INTRODUCTION AND OVERVIEW OF MANUFACTURING

1. What is Manufacturing?
2. Materials in Manufacturing
3. Manufacturing Processes
4. Production Systems

Manufacturing is Important

- Technologically
- Economically
- Historically

Manufacturing - Technologically Important

- Technology - the application of science to provide society and its members with those things that are needed or desired
- Technology provides the products that help our society and its members live better
- What do these products have in common?
  - They are all manufactured
- Manufacturing is the essential factor that makes technology possible

Manufacturing - Economically Important

- Manufacturing is one way by which nations create material wealth

U.S. economy:	
Sector	**% of GNP**
Manufacturing	20%
Agriculture, minerals, etc.	5%
Construction & utilities	5%
Service sector – retail, transportation, banking, communication, education, and government	70%

Manufacturing - Historically Important

- Throughout history, human cultures that were better at making things were more successful
- Making better tools meant better crafts & weapons
  - Better crafts allowed people to live better
  - Better weapons allowed them to conquer other cultures in times of conflict
- To a significant degree, the history of civilization is the history of humans' ability to make things

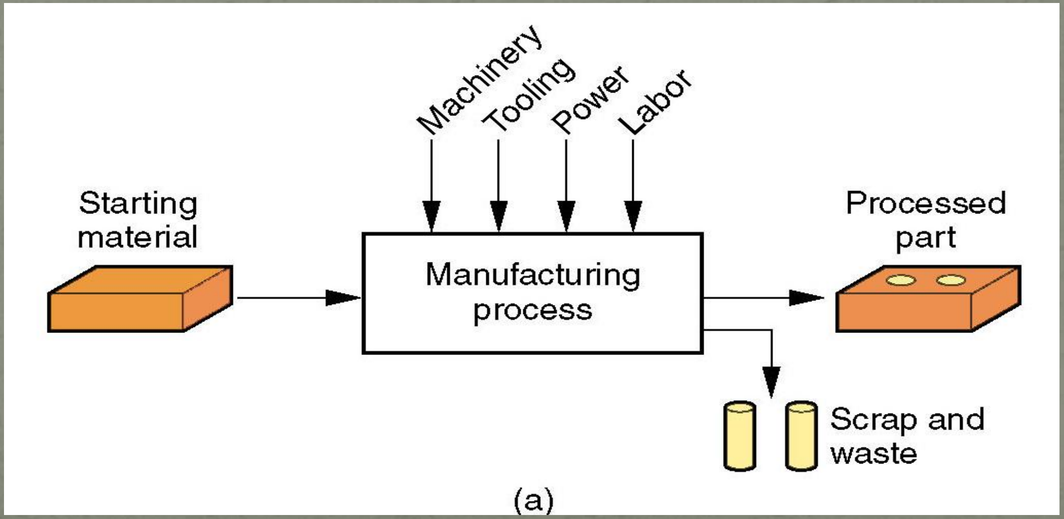
What is Manufacturing?

- The word *manufacture* is derived from two Latin words *manus* (hand) and *factus* (make); the combination means “made by hand”
- “Made by hand” accurately described the fabrication methods that were used when the English word “manufacture” was first coined around 1567 A.D.
- Most modern manufacturing operations are accomplished by mechanized and automated equipment that is supervised by human workers

Manufacturing - Technologically

- Application of physical and chemical processes to alter the geometry, properties, and/or appearance of a starting material to make parts or products
  - Manufacturing also includes assembly
  - Almost always carried out as a sequence of operations

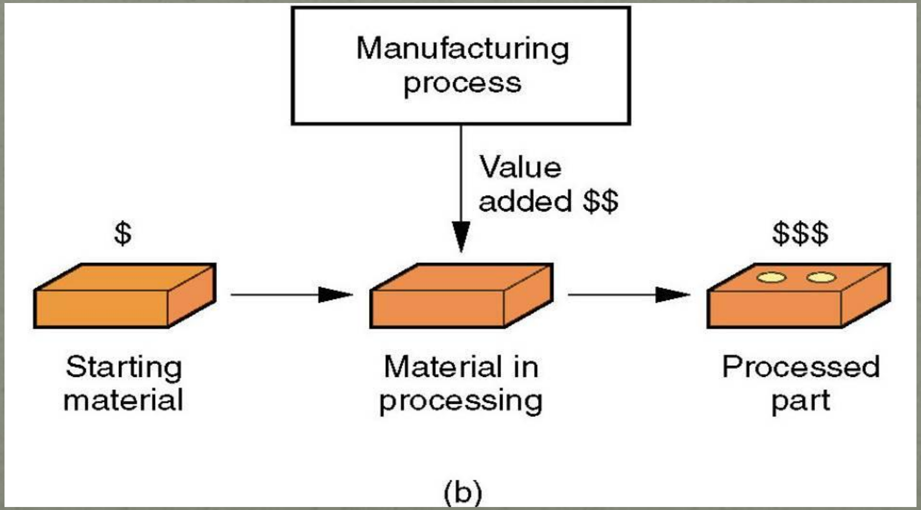
Figure 1.1 (a) Manufacturing as a technical process



Manufacturing - Economically

- Transformation of materials into items of greater value by means of one or more processing and/or assembly operations
  - Manufacturing *adds value* to the material by changing its shape or properties, or by combining it with other materials

Figure 1.1 (b) Manufacturing as an economic process



Manufacturing Industries

- Industry consists of enterprises and organizations that produce or supply goods and services
- Industries can be classified as:
  1. Primary industries - those that cultivate and exploit natural resources, e.g., farming, mining
  2. Secondary industries - take the outputs of primary industries and convert them into consumer and capital goods - manufacturing is the principal activity
  3. Tertiary industries - service sector

Manufacturing Industries - continued

- Secondary industries include manufacturing, construction, and electric power generation
- Manufacturing includes several industries whose products are not covered in this book; e.g., apparel, beverages, chemicals, and food processing
- For our purposes, manufacturing means production of hardware
  - Nuts and bolts, forgings, cars, airplanes, digital computers, plastic parts, and ceramic products

Production Quantity *Q*

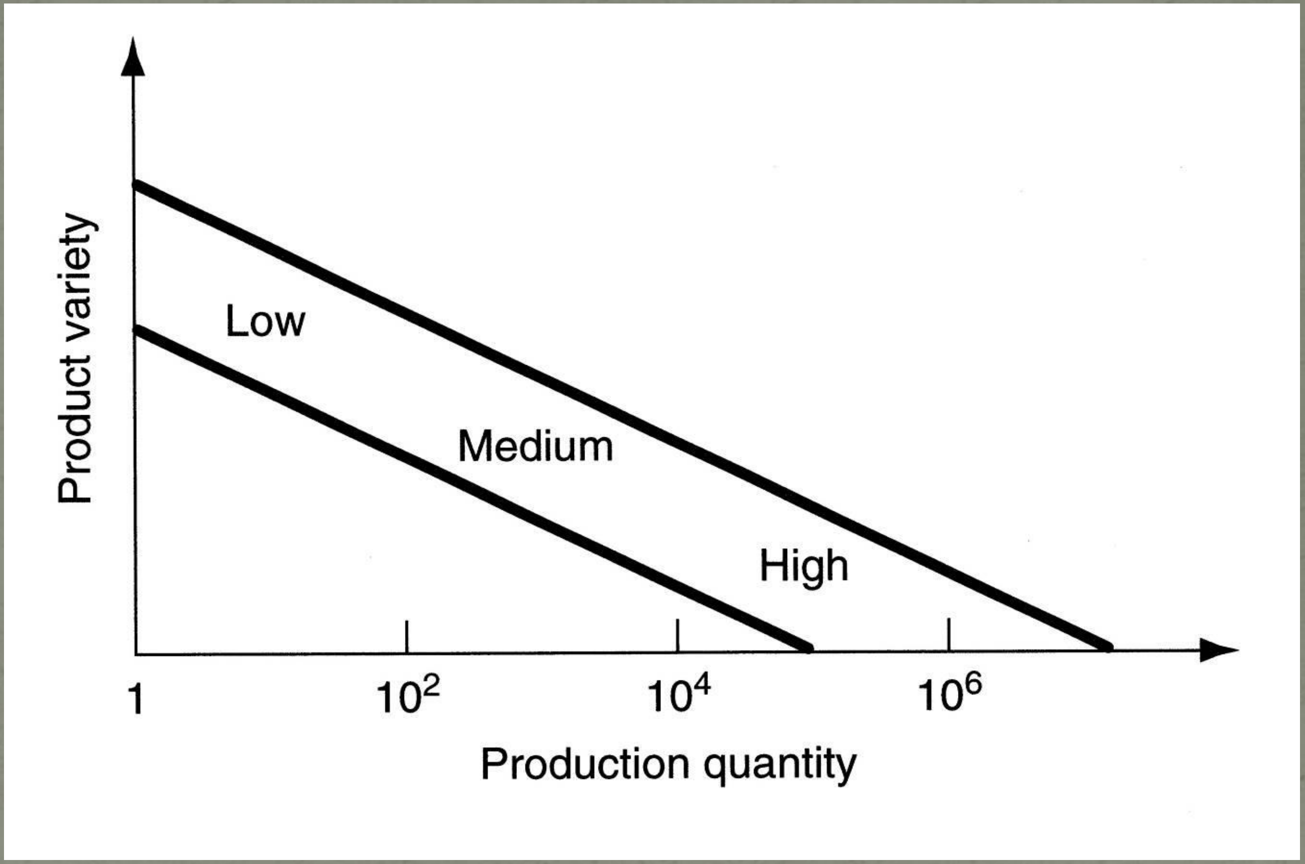
- The quantity of products *Q* made by a factory has an important influence on the way its people, facilities, and procedures are organized
- Annual production quantities can be classified into three ranges:

Production range	Annual Quantity *Q*
Low production	1 to 100 units
Medium production	100 to 10,000 units
High production	10,000 to millions of

Product Variety *P*

- Product variety *P* refers to different product types or models produced in the plant
- Different products have different features
  - They are intended for different markets
  - Some have more parts than others
- The number of different product types made each year in a factory can be counted
- When the number of product types made in the factory is high, this indicates high product variety

P versus *Q* in Factory Operations



- Figure 1.2 P-Q Relationship

More About Product Variety

- Although *P* is a quantitative parameter, it is much less exact than *Q* because details on how much the designs differ is not captured simply by the number of different designs
  - *Soft product variety* - small differences between products, e.g., between car models made on the same production line, with many common parts among models
  - *Hard product variety* - products differ substantially, e.g., between a small car and a large truck, with few common parts (if any)

Manufacturing Capability

- A manufacturing plant consists of *processes* and *systems* (and people, of course) designed to transform a certain limited range of *materials* into products of increased value
- The three building blocks - materials, processes, and systems - are the subject of modern manufacturing
- Manufacturing capability includes:
    1. Technological processing capability
    2. Physical product limitations
    3. Production capacity

1. Technological Processing Capability

- The available set of manufacturing processes in the plant (or company)
- Certain manufacturing processes are suited to certain materials
  - By specializing in certain processes, the plant is also specializing in certain materials
- Includes not only the physical processes, but also the expertise of the plant personnel
- Examples:
  - A machine shop cannot roll steel
  - A steel mill cannot build cars

2. Physical Product Limitations

- Given a plant with a certain set of processes, there are size and weight limitations on the parts or products that can be made in the plant
- Product size and weight affect:
  - Production equipment
  - Material handling equipment
- Production, material handling equipment, and plant size must be planned for products that lie within a certain size and weight range

3. Production Capacity

- Defined as the maximum quantity that a plant can produce in a given time period (e.g., month or year) under assumed operating conditions
- Operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and so on
- Usually measured in terms of output units, such as tons of steel or number of cars produced by the plant
- Also called *plant capacity*

Materials in Manufacturing

- Most engineering materials can be classified into one of three basic categories:
  1. Metals
  2. Ceramics
  3. Polymers
- Their chemistries are different
- Their mechanical and physical properties are dissimilar
- These differences affect the manufacturing processes that can be used to produce products from them

In Addition: Composites

- Nonhomogeneous mixtures of the other three basic types rather than a unique category

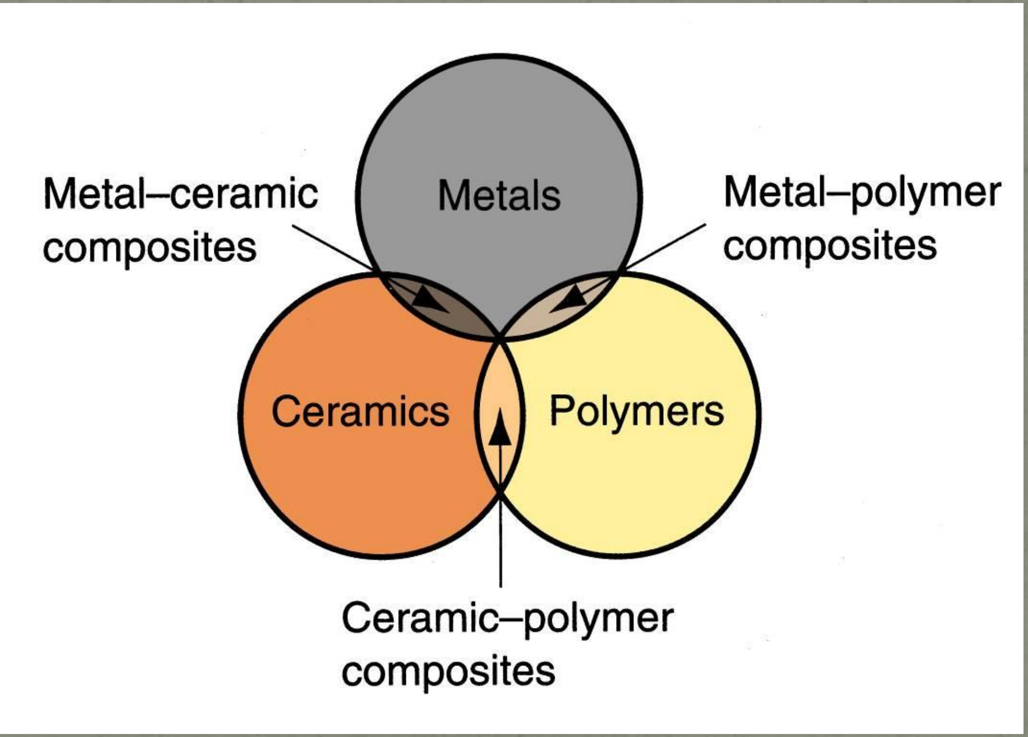


Figure 1.3 Venn diagram of three basic material types plus composites

1. Metals

- Usually *alloys*, which are composed of two or more elements, at least one of which is metallic
- Two basic groups:
  1. Ferrous metals - based on iron, comprises about 75% of metal tonnage in the world:
     - Steel = Fe-C alloy (0.02 to 2.11% C)
     - Cast iron = Fe-C alloy (2% to 4% C)
  2. Nonferrous metals - all other metallic elements and their alloys: aluminum, copper, magnesium, nickel, silver, tin, titanium, etc.

2. Ceramics

- Compounds containing metallic (or semi-metallic) and nonmetallic elements.
- Typical nonmetallic elements are oxygen, nitrogen, and carbon
- For processing, ceramics divide into:
  1. Crystalline ceramics – includes:
     - Traditional ceramics, such as clay (hydrous aluminum silicates)
     - Modern ceramics, such as alumina (Al_2O_3)
  2. Glasses – mostly based on silica (SiO_2)

3. Polymers

- Compound formed of repeating structural units called *mers*, whose atoms share electrons to form very large molecules
- Three categories:
  1. Thermoplastic polymers - can be subjected to multiple heating and cooling cycles without altering molecular structure
  2. Thermosetting polymers - molecules chemically transform (cure) into a rigid structure – cannot be reheated
  3. Elastomers - shows significant elastic behavior

4. Composites

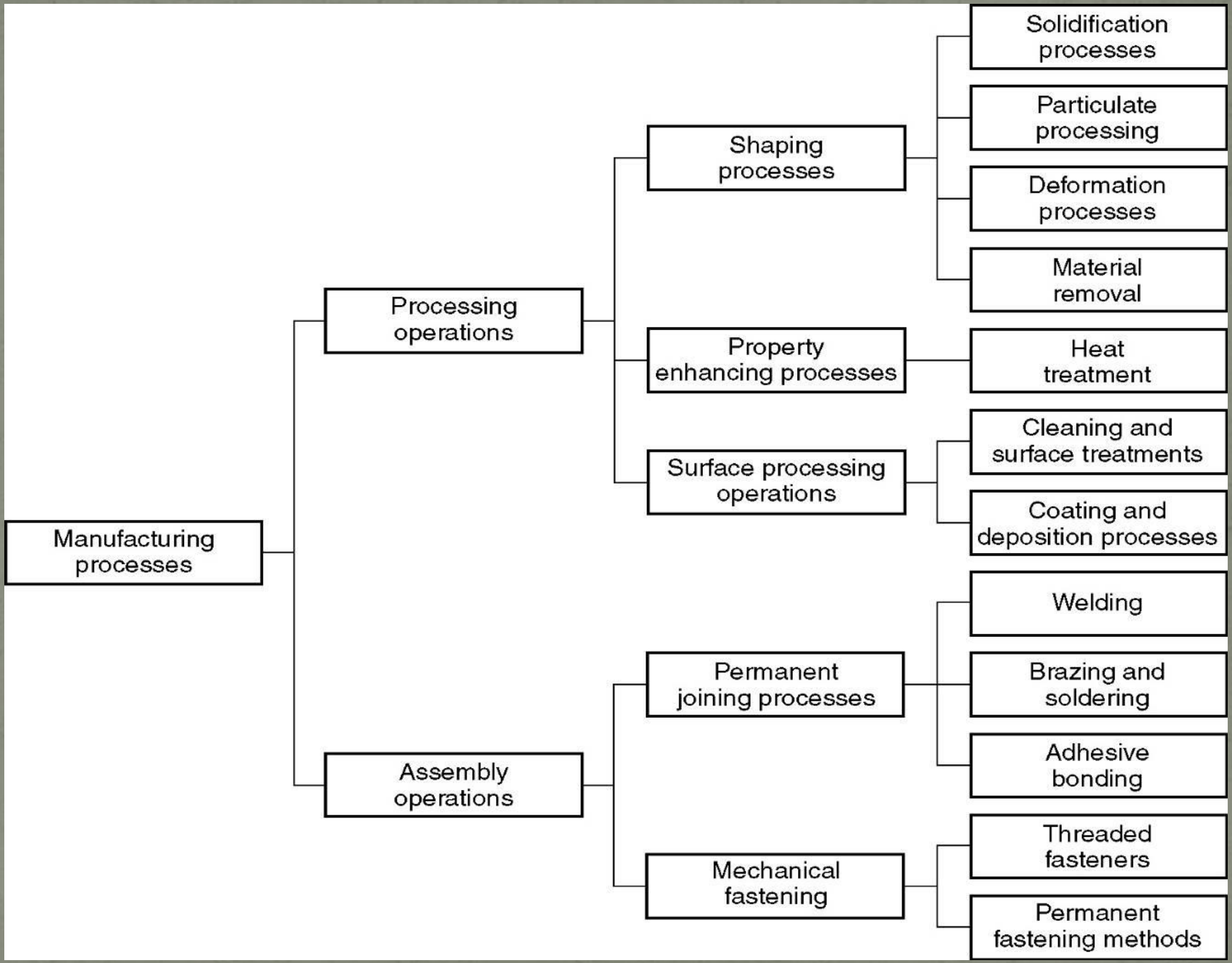
- Material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to its constituents
  - *Phase* - homogeneous mass of material, such as grains of identical unit cell structure in a solid metal
  - Usual structure consists of particles or fibers of one phase mixed in a second phase
  - Properties depend on components, physical shapes of components, and the way they are combined to form the final material

Manufacturing Processes

- Two basic types:

1. Processing operations - transform a work material from one state of completion to a more advanced state
   - Operations that change the geometry, properties, or appearance of the starting material
2. Assembly operations - join two or more components to create a new entity

Figure 1.4 Classification of manufacturing processes



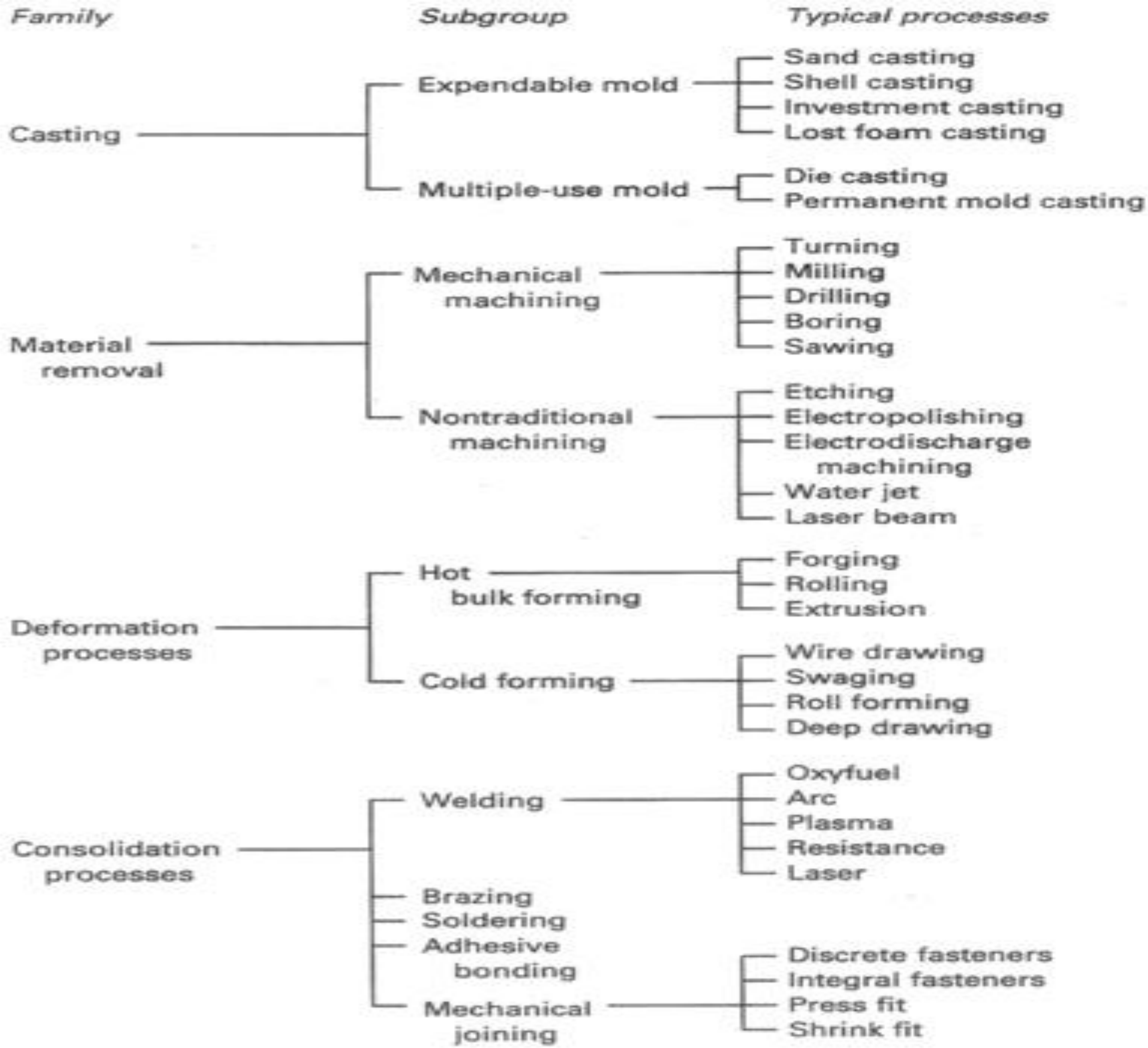


FIGURE 13-1 Materials processing families, subgroups, and typical processes.

