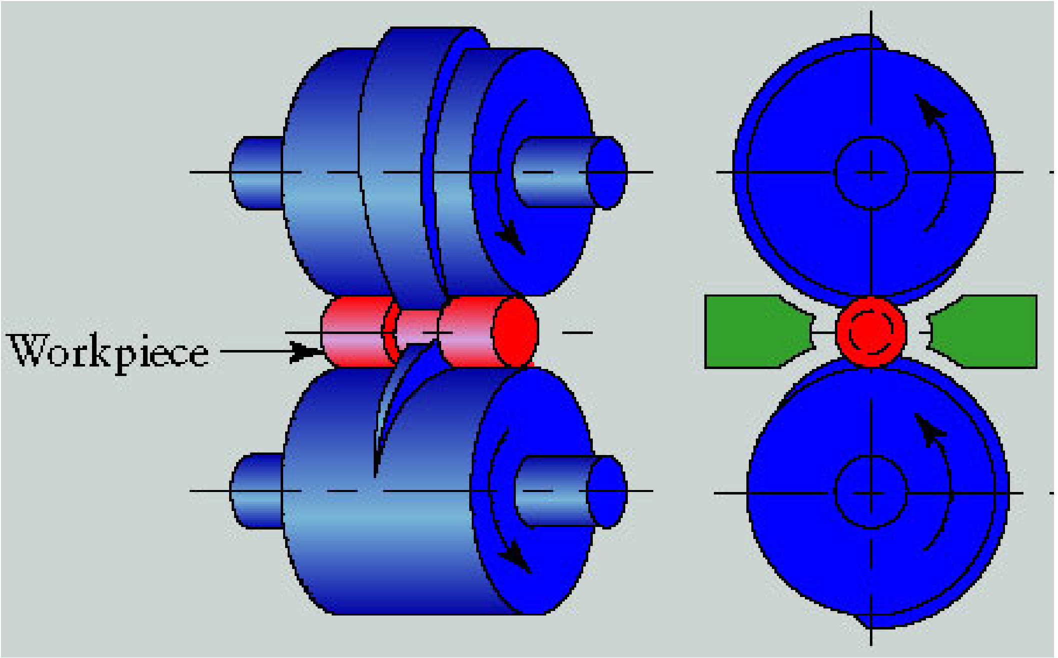


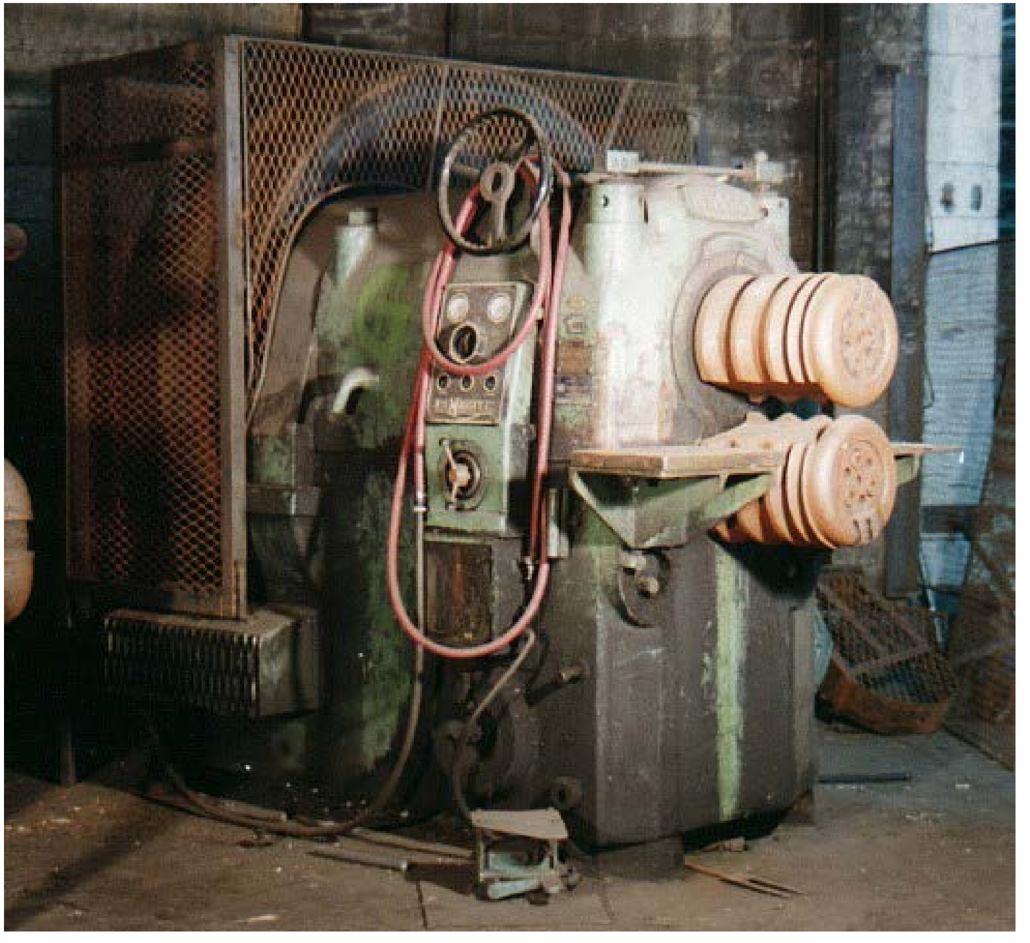
Figure 16-19 (Top) Roll-forging machine in operation. (Right) Rolls from a roll-forging machine and the various stages in roll forging a part. (Courtesy of Ajax Manufacturing Company, Euclid, OH)

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

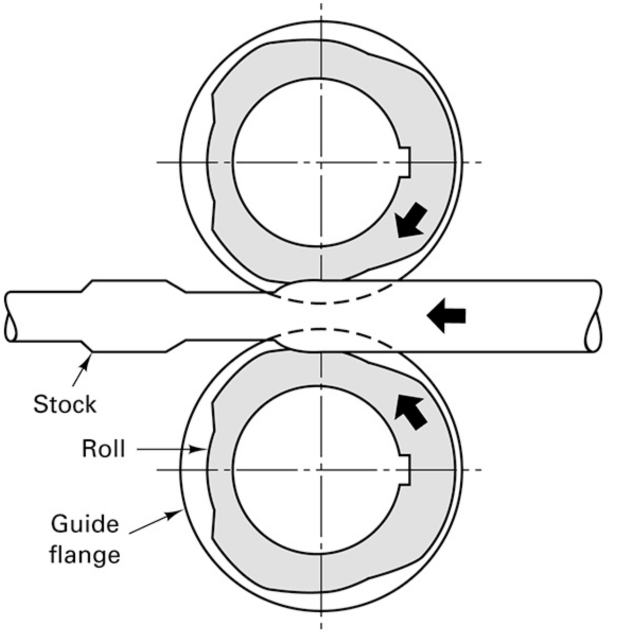


Figure 16-20 Schematic of the roll-forging process showing the two shaped rolls and the stock being formed. (*Courtesy of Forging Industry Association, Cleveland, OH.)*

Swaging

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

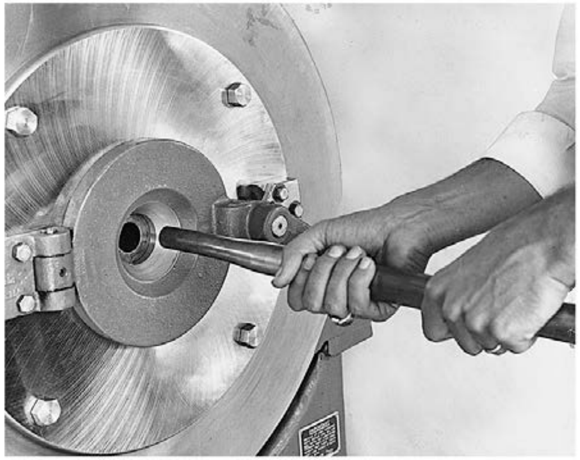


Figure 16-23 (Below) A variety of swaged parts, some with internal details. (*Courtesy of Cincinnati Milacron, Inc. Cincinnati, OH.)*

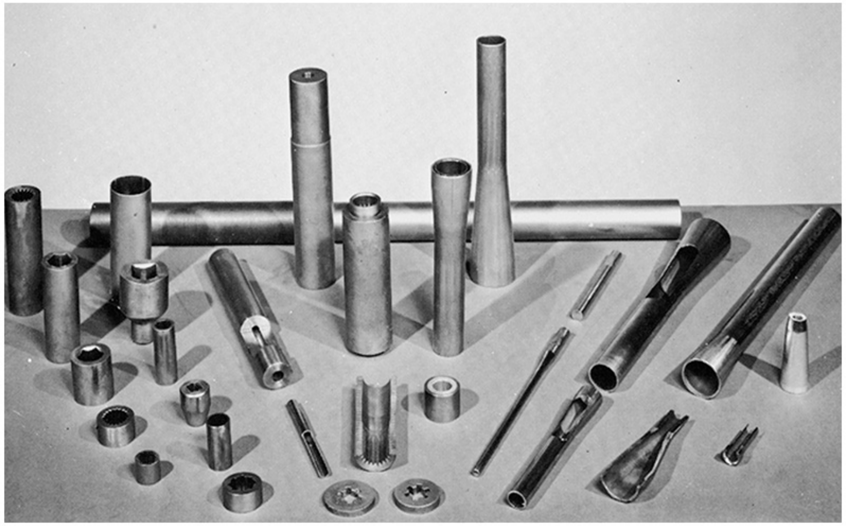
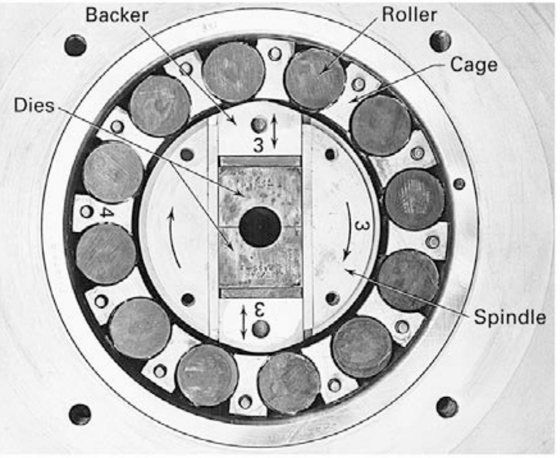
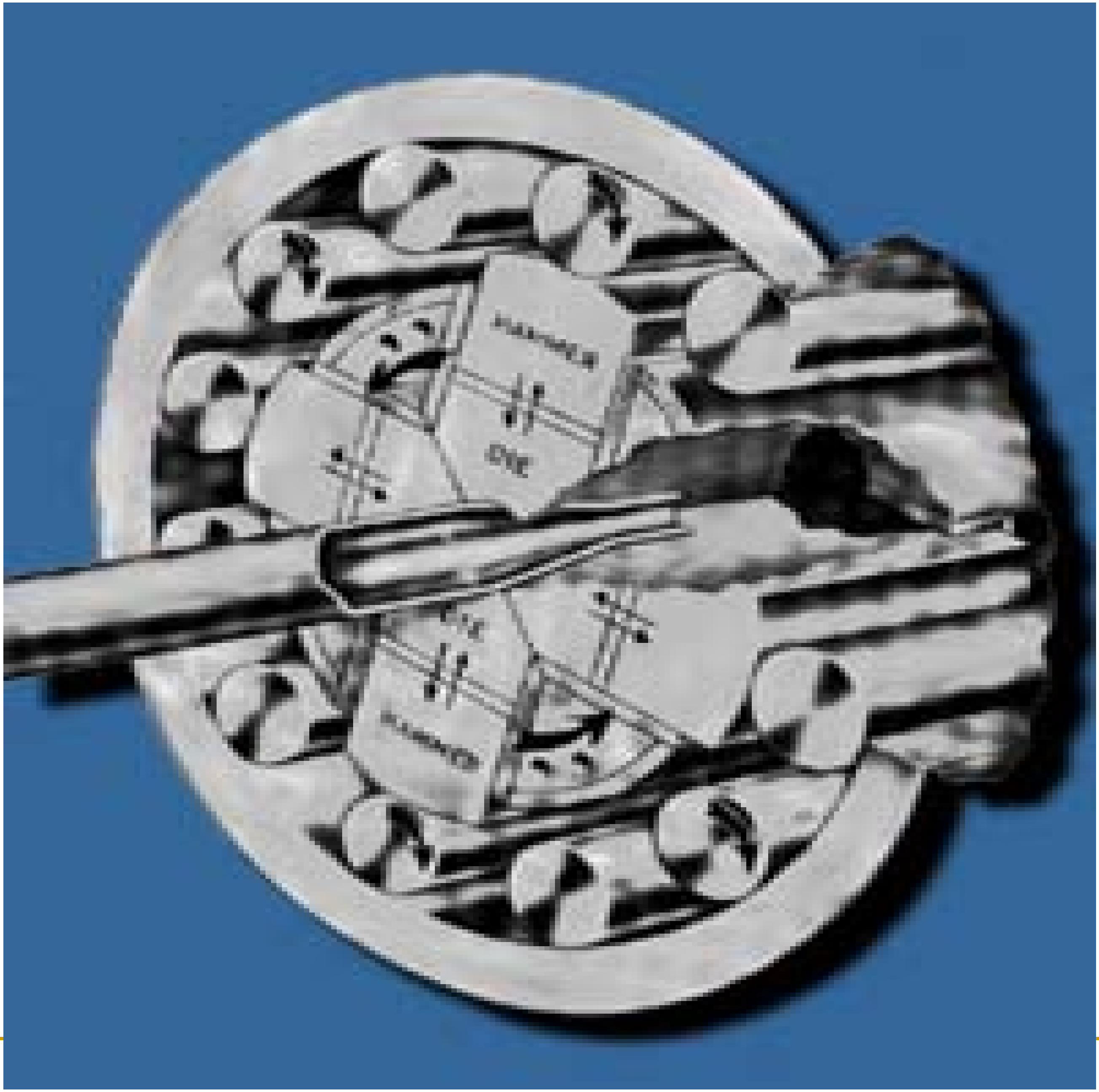


Figure 16-22 (Right) Basic components and motions of a rotary swaging machine. (Note: The cover plate has been removed to reveal the interior workings.) (*Courtesy of the Timkin Company, Canton, OH.)*





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

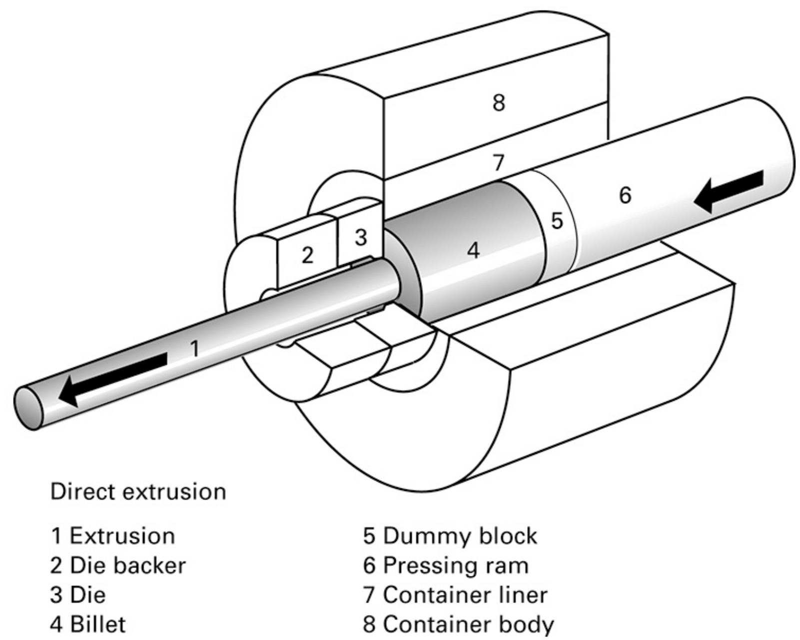


Figure 16-25 Direct extrusion schematic showing the various equipment components. (*Courtesy of Danieli Wean United, Cranberry Township, PA*.)

Typical Extruded Products

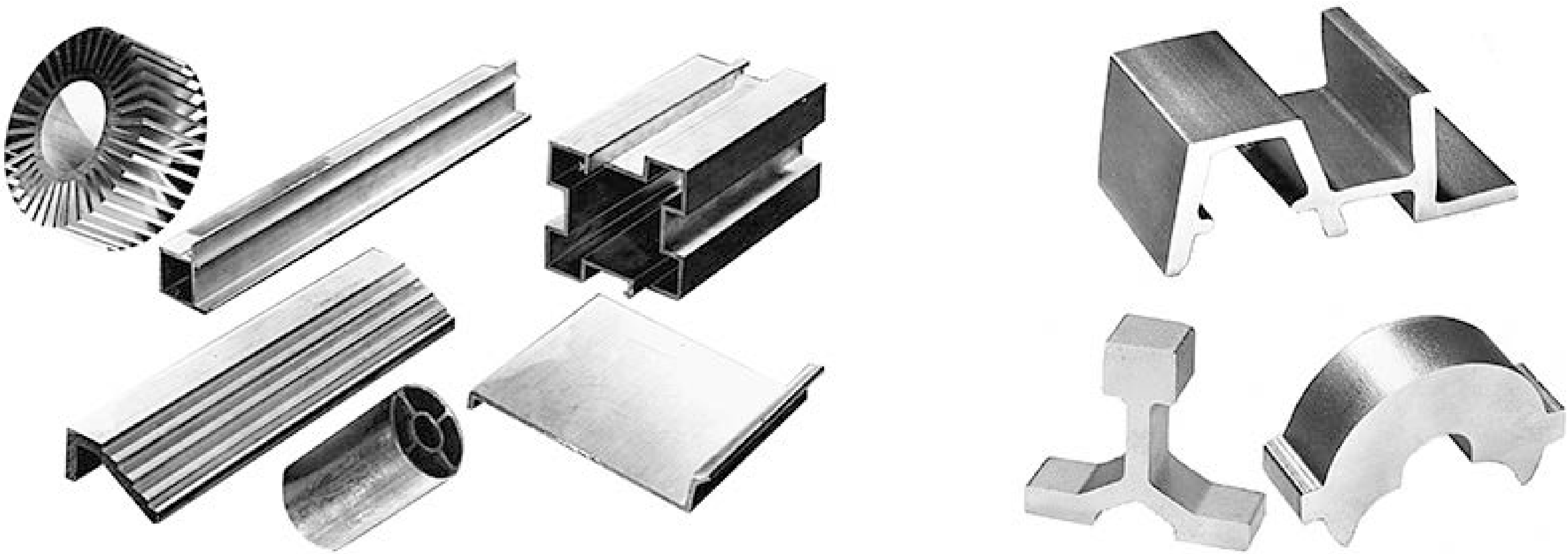


Figure 16-26 Typical shapes produced by extrusion. (Left) Aluminum products. (*Courtesy of Aluminum Company of America, Pittsburgh, PA*.) (Right) Steel products. (*Courtesy of Allegheny Ludlum Steel Corporation, Pittsburgh, PA*.)