Processing Operations

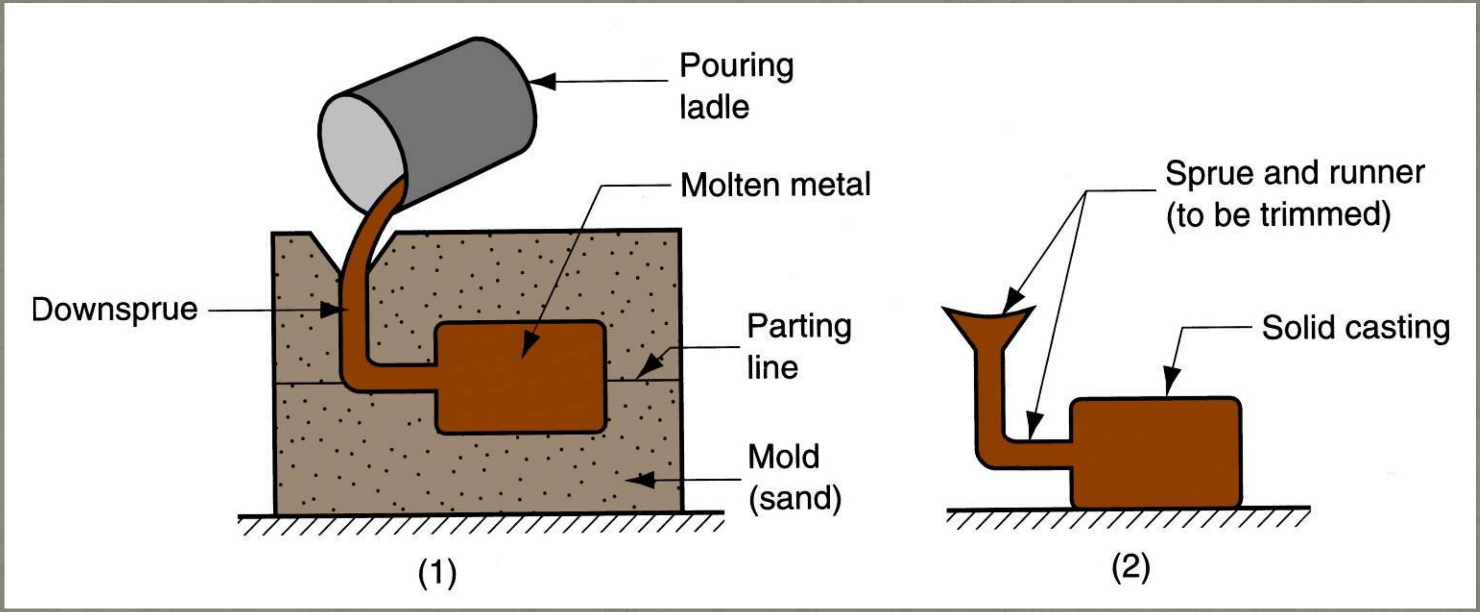
- Alters a material's shape, physical properties, or appearance in order to add value
- Three categories of processing operations:

1. Shaping operations - alter the geometry of the starting work material
2. Property-enhancing operations - improve physical properties without changing shape
3. Surface processing operations - to clean, treat, coat, or deposit material on exterior surface of the work

Shaping Processes – Four Categories

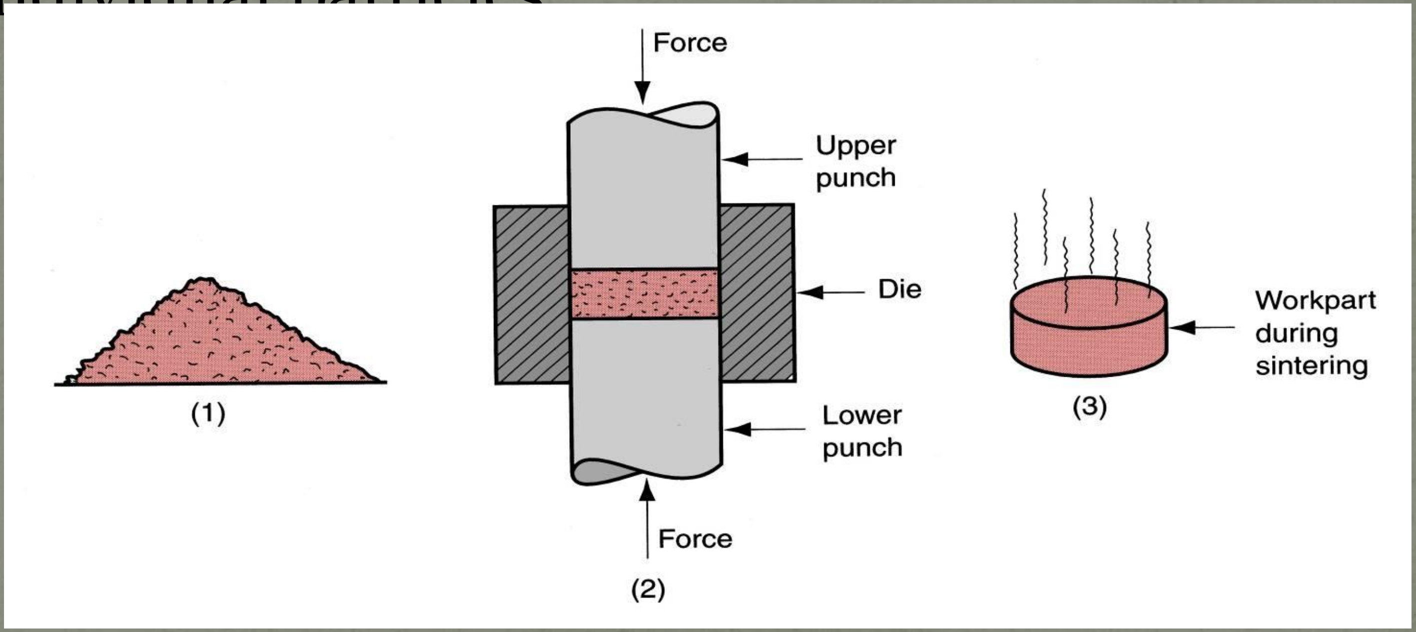
1. Solidification processes - starting material is a heated liquid or semifluid
2. Particulate processing - starting material consists of powders
3. Deformation processes - starting material is a ductile solid (commonly metal)
4. Material removal processes - starting material is a ductile or brittle solid

Solidification Processes

- Starting material is heated sufficiently to transform it into a liquid or highly plastic state
- Examples: metal casting, plastic molding
- 

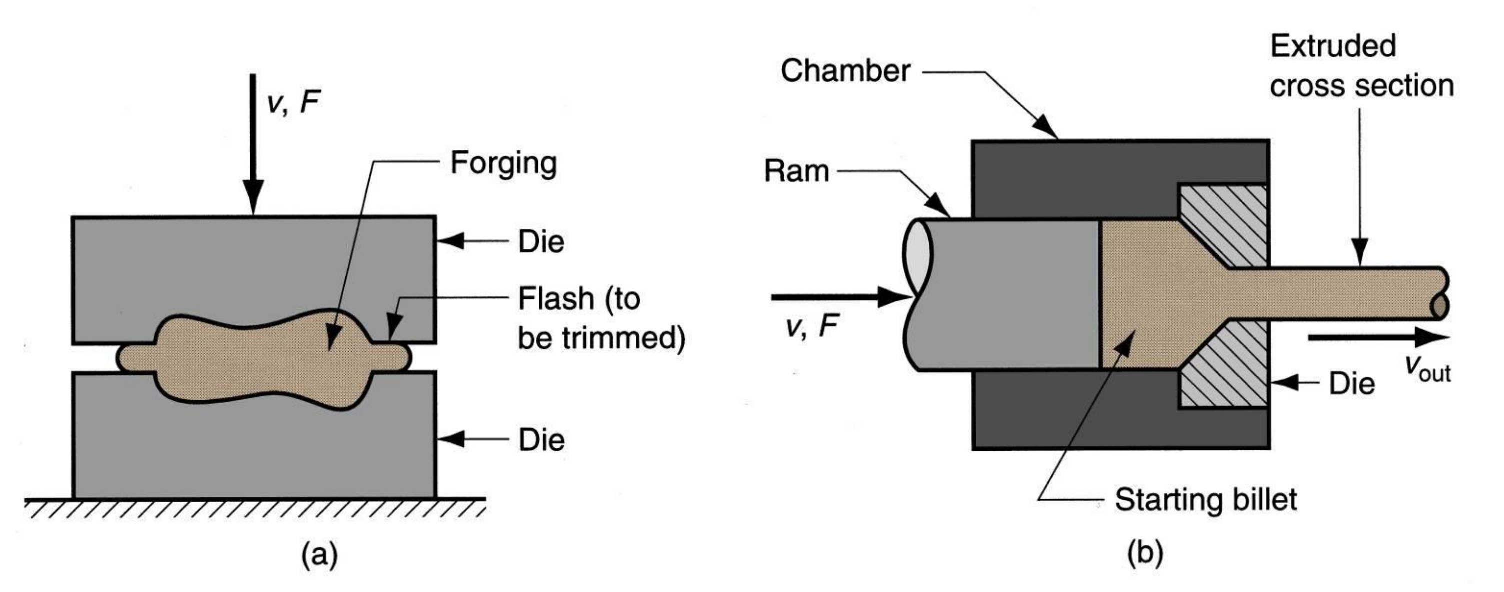
Particulate Processing

- Starting materials are powders of metals or ceramics
- Usually involves pressing and sintering, in which powders are first compressed and then heated to bond the individual particles



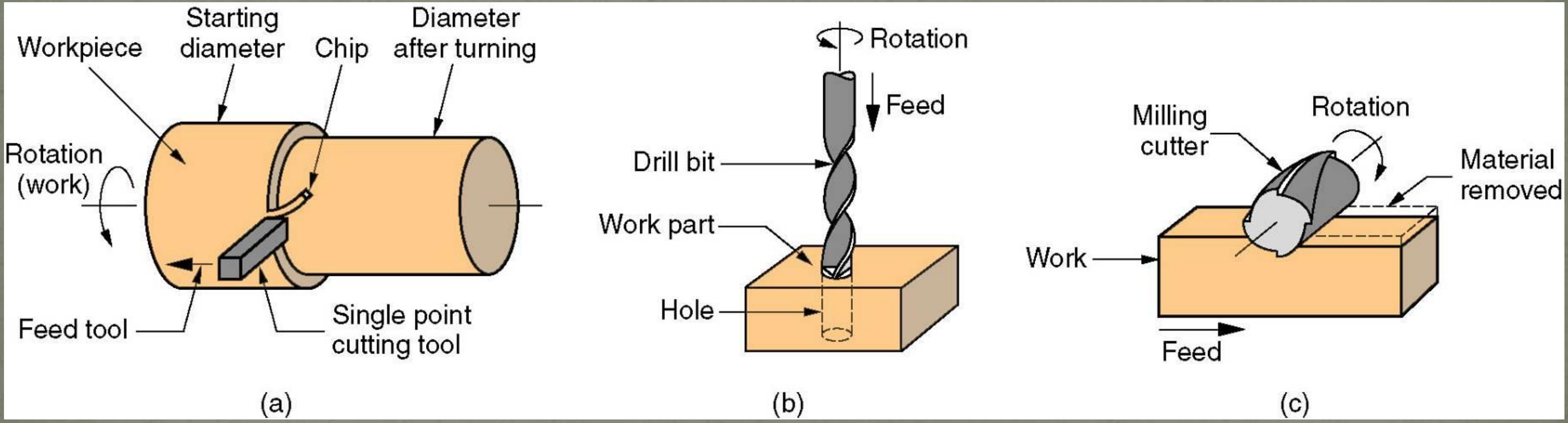
Deformation Processes

- Starting workpart is shaped by application of forces that exceed the yield strength of the material
- Examples: (a) forging, (b) extrusion



Material Removal Processes

- Excess material removed from the starting piece so what remains is the desired geometry
- Examples: machining such as turning, drilling, and milling; also grinding and nontraditional processes



Waste in Shaping Processes

- Desirable to minimize waste in part shaping
- Material removal processes are wasteful in unit operations, simply by the way they work
- Most casting, molding, and particulate processing operations waste little material
- Terminology for minimum waste processes:
  - *Net shape* processes - when most of the starting material is used and no subsequent machining is required
  - *Near net shape* processes - when minimum amount of machining is required

Property-Enhancing Processes

- Performed to improve mechanical or physical properties of work material
- Part shape is not altered, except unintentionally
  - Example: unintentional warping of a heat treated part
- Examples:
  - Heat treatment of metals and glasses
  - Sintering of powdered metals and ceramics

Surface Processing Operations

- Cleaning - chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface
- Surface treatments - mechanical working such as sand blasting, and physical processes like diffusion
- Coating and thin film deposition - coating exterior surface of the workpart

Assembly Operations

- Two or more separate parts are joined to form a new entity
- Types of assembly operations:
  1. Joining processes – create a permanent joint
     - Welding, brazing, soldering, and adhesive bonding
  2. Mechanical assembly – fastening by mechanical methods
     - Threaded fasteners (screws, bolts and nuts); press fitting, expansion fits

Production Systems

- People, equipment, and procedures used for the combination of materials and processes that constitute a firm's manufacturing operations
- A manufacturing firm must have systems and procedures to efficiently accomplish its type of production
- Two categories of production systems:
  - Production facilities
  - Manufacturing support systems
- Both categories include people (people make the systems work)

Production Facilities

- The factory, production equipment, and material handling systems
- Production facilities "touch" the product
- Includes the way the equipment is arranged in the factory - the *plant layout*
- Equipment usually organized into logical groupings, called *manufacturing systems*
  - Examples:
    - Automated production line
    - Machine cell consisting of an industrial robot and two machine tools

Facilities versus Product Quantities

- A company designs its manufacturing systems and organizes its factories to serve the particular mission of each plant
- Certain types of production facilities are recognized as the most appropriate for a given type of manufacturing:
  1. Low production – 1 to 100
  2. Medium production – 100 to 10,000
  3. High production – 10,000 to >1,000,000
- Different facilities are required for each of the three quantity ranges

Low Production

- *Job shop* is the term used for this type of production facility
- A job shop makes low quantities of specialized and customized products
  - Products are typically complex, e.g., space capsules, prototype aircraft, special machinery
- Equipment in a job shop is general purpose
- Labor force is highly skilled
- Designed for maximum flexibility

Medium Production

- Two different types of facility, depending on product variety:
- *Batch production*
  - Suited to hard product variety
  - Setups required between batches
- *Cellular manufacturing*
  - Suited to soft product variety
  - Worker cells organized to process parts without setups between different part styles

High Production

- Often referred to as *mass production*
  - High demand for product
  - Manufacturing system dedicated to the production of that product
- Two categories of mass production:
  1. Quantity production
  2. Flow line production

Quantity Production

- Mass production of single parts on single machine or small numbers of machines
- Typically involves standard machines equipped with special tooling
- Equipment is dedicated full-time to the production of one part or product type
- Typical layouts used in quantity production are product layout and cellular layout

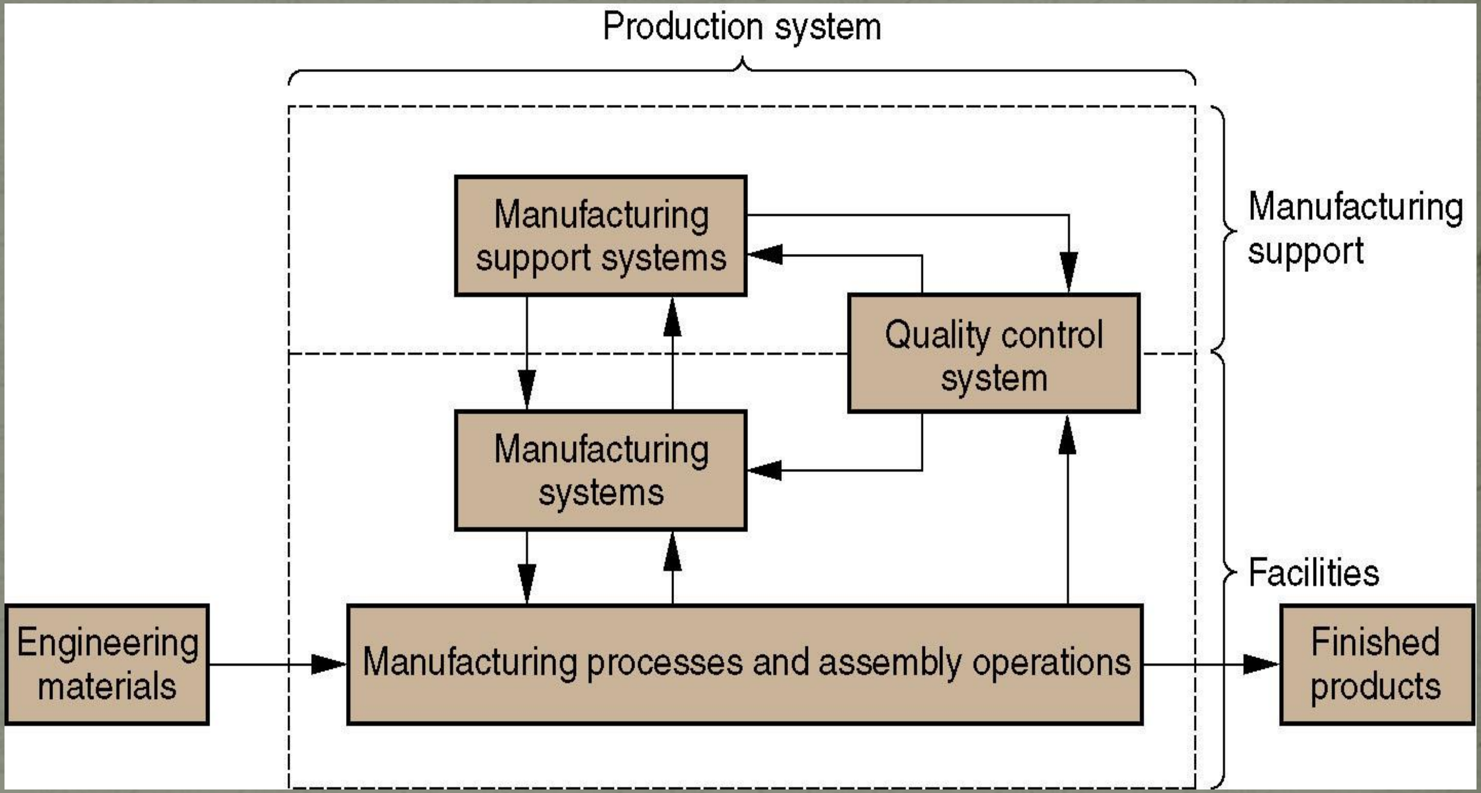
Flow Line Production

- Multiple machines or workstations arranged in sequence, e.g., production lines
- Product is complex
  - Requires multiple processing and/or assembly operations
- Work units are physically moved through the sequence to complete the product
- Workstations and equipment are designed specifically for the product to maximize efficiency

Manufacturing Support Systems

- A company must organize itself to design the processes and equipment, plan and control production, and satisfy product quality requirements
- Accomplished by manufacturing support systems - people and procedures by which a company manages its production operations
- Typical departments:
    1. Manufacturing engineering
    2. Production planning and control
    3. Quality control

Overview of Major Topics



- Figure 1.10 Overview of production system and major topics in *Fundamentals of Modern Manufacturing*.

Why study Manufacture?

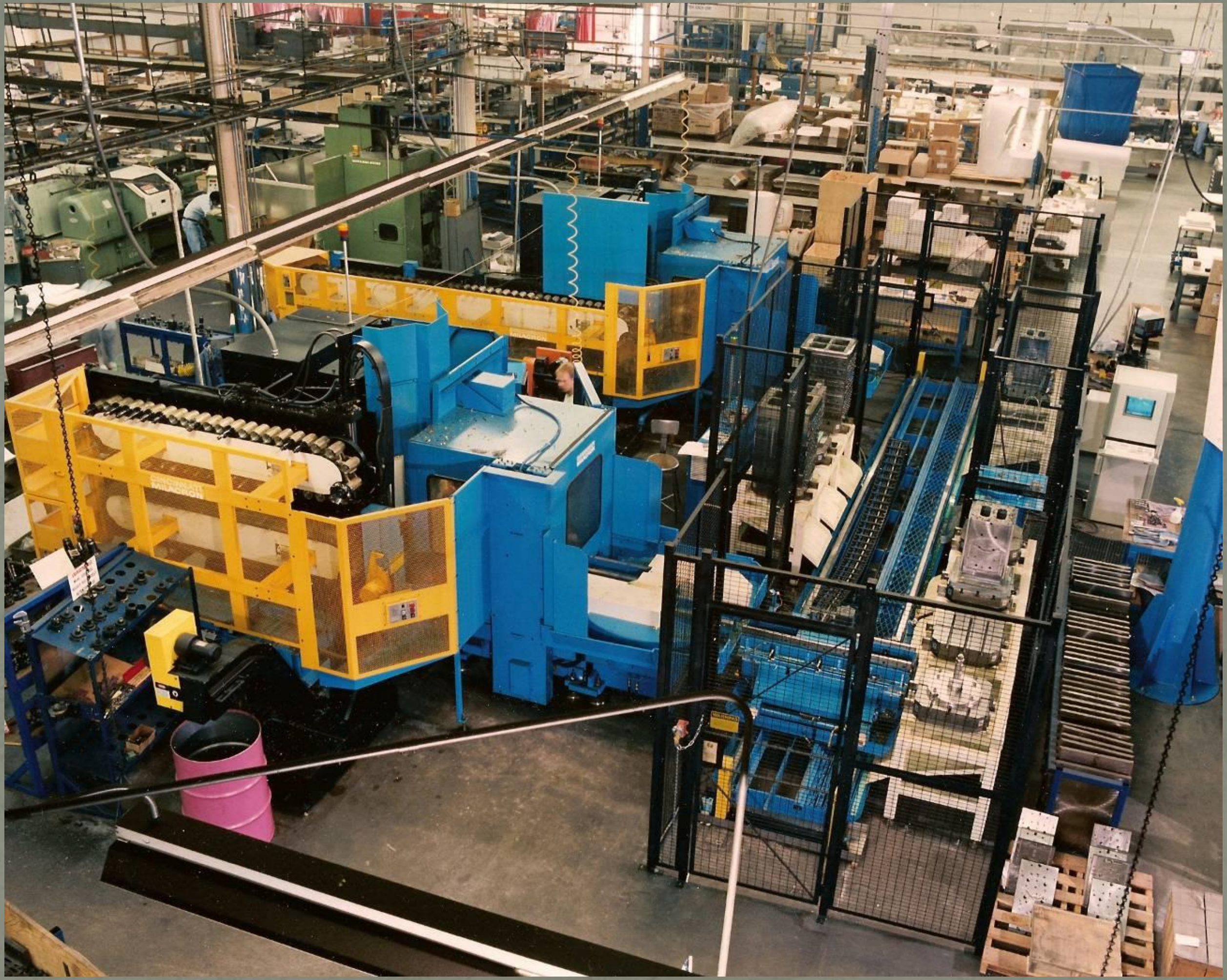
- Manufacturing core to economic activity!
- As a *designer*: understand the limitations available
  - Tolerances
  - Production rates
  - Economic issues
- In general: develop analytic skills, specifically for process oriented tasks

Design Issues

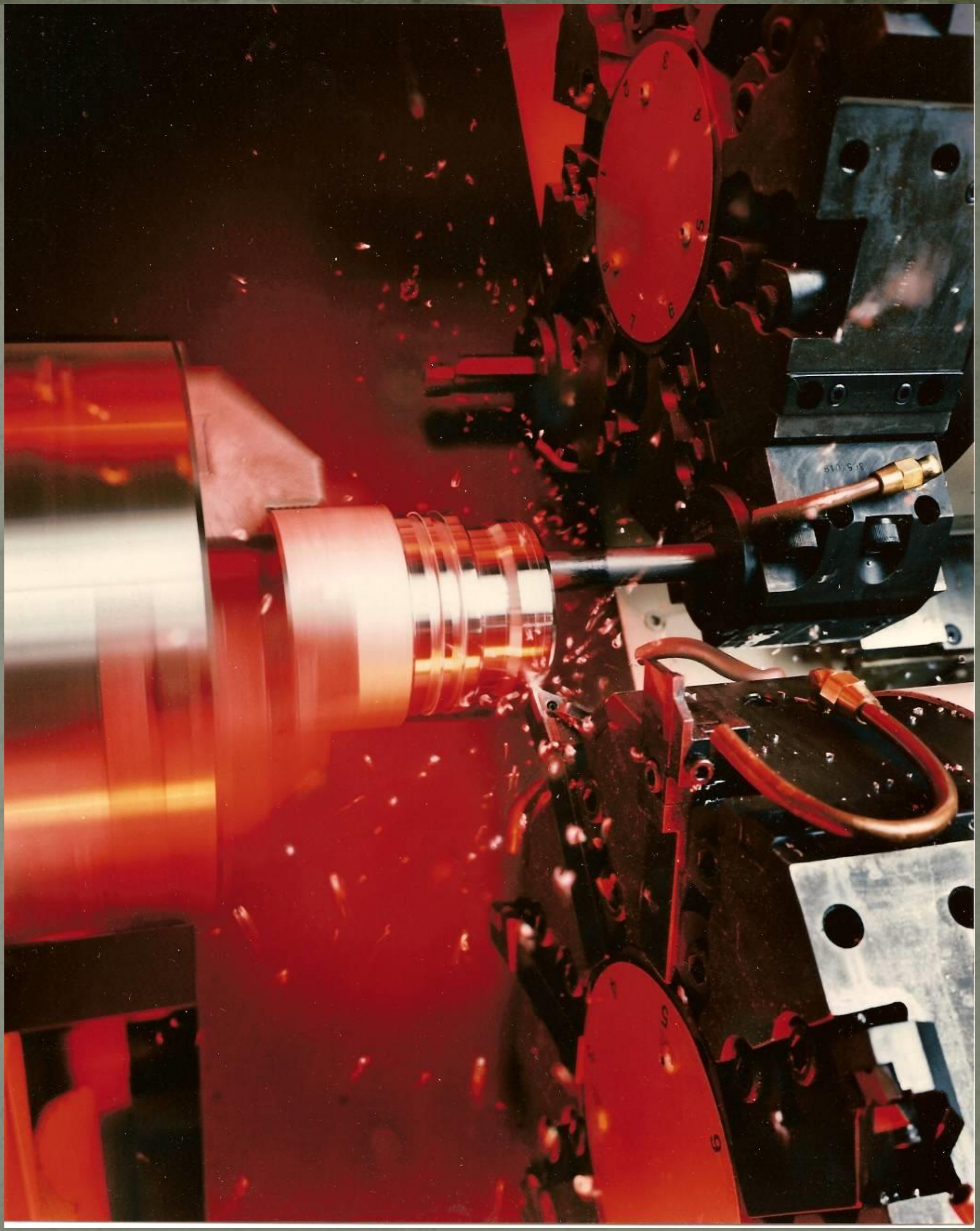
- Designer must consider:
  - What processes are available/relevant for the product?
  - What tolerances can be achieved, and are these sufficient?
  - Are there any design features that need to be incorporated (eg webbing, round edges, etc)?
  - Can the expected production rate be met?
  - How will the product be assembled?

A spectacular scene in steelmaking is charging of a basic oxygen furnace, in which molten pig iron produced in a blast furnace is poured into the BOF. Temperatures are around 1650°C (3000 ° F).

A machining cell consisting of two horizontal machining centers supplied by an in-line pallet shuttle (photo courtesy of Cincinnati Milacron).

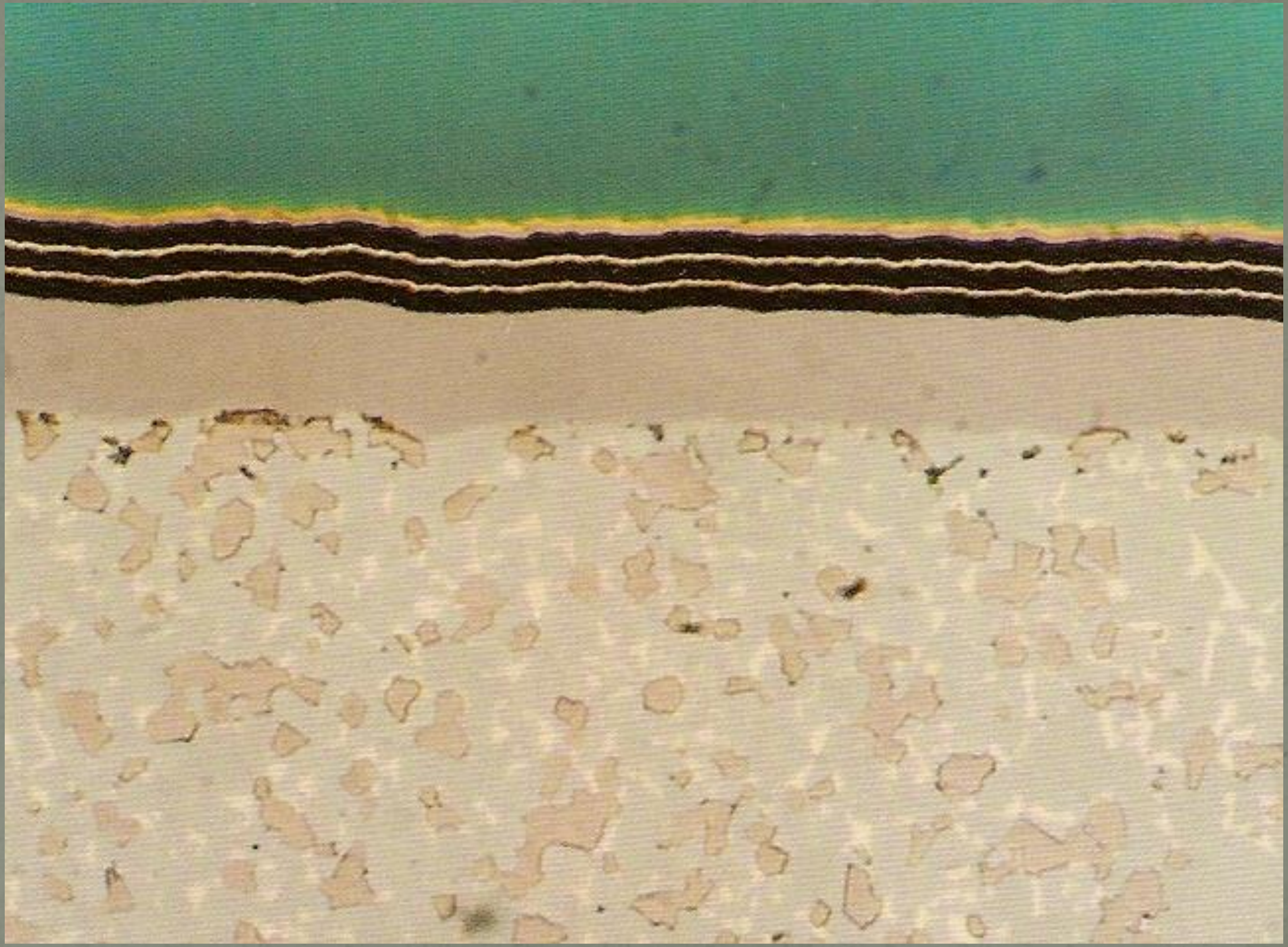


A robotic arm performs unloading and loading operation in a turning center using a dual gripper (photo courtesy of Cincinnati Milacron).

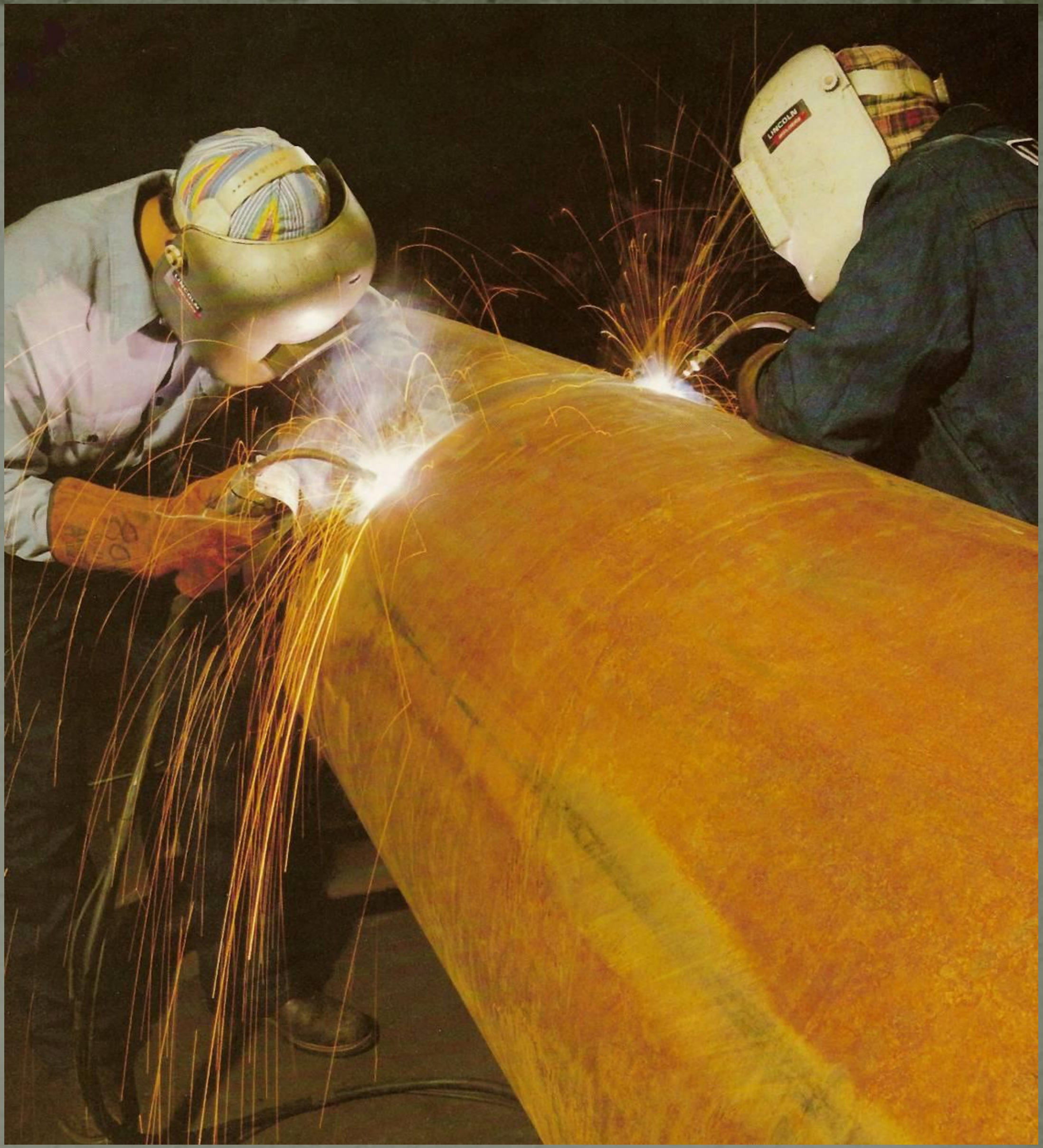


Metal chips fly in a high speed turning operation performed on a computer numerical control turning center (photo courtesy of Cincinnati Milacron).

Photomicrograph of the cross section of multiple coatings of titanium nitride and aluminum oxide on a cemented carbide substrate (photo courtesy of Kennametal Inc.).

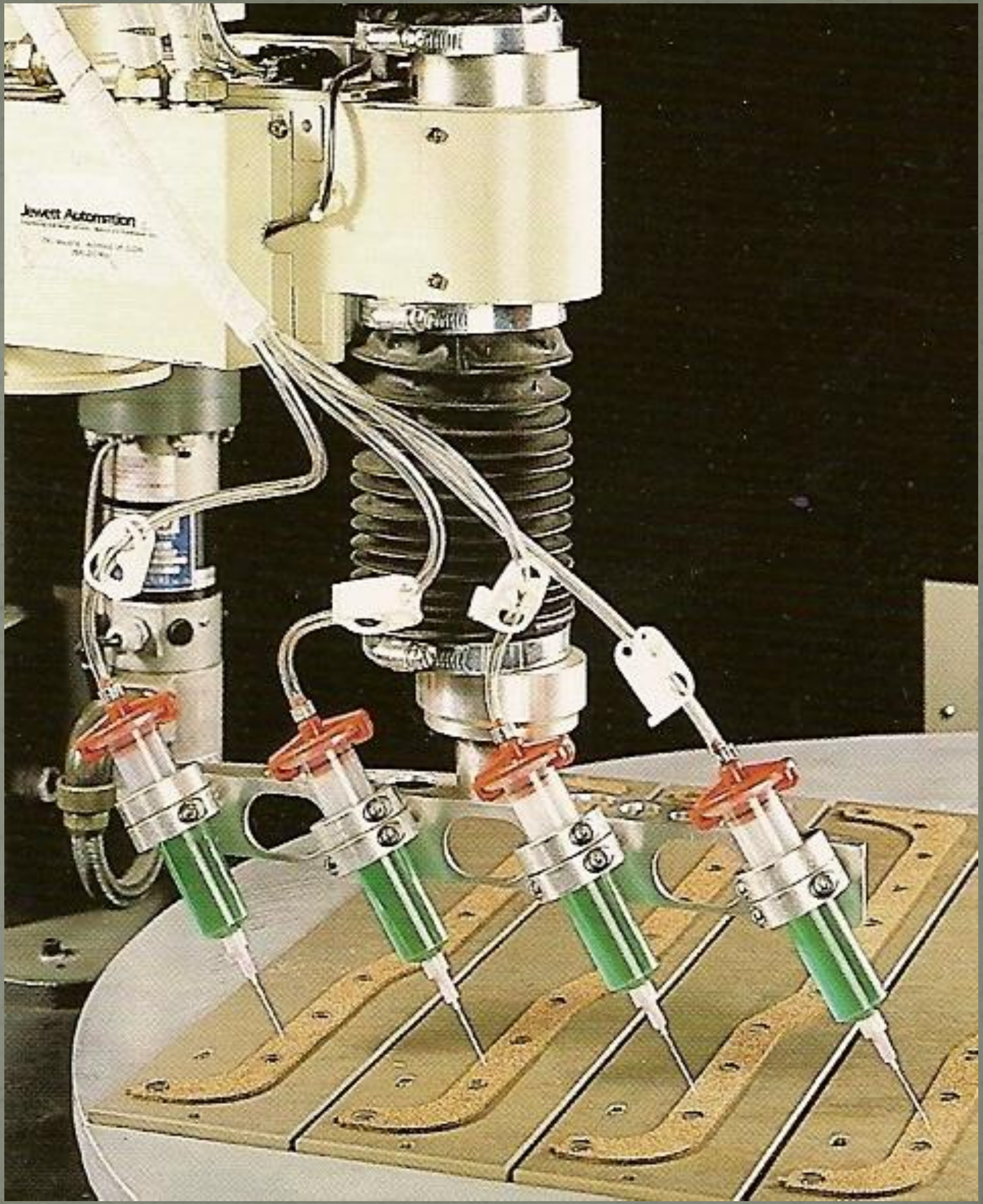


A batch of silicon wafers enters a furnace heated to 1000°C (1800°F) during fabrication of integrated circuits under clean room conditions (photo courtesy of Intel Corporation).

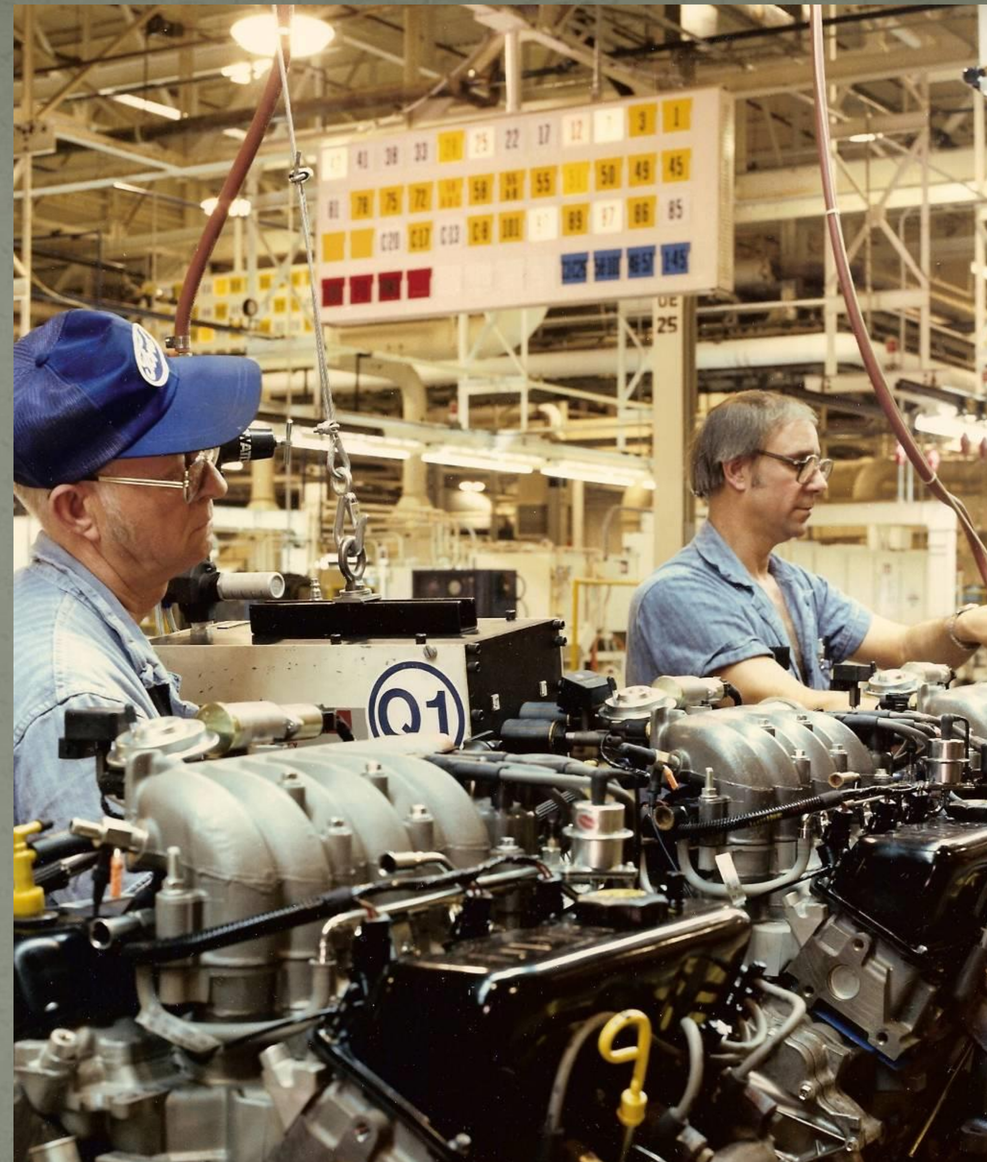


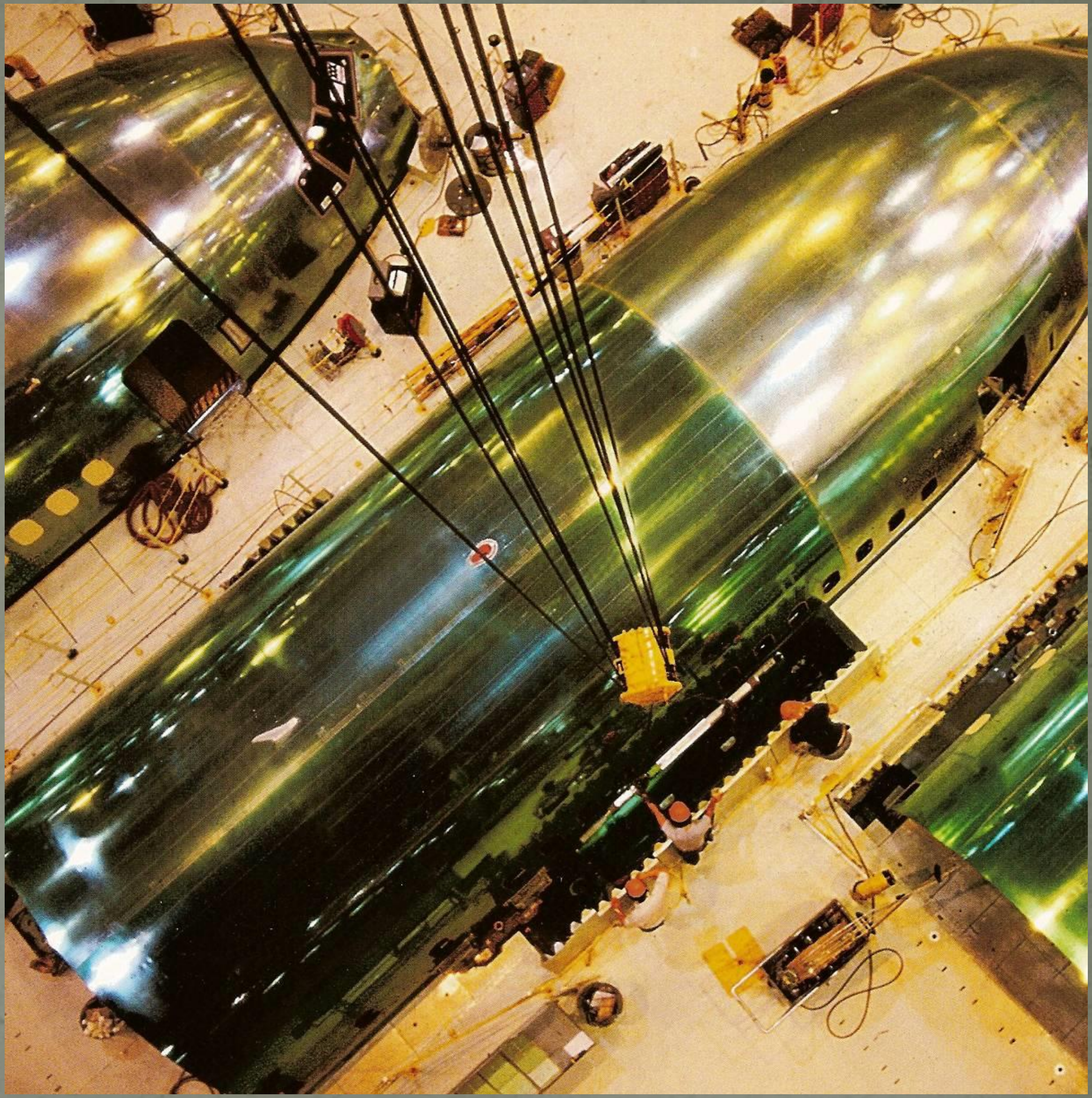
Two welders perform arc welding on a large steel pipe section (photo courtesy of Lincoln Electric Company).

Automated dispensing of adhesive onto component parts prior to assembly (photo courtesy of EFD, Inc.).



Assembly workers on an engine assembly line (photo courtesy of Ford Motor Company).





Assembly operations on the Boeing 777 (photo courtesy of Boeing Commercial Airplane Co.).

Casting
Manufacturing Processes

FUNDAMENTALS OF METAL CASTING

- Overview of Casting Technology
- Heating and Pouring
- Solidification and Cooling

Solidification Processes

Starting work material is either a liquid or is in a highly plastic condition, and a part is created through solidification of the material

- Solidification processes can be classified according to engineering material processed:
  - Metals
  - Ceramics, specifically glasses
  - Polymers and polymer matrix composites (PMCs)

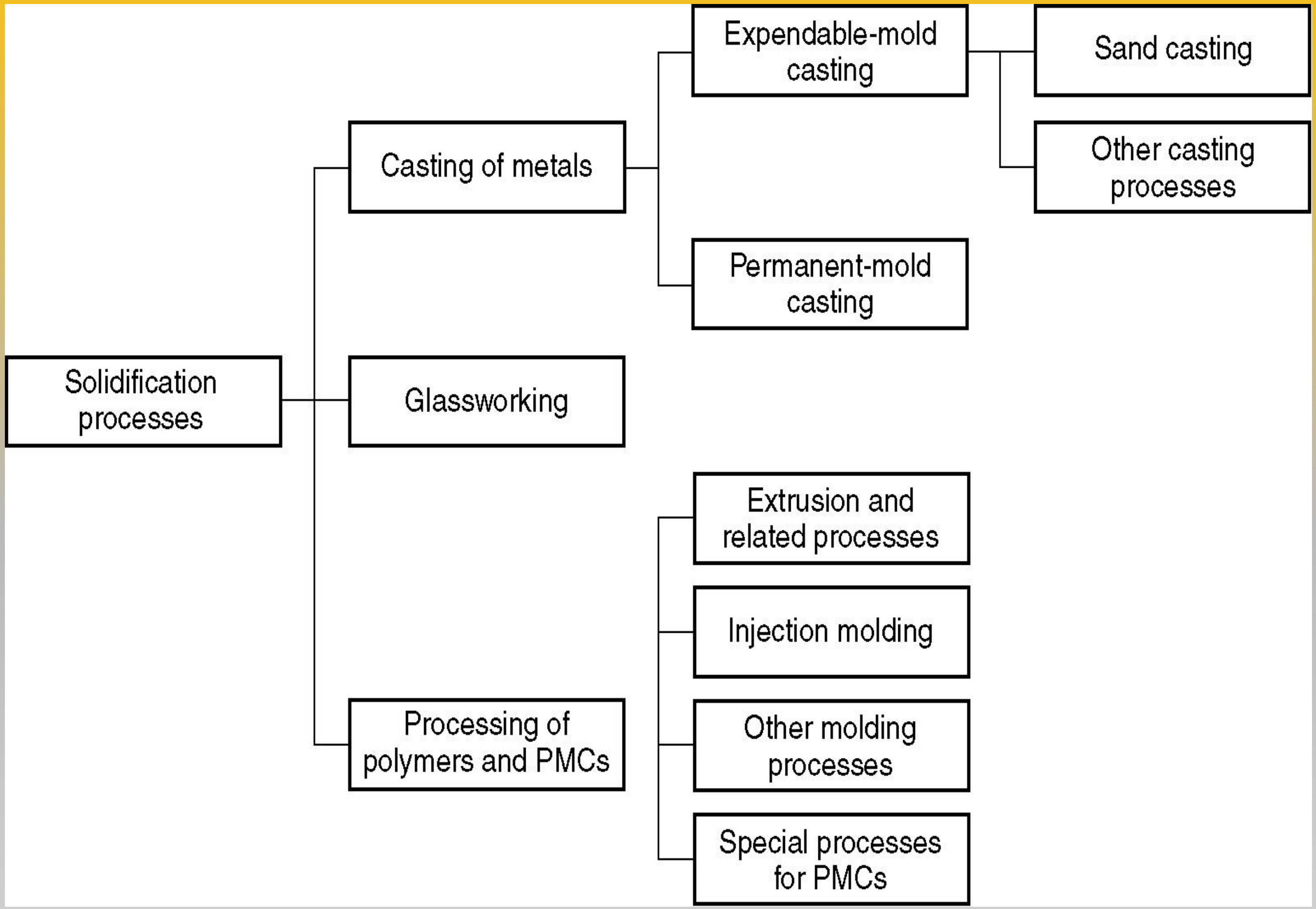


Figure 10.1 Classification of solidification processes.

Casting

Process in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity

- The term *casting* also applies to the part made in the process
- Steps in casting seem simple:
  1. Melt the metal
  2. Pour it into a mold
  3. Let it freeze

Capabilities and Advantages of Casting

- Can create complex part geometries
- Can create both external and internal shapes
- Some casting processes are *net shape;* others are *near net shape*
- Can produce very large parts
- Some casting methods are suited to mass production

Disadvantages of Casting

- Different disadvantages for different casting processes:
  - Limitations on mechanical properties
  - Poor dimensional accuracy and surface finish for some processes; e.g., sand casting
  - Safety hazards to workers due to hot molten metals
  - Environmental problems

Parts Made by Casting

- Big parts: engine blocks and heads for automotive vehicles, wood burning stoves, machine frames, railway wheels, pipes, big bells, big statues, and pump housings
- Small parts: dental crowns, jewelry, small statues, and frying pans
- All varieties of metals can be cast, ferrous and nonferrous

Overview of Casting Technology

- Casting is usually performed in a foundry

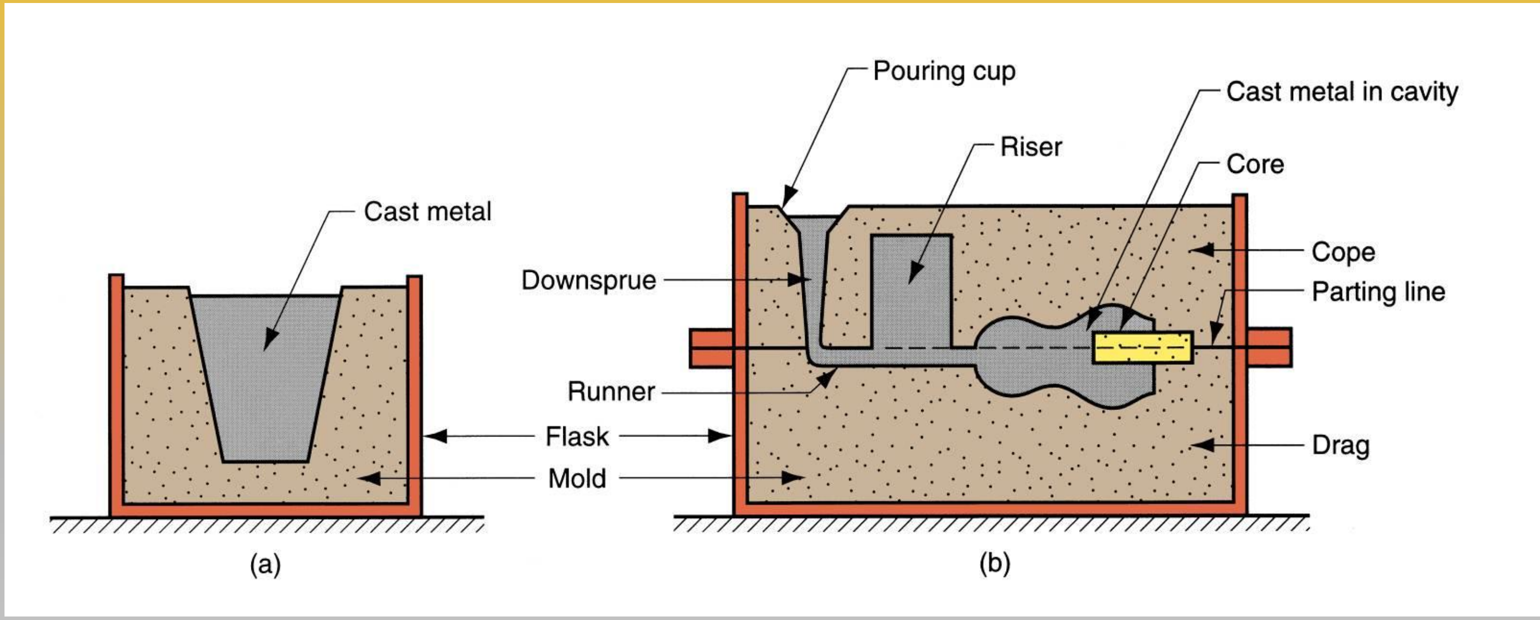
Foundry = factory equipped for making molds, melting and handling molten metal, performing the casting process, and cleaning the finished casting

- Workers who perform casting are called *foundry men*

The Mold in Casting

- **Contains cavity whose geometry determines part shape**
  - **Actual size and shape of cavity must be slightly oversized to allow for shrinkage of metal during solidification and cooling**
  - **Molds are made of a variety of materials, including sand, plaster, ceramic, and metal**

Open Molds and Closed Molds



Two forms of mold: (a) open mold, simply a container in the shape of the desired part; and (b) closed mold, in which the mold geometry is more complex and requires a gating system (passageway) leading into the cavity.