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

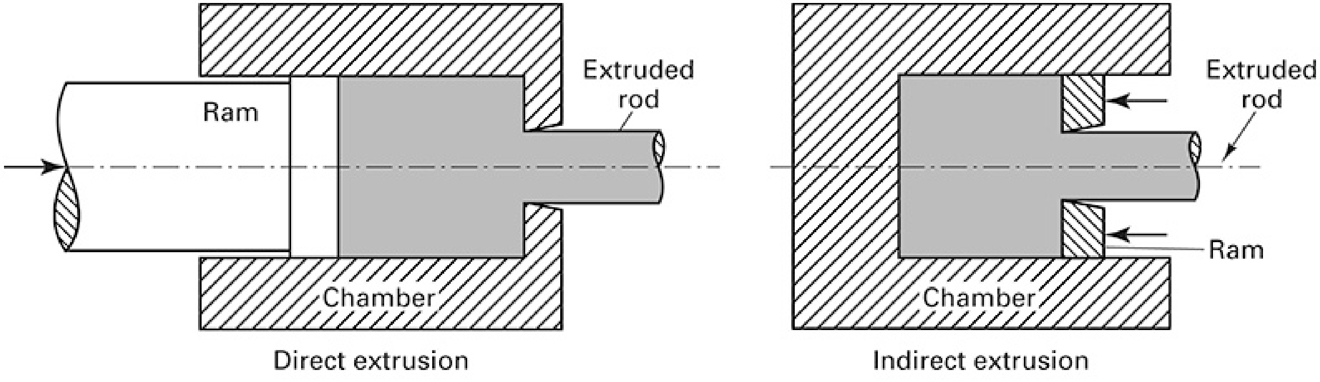


Figure 16-27 Direct and indirect extrusion. In direct extrusion, the ram and billet both move and friction between the billet and the chamber opposes forward motion. For indirect extrusion, the billet is stationary. There is no billet-chamber friction, since there is no relative motion.

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

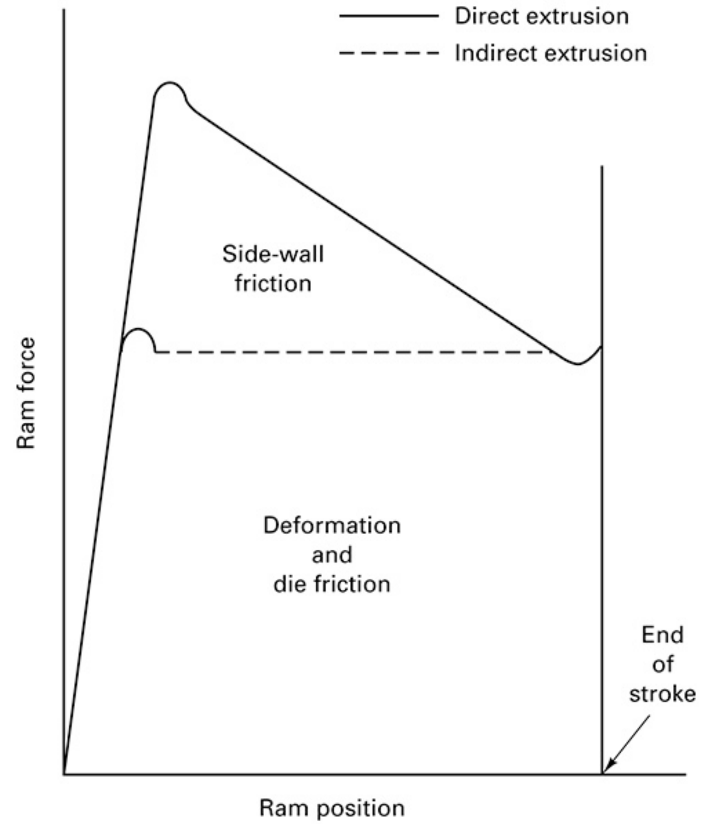


Figure 16-28 Diagram of the ram force versus ram position for both direct and indirect extrusion of the same product. The area under the curve corresponds to the amount of work (force x distance) performed. The difference between the two curves is attributed to billet-chamber friction.

Extrusion of Hollow Shapes

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

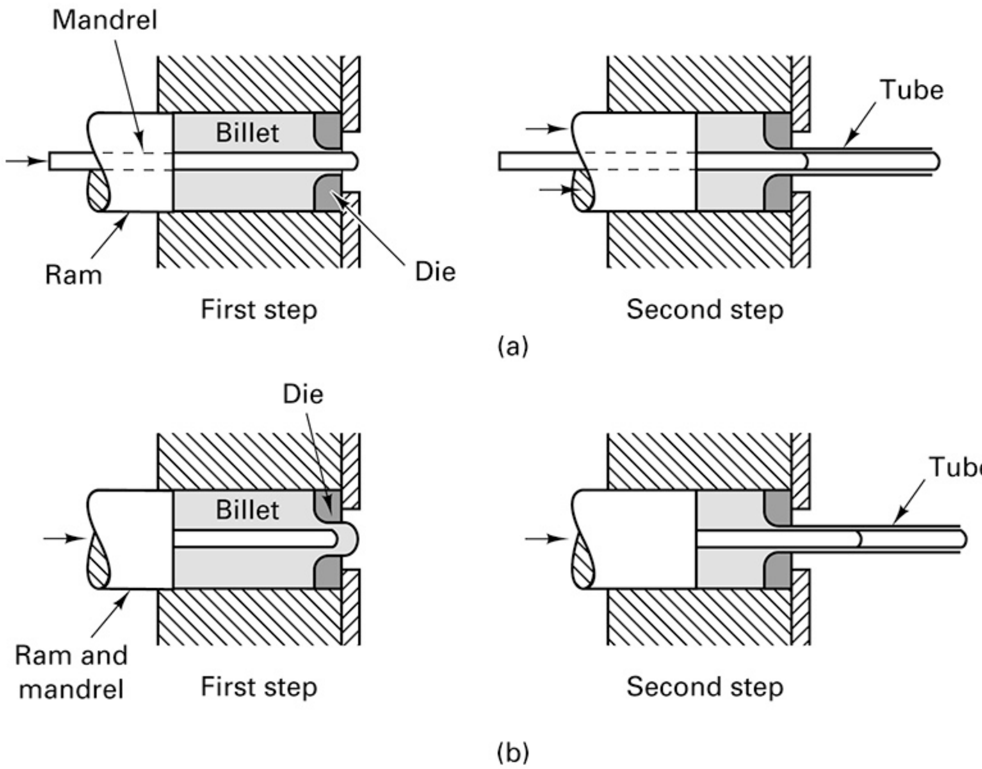


Figure 16-30 Two methods of extruding hollow shapes using internal mandrels. In part (a) the mandrel and ram have independent motions; in part (b) they move as a single unit.

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

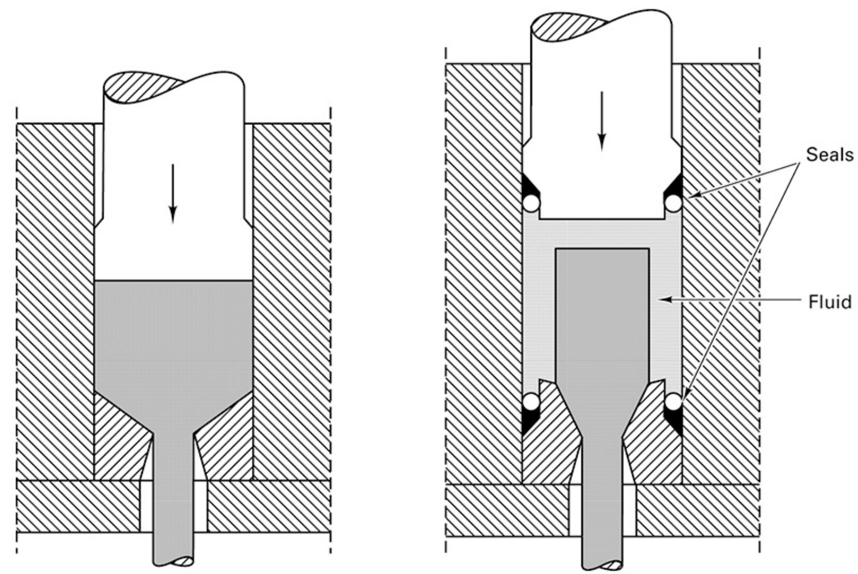


Figure 16-32 Comparison of conventional (left) and hydrostatic (right) extrusion. Note the addition of the pressurizing fluid and the O-ring and miter-ring seals on both the die and ram.

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

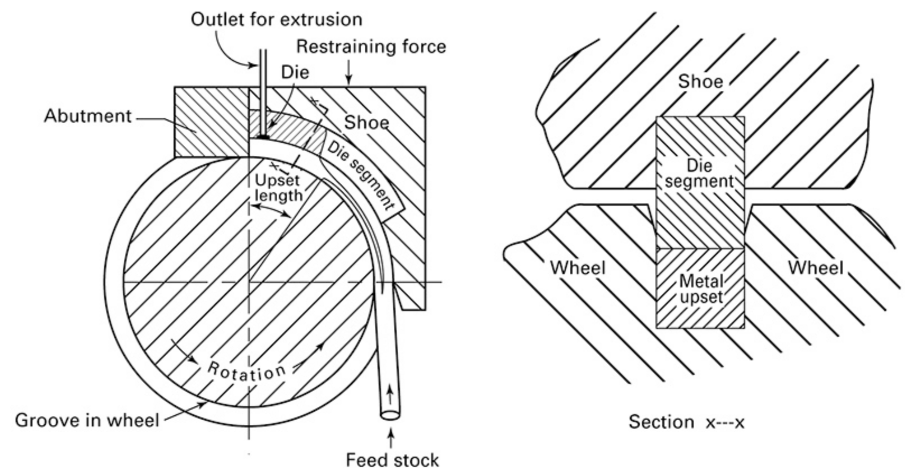


Figure 16-33 Cross-sectional schematic of the Conform continuous extrusion process. The material upsets at the abutment and extrudes. Section x-x shows the material in the shoe.

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

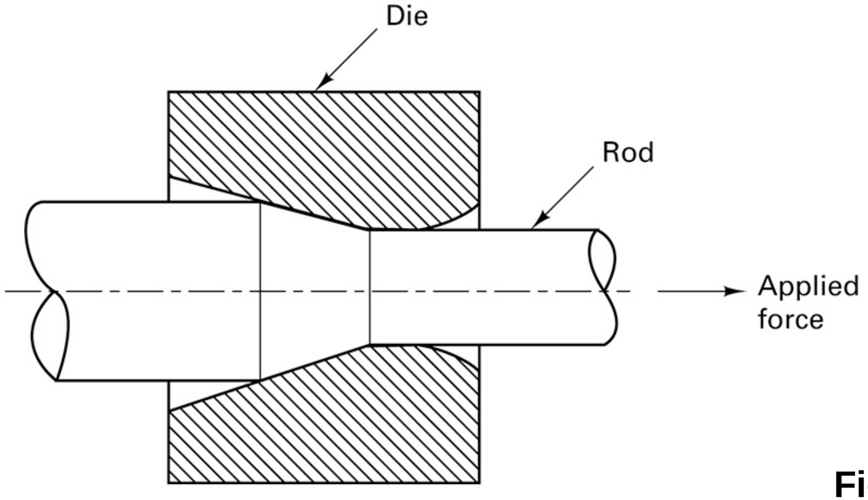


Figure 16-34 Schematic drawing of the rod-or bar-drawing process.

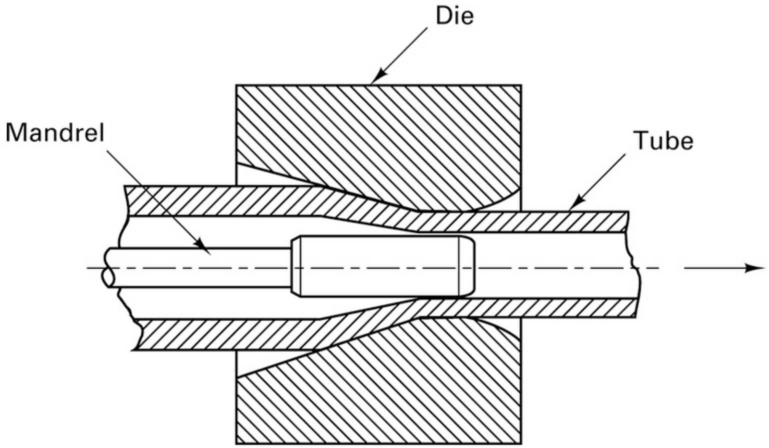


Figure 16-36 Cold-drawing smaller tubing from larger tubing. The die sets the outer dimension while the stationary mandrel sizes the inner diameter.

Tube and Wire Drawing

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

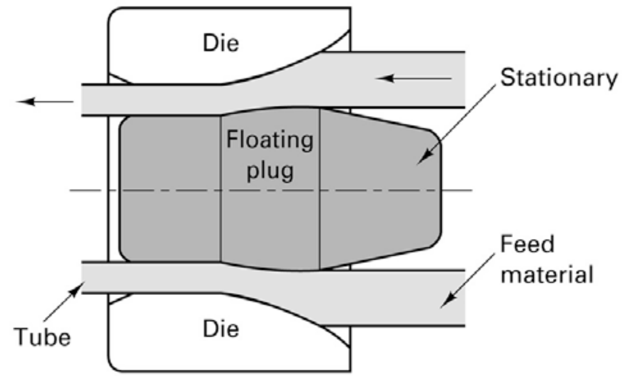


Figure 16-37 (Above) Tube drawing with a floating plug.

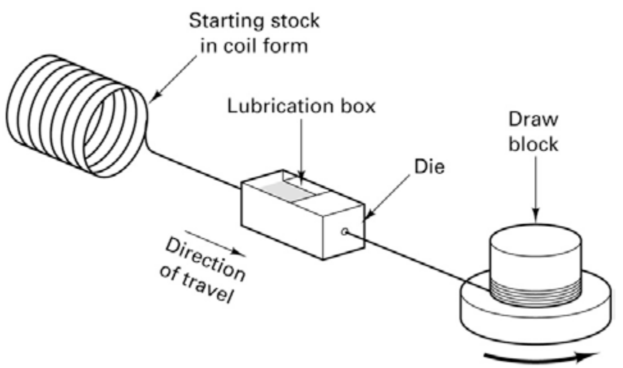


Figure 16-38 Schematic of wire drawing with a rotating draw block. The rotating motor on the draw block provides a continuous pull on the incoming wire.

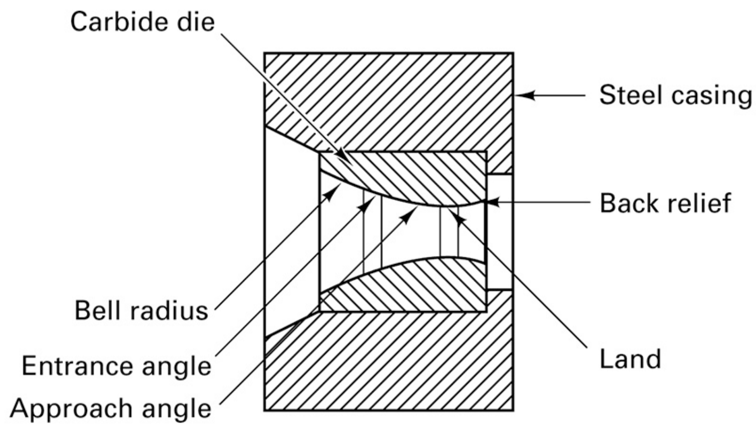


Figure 16-39 Cross section through a typical carbide wire-drawing die showing the characteristic regions of the contour.

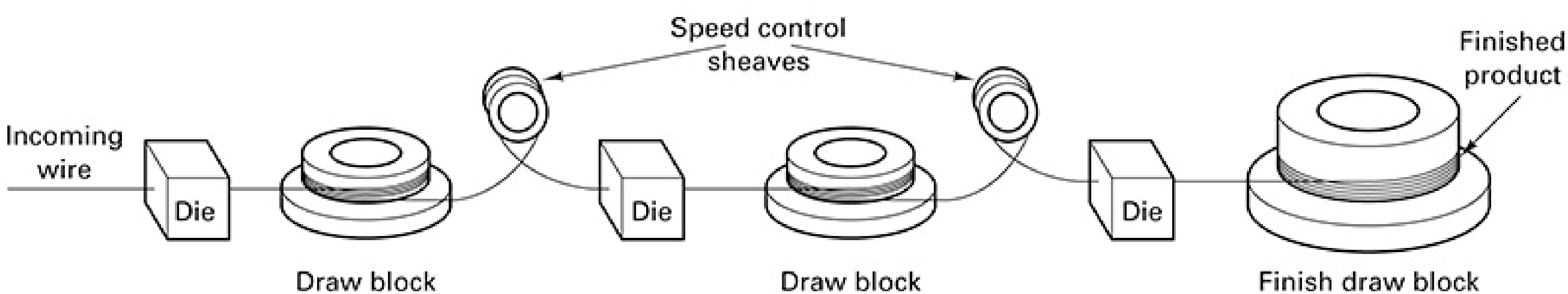


Figure 16-40 Schematic of a multistation synchronized wire-drawing machine. To prevent accumulation or breakage, it is necessary to ensure that the same volume of material passes through each station in a given time. The loops around the sheaves between the stations use wire tensions and feedback electronics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

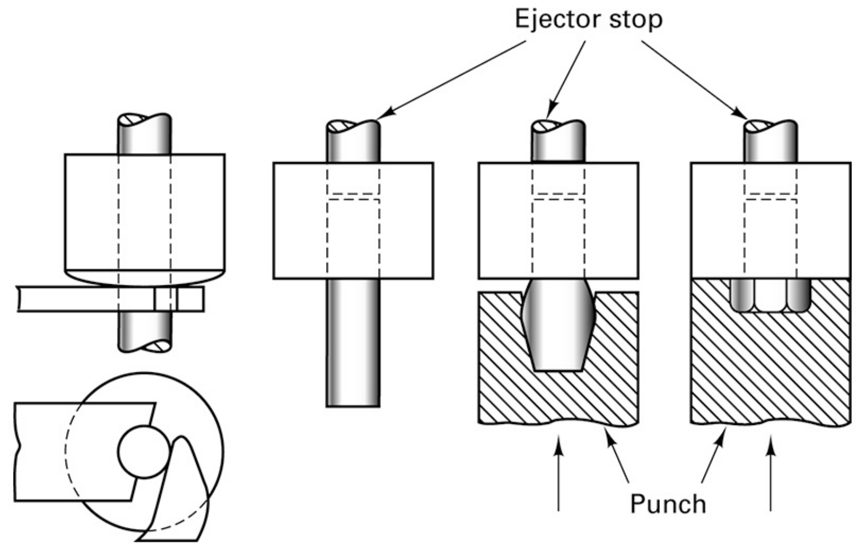
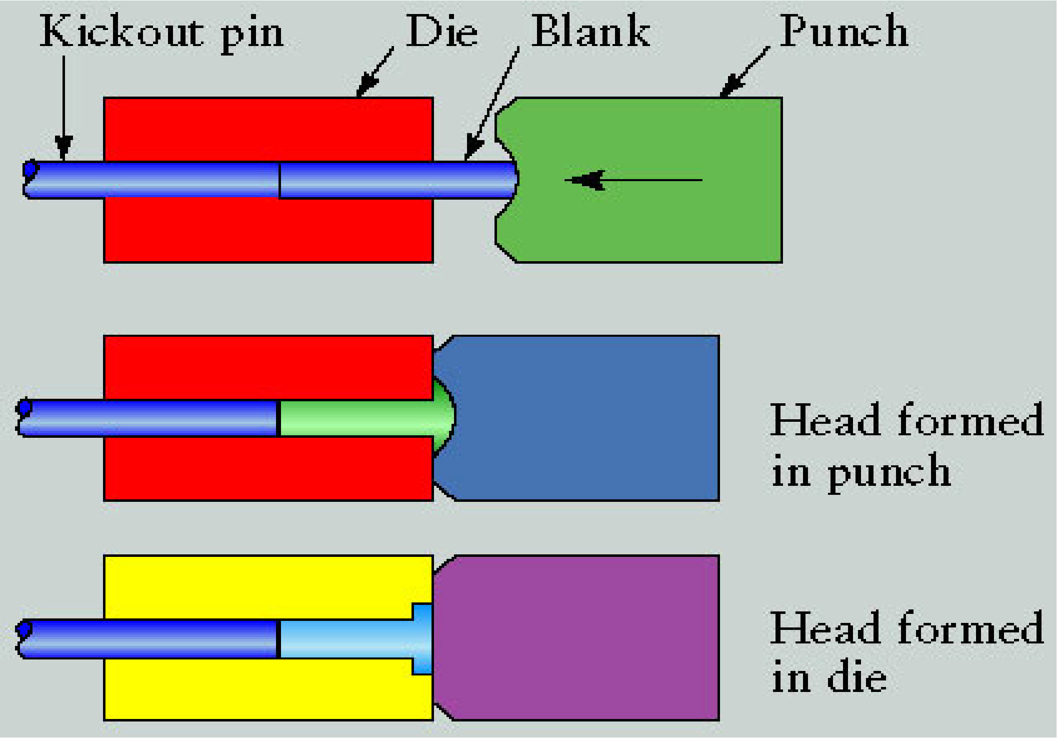


Figure 16-41 Typical steps in a shearing and cold-heading operation.