Two Categories of Casting Process

1. *Expendable mold processes* – uses an *expendable mold* which must be destroyed to remove casting
   - Mold materials: sand, plaster, and similar materials, plus binders
2. *Permanent mold processes* – uses a *permanent mold* which can be used many times to produce many castings
   - Made of metal (or, less commonly, a ceramic refractory material

Advantages and Disadvantages

- More intricate geometries are possible with expendable mold processes
- Part shapes in permanent mold processes are limited by the need to open mold
- Permanent mold processes are more economic in high production operations

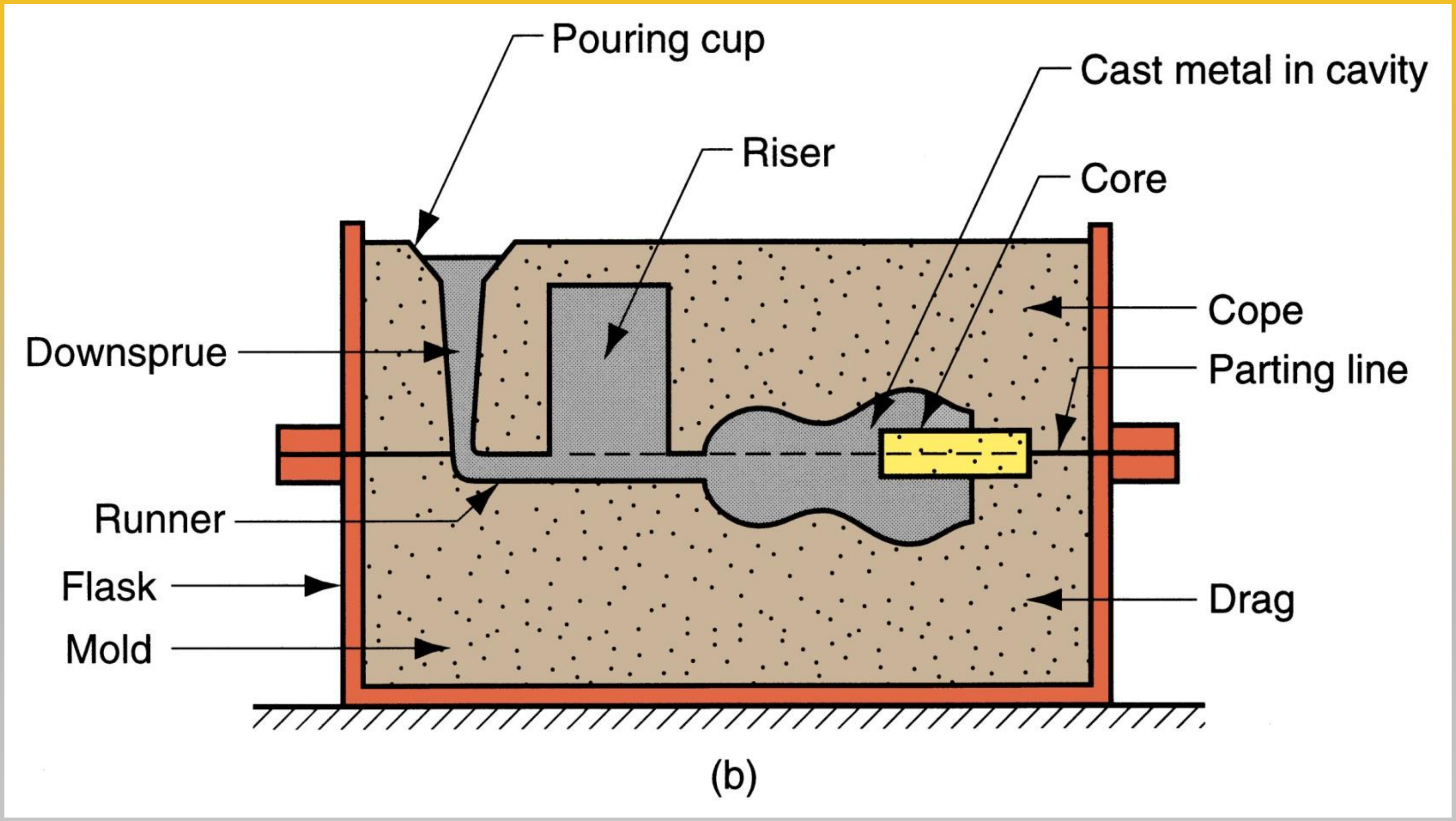


Figure 10.2 (b) Sand casting mold

Sand Casting Mold Terms

- Mold consists of two halves:
  - *Cope* = upper half of mold
  - *Drag* = bottom half
- Mold halves are contained in a box, called a *flask*
- The two halves separate at the *parting line*

Forming the Mold Cavity

- Mold cavity is formed by packing sand around a *pattern*, which has the shape of the part
- When the pattern is removed, the remaining cavity has desired shape of cast part
- The pattern is usually oversized to allow for shrinkage of metal as it solidifies and cools
- Sand for the mold is moist and contains a binder to maintain shape

Use of a Core in the Mold Cavity

- The mold cavity provides the external surfaces of the cast part
- In addition, a casting may have internal surfaces, determined by a *core*, placed inside the mold cavity to define the interior geometry of part
- In sand casting, cores are generally made of sand

Gating System

Channel through which molten metal flows into cavity from outside of mold

- Consists of a *downsprue*, through which metal enters a *runner* leading to the main cavity
- At top of downsprue, a *pouring cup* is often used to minimize splash and turbulence as the metal flows into downsprue

Riser

Reservoir in the mold which is a source of liquid metal to compensate for shrinkage during solidification

- The riser must be designed to freeze after the main casting in order to satisfy its function

Heating the Metal

- Heating furnaces are used to heat the metal to molten temperature sufficient for casting
- The heat required is the sum of:
  1. Heat to raise temperature to melting point
  2. Heat of fusion to convert from solid to liquid
  3. Heat to raise molten metal to desired temperature for pouring

Pouring the Molten Metal

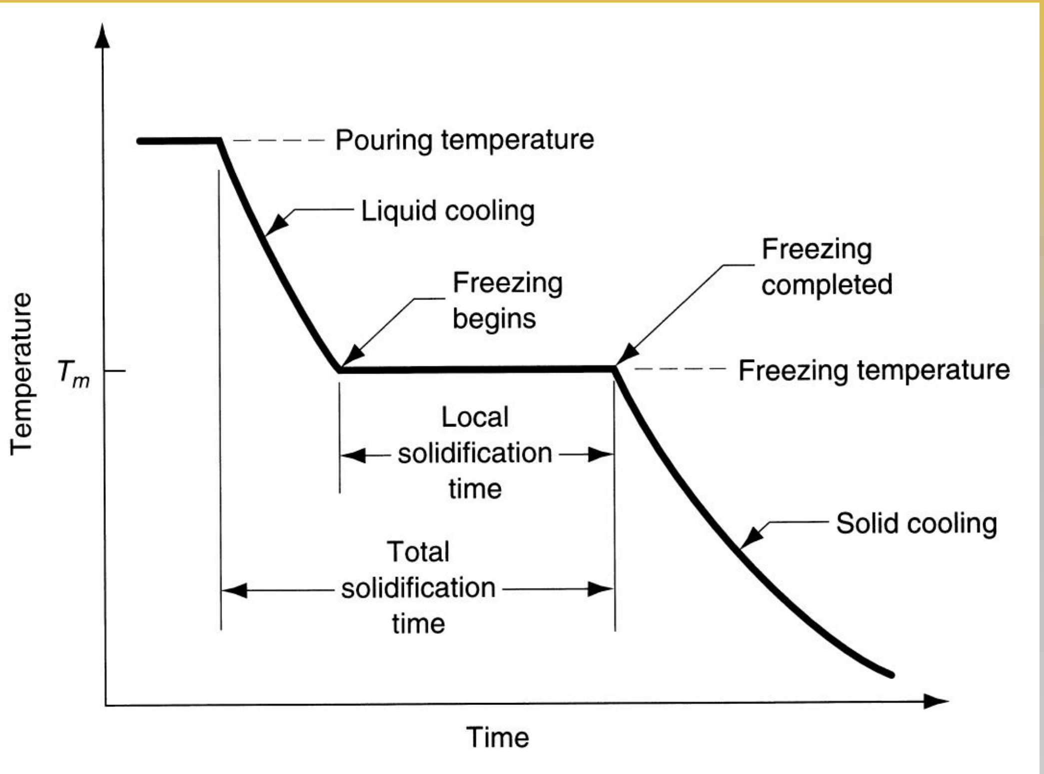
- For this step to be successful, metal must flow into all regions of the mold, most importantly the main cavity, before solidifying
- Factors that determine success:
  - Pouring temperature
  - Pouring rate
  - Turbulence

Solidification of Metals

Transformation of molten metal back into solid state

- Solidification differs depending on whether the metal is a pure element or an alloy

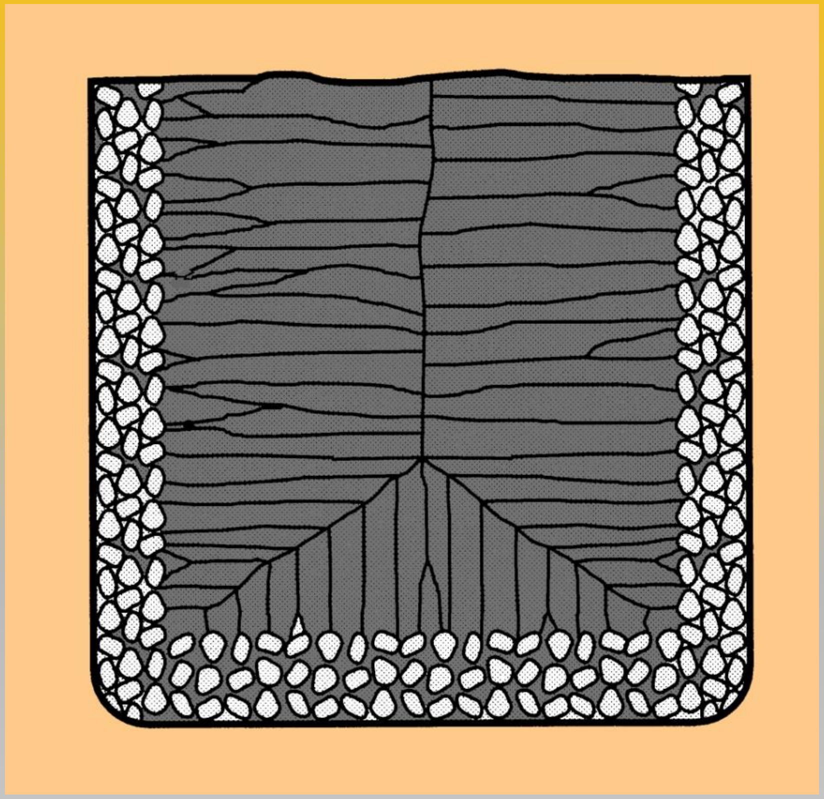
A pure metal solidifies at a constant temperature equal to its freezing point (same as melting point)



Cooling curve for a pure metal during casting

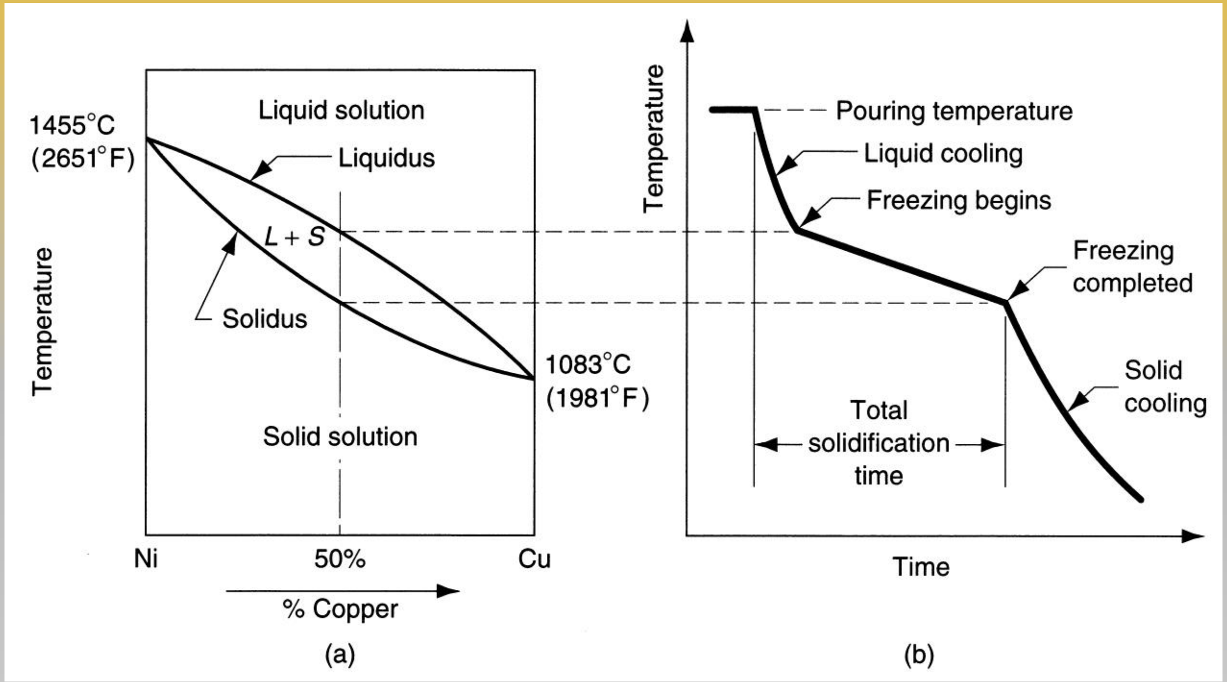
Solidification of Pure Metals

- Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring
- Skin thickness increases to form a shell around the molten metal as solidification progresses
- Rate of freezing depends on heat transfer into mold, as well as thermal properties of the metal

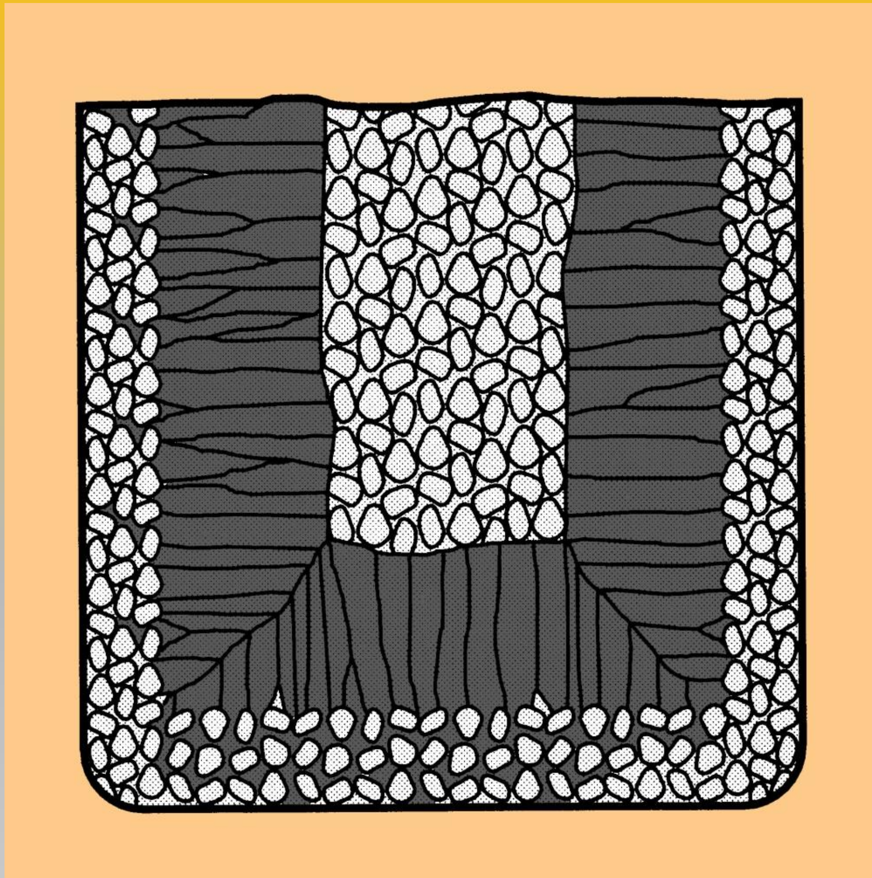


Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting

Most alloys freeze over a temperature range rather than at a single temperature



Phase diagram for a copper-nickel alloy system and (b) associated cooling curve for a 50%Ni-50%Cu composition during casting



Characteristic grain structure in an alloy casting, showing segregation of alloying components in center of casting

Solidification Time

- Solidification takes time
- Total solidification time T_{TS} = time required for casting to solidify after pouring
- T_{TS} depends on size and shape of casting by relationship known as *Chvorinov's Rule*

$$TST = C_m \left(\frac{V}{A} \right)^n$$

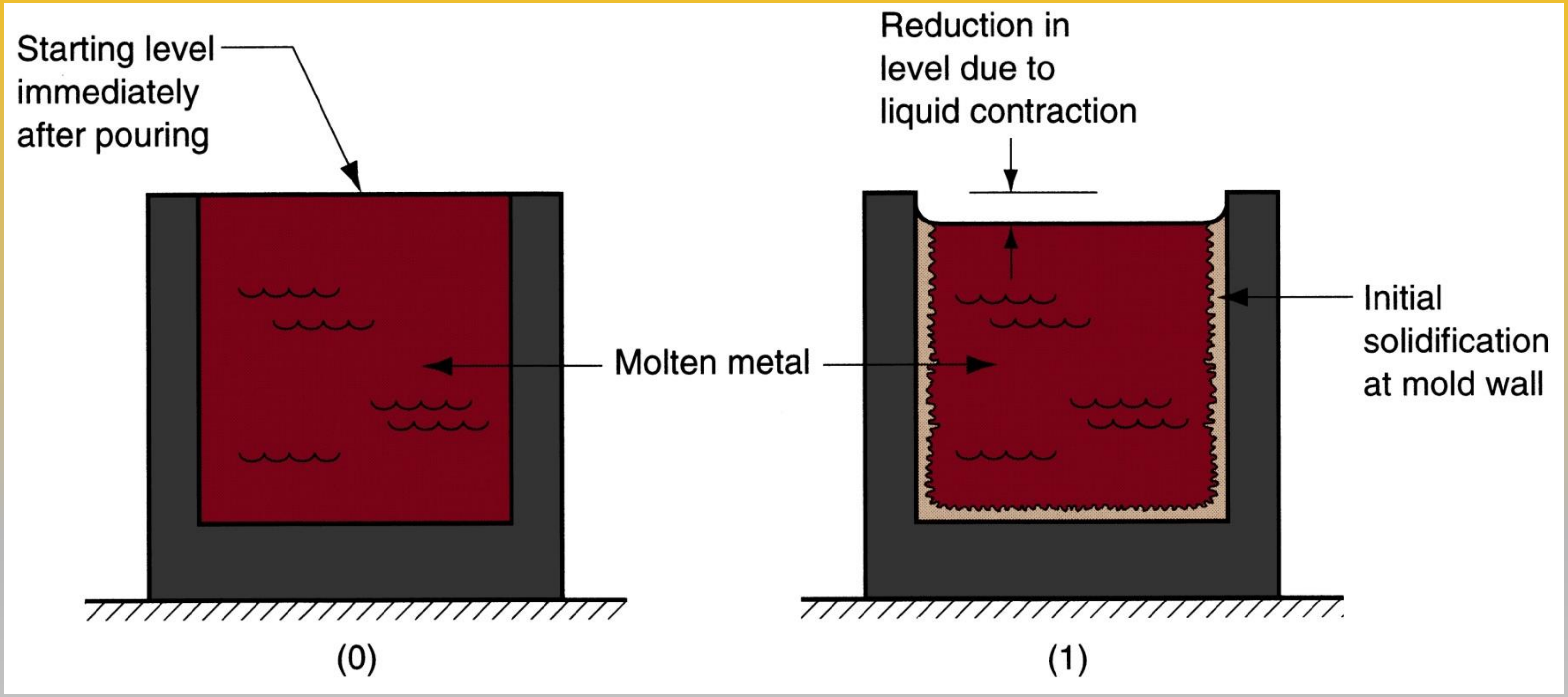
where TST = total solidification time; V = volume of the casting; A = surface area of casting; n = exponent with typical value = 2; and C_m is *mold constant.*

Mold Constant in Chvorinov's Rule

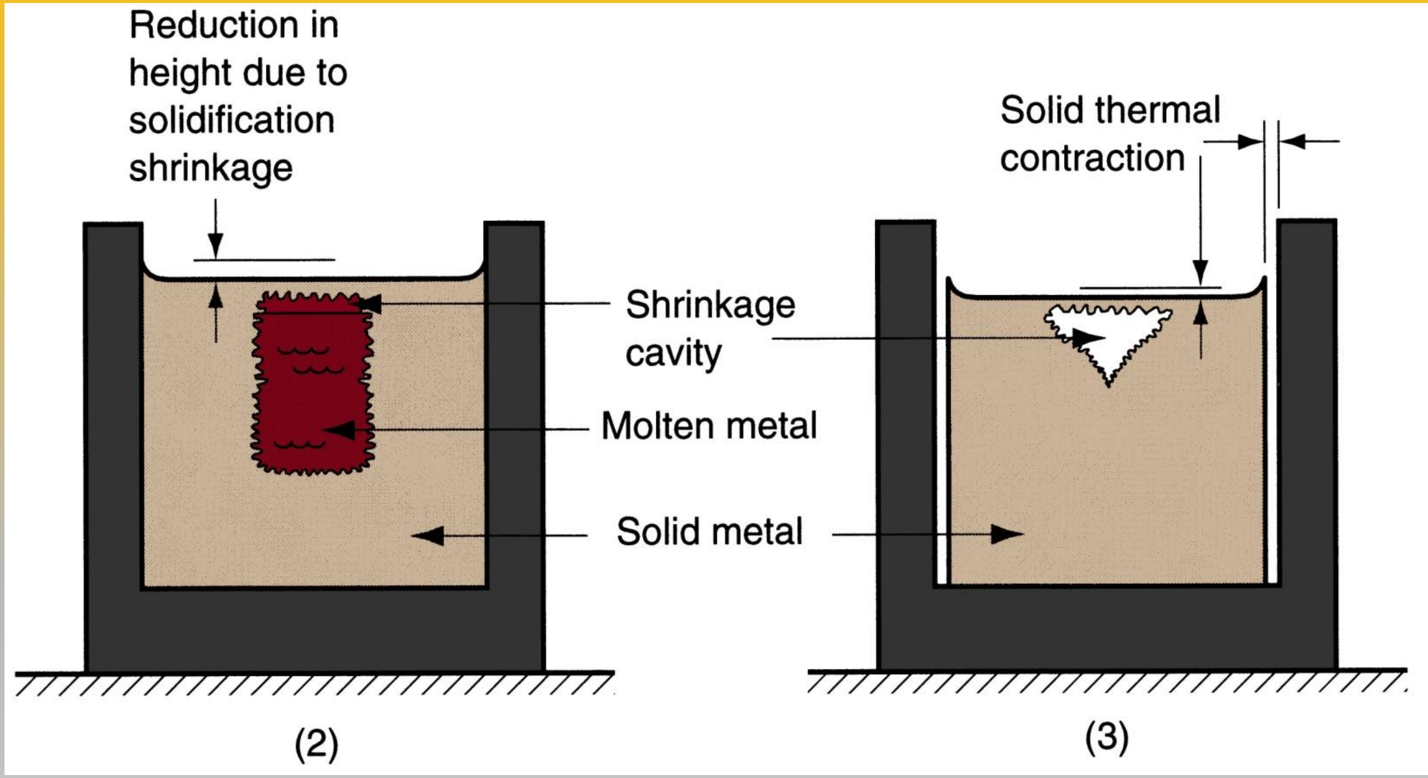
- C_m depends on mold material, thermal properties of casting metal, and pouring temperature relative to melting point
- Value of C_m for a given casting operation can be based on experimental data from previous operations carried out using same mold material, metal, and pouring temperature, even though the shape of the part may be quite different

What Chvorinov's Rule Tells Us

- A casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio
  - To feed molten metal to main cavity, *TST* for riser must be greater than *TST* for main casting
- Since riser and casting mold constants will be equal, design the riser to have a larger volume-to-area ratio so that the main casting solidifies first
  - This minimizes the effects of shrinkage



Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling (dimensional reductions are exaggerated for clarity in sketches)



reduction in height and formation of shrinkage cavity caused by solidification shrinkage; (3) further reduction in height and diameter due to thermal contraction during cooling of the solid metal (dimensional reductions are exaggerated for clarity in our sketches)

Solidification Shrinkage

- Occurs in nearly all metals because the solid phase has a higher density than the liquid phase
- Thus, solidification causes a reduction in volume per unit weight of metal
- Exception: cast iron with high C content
  - Graphitization during final stages of freezing causes expansion that counteracts volumetric decrease associated with phase change

Shrinkage Allowance

- Patternmakers account for solidification shrinkage and thermal contraction by making mold cavity oversized
- Amount by which mold is made larger relative to final casting size is called *pattern shrinkage allowance*
- Casting dimensions are expressed linearly, so allowances are applied accordingly

Directional Solidification

- To minimize damaging effects of shrinkage, it is desirable for regions of the casting most distant from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the riser(s)
  - Thus, molten metal is continually available from risers to prevent shrinkage voids
  - The term *directional solidification* describes this aspect of freezing and methods by which it is controlled

Achieving Directional Solidification

- Desired directional solidification is achieved using Chvorinov's Rule to design the casting itself, its orientation in the mold, and the riser system that feeds it
- Locate sections of the casting with lower V/A ratios away from riser, so freezing occurs first in these regions, and the liquid metal supply for the rest of the casting remains open
- *Chills* - internal or external heat sinks that cause rapid freezing in certain regions of the casting

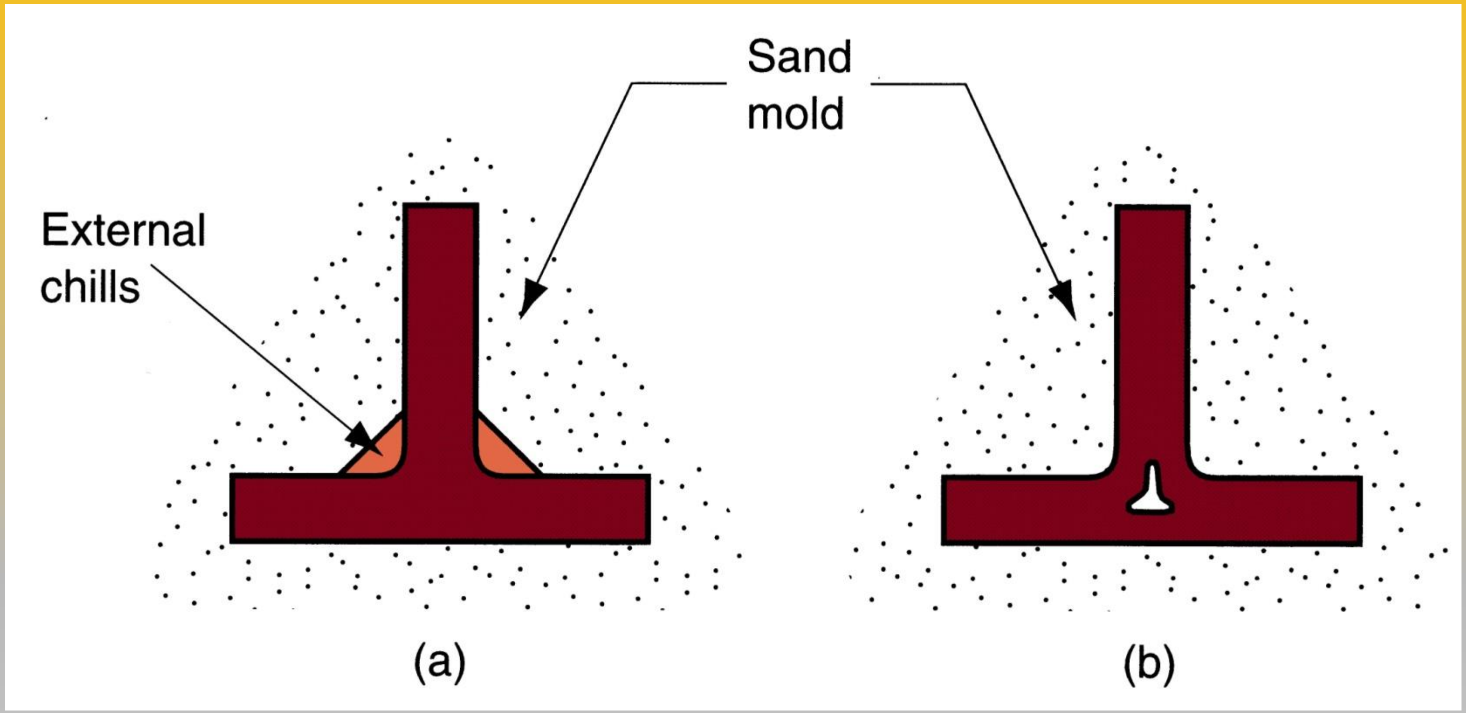


Figure 10.9 - (a) External chill to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used

Riser Design

- Riser is waste metal that is separated from the casting and remelted to make more castings
- To minimize waste in the unit operation, it is desirable for the volume of metal in the riser to be a minimum
- Since the geometry of the riser is normally selected to maximize the V/A ratio, this allows reduction of riser volume as much as possible

METAL CASTING PROCESSES

- Sand Casting
- Other Expendable Mold Casting Processes
- Permanent Mold Casting Processes
- Foundry Practice
- Casting Quality
- Metals for Casting
- Product Design Considerations

Categories of Metal Casting Processes

1. *Expendable mold processes* - mold is sacrificed to remove part
   - Advantage: more complex shapes possible
   - Disadvantage: production rates often limited by time to make mold rather than casting itself
2. *Permanent mold processes* - mold is made of metal and can be used to make many castings
   - Advantage: higher production rates
   - Disadvantage: geometries limited by need to open mold

Overview of Sand Casting

- Most widely used casting process, accounting for a significant majority of total tonnage cast
- Nearly all alloys can be sand casted, including metals with high melting temperatures, such as steel, nickel, and titanium
- Parts ranging in size from small to very large
- Production quantities from one to millions

Steps in Sand Casting

1. Pour molten metal into sand mold
2. Allow metal to solidify
3. Break up the mold to remove casting
4. Clean and inspect casting
5. Heat treatment of casting is sometimes required to improve metallurgical properties

Making the Sand Mold

- The *cavity* in the sand mold is formed by packing sand around a pattern, then separating the mold into two halves and removing the pattern
- The mold must also contain gating and riser system
- If casting is to have internal surfaces, a *core* must be included in mold
- A new sand mold must be made for each part produced

Desirable Mold Properties and Characteristics

- *Strength* - to maintain shape and resist erosion
- *Permeability* - to allow hot air and gases to pass through voids in sand
- *Thermal stability* - to resist cracking on contact with molten metal
- *Collapsibility* - ability to give way and allow casting to shrink without cracking the casting
- *Reusability* - can sand from broken mold be reused to make other molds?

Other Expendable Mold Casting Processes

- Shell Molding
- Vacuum Molding
- Expanded Polystyrene Process
- Investment Casting
- Plaster Mold and Ceramic Mold Casting

Shell Molding

Casting process in which the mold is a thin shell of sand held together by thermosetting resin binder

- Developed in Germany during early 1940s

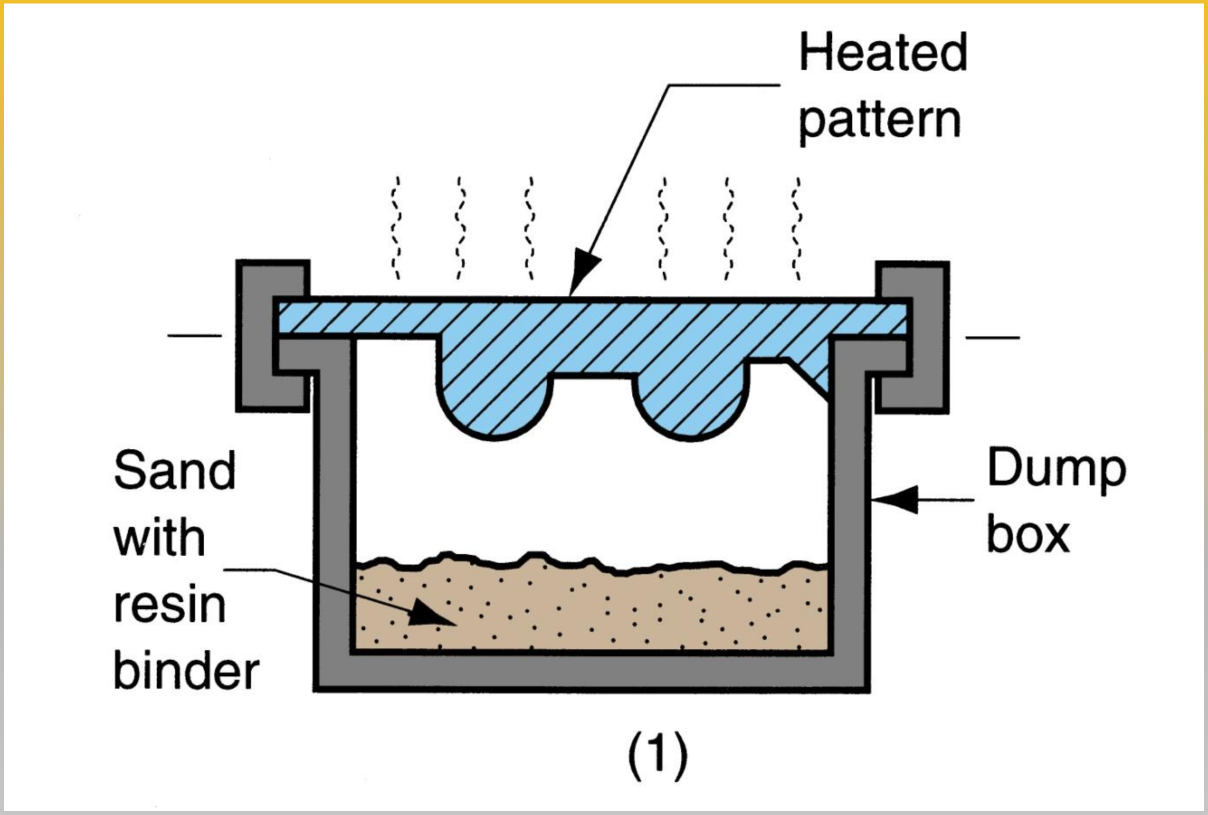


Figure 11.5 - Steps in shell-molding: (1) a match-plate or cope-and-drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin

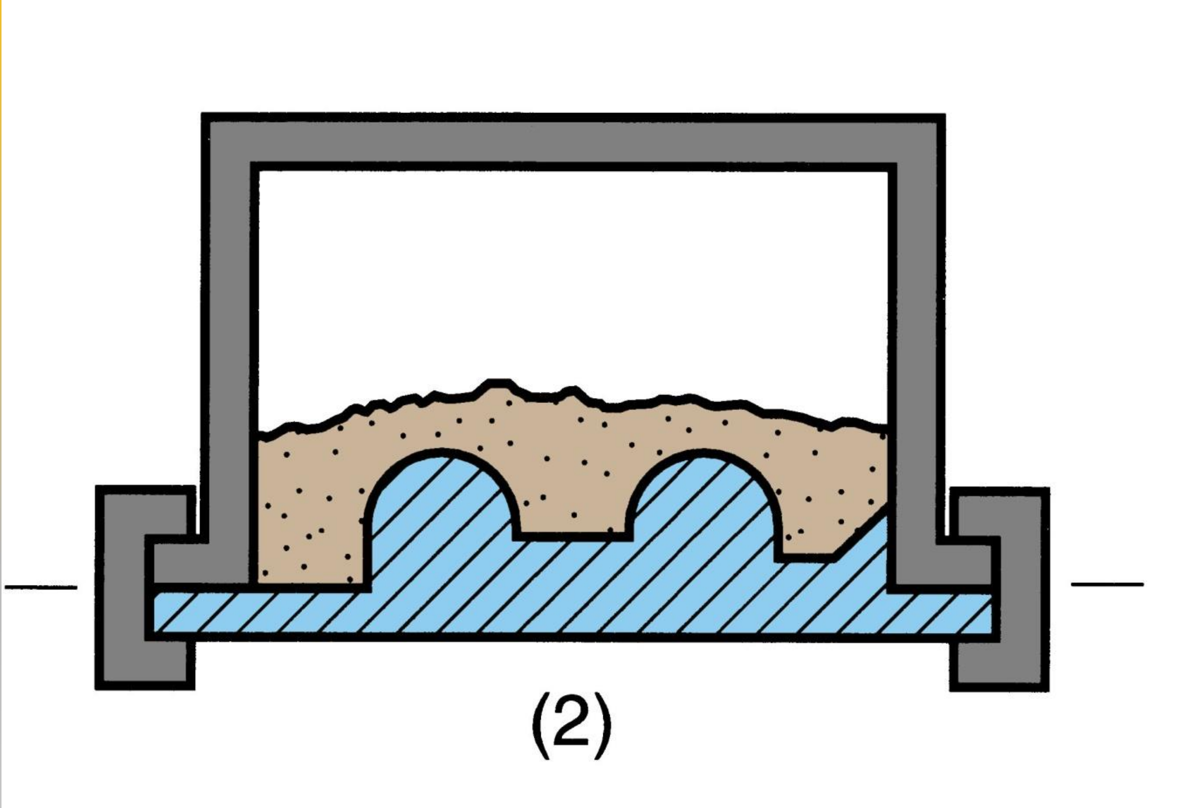


Figure 11.5 - Steps in shell-molding: (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell

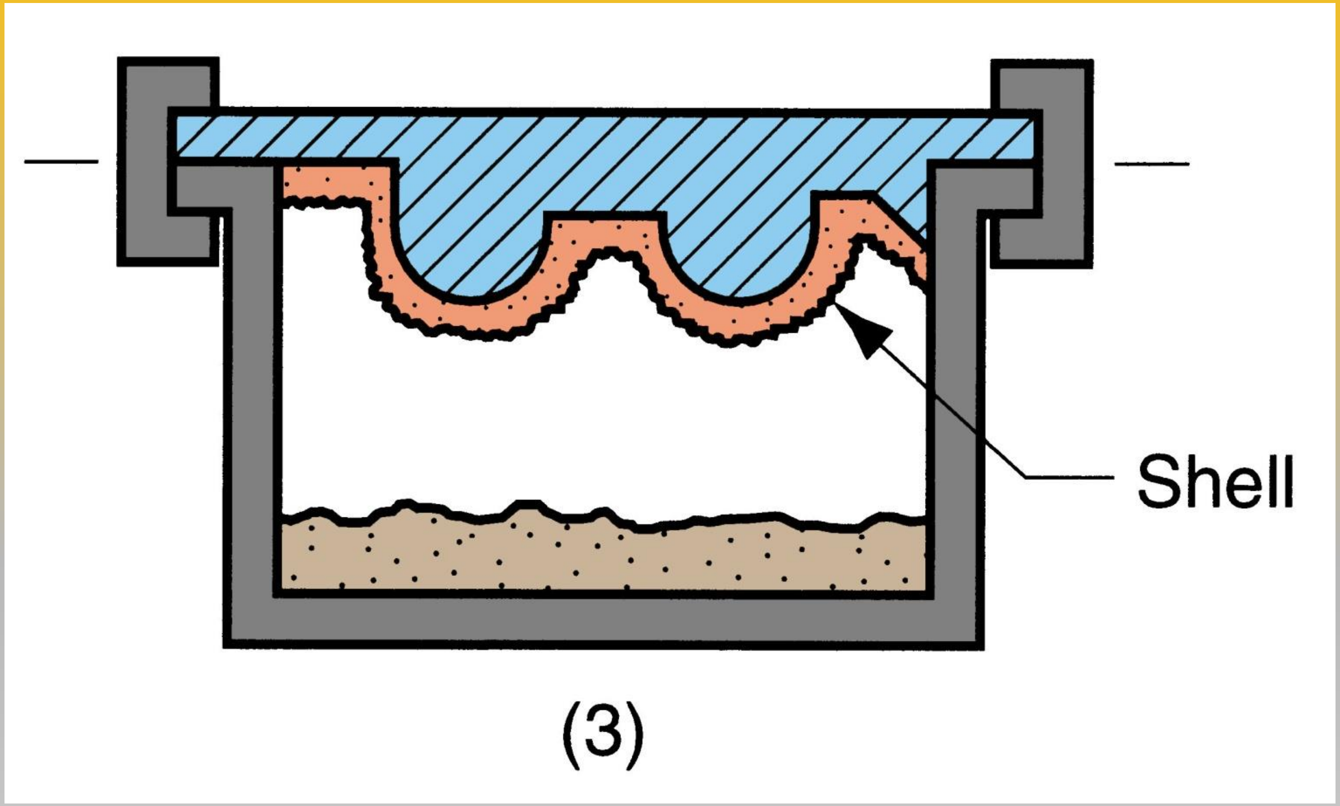


Figure 11.5 - Steps in shell-molding: (3) box is repositioned so that loose uncured particles drop away

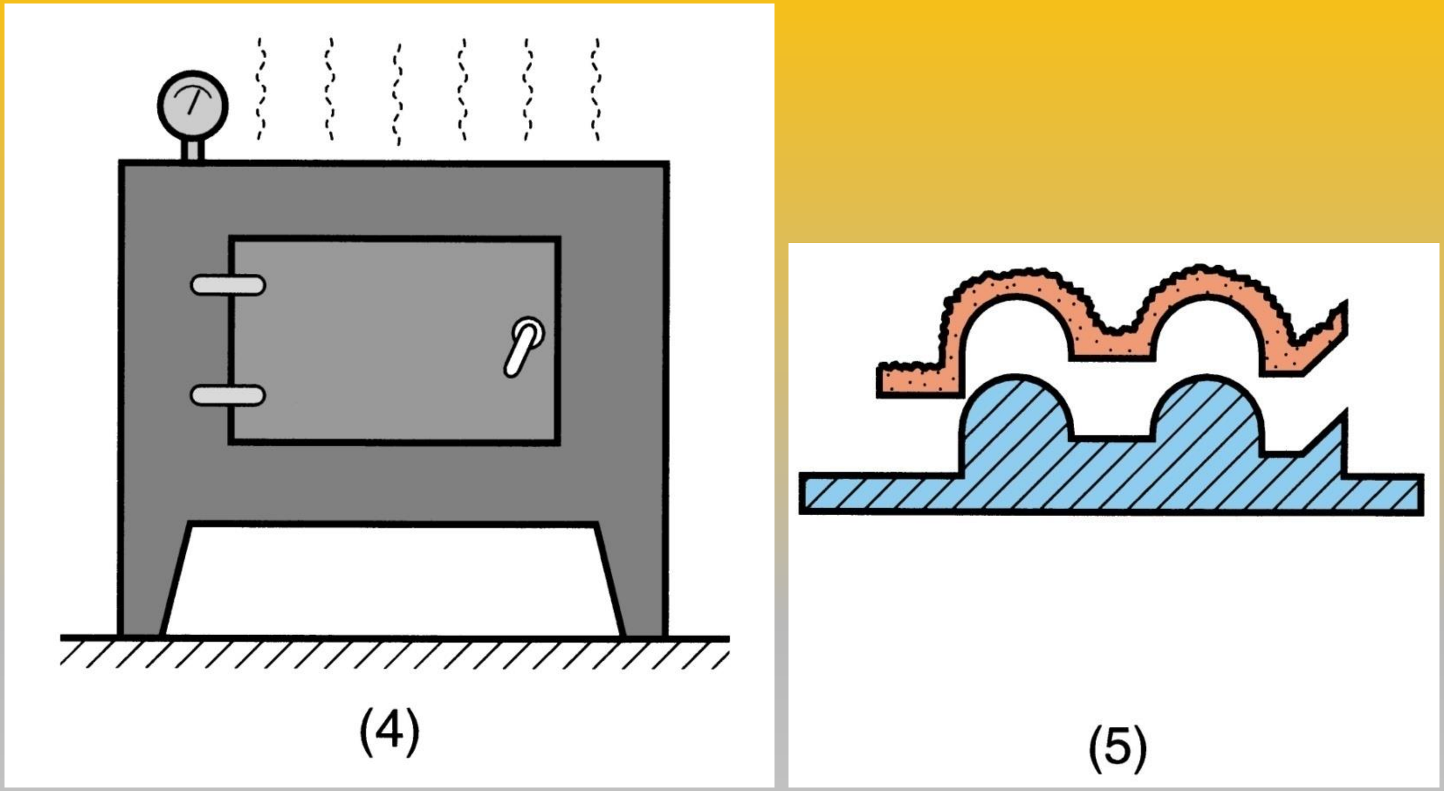


Figure 11.5 - Steps in shell-molding:

(4) sand shell is heated in oven for several minutes to complete curing

(5) shell mold is stripped from the pattern

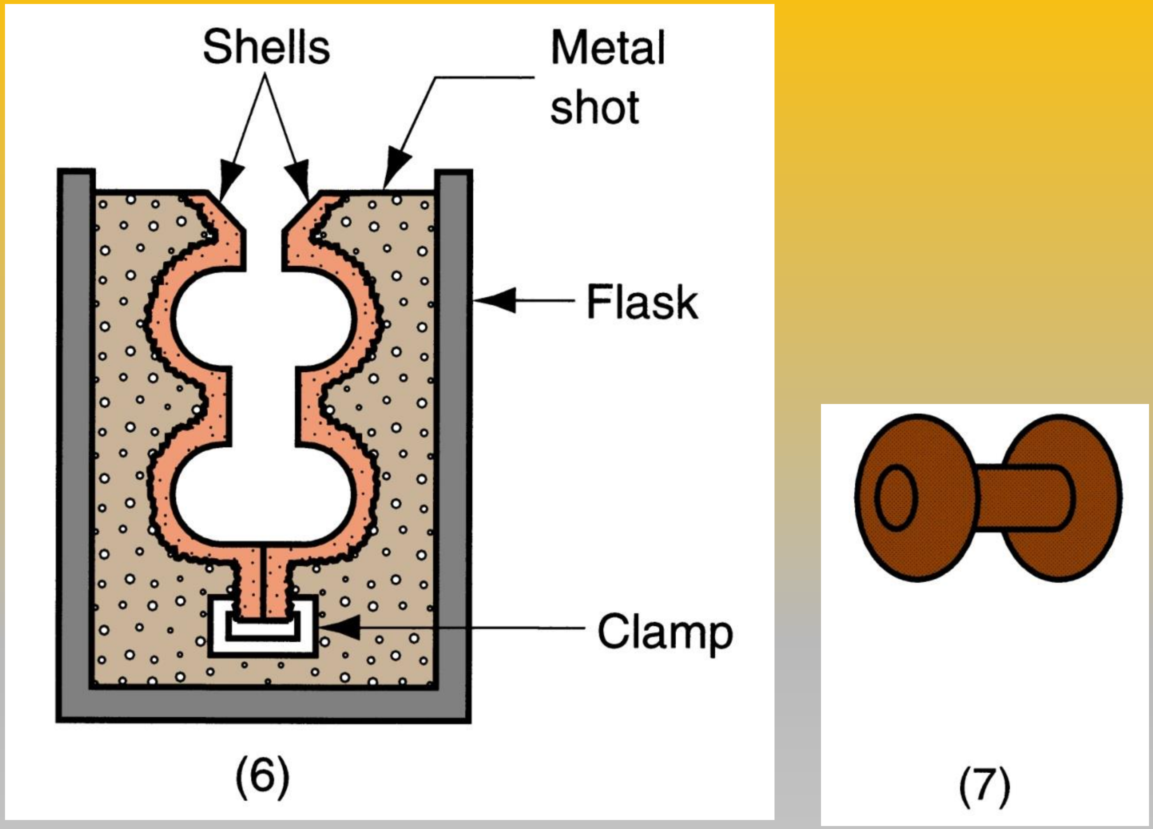


Figure 11.5 - Steps in shell-molding:

(6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished

(7) the finished casting with sprue removed

Advantages and Disadvantages of Shell Molding

- Advantages:
  - Smoother cavity surface permits easier flow of molten metal and better surface finish on casting
  - Good dimensional accuracy
  - Machining often not required
  - Mold collapsibility usually avoids cracks in casting
  - Can be mechanized for mass production
- Disadvantages:
  - More expensive metal pattern
  - Difficult to justify for small quantities

Expanded Polystyrene Process

Uses a mold of sand packed around a polystyrene foam pattern which vaporizes when molten metal is poured into mold

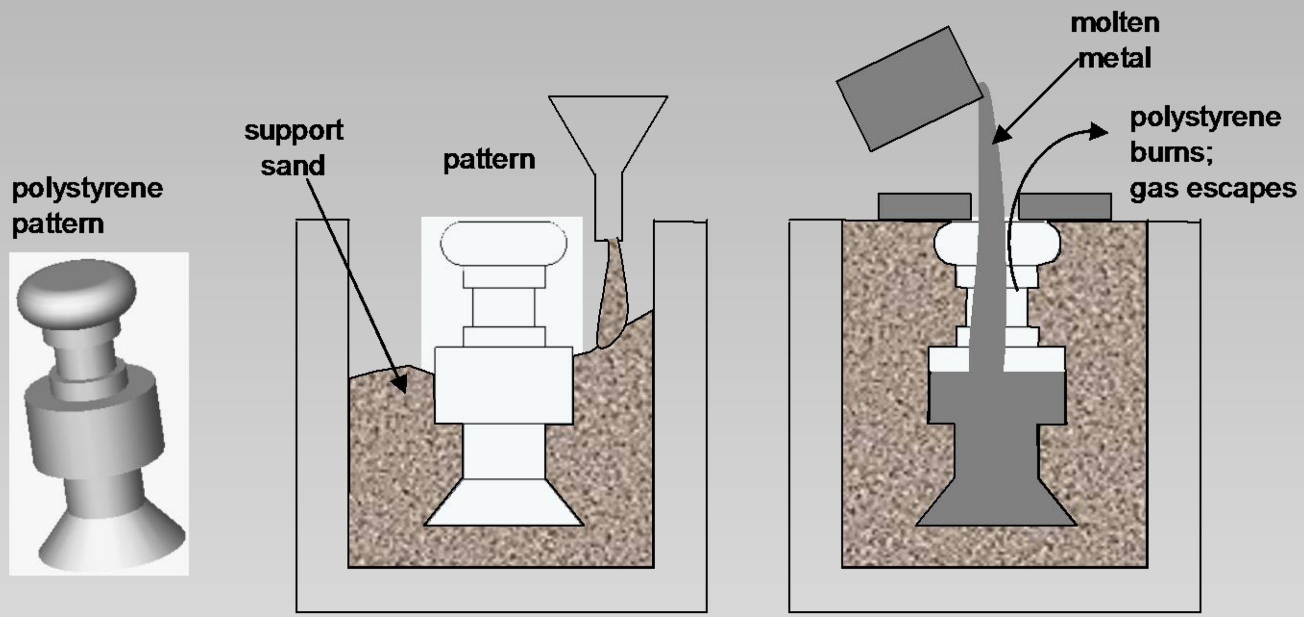
- Other names: *lost-foam process*, *lost pattern process*, *evaporative-foam process*, and *full-mold process*
- Polystyrene foam pattern includes sprue, risers, gating system, and internal cores (if needed)
- Mold does not have to be opened into cope and drag sections

Advantages and Disadvantages of Expanded Polystyrene Process

- Advantages:
  - Pattern need not be removed from the mold
  - Simplifies and expedites mold-making, since two mold halves (cope and drag) are not required as in a conventional green-sand mold
- Disadvantages:
  - A new pattern is needed for every casting
  - Economic justification of the process is highly dependent on cost of producing patterns

Expendable Mold Casting

- Styrofoam pattern
- dipped in refractory slurry → dried
- sand (support)
- pour liquid metal
- foam evaporates, metal fills the shell
- cool, solidify
- break shell → part



Applications of Expanded Polystyrene Process

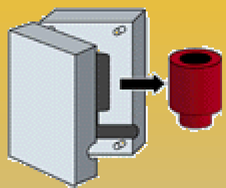
- Mass production of castings for automobile engines
- Automated and integrated manufacturing systems are used to
  - Mold the polystyrene foam patterns and then
  - Feed them to the downstream casting operation

Investment Casting (Lost Wax Process)

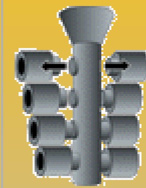
A pattern made of wax is coated with a refractory material to make mold, after which wax is melted away prior to pouring molten metal

- "Investment" comes from one of the less familiar definitions of "invest" - "to cover completely," which refers to coating of refractory material around wax pattern
- It is a precision casting process - capable of castings of high accuracy and intricate detail

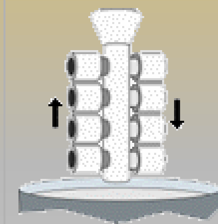
Investment casting (lost wax casting)



(a) Wax pattern
(injection molding)

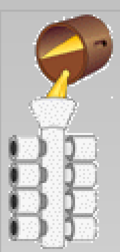


(b) Multiple patterns
assembled to wax sprue

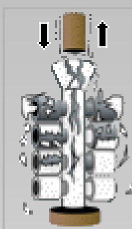


(c) Shell built →
immerse into ceramic slurry
→ immerse into fine sand
(few layers)

(d) dry ceramic
melt out the wax
fire ceramic (burn wax)



(e) Pour molten metal (gravity)
→ cool, solidify
[Hollow casting:
pouring excess metal before solidification



(f) Break ceramic shell
(vibration or water blasting)

(g) Cut off parts
(high-speed friction saw)
→ finishing (polish)