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

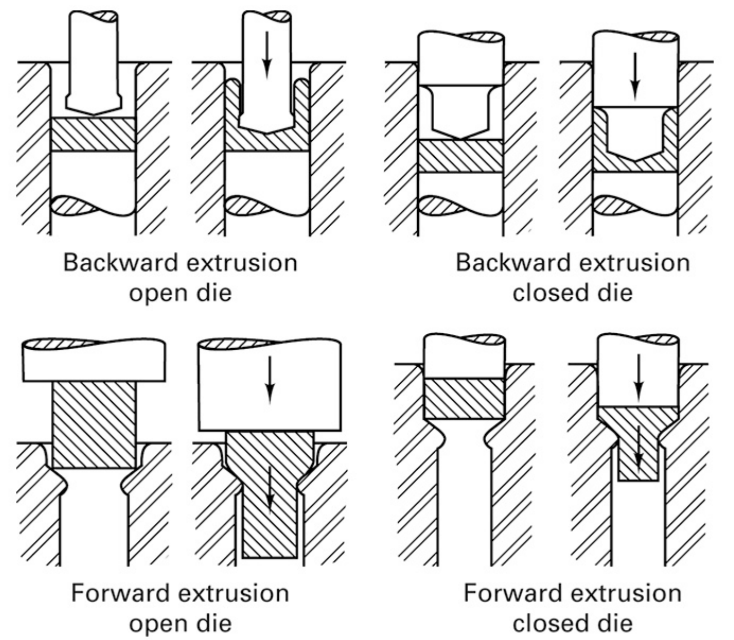


Figure 16-43 Backward and forward extrusion with open and closed dies.

Cold Extrusion

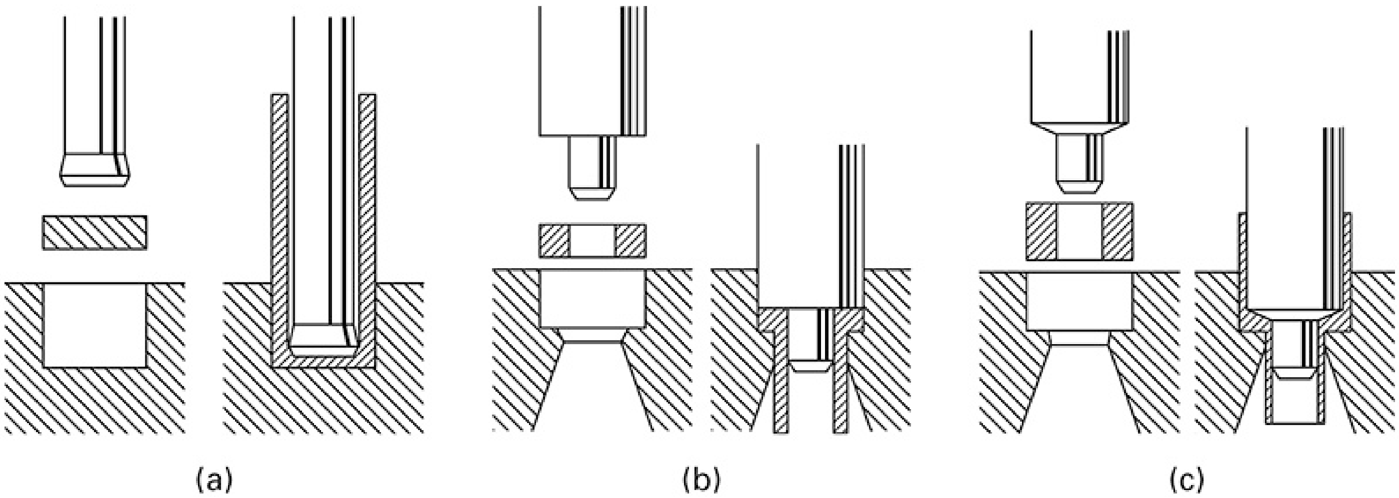


Figure 16-44 (a) Reverse (b) forward (c) combined forms of cold extrusion. (Courtesy the Aluminum Association, Arlington, VA.)

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.)

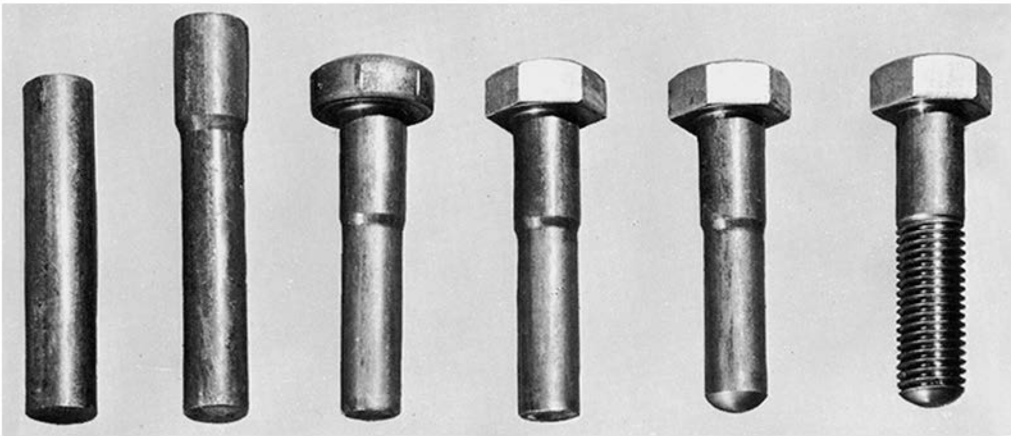


Figure 16-46 Cold-forming sequence involving cutoff, squaring, two extrusions, an upset, and a trimming operation. Also shown are the finished part and the trimmed scrap. (*Courtesy of National Machinery Co., Tiffin, OH*.)

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

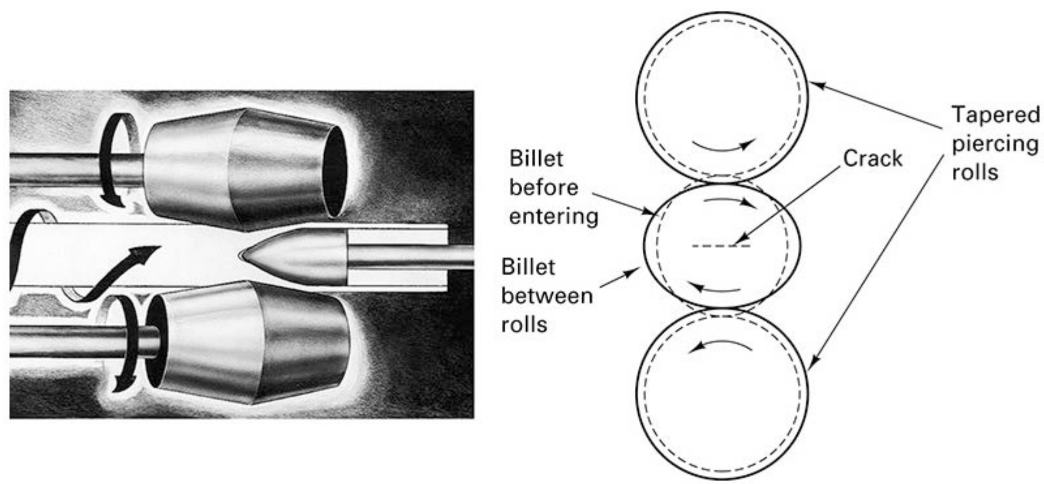


Figure 16-50 (Left) Principle of the Mannesmann process of producing seamless tubing. (*Courtesy of American Brass Company, Cleveland, OH.)* (Right) Mechanism of crack formation in the Mannesmann process.

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.

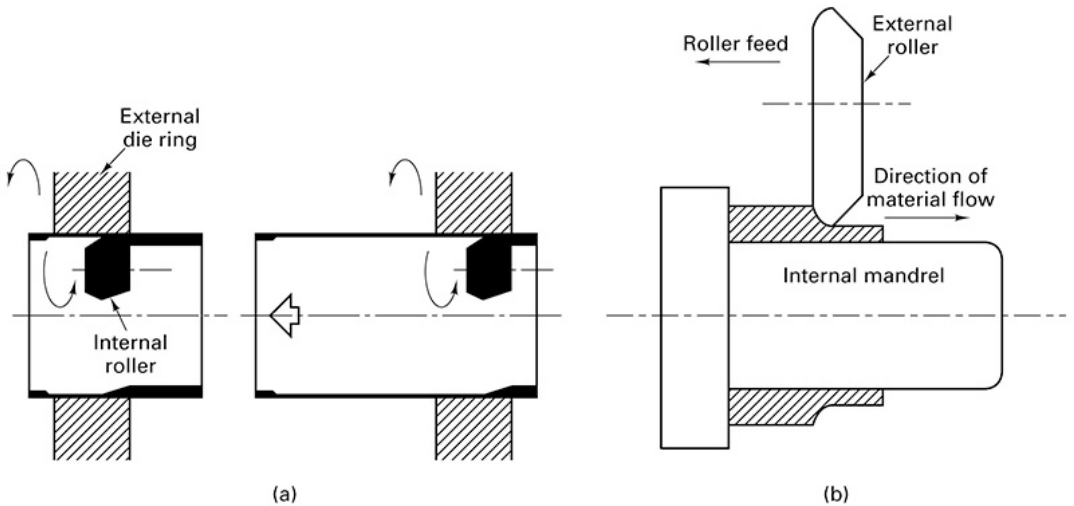
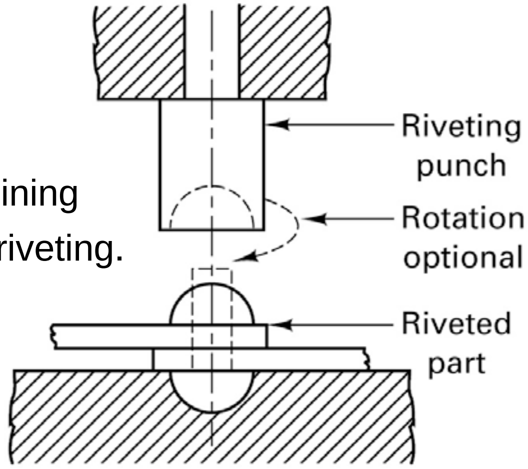


Figure 16-52 Joining components by riveting.



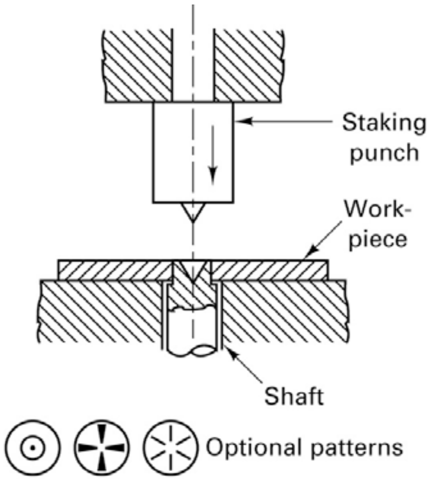
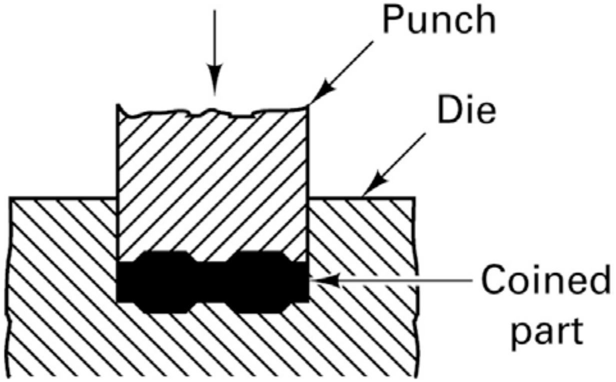


Figure 16-54 Permanently attaching a shaft to a plate by staking.

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.



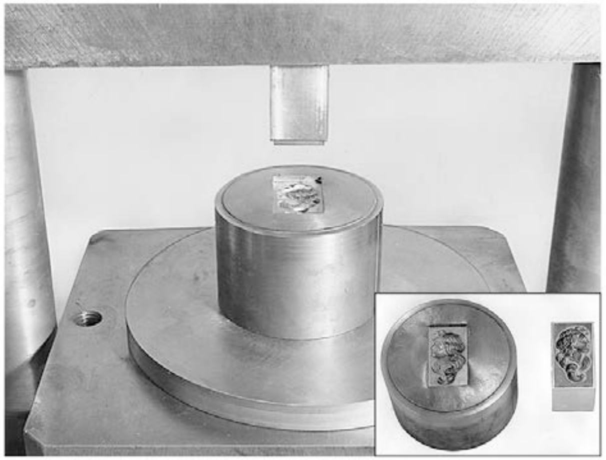


Figure 16-56 Hubbing a die block in a hydraulic press. Inset shows close-up of the hardened hub and the impression in the die block. The die block is contained in a reinforcing ring. The upper surface of the die block is then machined flat to remove the bulged metal.

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 17:
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

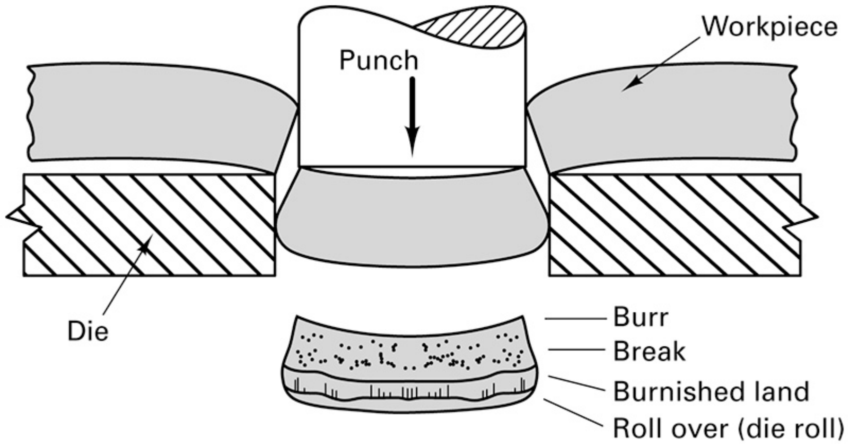


Figure 17-1 (Left) Simple blanking with a punch and die.

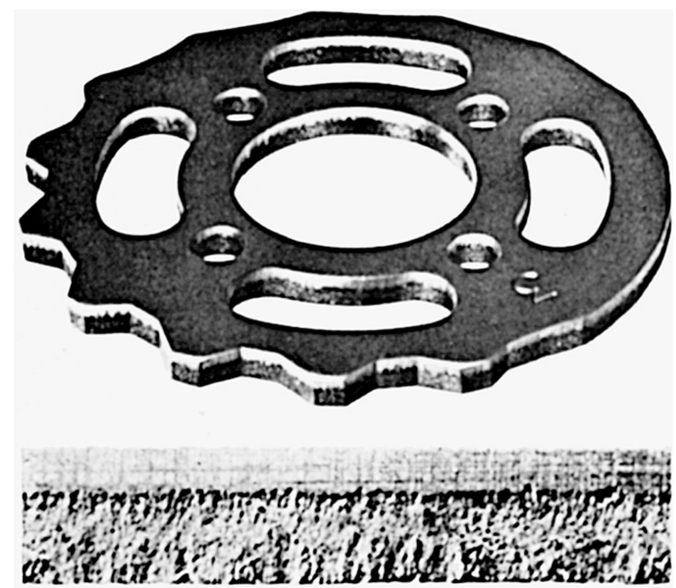
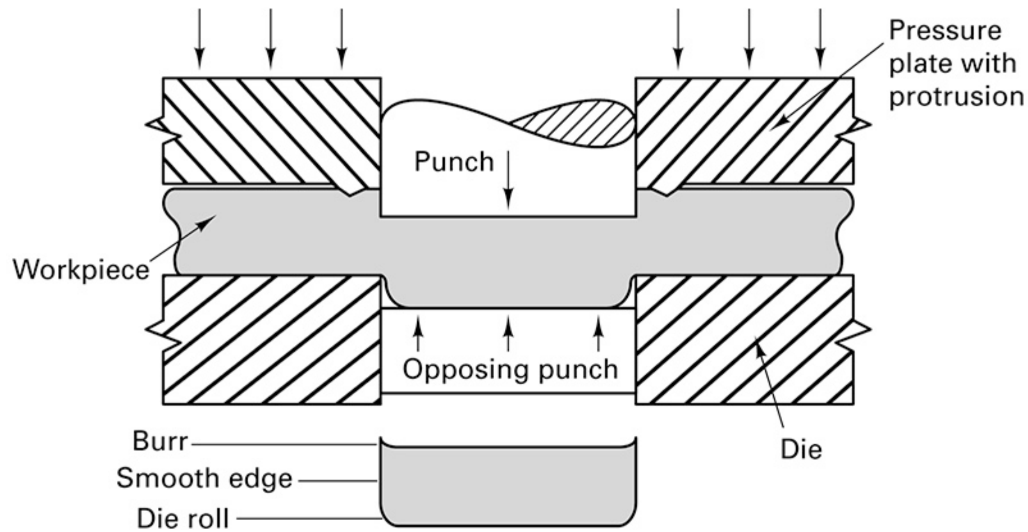


Figure 17-2 (Right) (Top) Conventionally sheared surface showing the distinct regions of deformation and fracture and (bottom) magnified view of the sheared edge. (*Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*

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.