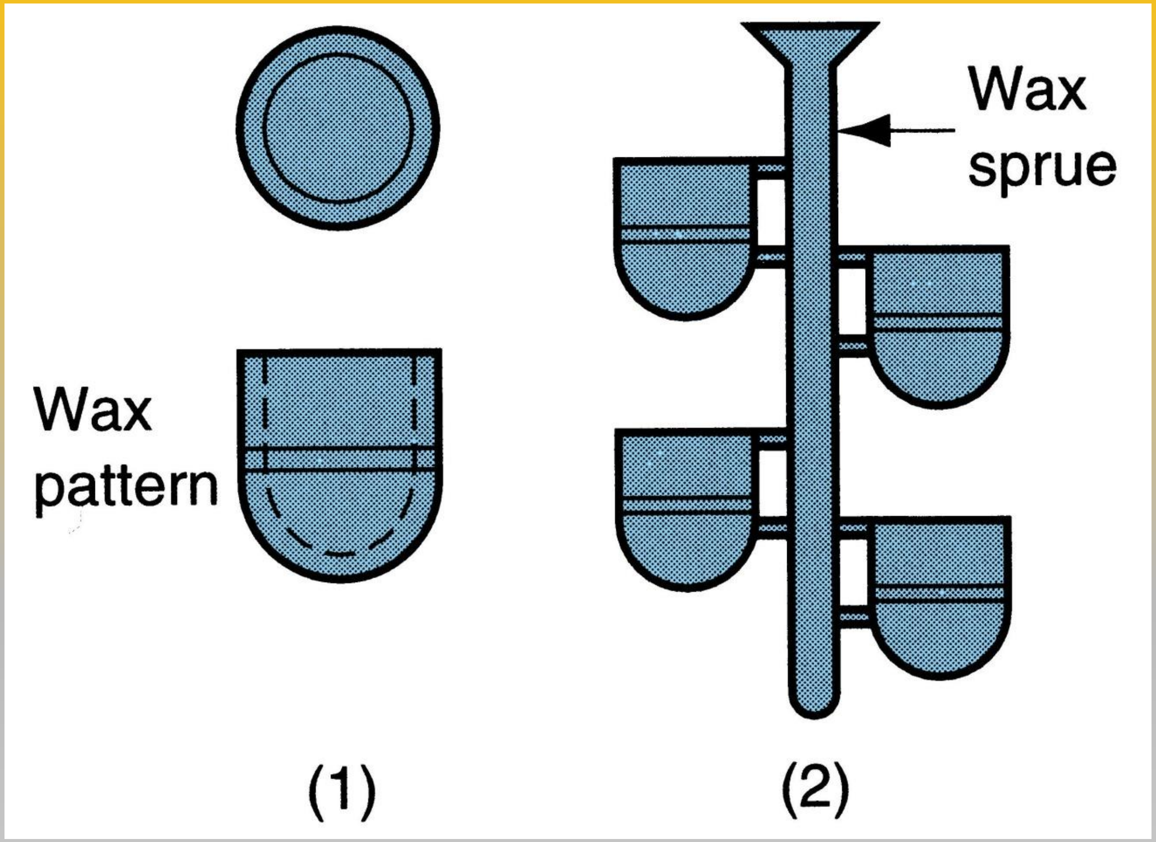


Figure 11.8 - Steps in investment casting:

(1) wax patterns are produced

(2) several patterns are attached to a sprue to form a pattern tree

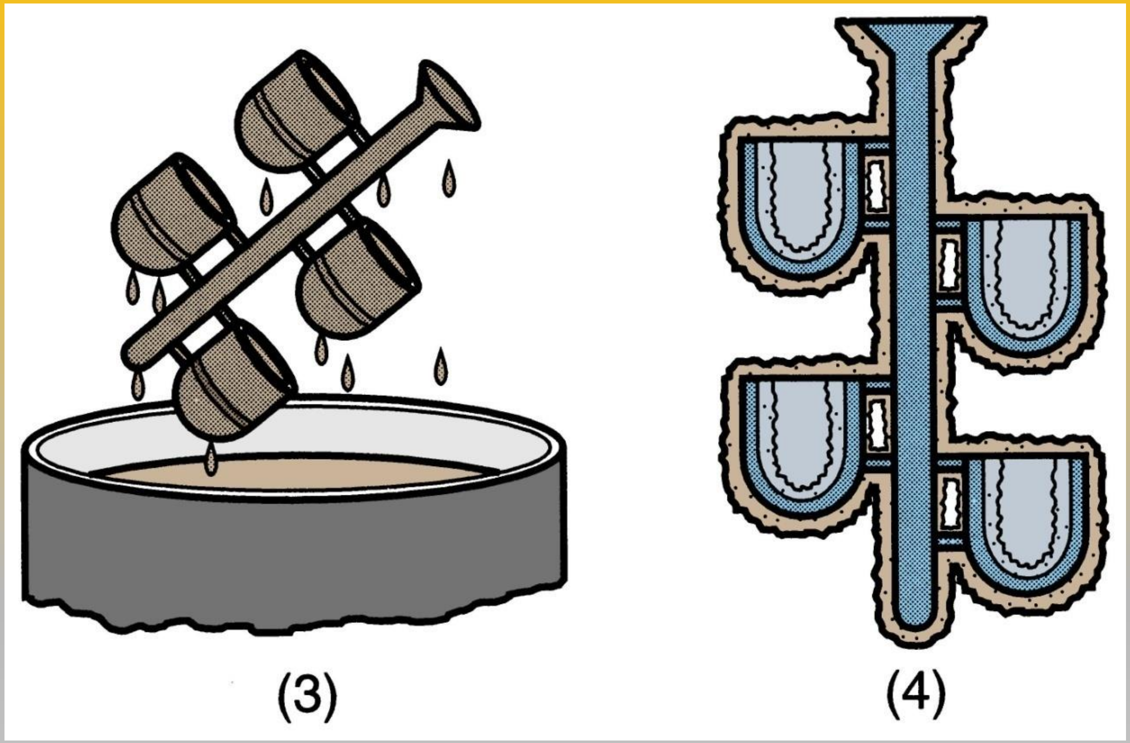


Figure 11.8 - Steps in investment casting:

(3) the pattern tree is coated with a thin layer of refractory material

(4) the full mold is formed by covering the coated tree with sufficient refractory material to make it rigid

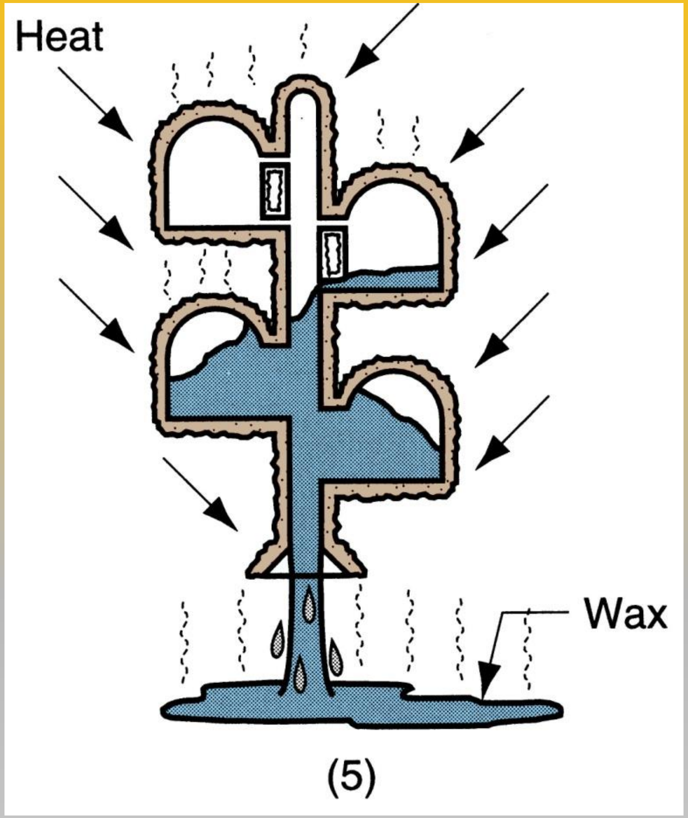


Figure 11.8 - Steps in investment casting:

(5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity

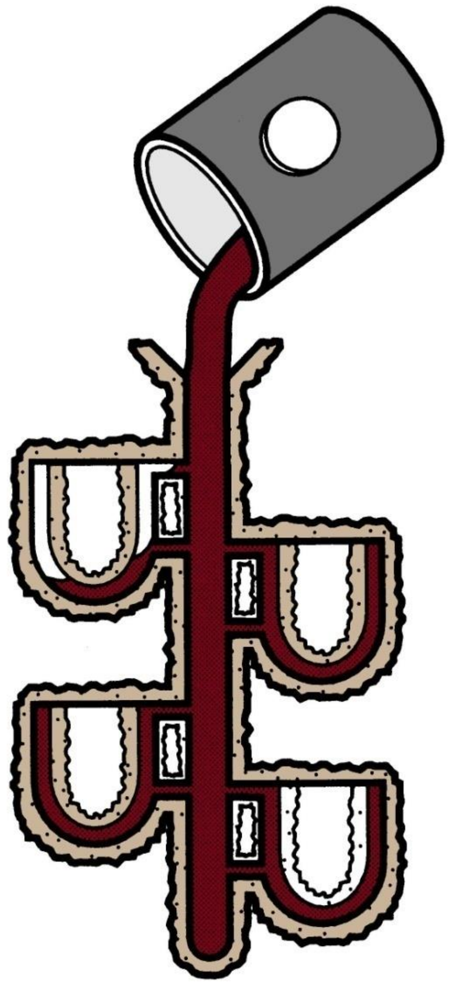

(6)

Figure 11.8 - Steps in investment casting:

(6) the mold is preheated to a high temperature, which ensures that all contaminants are eliminated from the mold; it also permits the liquid metal to flow more easily into the detailed cavity; the molten metal is poured; it solidifies

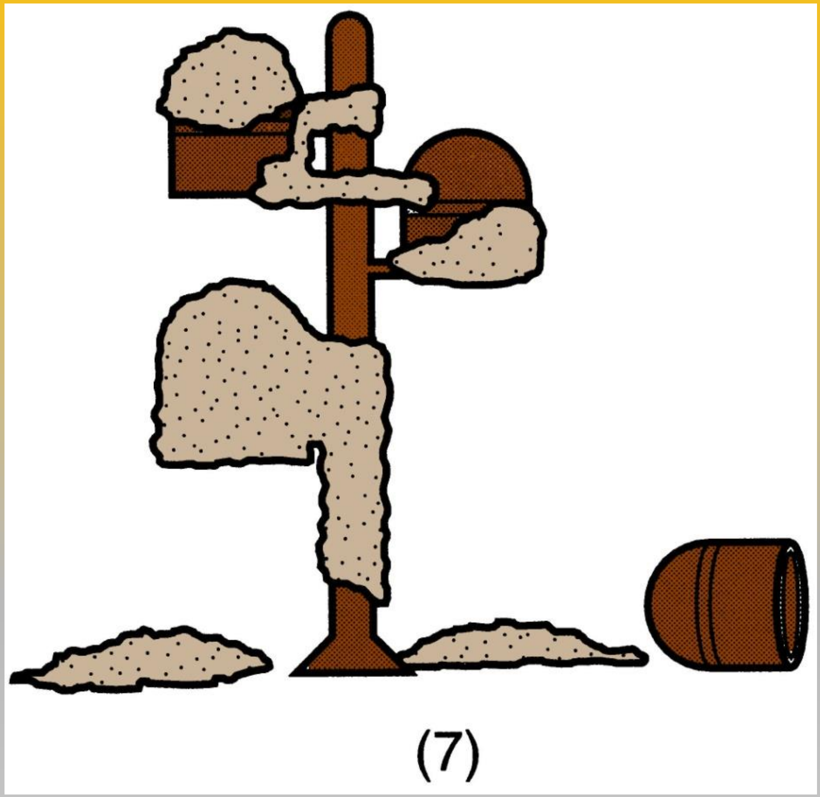


Figure 11.8 - Steps in investment casting:

(7) the mold is broken away from the finished casting - parts are separated from the sprue

Advantages and Disadvantages of Investment Casting

- Advantages:
  - Parts of great complexity and intricacy can be cast
  - Close dimensional control and good surface finish
  - Wax can usually be recovered for reuse
  - Additional machining is not normally required - this is a net shape process
- Disadvantages
  - Many processing steps are required
  - Relatively expensive process

Plaster Mold Casting

Similar to sand casting except mold is made of plaster of Paris (gypsum - $CaSO_4$-$2H_2O$)

- In mold-making, plaster and water mixture is poured over plastic or metal pattern and allowed to set
  - Wood patterns not generally used due to extended contact with water
- Plaster mixture readily flows around pattern, capturing its fine details and good surface finish

Advantages and Disadvantages of Plaster Mold Casting

- Advantages:
  - Good dimensional accuracy and surface finish
  - Capability to make thin cross-sections in casting
- Disadvantages:
  - Moisture in plaster mold causes problems:
    - *Mold must be baked to remove moisture*
    - *Mold strength is lost when is over-baked, yet moisture content can cause defects in product*
  - Plaster molds cannot stand high temperatures, so limited to lower melting point alloys

Ceramic Mold Casting

Similar to plaster mold casting except that mold is made of refractory ceramic materials that can withstand higher temperatures than plaster

- Ceramic molding can be used to cast steels, cast irons, and other high-temperature alloys
- Applications similar to those of plaster mold casting except for the metals cast
- Advantages (good accuracy and finish) also similar

Permanent Mold Casting Processes

- Economic disadvantage of expendable mold casting: a new mold is required for every casting
- In permanent mold casting, the mold is reused many times
- The processes include:
  - Basic permanent mold casting
  - Die casting
  - Centrifugal casting

The Basic Permanent Mold Process

Uses a metal mold constructed of two sections designed for easy, precise opening and closing

- Molds used for casting lower melting point alloys are commonly made of steel or cast iron
- Molds used for casting steel must be made of refractory material, due to the very high pouring temperatures

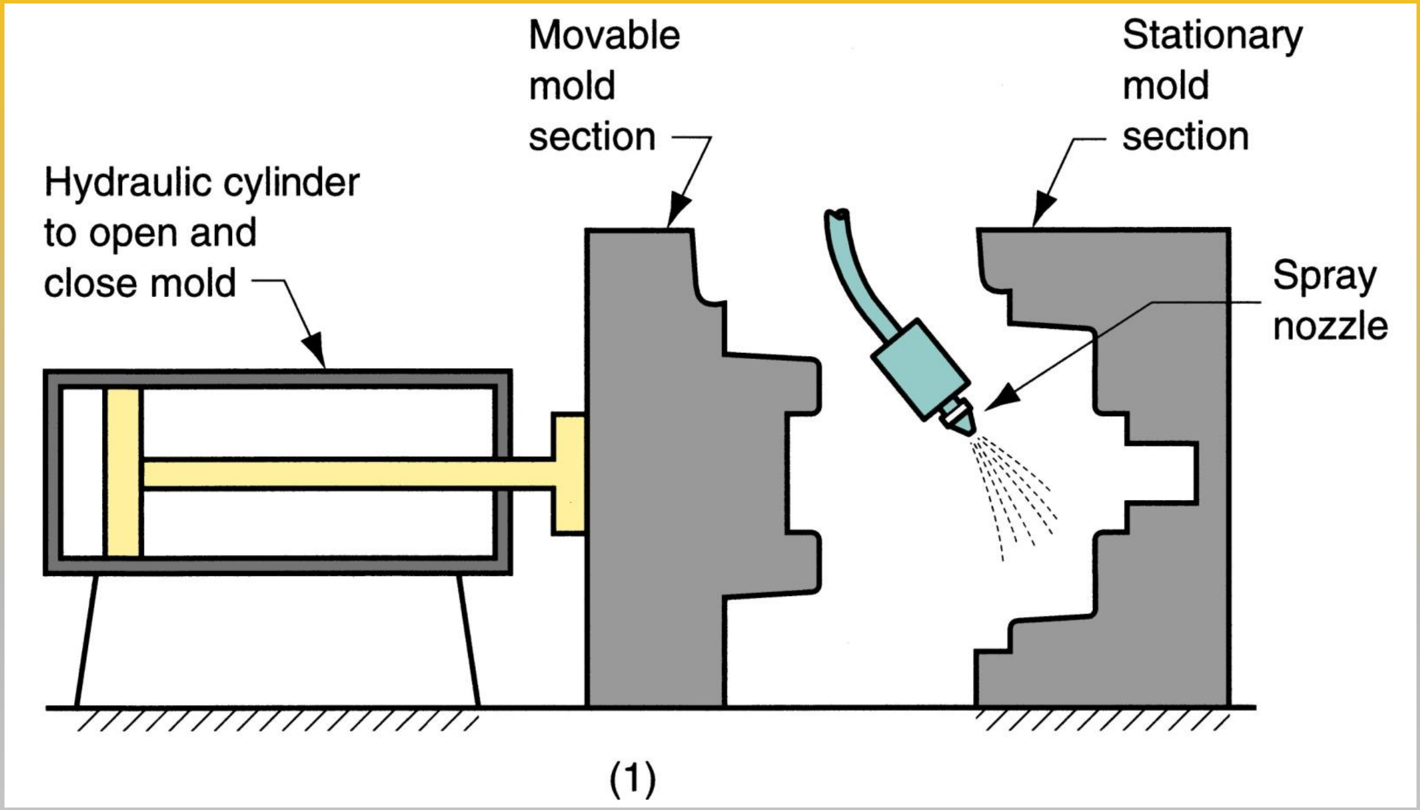


Figure 11.10 - Steps in permanent mold casting:

(1) mold is preheated and coated

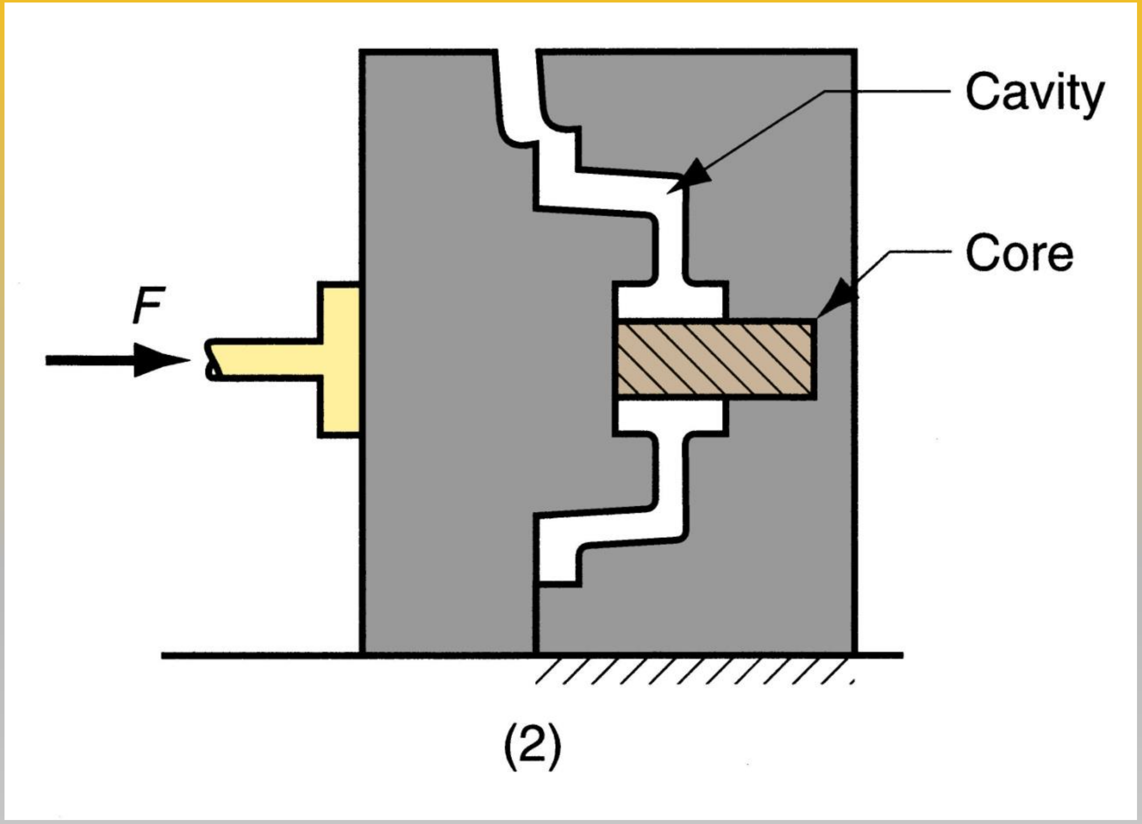


Figure 11.10 - Steps in permanent mold casting:
(2) cores (if used) are inserted and mold is closed

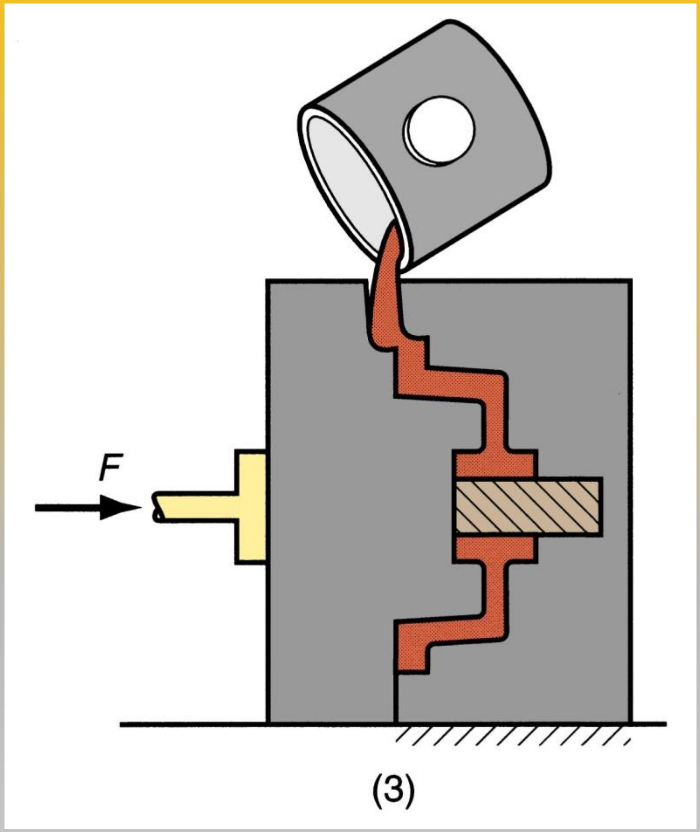


Figure 11.10 - Steps in permanent mold casting:

(3) molten metal is poured into the mold

Advantages and Limitations of Permanent Mold Casting

- Advantages:
  - Good dimensional control and surface finish
  - More rapid solidification caused by the cold metal mold results in a finer grain structure, so stronger castings are produced
- Limitations:
  - Generally limited to metals of lower melting point
  - Simple part geometries compared to sand casting because of the need to open the mold
  - High cost of mold

Applications of Permanent Mold Casting

- Due to high mold cost, process is best suited to high volume production and can be automated accordingly
- Typical parts: automotive pistons, pump bodies, and certain castings for aircraft and missiles
- Metals commonly cast: aluminum, magnesium, copper-base alloys, and cast iron

Die Casting

A permanent mold casting process in which molten metal is injected into mold cavity under high pressure

- Pressure is maintained during solidification, then mold is opened and part is removed
- Molds in this casting operation are called *dies*; hence the name die casting
- Use of high pressure to force metal into die cavity is what distinguishes this from other permanent mold processes

Die Casting Machines

- Designed to hold and accurately close two mold halves and keep them closed while liquid metal is forced into cavity
- Two main types:
  1. Hot-chamber machine
  2. Cold-chamber machine

Hot-Chamber Die Casting

Metal is melted in a container, and a piston injects liquid metal under high pressure into the die

- High production rates - 500 parts per hour not uncommon
- Applications limited to low melting-point metals that do not chemically attack plunger and other mechanical components
- Casting metals: zinc, tin, lead, and magnesium

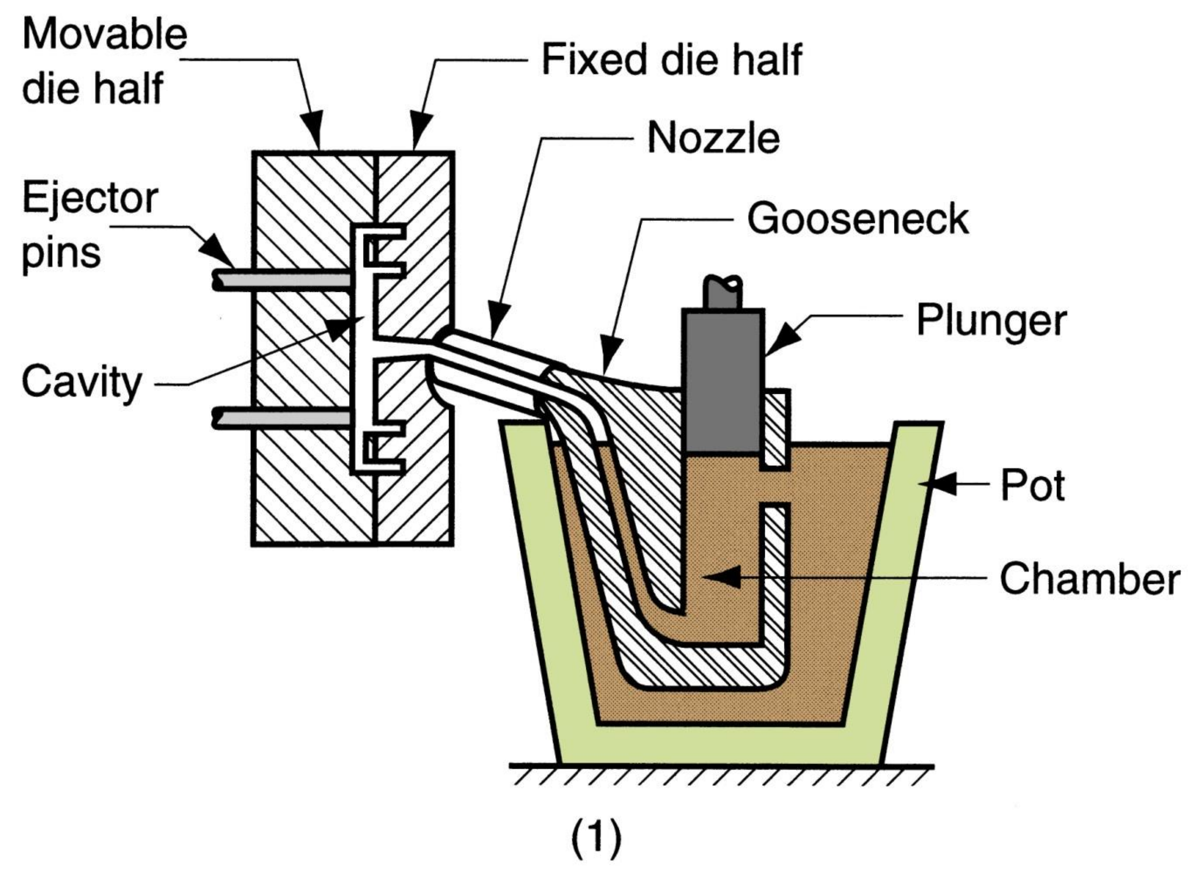


Figure 11.13 - Cycle in hot-chamber casting:

(1) with die closed and plunger withdrawn, molten metal flows into the chamber

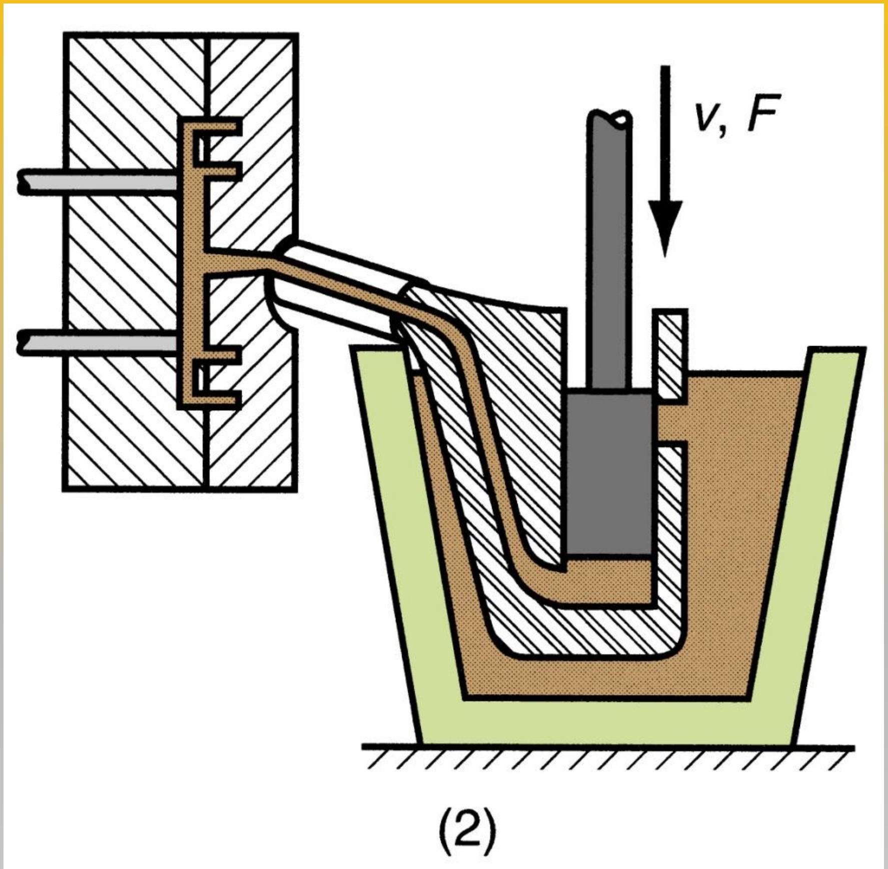


Figure 11.13 - Cycle in hot-chamber casting:
(2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification

Cold-Chamber Die Casting Machine

Molten metal is poured into unheated chamber from external melting container, and a piston injects metal under high pressure into die cavity

- High production but not usually as fast as hot-chamber machines because of pouring step
- Casting metals: aluminum, brass, and magnesium alloys
- Advantages of hot-chamber process favor its use on low melting-point alloys (zinc, tin, lead)

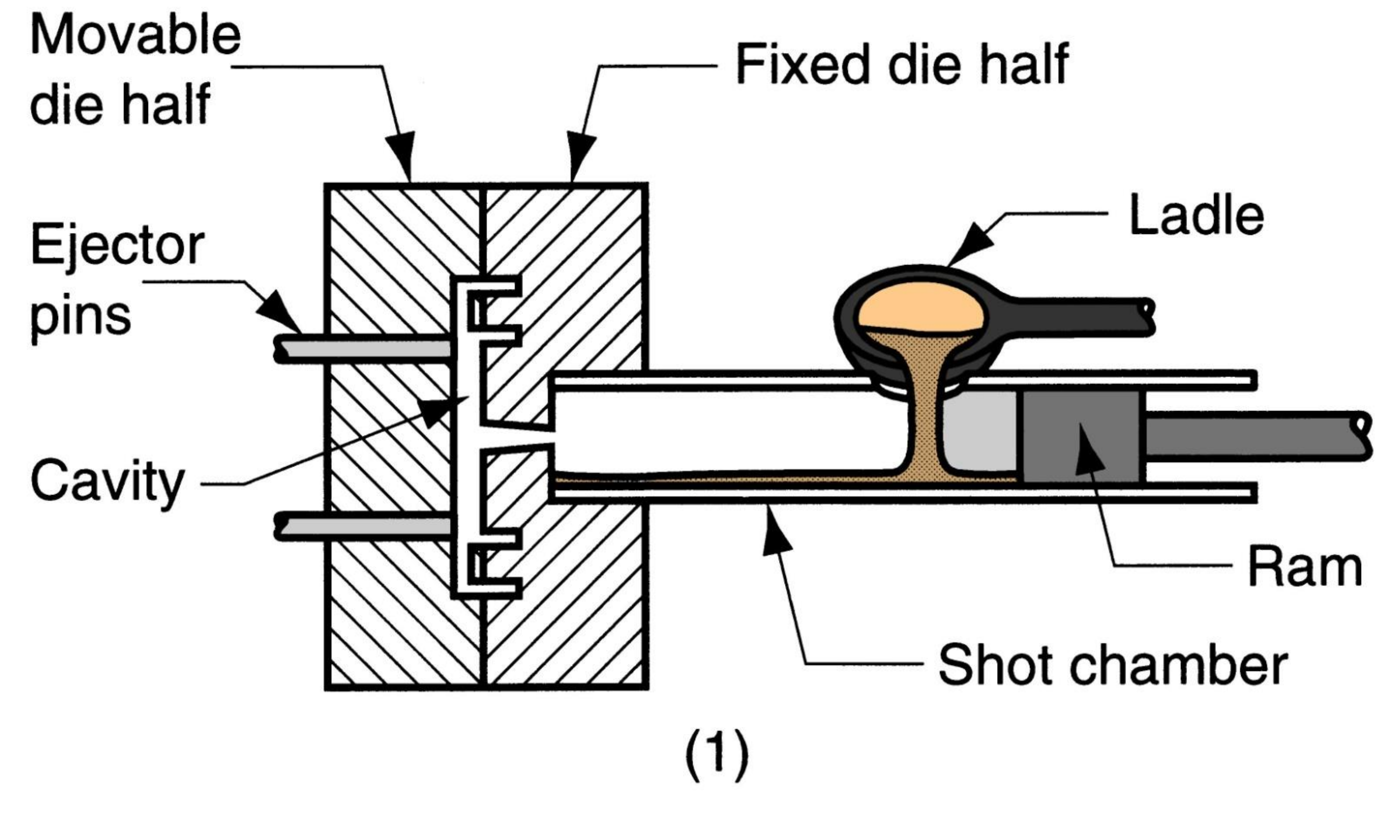


Figure 11.14 - Cycle in cold-chamber casting:
(1) with die closed and ram withdrawn, molten metal is poured into the chamber

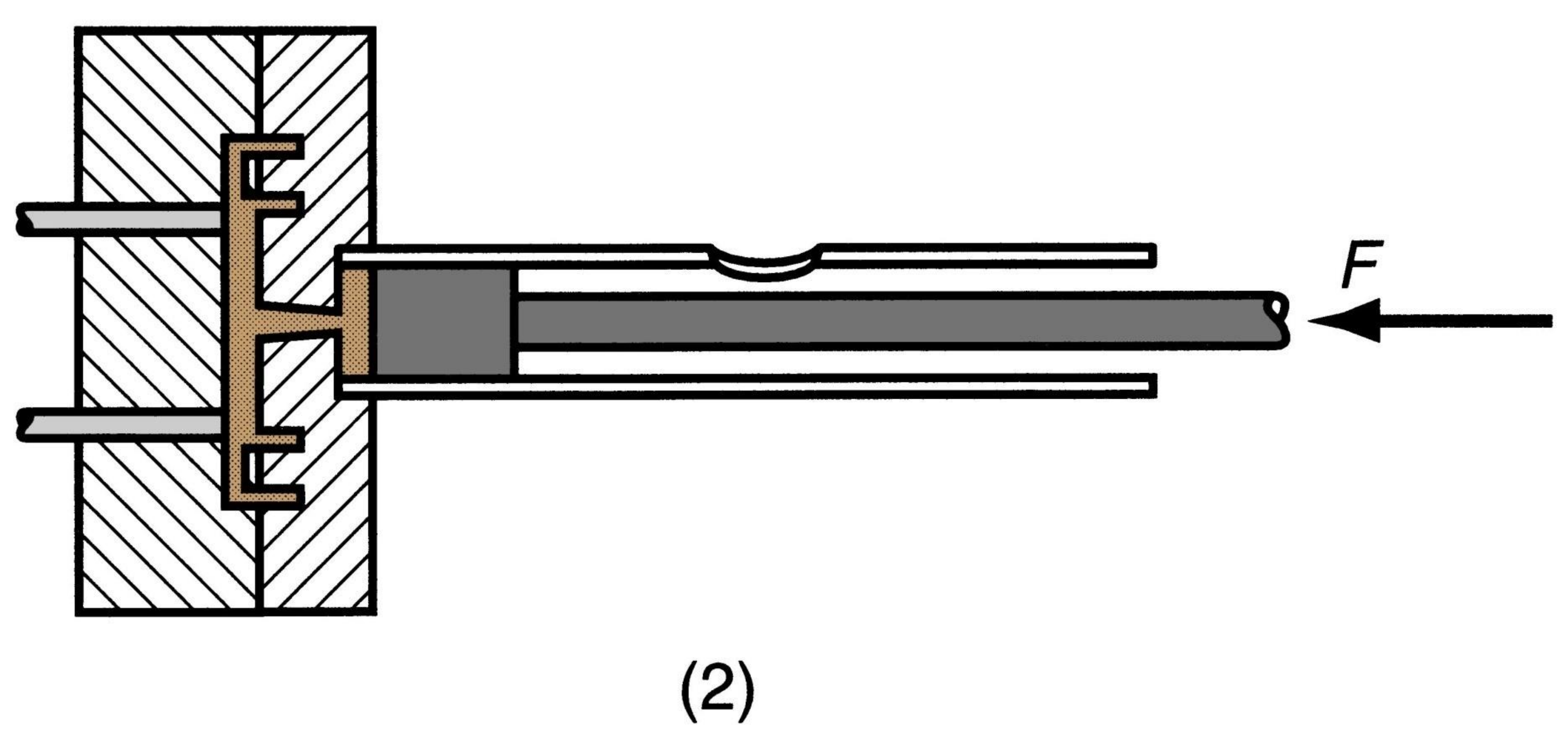


Figure 11.14 - Cycle in cold-chamber casting:
(2) ram forces metal to flow into die, maintaining pressure during cooling and solidification

Molds for Die Casting

- Usually made of tool steel, mold steel, or maraging steel
- Tungsten and molybdenum (good refractory qualities) used to die cast steel and cast iron
- Ejector pins required to remove part from die when it opens
- Lubricants must be sprayed into cavities to prevent sticking

Advantages and Limitations of Die Casting

- Advantages:
  - Economical for large production quantities
  - Good dimensional accuracy and surface finish
  - Thin sections are possible
  - Rapid cooling provides small grain size and good strength to casting
- Disadvantages:
  - Generally limited to metals with low metal points
  - Part geometry must allow removal from die cavity

Centrifugal Casting

A group of casting processes in which the mold is rotated at high speed so centrifugal force distributes molten metal to outer regions of die cavity

- The group includes:
  - True centrifugal casting
  - Semicentrifugal casting
  - Centrifuge casting

True Centrifugal Casting

Molten metal is poured into rotating mold to produce a tubular part

- In some operations, mold rotation commences after pouring rather than before
- Parts: pipes, tubes, bushings, and rings
- Outside shape of casting can be round, octagonal, hexagonal, etc., but inside shape is (theoretically) perfectly round, due to radially symmetric forces

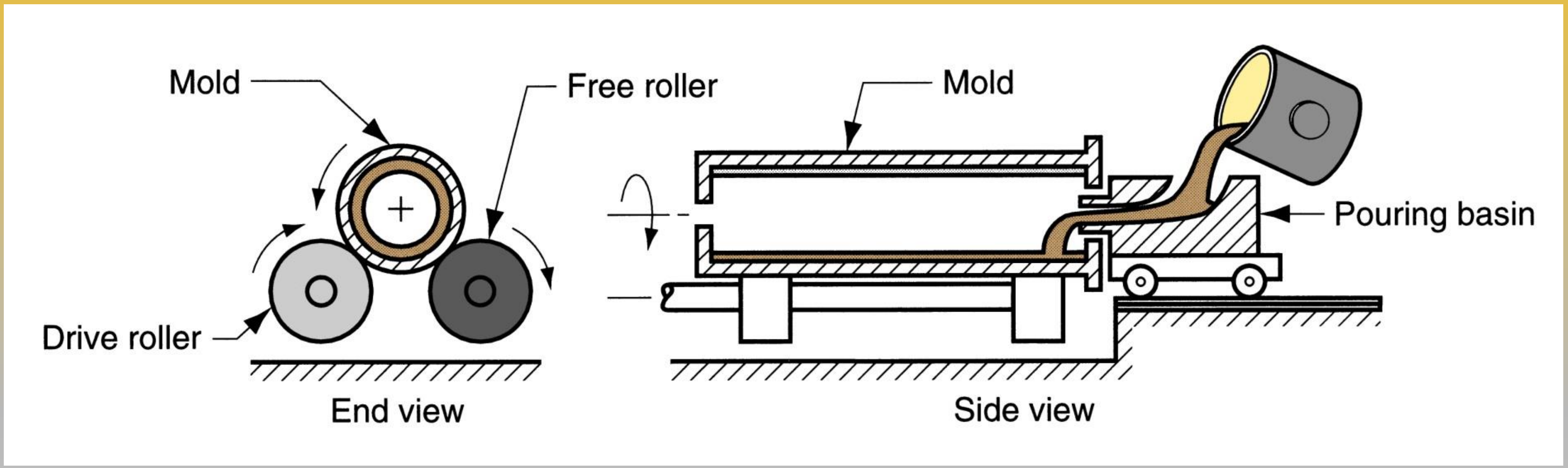


Figure 11.15 - Setup for true centrifugal casting

Casting Quality

- There are numerous opportunities for things to go wrong in a casting operation, resulting in quality defects in the product
- The defects can be classified as follows:
  - Defects common to all casting processes
  - Defects related to sand casting process

Misrun

A casting that has solidified before completely filling mold cavity

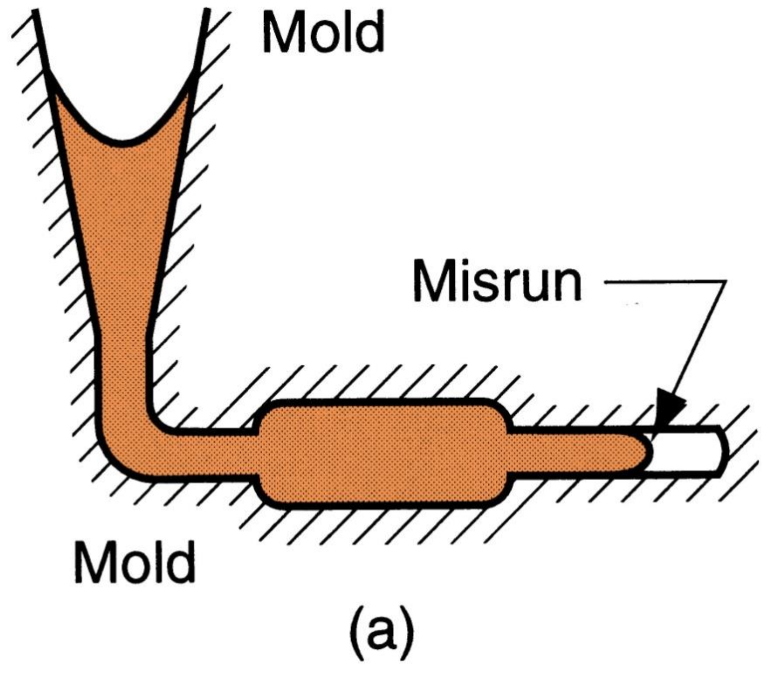


Figure 11.22 - Some common defects in castings: (a) misrun

Cold Shut

Two portions of metal flow together but there is a lack of fusion due to premature freezing

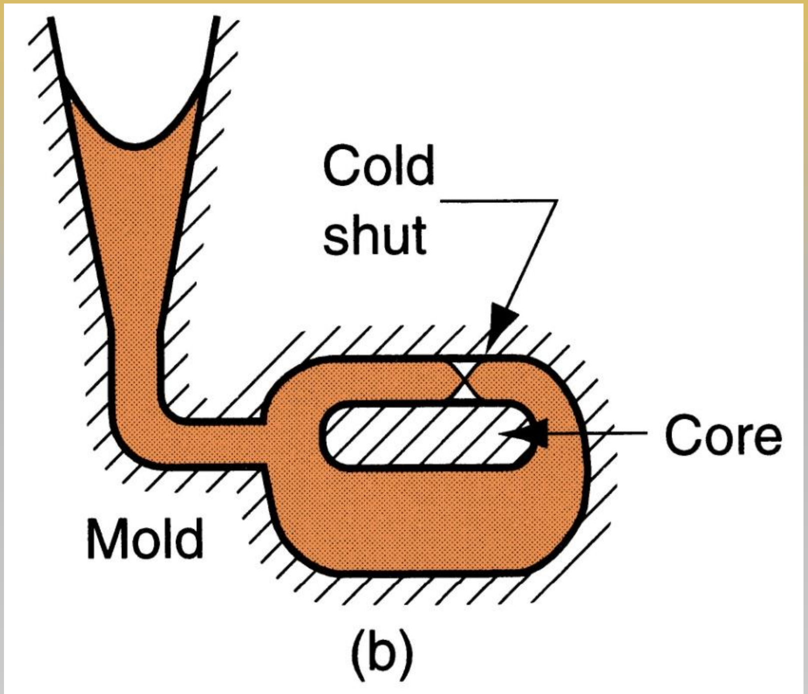


Figure 11.22 - Some common defects in castings: (b) cold shut

Cold Shot

Metal splatters during pouring and solid globules form and become entrapped in casting

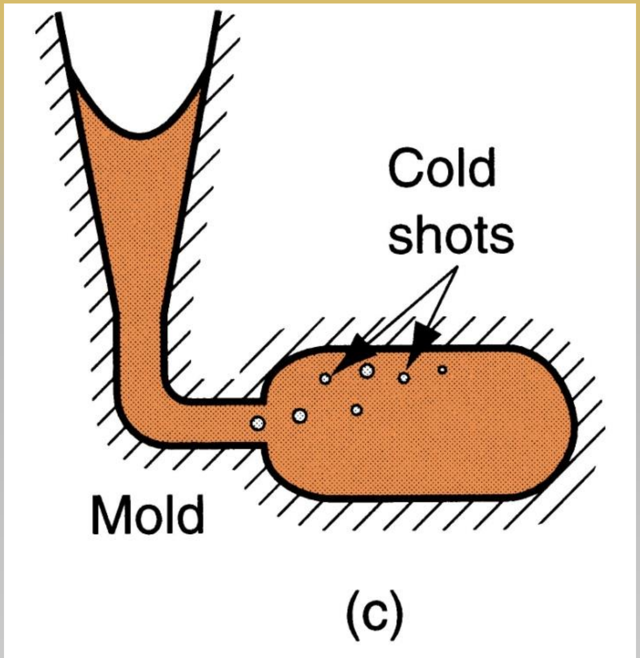


Figure 11.22 - Some common defects in castings: (c) cold shot

Shrinkage Cavity

Depression in surface or internal void caused by solidification shrinkage that restricts amount of molten metal available in last region to freeze

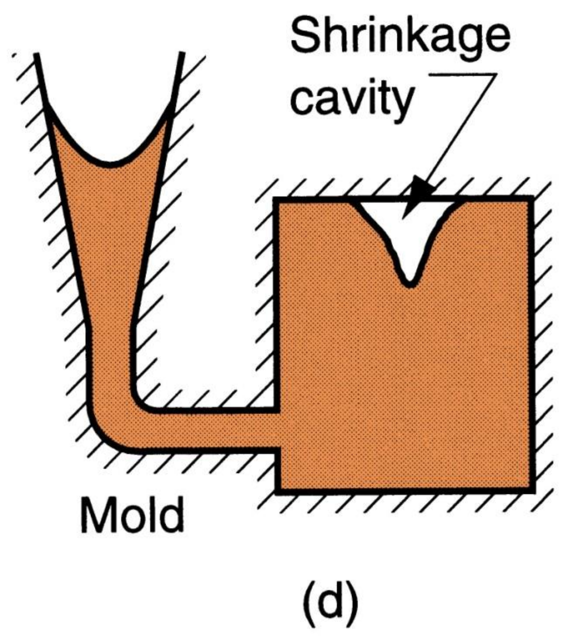


Figure 11.22 - Some common defects in castings: (d) shrinkage cavity

Sand Blow

Balloon-shaped gas cavity caused by release of mold gases during pouring

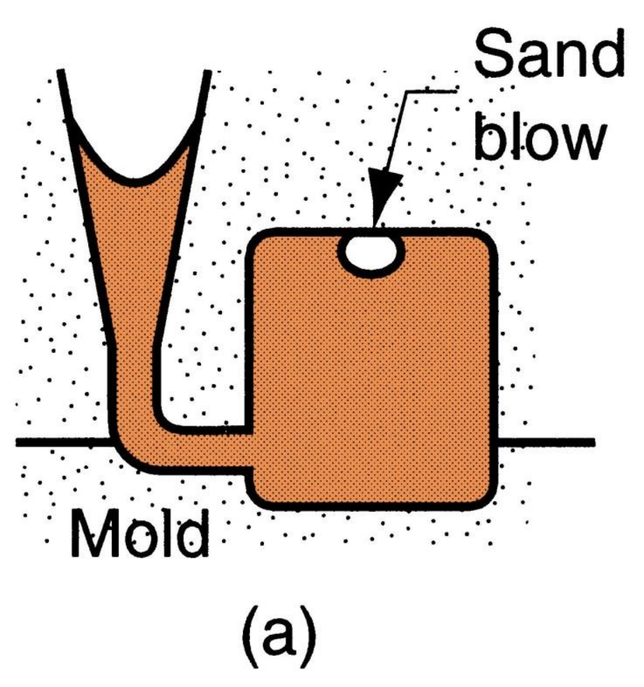


Figure 11.23 - Common defects in sand castings: (a) sand blow

Pin Holes

Formation of many small gas cavities at or slightly below surface of casting

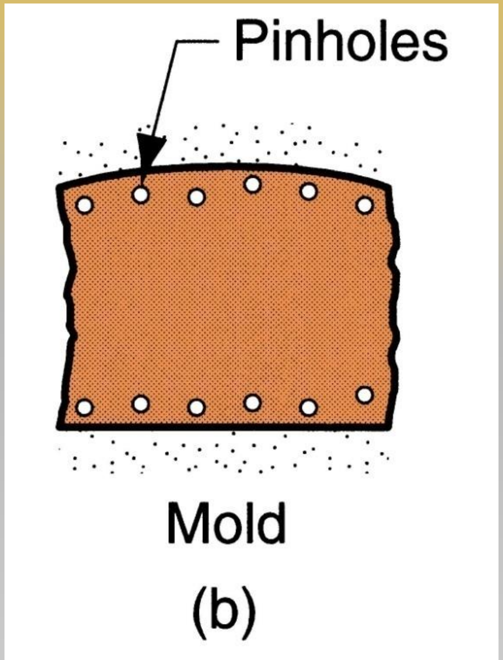


Figure 11.23 - Common defects in sand castings: (b) pin holes

Penetration

When fluidity of liquid metal is high, it may penetrate into sand mold or sand core, causing casting surface to consist of a mixture of sand grains and metal

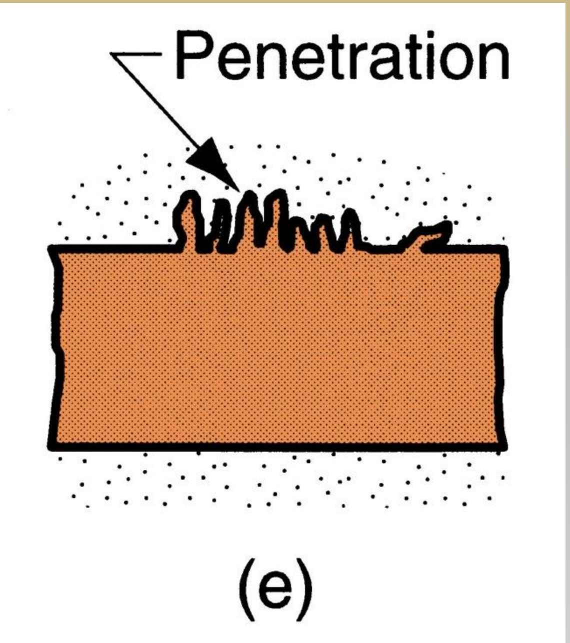


Figure 11.23 - Common defects in sand castings: (e) penetration

Mold Shift

A step in cast product at parting line caused by sidewise relative displacement of cope and drag

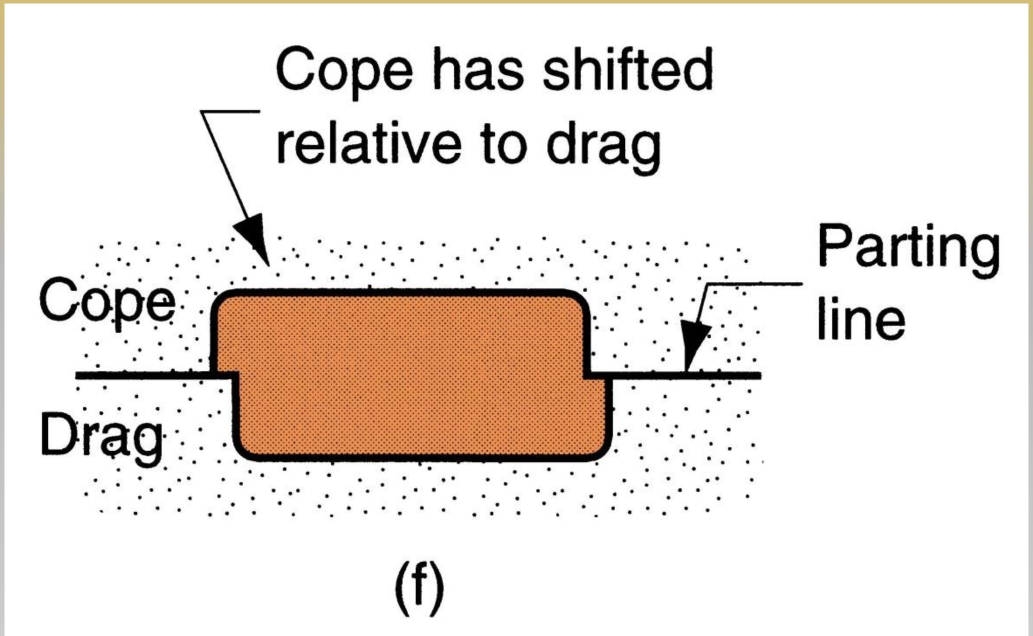


Figure 11.23 - Common defects in sand castings: (f) mold shift

Metals for Casting

- Most commercial castings are made of alloys rather than pure metals
  - Alloys are generally easier to cast, and properties of product are better
- Casting alloys can be classified as:
  - Ferrous
  - Nonferrous