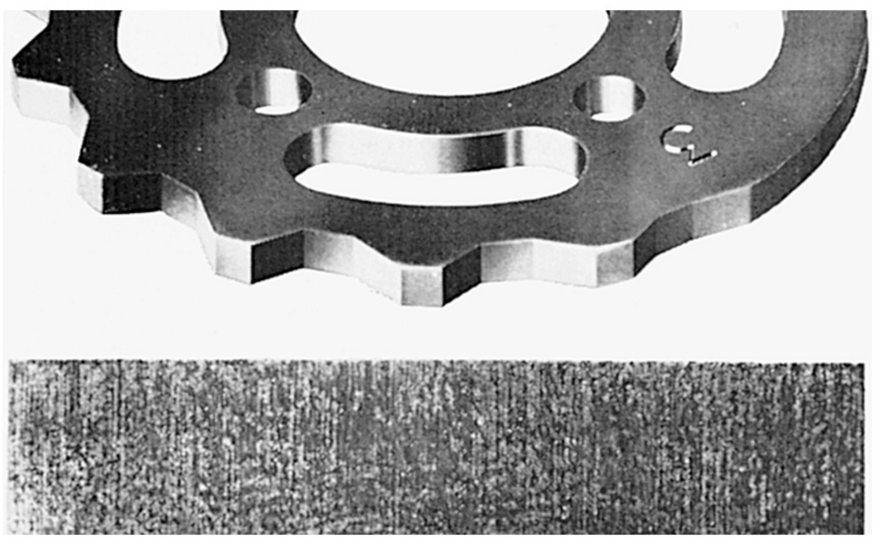


Figure 17-4 Fineblanked surface of the same component as shown in Figure 17-2. (*Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*

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

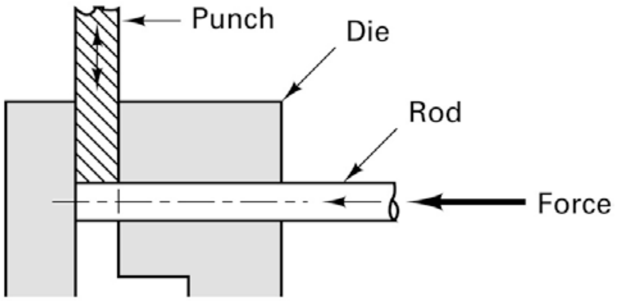


Figure 17-5 Method of smooth shearing a rod by putting it into compression during shearing.

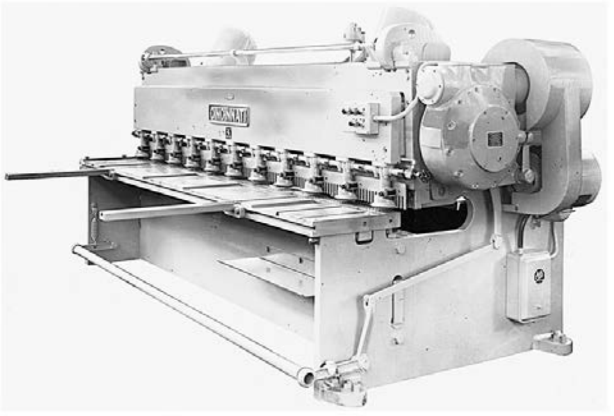


Figure 17-6 A 3-m (10ft) power shear for 6.5 mm (1/4-in.) steel. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

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

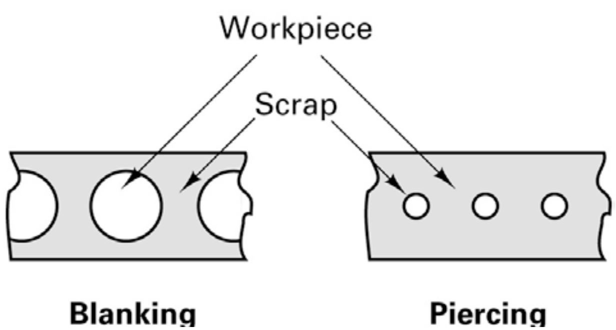


Figure 17-7 Schematic showing the difference between piercing and blanking.

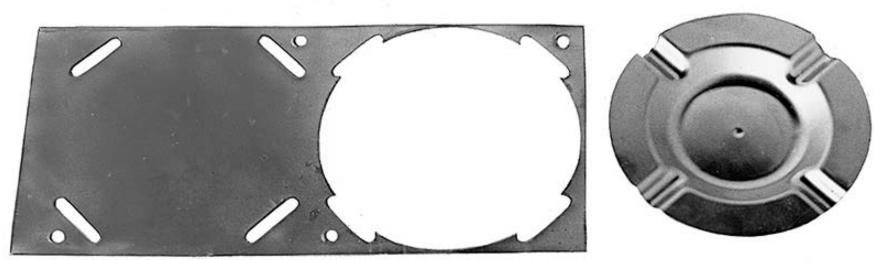


Figure 17-8 (Above) (Left to Right) Piercing, lancing, and blanking precede the forming of the final ashtray. The small round holes assist positioning and alignment.

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

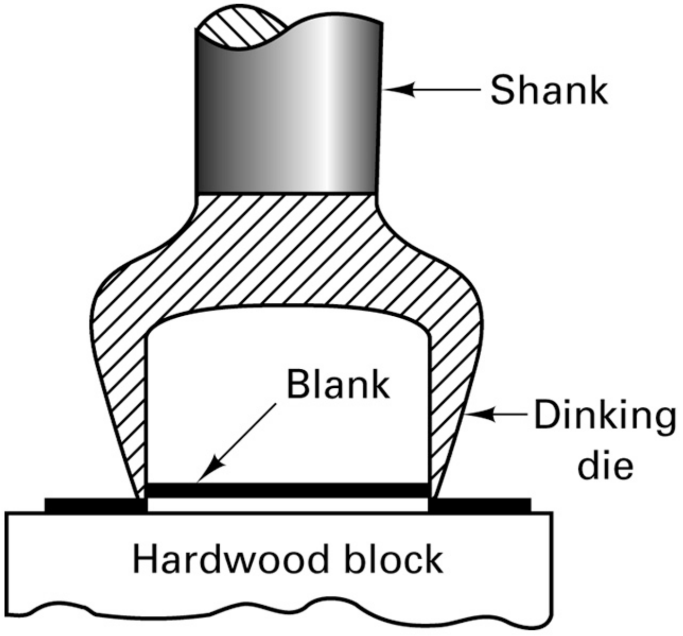


Figure 17-10 The dinking process.

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

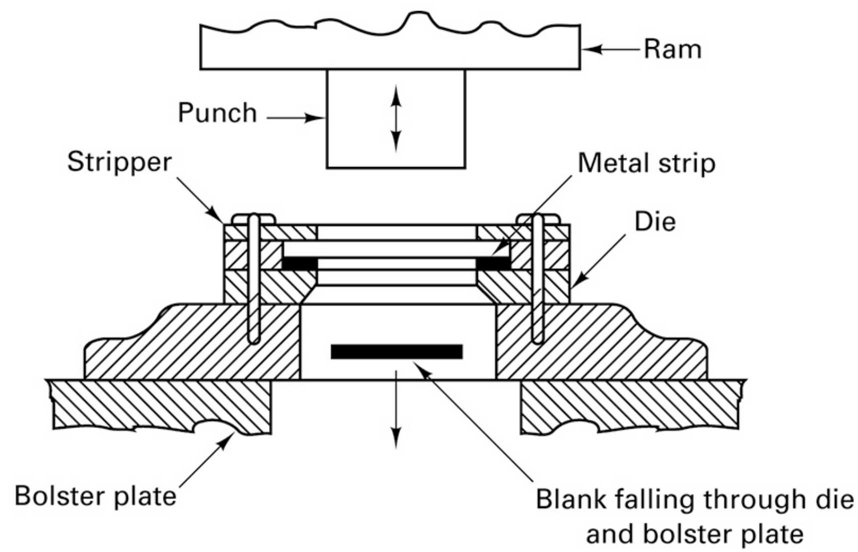


Figure 17-11 The basic components of piercing and blanking dies.

Blanking Operations

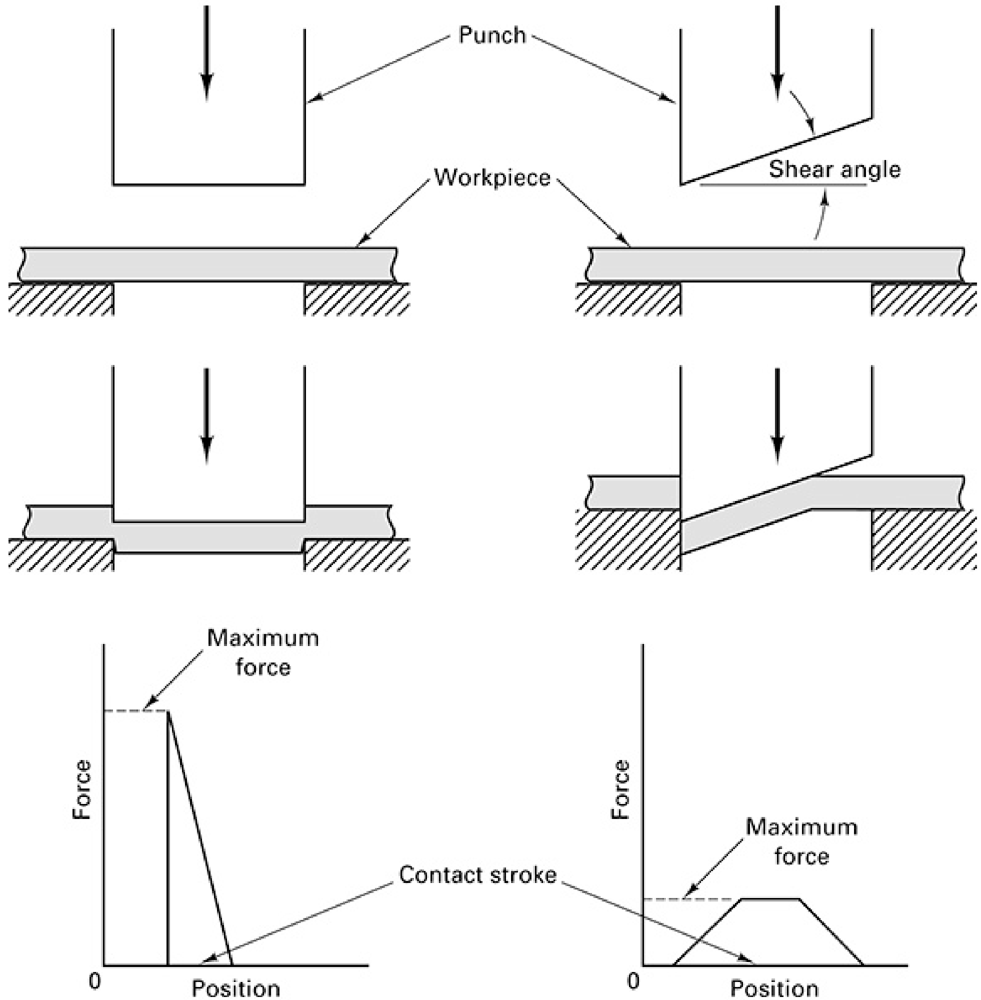
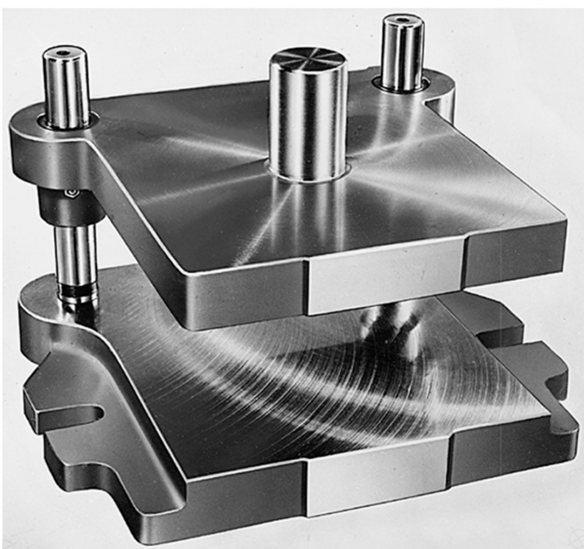


Figure 17-12 Blanking with a square-faced punch (left) and one containing angular shear (right). Note the difference in maximum force and contact stroke. The total work (the are under the curve) is the same for both processes.

Blanking Operations

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



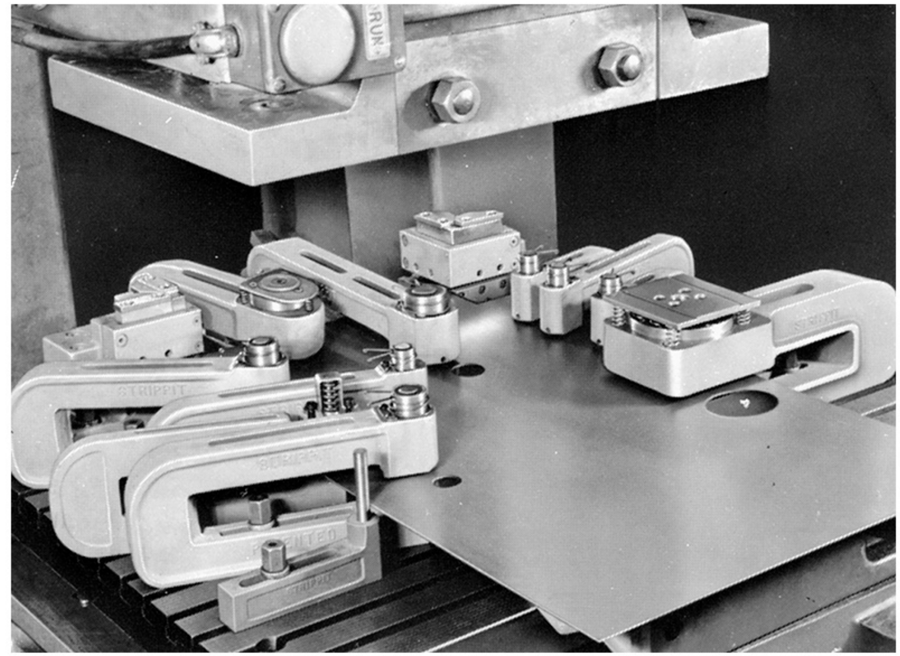


Figure 17-14 (Above) A piercing and blanking setup using self-contained subpress tool units. (*Courtesy of Strippit Division, Houdaille Industries, Inc., Akron, NY.)*

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

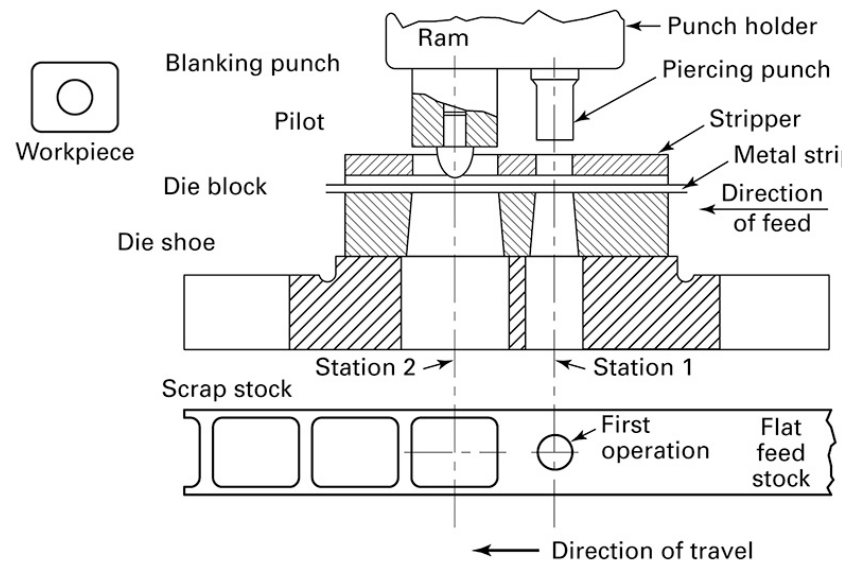


Figure 17-16 Progressive piercing and blanking die for making a square washer. Note that the punches are of different length.

Design Example

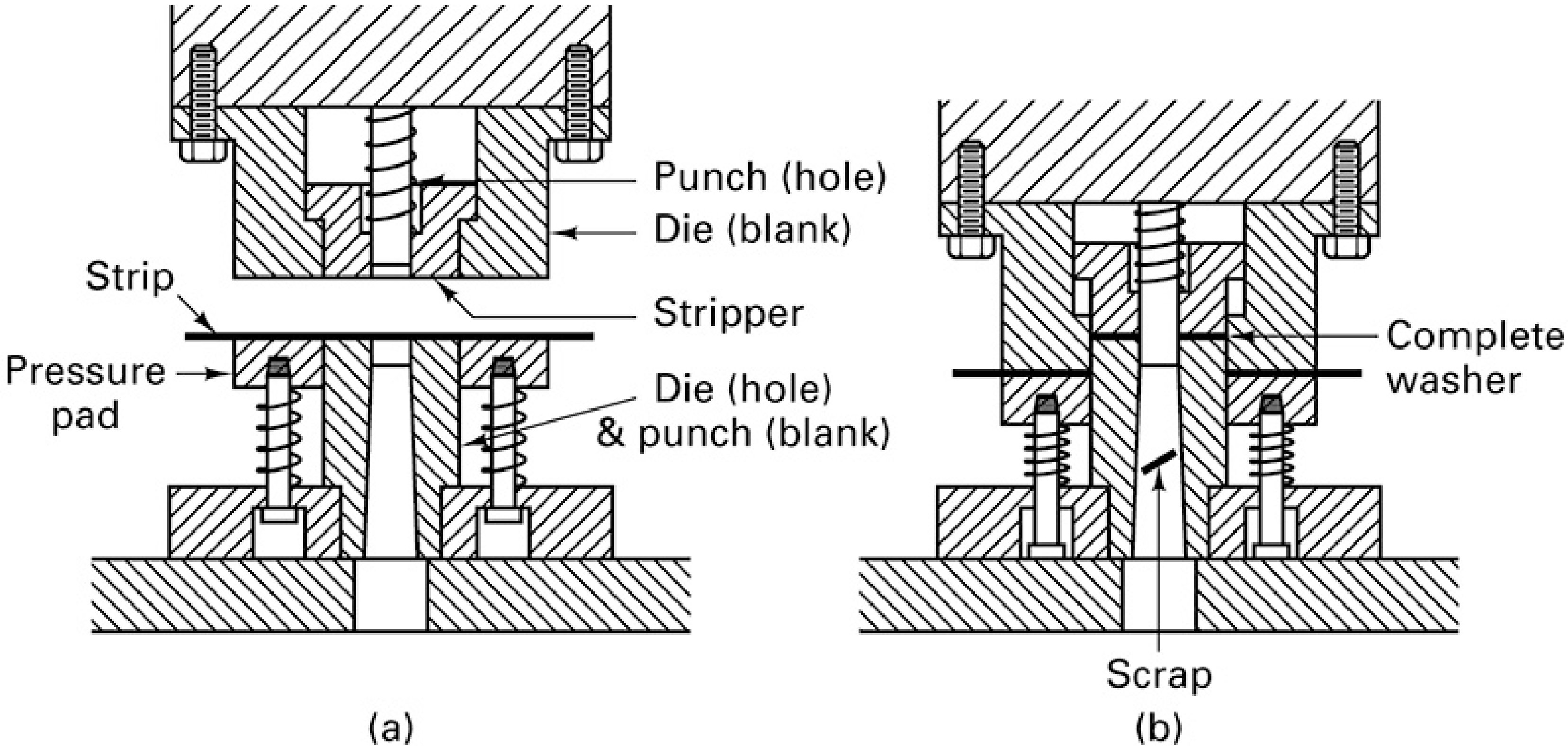


Figure 17-18 Method for making a simple washer in a compound piercing and blanking die. Part is blanked (a) and subsequently pierced (b) in the same stroke. The blanking punch contains the die for piercing.

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

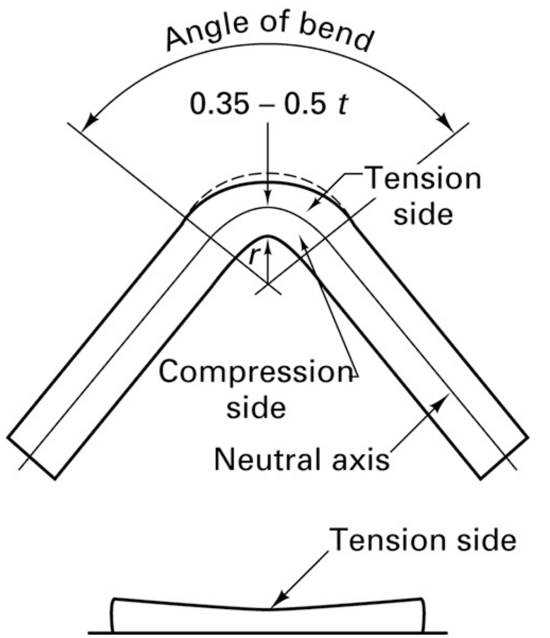


Figure 17-19 (Top) Nature of a bend in sheet metal showing tension on the outside and compression on the inside. (Bottom) The upper portion of the bend region, viewed from the side, shows how the center portion will thin more than the edges.

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

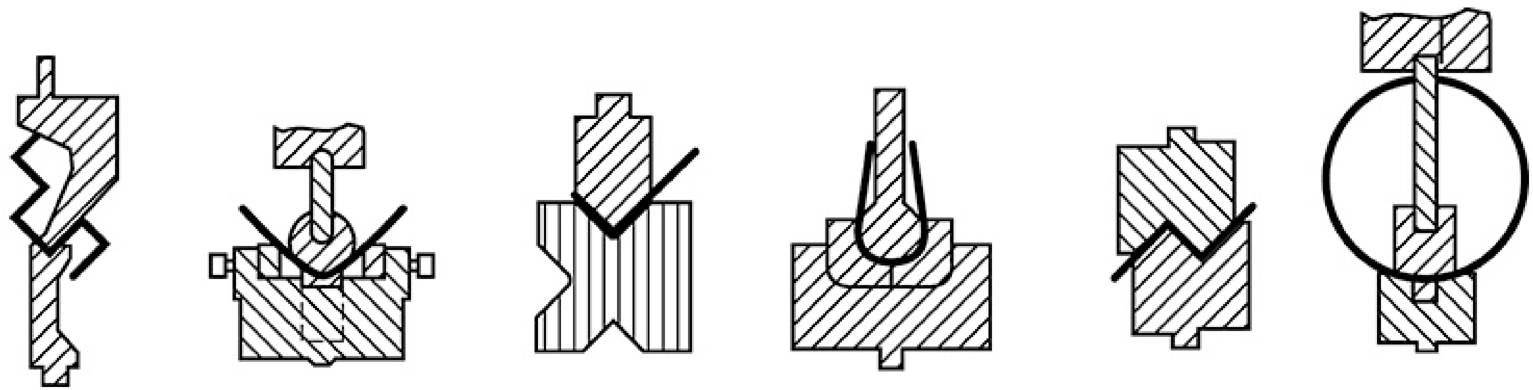


Figure 17-22 Press brake dies can form a variety of angles and contours. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

Bar Folder

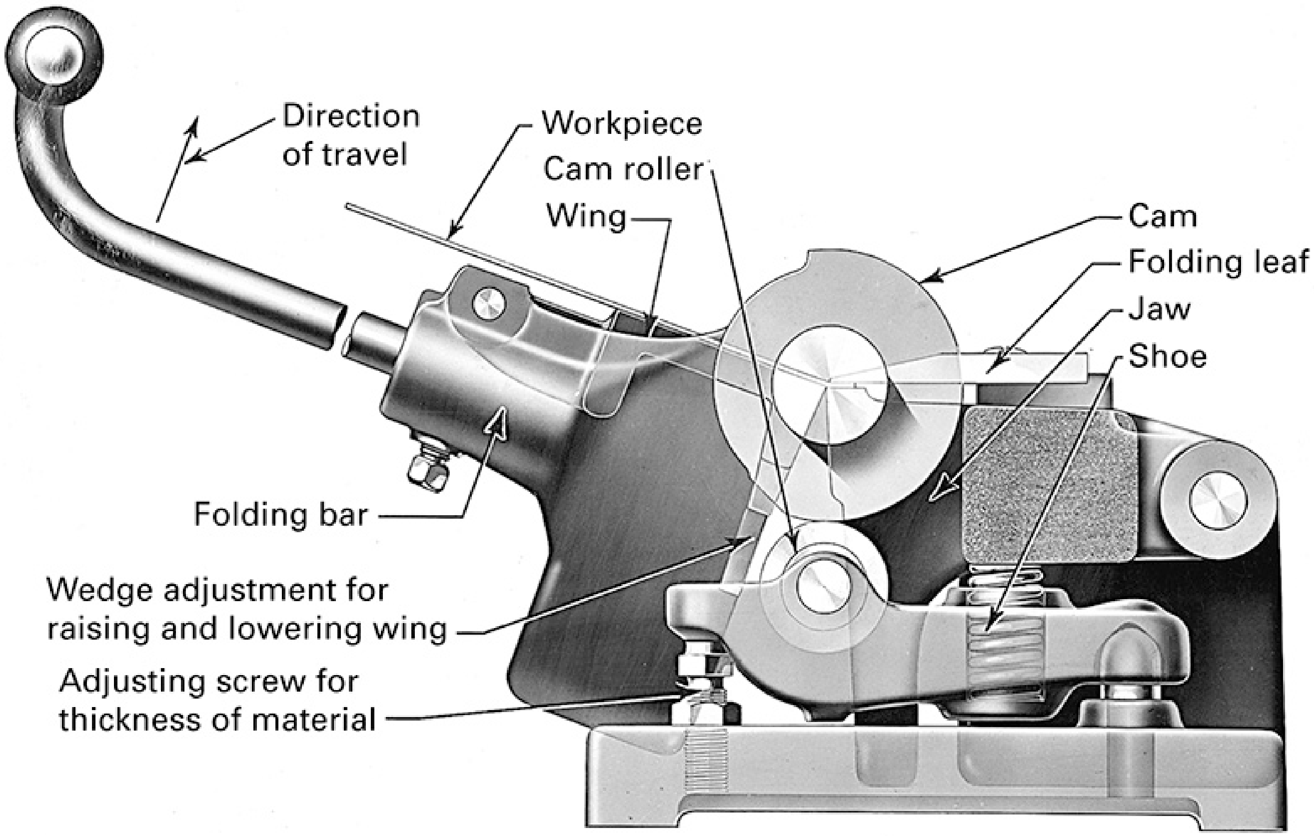


Figure 17-20 Phantom section of a bar folder, showing position and operation of internal components. (*Courtesy of Niagara Machine and Tool Works, Buffalo, N.Y.)*

Press Brake

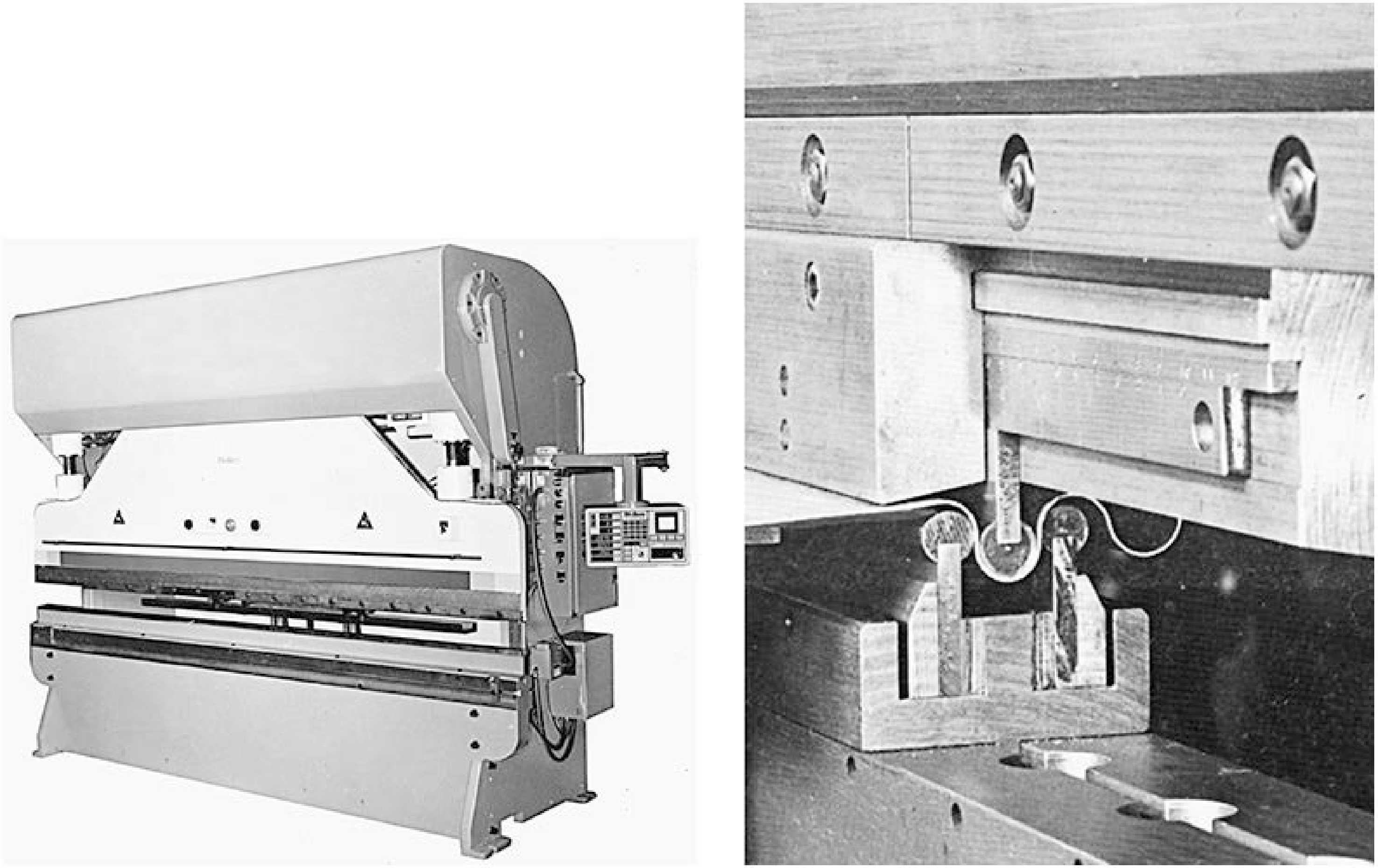


Figure 17-21 (Left) Press brake with CNC gauging system. (*Courtesy of DiAcro Division, Acrotech Inc., Lake City, MN.)* (Right) Close-up view of press brake dies forming corrugations. (*Courtesy of Cincinnati Incorporated, Cincinnati, OH.)*

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

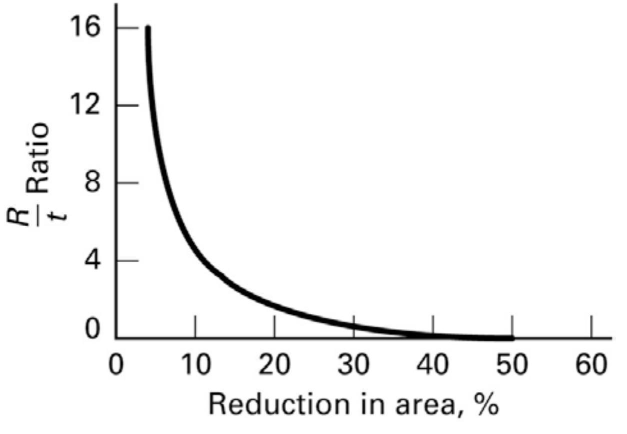


Figure 17-24 Relationship between the minimum bend radius (relative to thickness) and the ductility of the metal being bent (as measured by the reduction in area in a uniaxial tensile test).

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

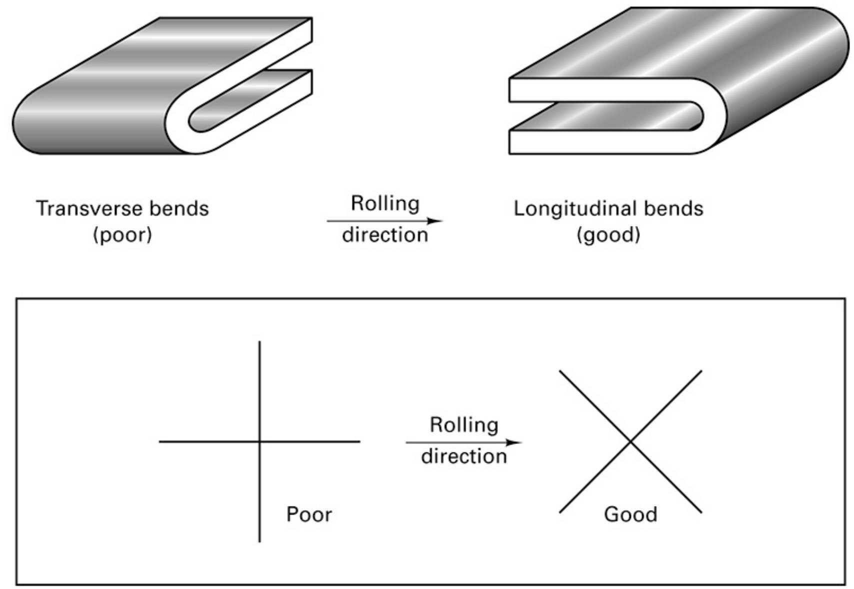
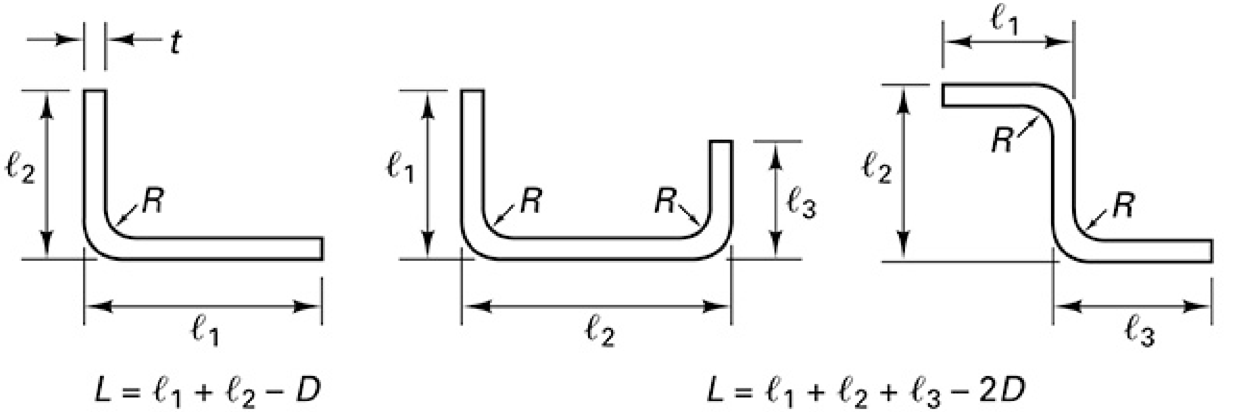


Figure 17-25 Bends should be made with the bend axis perpendicular to the rolling direction. When intersecting bends are made, both should be at an angle to the rolling direction, as shown.

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



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

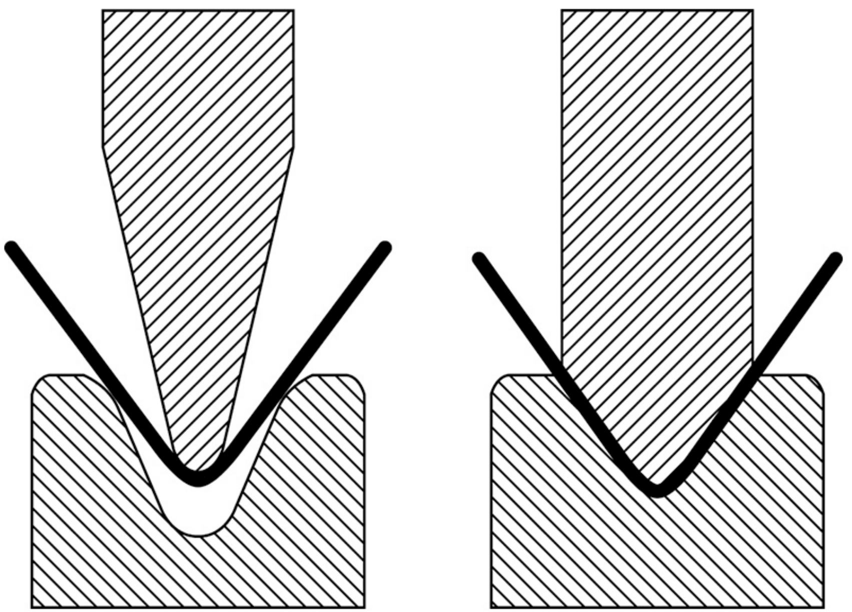
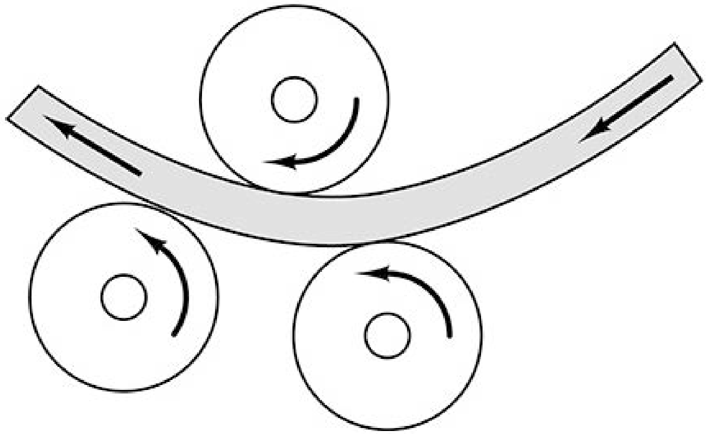


Figure 17-27 Comparison of air-bend (left) and bottoming (right) press brake dies. With the air-bend die, the amount of bend is controlled by the bottoming position of the upper die.

Roll Bending

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



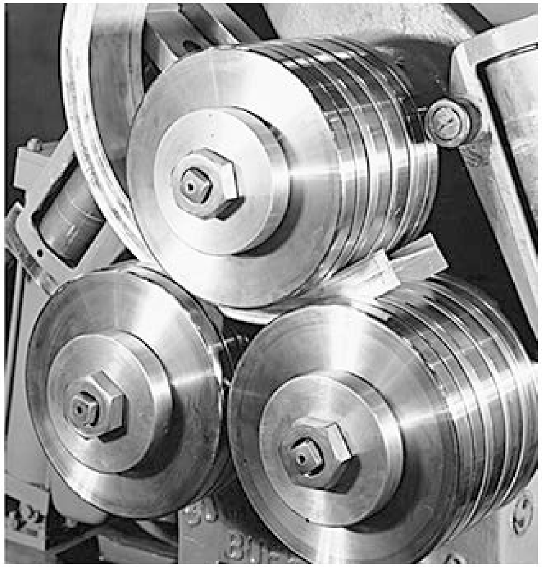


Figure 17-28 (Left) Schematic of the roll-bending process; (right) the roll bending of an I-beam section. Note how the material is continuously subjected to three-point bending. (*Courtesy of Buffalo Forge Company, Buffalo, NY.)*

Draw Bending, Compression Bending, and Press Bending

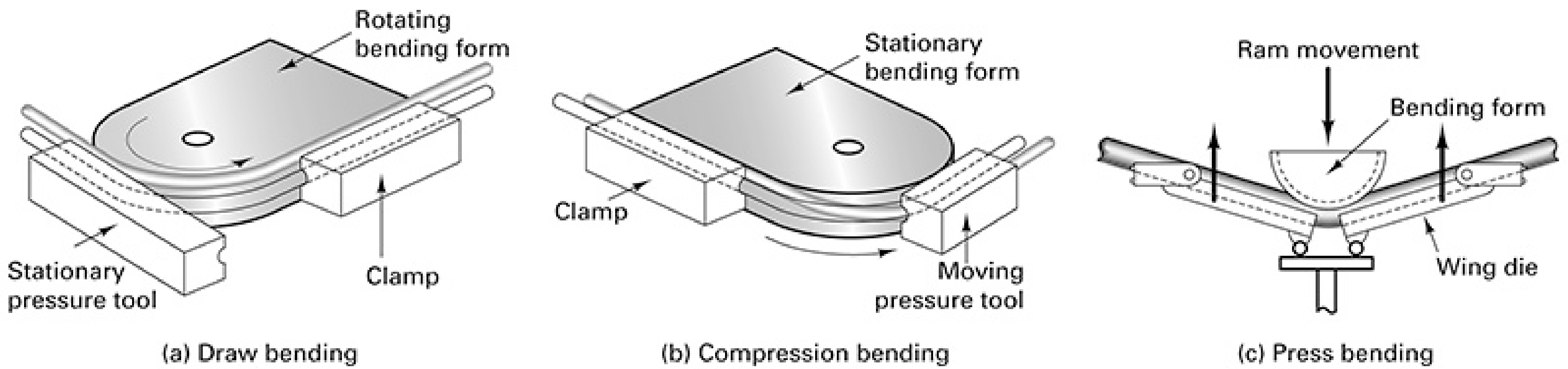


Figure 17-29 (a) Draw bending, in which the form block rotates; (b) compression bending, in which a moving tool compresses the workpiece against a stationary form; (c) press bending, where the press ram moves the bending form.

Tube Bending

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

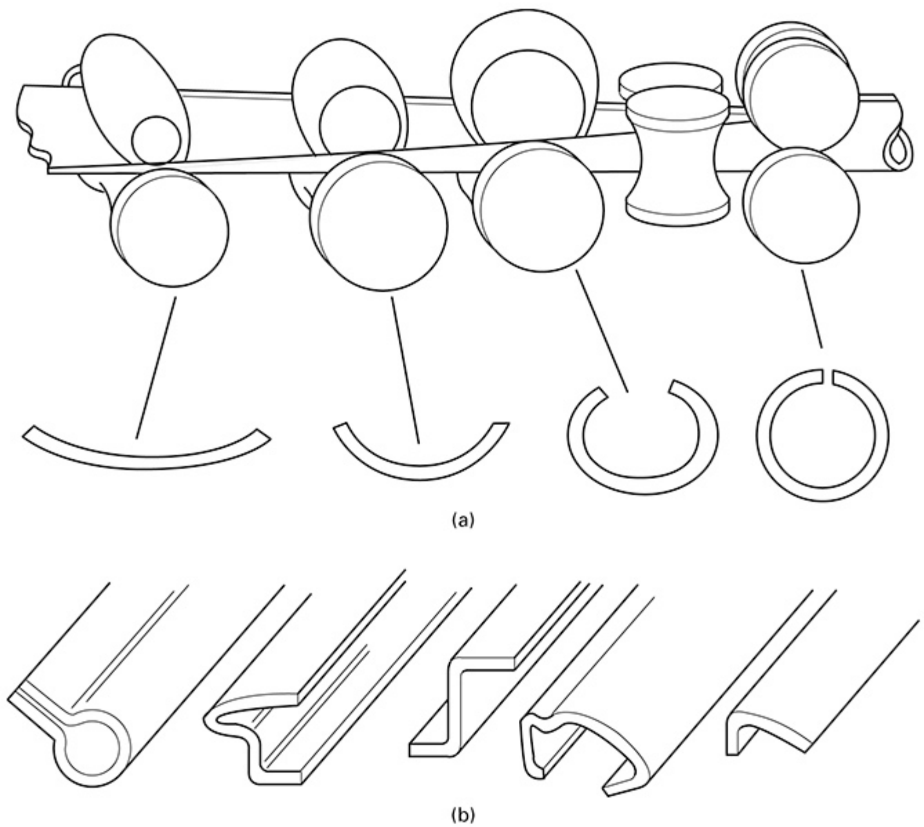


Figure 17-30 (a) Schematic representation of the cold roll-forming process being used to convert sheet or plate into tube. (b) Some typical shapes produced by roll forming.

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

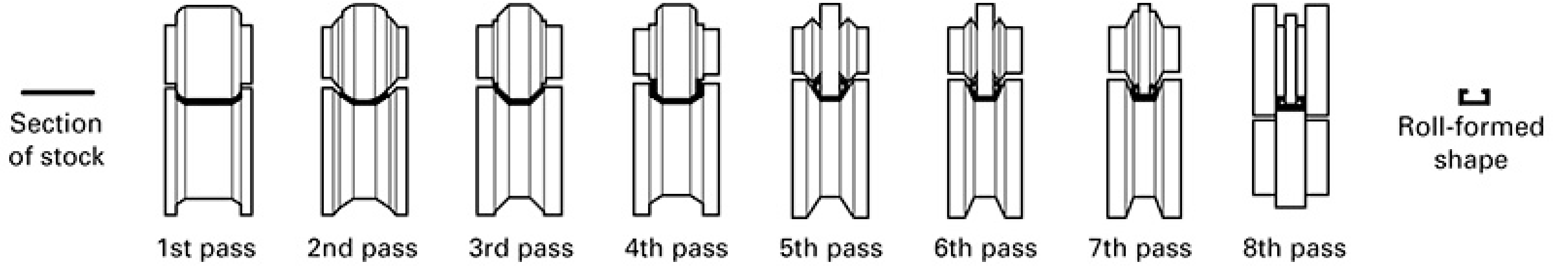


Figure 17-31 Eight-roll sequence for the roll forming of a box channel. (*Courtesy of the Aluminum Association, Washington, DC.)*

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

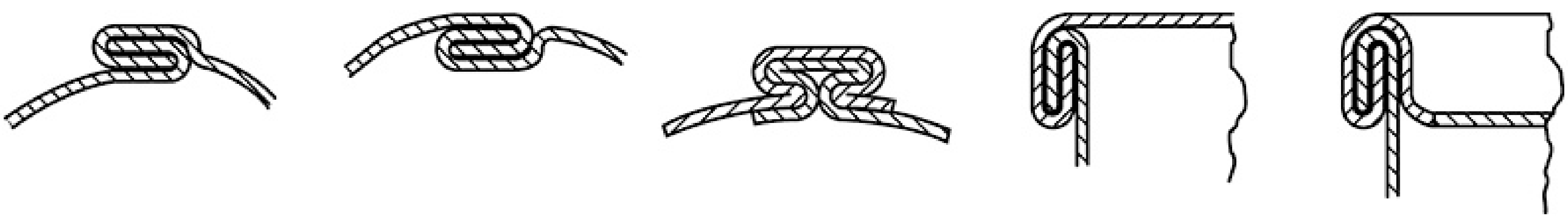


Figure 17-31 Various types of seams used on sheet metal.

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

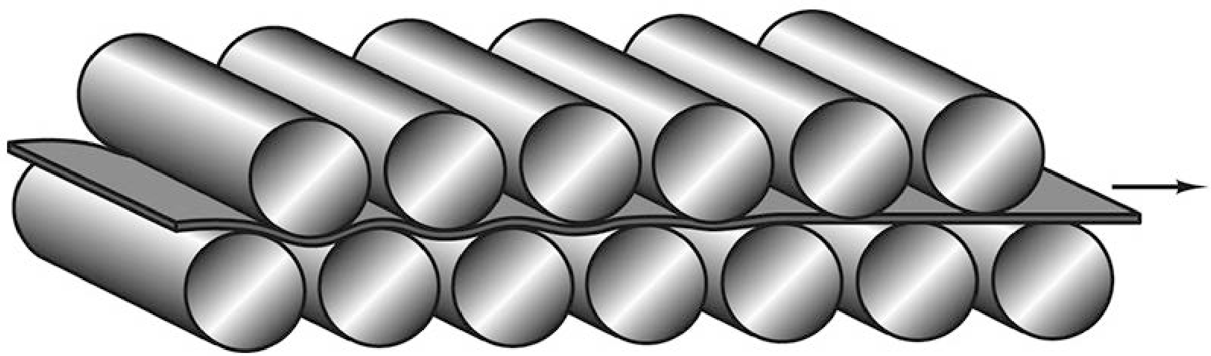


Figure 17-33 Method of straightening rod or sheet by passing it through a set of straightening rolls. For rods, another set of rolls is used to provide straightening in the transverse direction.

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

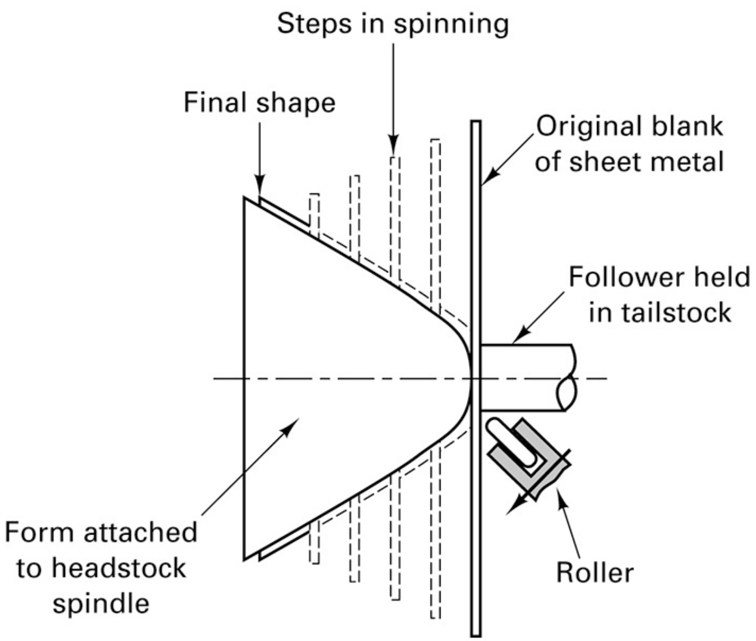
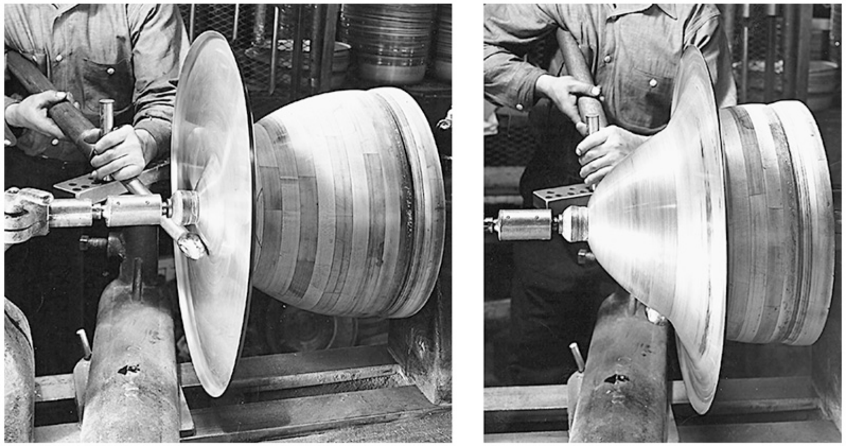


Figure 17-34 (Above) Progressive stages in the spinning of a sheet metal product.

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



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

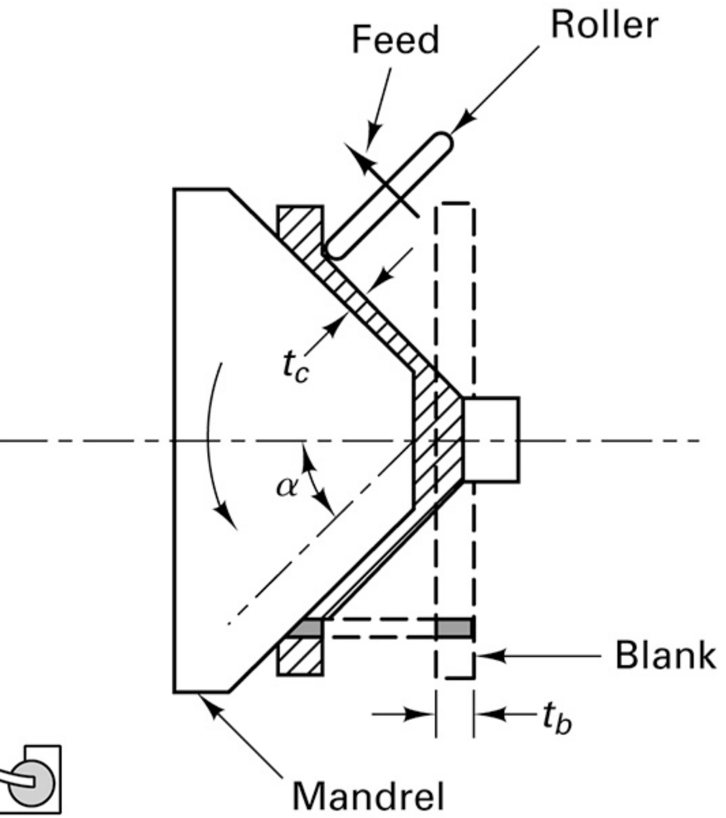


Figure 17-36 Schematic representation of the basic shear-forming process.

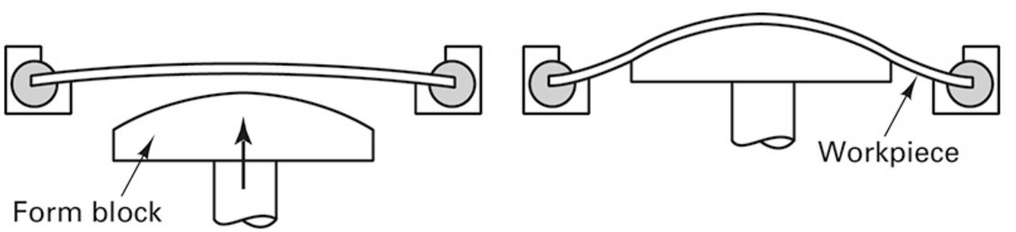


Figure 17-39 Schematic of a stretch-forming operation.

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

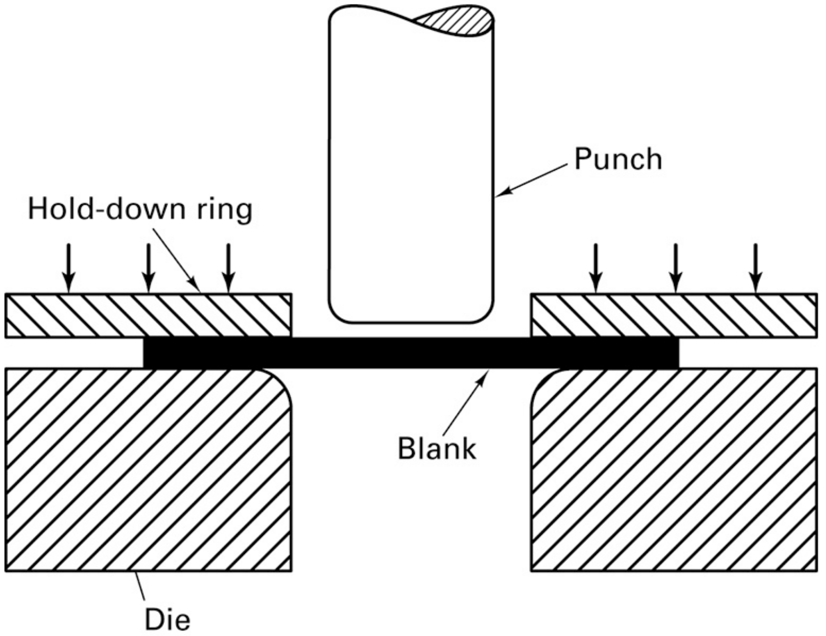


Figure 17-40 Schematic of the deep-drawing process.

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

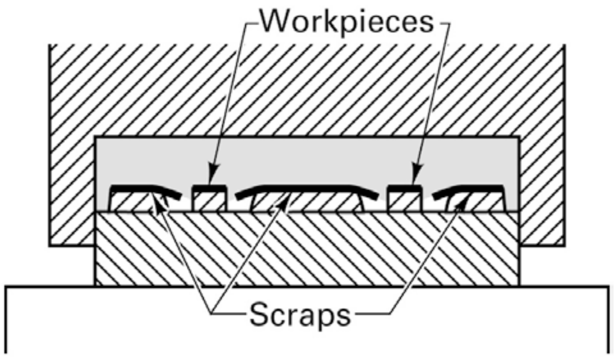


Figure 17-47 Method of blanking sheet metal using the Guerin process.

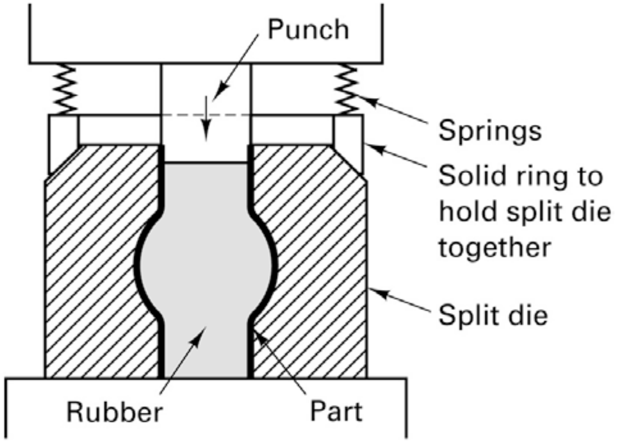


Figure 17-48 Method of bulging tubes with rubber tooling.

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

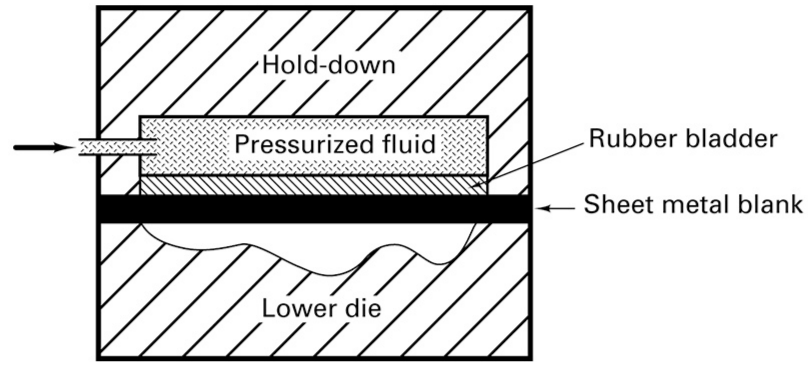


Figure 17-50 (Above) One form of sheet hydroforming.

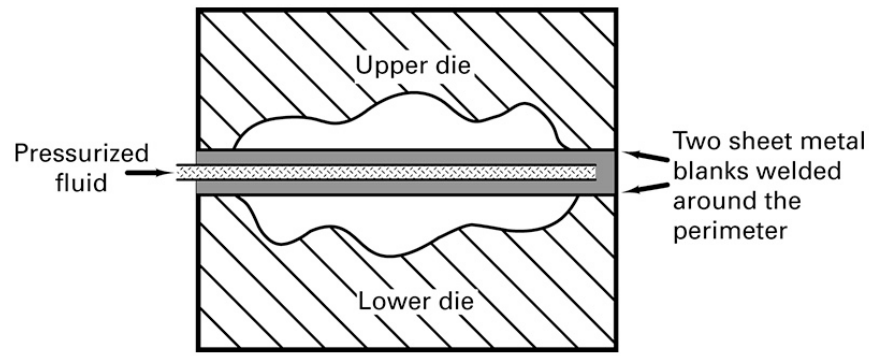


Figure 17-51 Two-sheet hydroforming, or pillow forming.

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

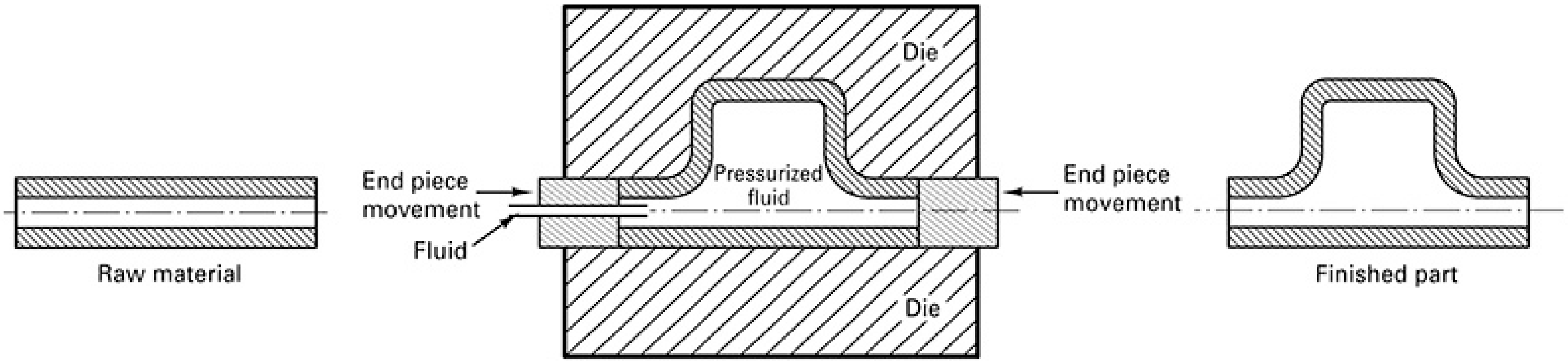


Figure 17-52 Tube hydroforming. (a) Process schematic.

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 Double Eccentric Cam Knuckle joint Toggle Screw Rack and pinion	Single slide Multiple slide

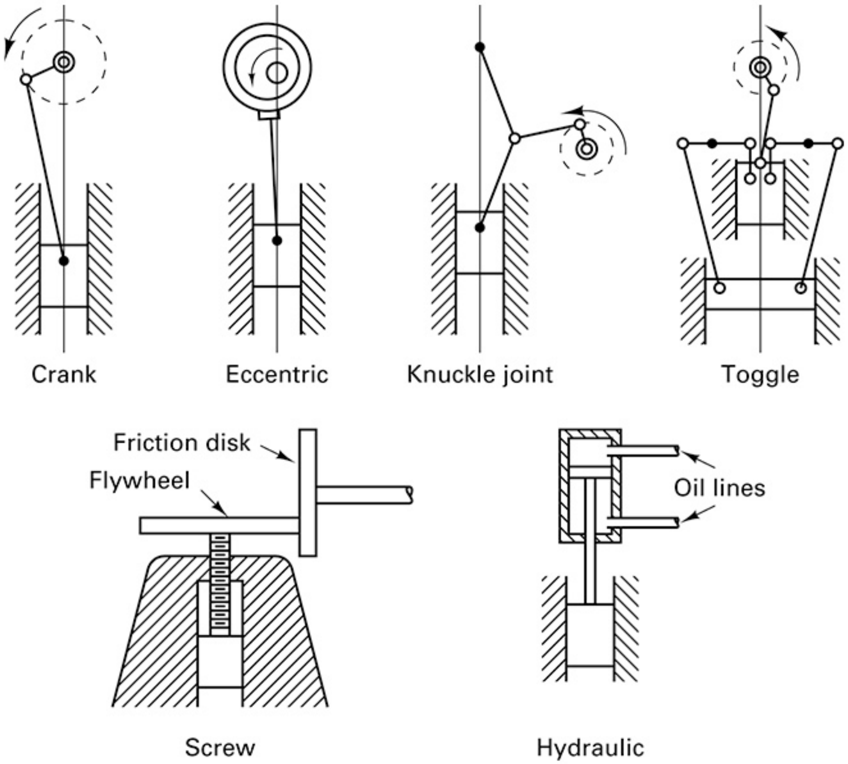


Figure 17-58 Schematic representation of the various types of press drive mechanisms.

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	

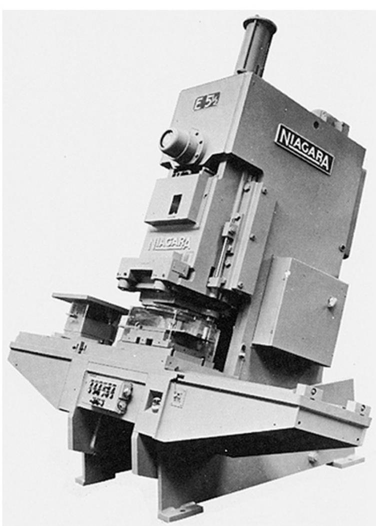
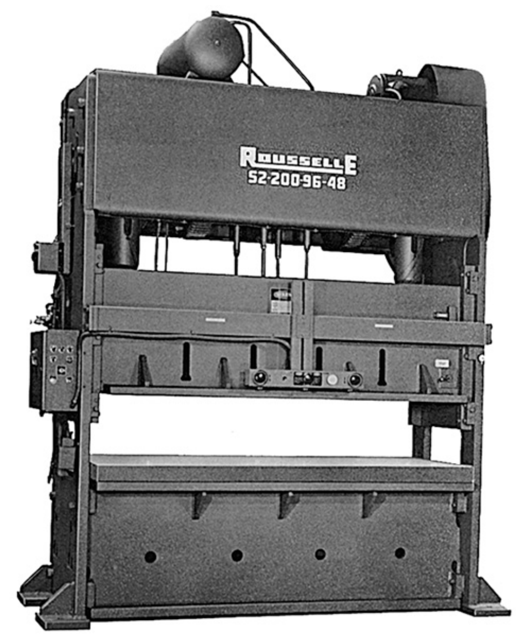


Figure 17-60 (Left) Inclinable gap-frame press with sliding bolster to accommodate two die sets for rapid change of tooling. (*Courtesy of Niagara Machine & Tool Works, Buffalo, NY.)*

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

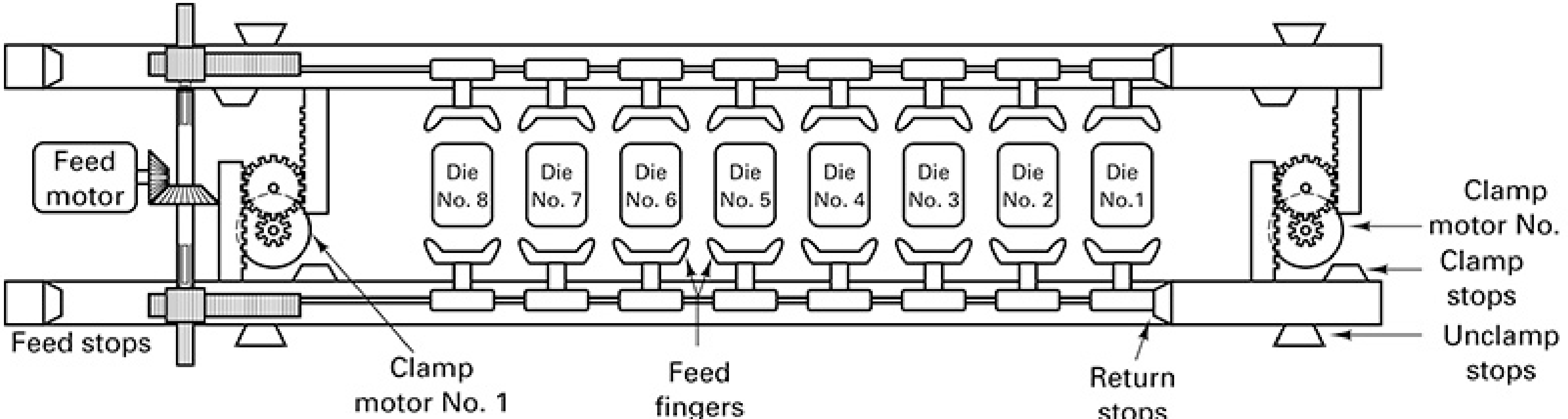


Figure 17-62 Schematic showing the arrangement of dies and the transfer mechanism used in transfer presses. (*Courtesy of Verson Allsteel Press Company, Chicago, IL.)*

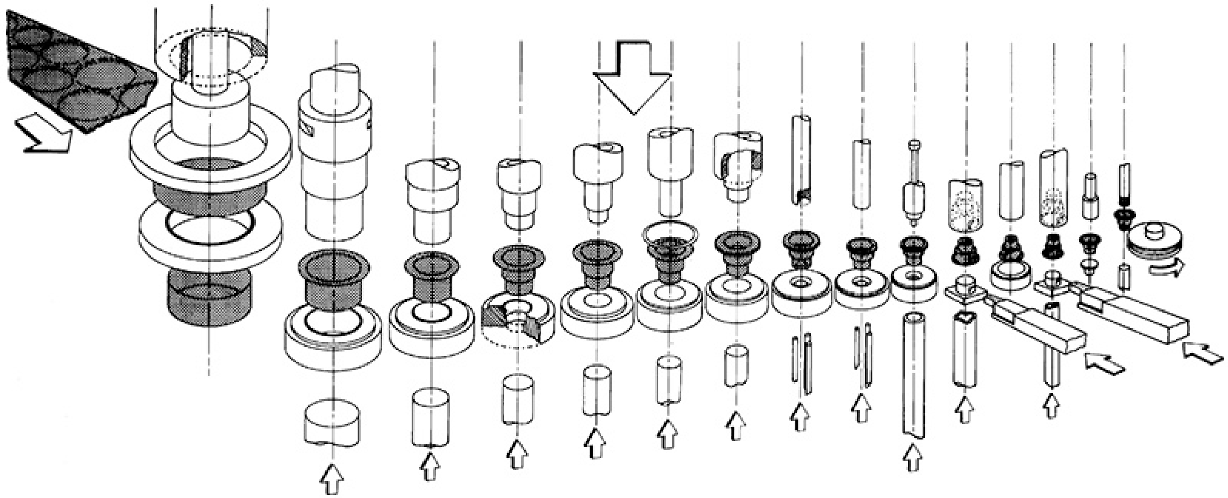


Figure 17-63 Various operations can be performed during the production of stamped and drawn parts on a transfer press. (Courtesy of U.S. Baird Corporation, Stratford, CT.)

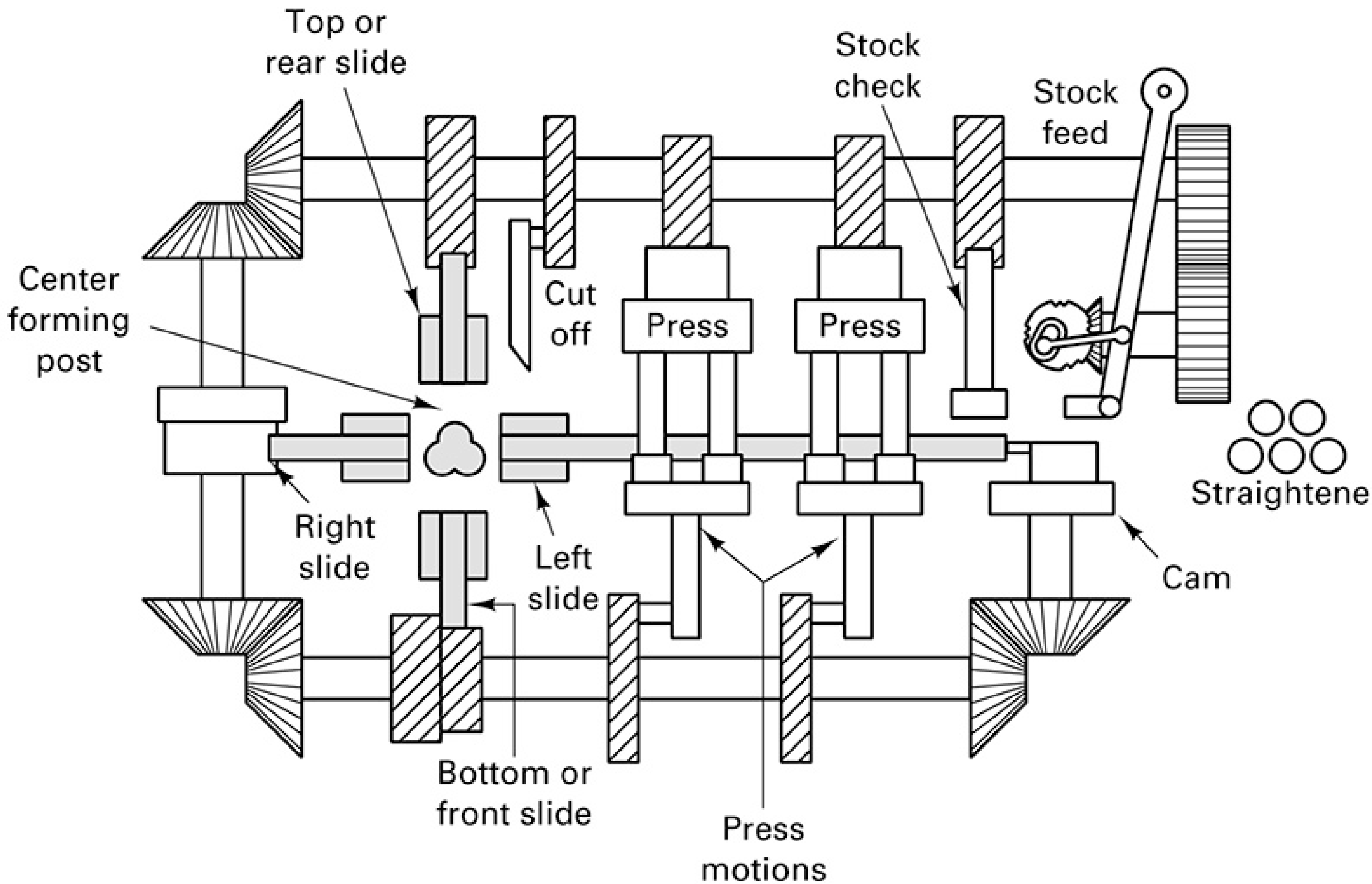


Figure 17-65 Schematic of the operating mechanism of a multislide machine. The material enters on the right and progresses toward the left as operations are performed. (*Courtesy of U.S. Baird Corporation, Stratford, CT.)*

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 18:
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

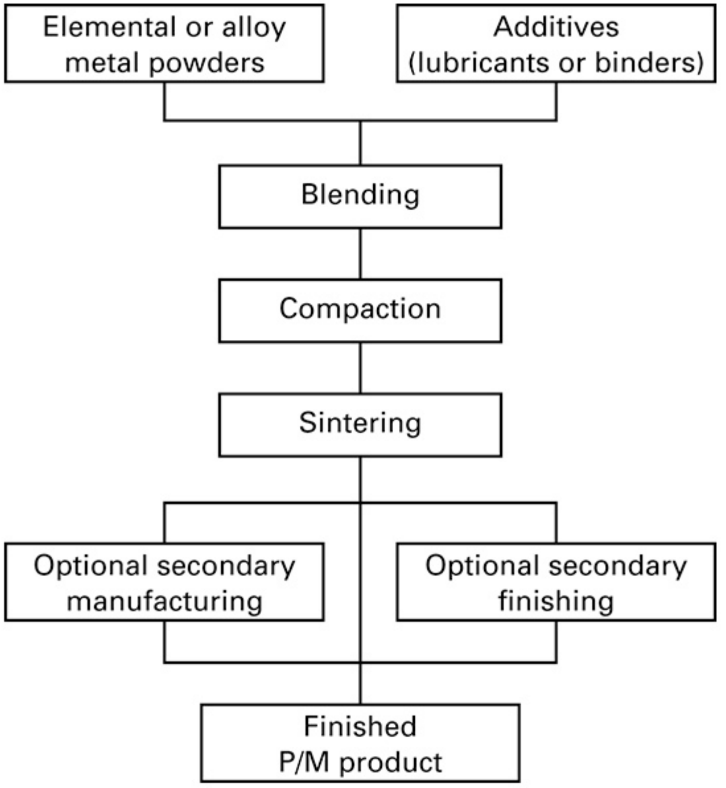


Figure 18-1 Simplified flow chart of the basic powder metallurgy process.

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

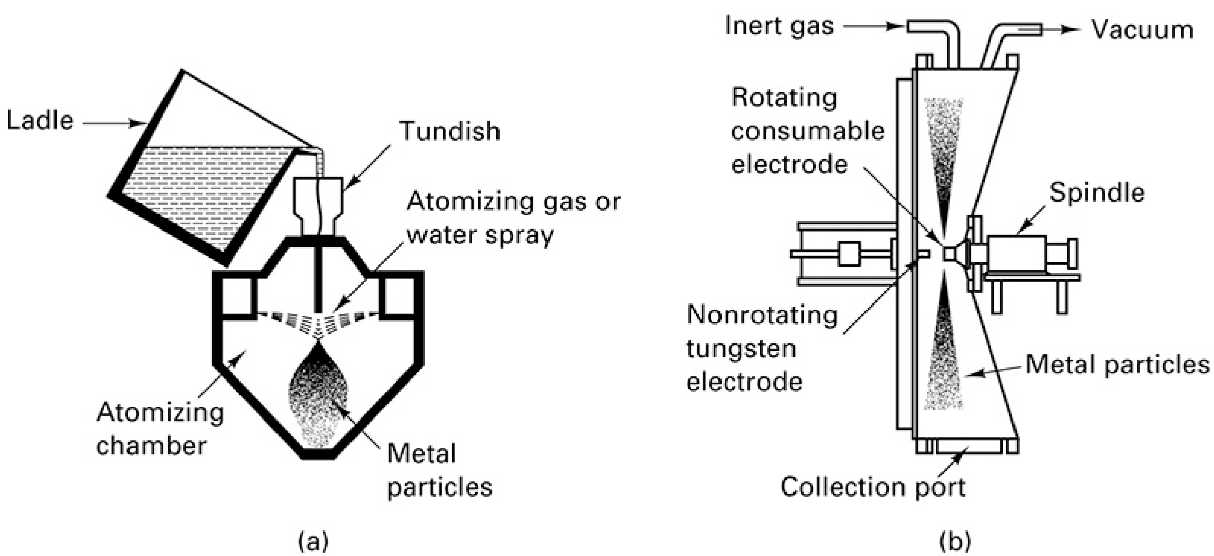


Figure 18-2 Two methods for producing metal powders: (a) melt atomization and (b) atomization from a rotating consumable electrode.

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)
- Amorhpus 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}	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

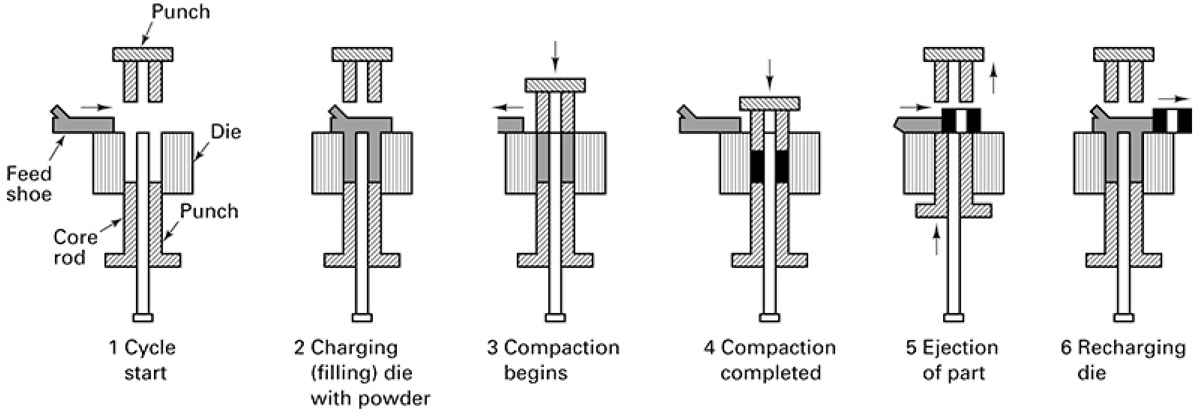


Figure 18-4 Typical compaction sequence for a single-level part, showing the functions of the feed shoe, die core rod, and upper and lower punches. Loose powder is shaded; compacted powder is solid black.

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

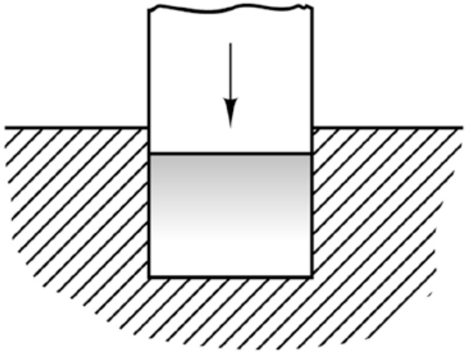


Figure 18-5 Compaction with a single moving punch, showing the resultant nonuniform density (shaded), highest where particle movement is the greatest.

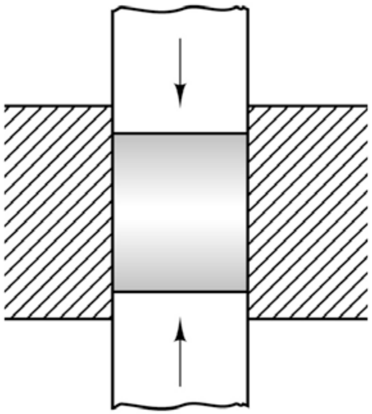
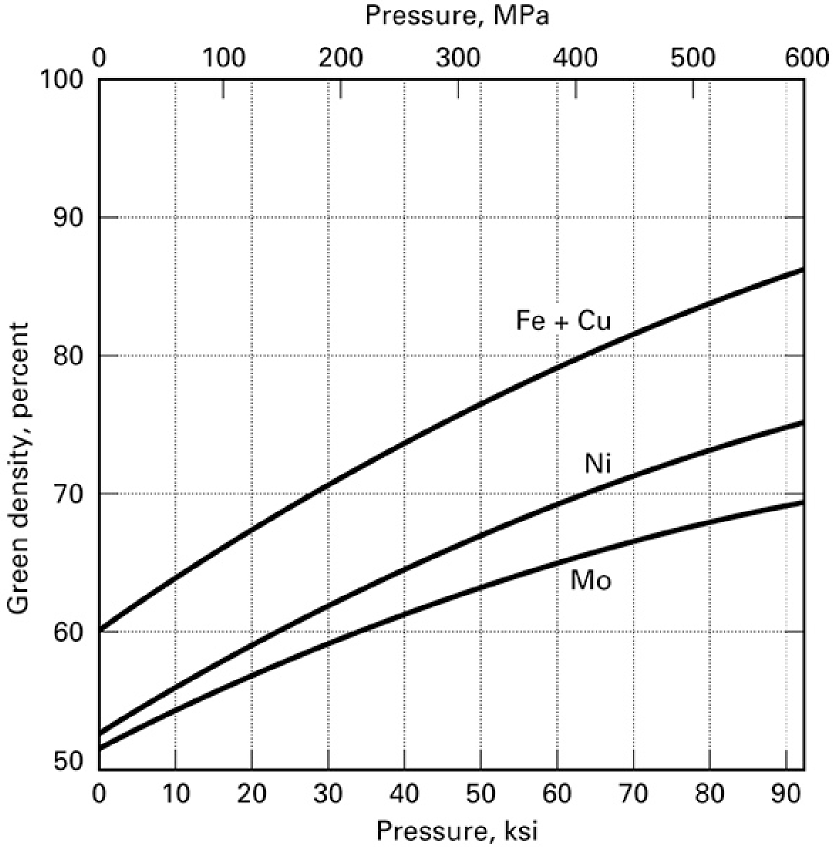


Figure 18-6 Density distribution obtained with a double-acting press and two moving punches. Note the increased uniformity compared to Figure 18-5. Thicker parts can be effectively compacted.

Effects of Compacting



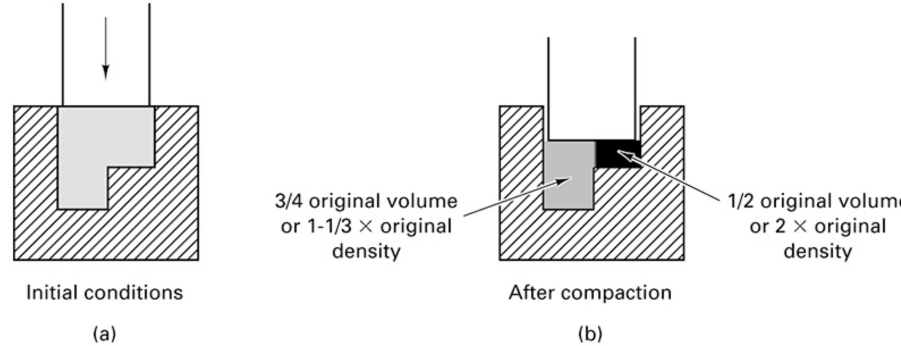


Figure 18-8 Compaction of a two-thickness part with only one moving punch. (a) Initial conditions; (b) after compaction by the upper punch. Note the drastic difference in compacted density.

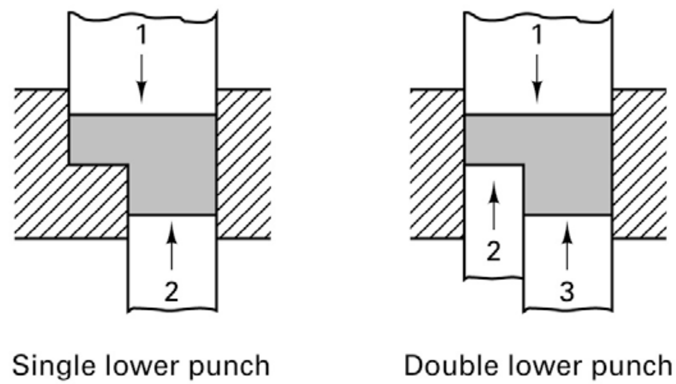


Figure 18-7 Effect of compacting pressure on green density (the density after compaction but before sintering). Separate curves are for several commercial powders.

Figure 18-9 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

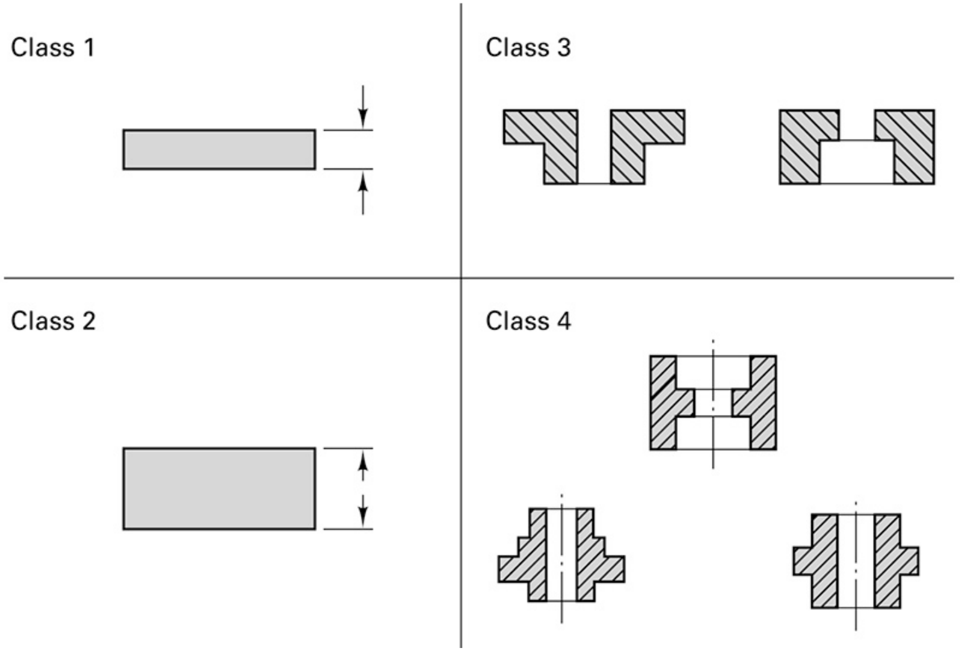


Figure 18-10 Sample geometries of the four basic classes of press-and-sinter powder metallurgy parts. Note the increased pressing complexity that would be required as class increases.

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

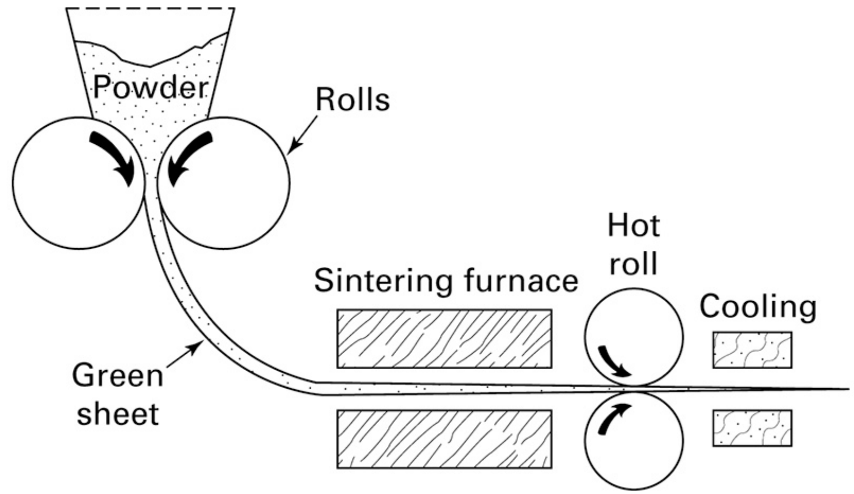


Figure 18-11 One method of producing continuous sheet products from powdered feedstock.

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

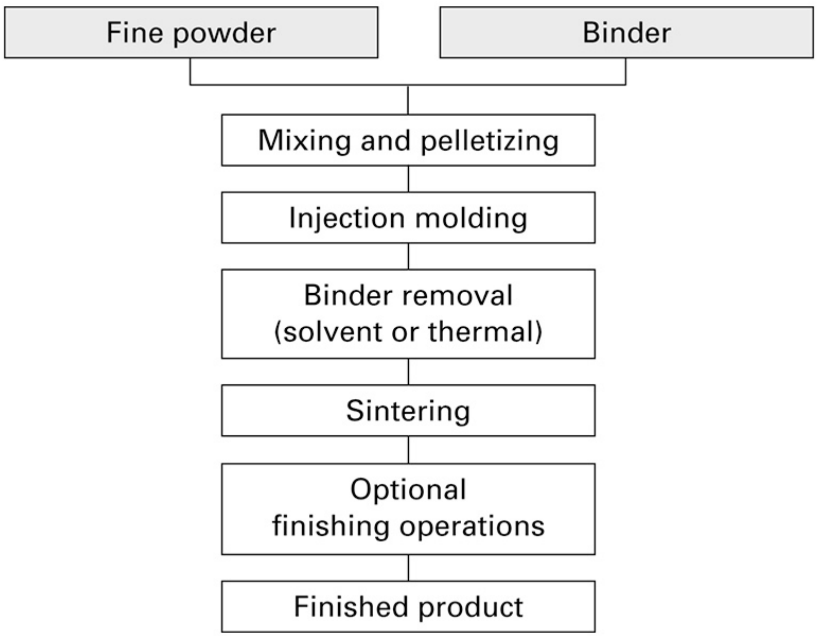


Figure 18-12 Flow chart of the metal injection molding process (MIM) used to produce small, intricate-shaped parts from metal powder.

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

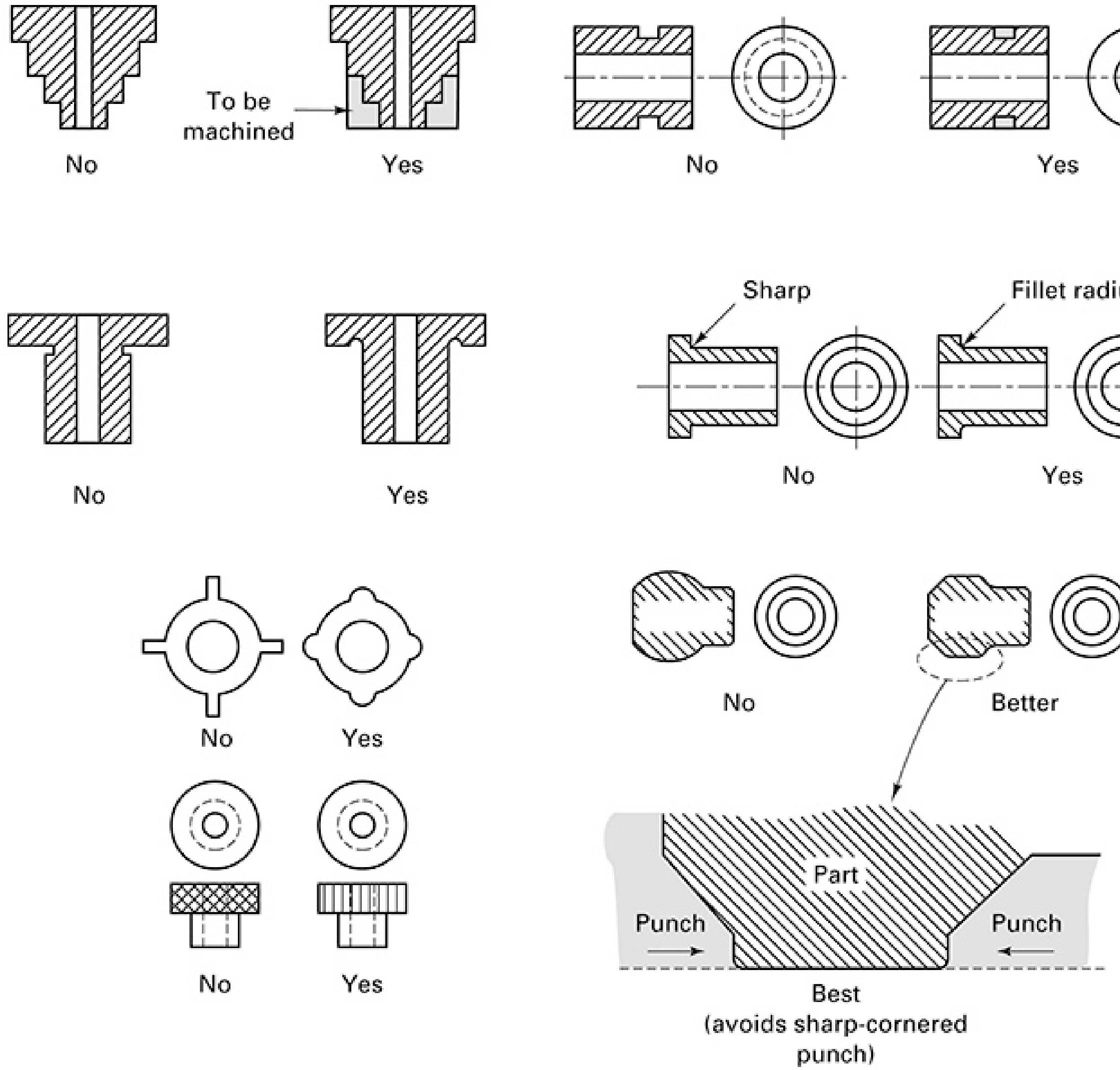


Figure 18-17 Examples of poor and good design features for powder metallurgy products. Recommendations are based on ease of pressing, design of tooling, uniformity of properties, and ultimate performance.

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