Ferrous Casting Alloys: Cast Iron

- Most important of all casting alloys
- Tonnage of cast iron castings is several times that of all other metals combined
- Several types: (1) gray cast iron, (2) nodular iron, (3) white cast iron, (4) malleable iron, and (5) alloy cast irons
- Typical pouring temperatures $\sim$ 1400°C (2500°F), depending on composition

Ferrous Casting Alloys: Steel

- The mechanical properties of steel make it an attractive engineering material
- The capability to create complex geometries makes casting an attractive shaping process
- Difficulties faced by the foundry working with steel:
  - Pouring temperature of steel is higher than for most other casting metals $\sim$ 1650°C (3000°F)
  - At these temperatures, steel readily oxidizes, so molten metal must be isolated from air
  - Molten steel has relatively poor fluidity

Nonferrous Casting Alloys: Aluminum

- Generally considered to be very castable
- Pouring temperatures low – melting temperature of aluminum $T_m = 660^{\circ}C$ ($1220^{\circ}F$)
- Properties:
  - Light weight
  - Range of strength properties by heat treatment
  - Ease of machining

Nonferrous Casting Alloys: Copper Alloys

- Includes bronze, brass, and aluminum bronze
- Properties:
  - Corrosion resistance
  - Attractive appearance
  - Good bearing qualities
- Limitation: high cost of copper
- Applications: pipe fittings, marine propeller blades, pump components, ornamental jewelry

Nonferrous Casting Alloys: Zinc Alloys

- Highly castable, commonly used in die casting
- Low melting point – melting point of zinc T_m = 419°C (786°F)
- Good fluidity for ease of casting
- Properties:
  - Low creep strength, so castings cannot be subjected to prolonged high stresses

Product Design Considerations: Geometric Simplicity

- Although casting can be used to produce complex part geometries, simplifying the part design will improve castability
- Avoiding unnecessary complexities:
  - Simplifies mold-making
  - Reduces the need for cores
  - Improves the strength of the casting

Product Design Considerations: Corners

- Sharp corners and angles should be avoided, since they are sources of stress concentrations and may cause hot tearing and cracks
- Generous fillets should be designed on inside corners and sharp edges should be blended

Product Design Considerations: Draft Guidelines

- In expendable mold casting, purpose of draft is to facilitate removal of pattern from mold (1° for sand casting)
- In permanent mold casting, purpose is to aid in removal of the part from the mold (2° to 3° for permanent mold processes)
- Similar tapers should be allowed if solid cores are used

Product Design Considerations: Dimensional Tolerances and Surface Finish

Significant differences in dimensional accuracies and finishes can be achieved in castings, depending on process:

- Poor dimensional accuracies and finish for sand casting
- Good dimensional accuracies and finish for die casting and investment casting

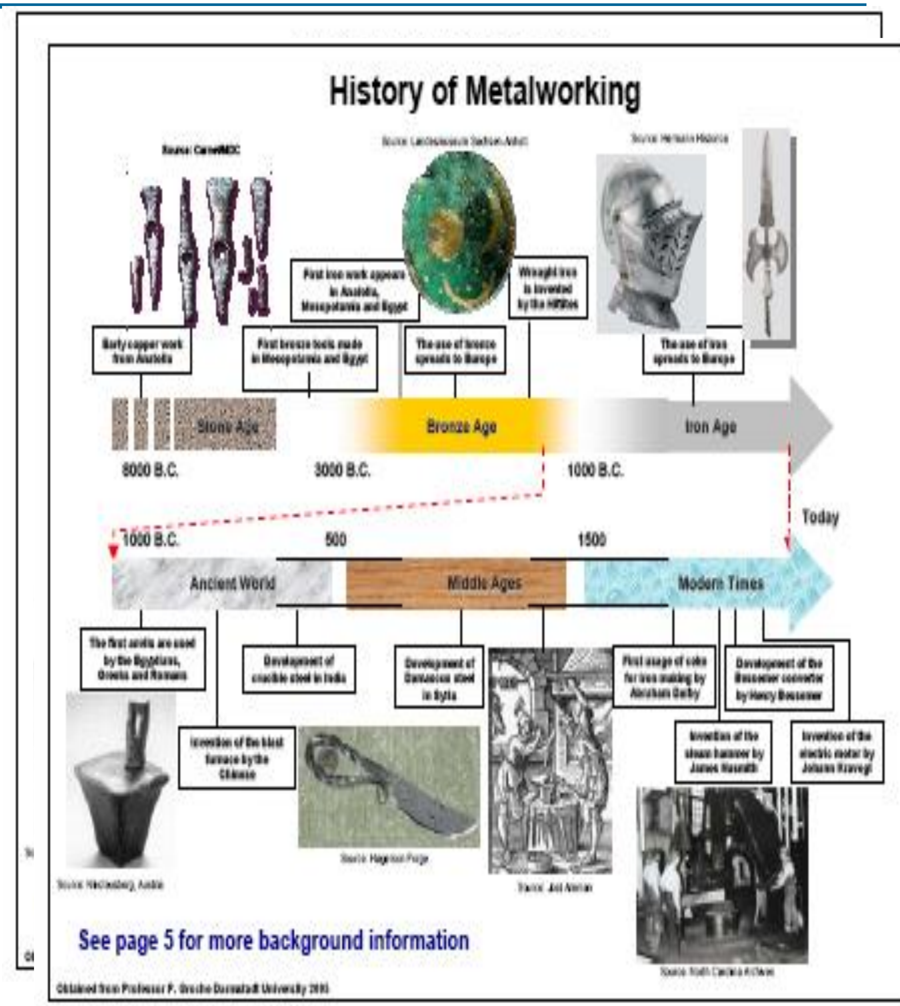
Product Design Considerations: Machining Allowances

- Almost all sand castings must be machined to achieve the required dimensions and part features
- Additional material, called the *machining allowance*, must be left on the casting in those surfaces where machining is necessary
- Typical machining allowances for sand castings are around 1.5 to 3 mm (1/16 to 1/4 in)

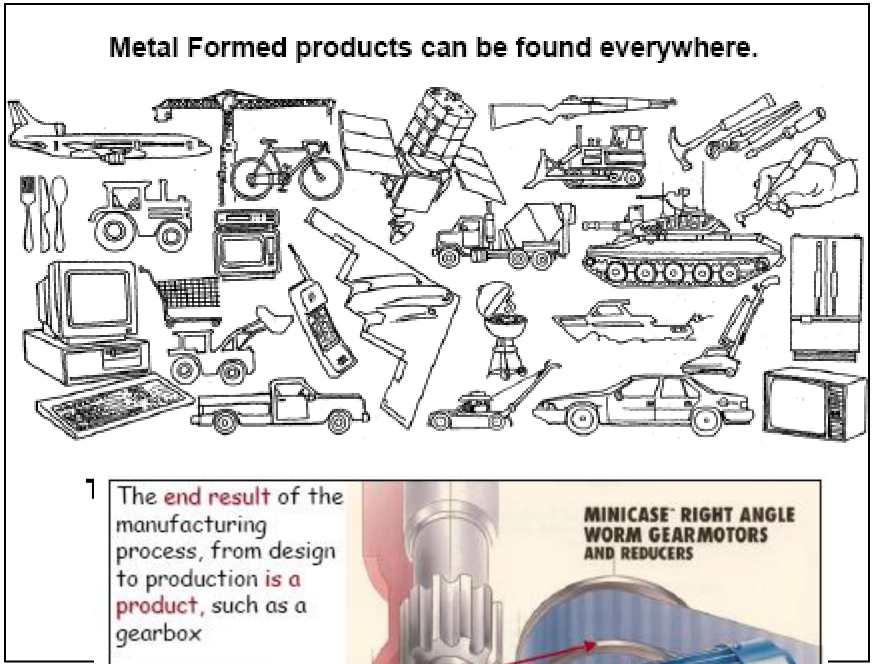
FUNDAMENTALS OF METAL FORMING

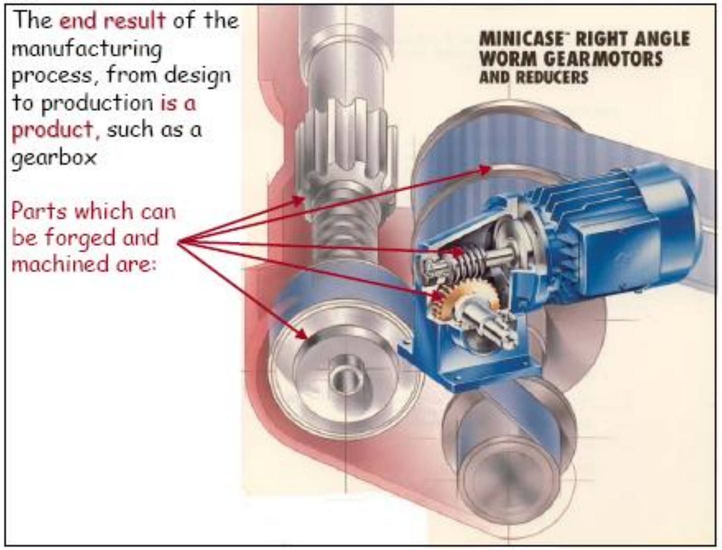
1. Overview of Metal Forming
2. Material Behavior in Metal Forming
3. Temperature in Metal Forming
4. Strain Rate Sensitivity
5. Friction and Lubrication in Metal Forming

- Large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces
- The tool, usually called a *die*, applies stresses that exceed the yield strength of the metal
- The metal takes a shape determined by the geometry of the die



- Stresses to plastically deform the metal are usually compressive
  - Examples: rolling, forging, extrusion
- However, some forming processes
  - Stretch the metal (tensile stresses)
  - Others bend the metal (tensile and compressive)
  - Still others apply shear stresses

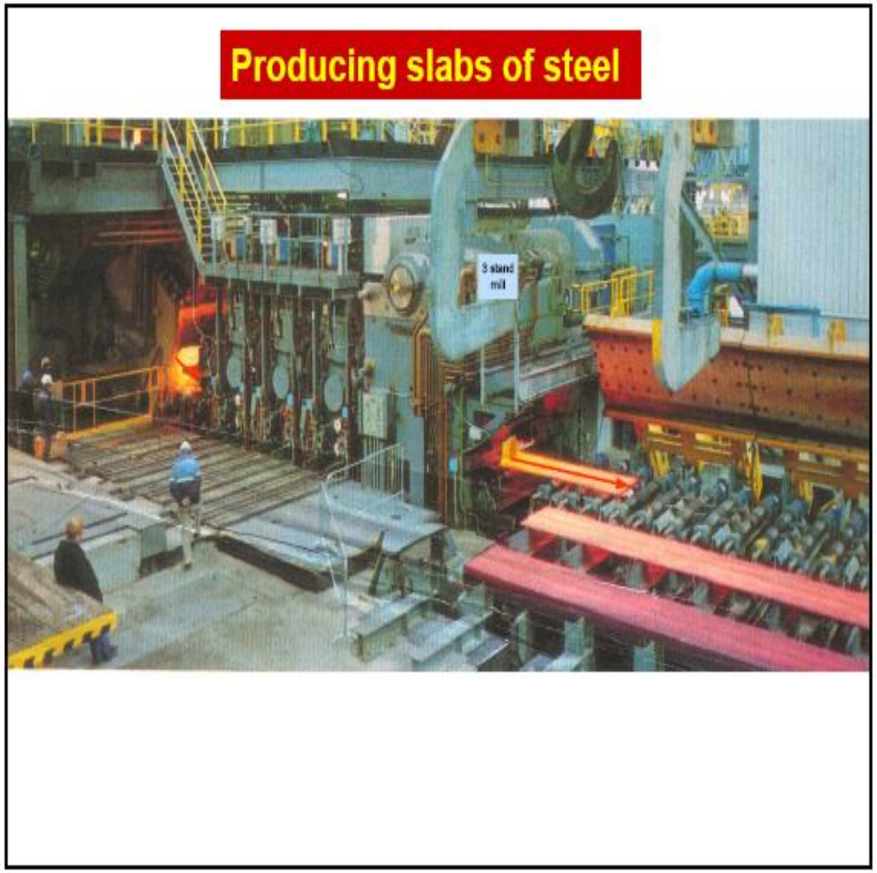




- Desirable material properties:
  - Low yield strength
  - High ductility
- These properties are affected by temperature:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction

1. Bulk deformation
   - Rolling
   - Forging
   - Extrusion
   - Wire and bar drawing
2. Sheet metalworking
   - Bending
   - Deep drawing
   - Cutting
   - Miscellaneous processes

- Characterized by significant deformations and massive shape changes
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios
- Starting work shapes include cylindrical billets and rectangular bars



- Independent Variables
  - Material
  - Starting Geometry
  - Tool and Die geometry
  - Lubrication
  - Speed of Operation
  - Starting Temp
  - Amount of Deform
- Dependent Variables
  - Force and Power required
  - Material Properties of the product
  - Surface finish
  - Nature of Materials flow during forming

MECHANICAL PROPERTIES OF MATERIALS

1. Stress-Strain Relationships
2. Hardness
3. Effect of Temperature on Properties
4. Fluid Properties
5. Viscoelastic Behavior of Polymers

Mechanical Properties in Design and Manufacturing

- Mechanical properties determine a material's behavior when subjected to mechanical stresses
  - Properties include elastic modulus, ductility, hardness, and various measures of strength
- Dilemma: mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult
  - The manufacturing engineer should appreciate the design viewpoint
  - And the designer should be aware of the manufacturing viewpoint

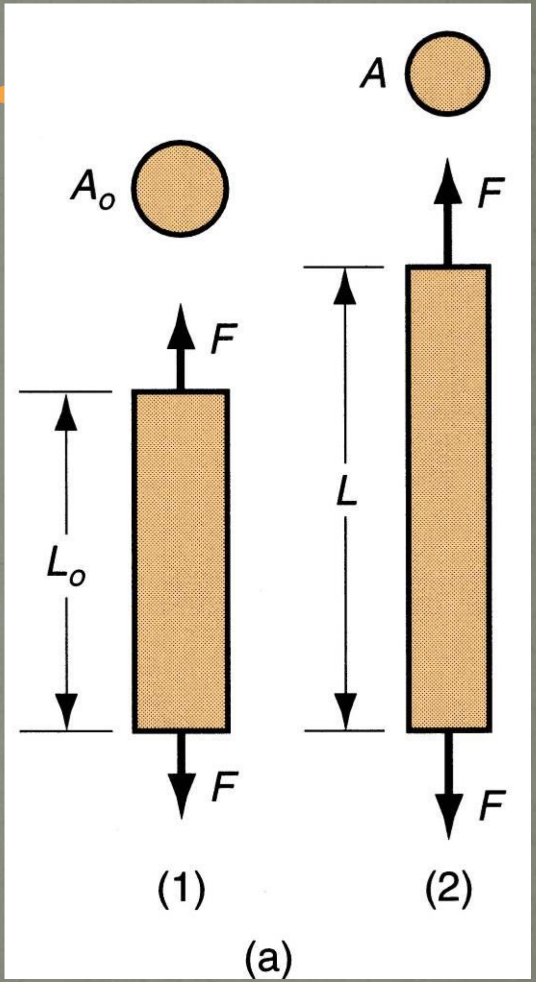
Stress-Strain Relationships

- Three types of static stresses to which materials can be subjected:
  1. Tensile - tend to stretch the material
  2. Compressive - tend to squeeze it
  3. Shear - tend to cause adjacent portions of material to slide against each other
- Stress-strain curve - basic relationship that describes mechanical properties for all three types

Tensile Test

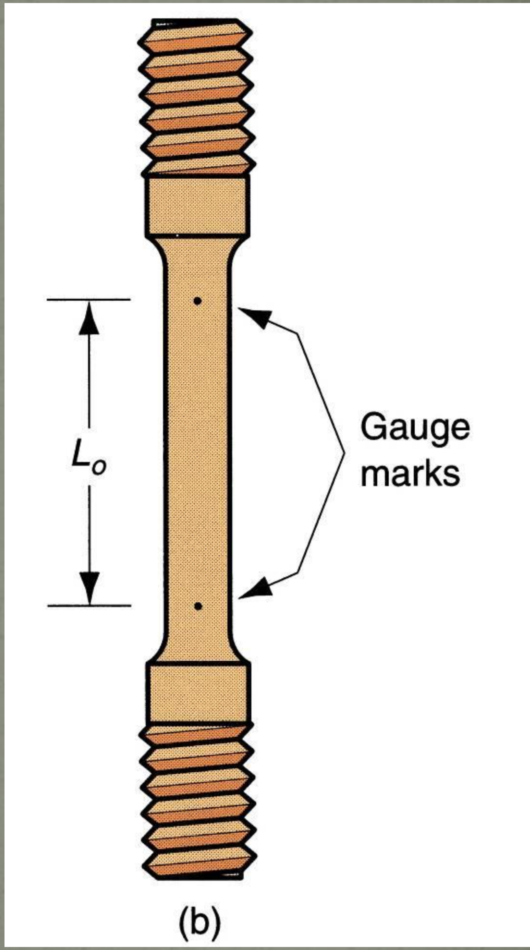
- Most common test for studying stress-strain relationship, especially metals
- In the test, a force pulls the material, elongating it and reducing its diameter

Figure 3.1 Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material



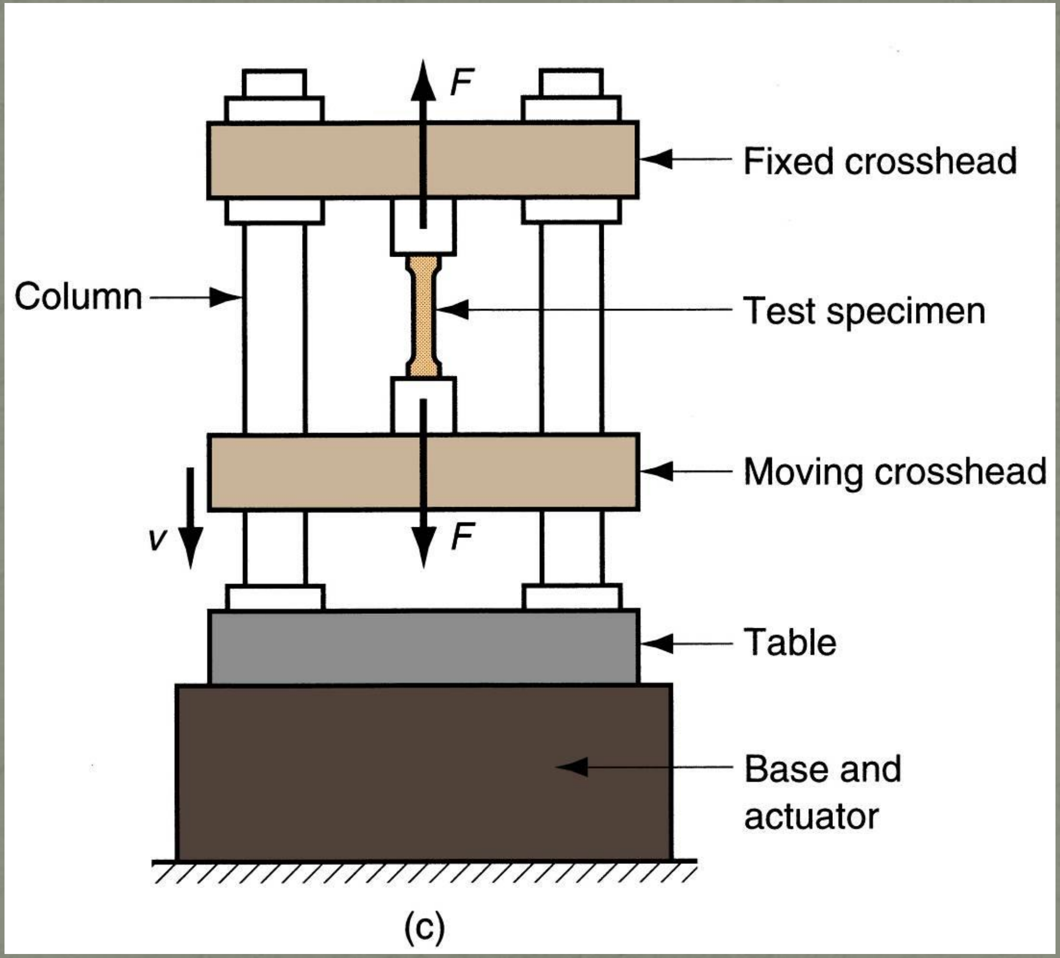
Tensile Test Specimen

- ASTM (American Society for Testing and Materials) specifies preparation of test specimen



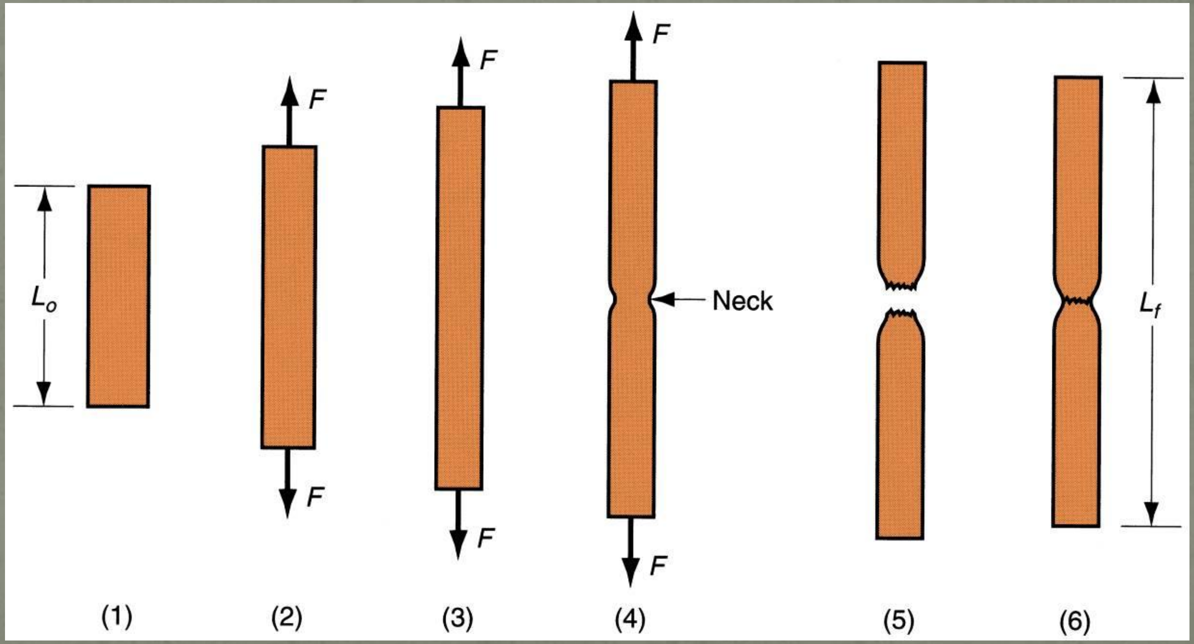
- Figure 3.1 Tensile test:
- (b) typical test specimen

Tensile Test Setup



Tensile Test Sequence

- Figure 3.2 Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.



Engineering Stress

- Defined as force divided by original area:

$$\sigma_e = \frac{F}{A_o}$$

where σ_e = engineering stress, F = applied force, and A_o = original area of test specimen

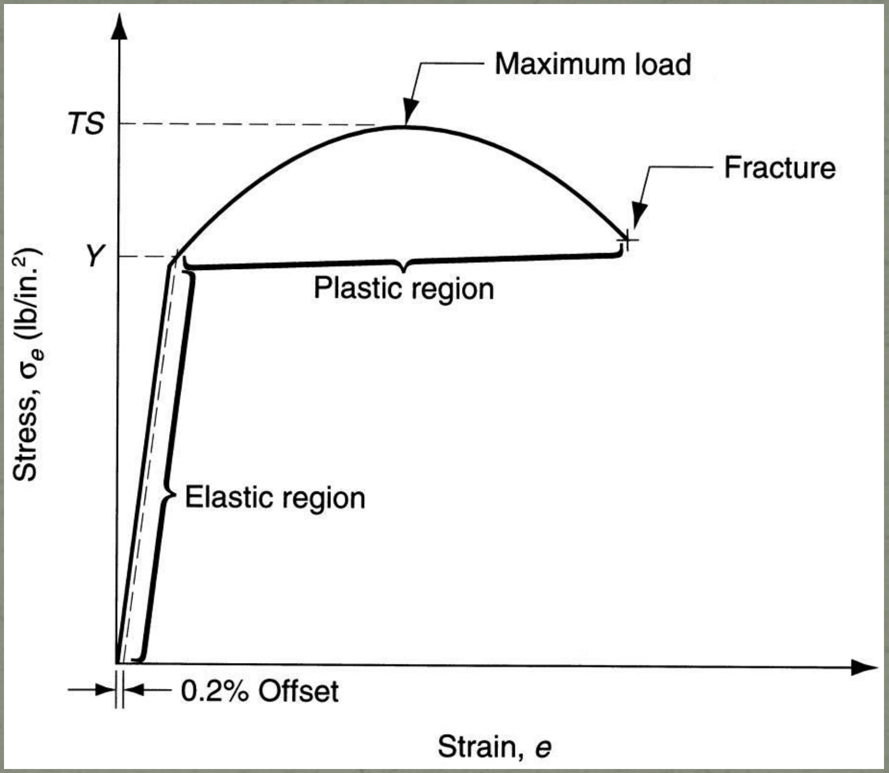
Engineering Strain

- Defined at any point in the test as

$$e = \frac{L - L_o}{L_o}$$

where e = engineering strain; L = length at any point during elongation; and L_o = original gage length

Typical Engineering Stress-Strain Plot



- Figure 3.3 Typical engineering stress-strain plot in a tensile test of a metal.

Two Regions of Stress-Strain Curve

- The two regions indicate two distinct forms of behavior:

1. Elastic region – prior to yielding of the material
2. Plastic region – after yielding of the material

Elastic Region in Stress-Strain Curve

- Relationship between stress and strain is linear
- Material returns to its original length when stress is removed
- Hooke's Law: $\sigma_e = E\,e$
-
- where E = *modulus of elasticity*
- E is a measure of the inherent stiffness of a material
- Its value differs for different materials

Yield Point in Stress-Strain Curve

- As stress increases, a point in the linear relationship is finally reached when the material begins to yield
  - *Yield point Y* can be identified by the change in slope at the upper end of the linear region
  - *Y* = a strength property
  - Other names for yield point = yield strength, yield stress, and elastic limit

Plastic Region in Stress-Strain Curve

- Yield point marks the beginning of plastic deformation
- The stress-strain relationship is no longer guided by Hooke's Law
- As load is increased beyond Y, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically

Tensile Strength in Stress-Strain Curve

- Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume
- Finally, the applied load *F* reaches a maximum value, and engineering stress at this point is called the *tensile strength TS* (a.k.a. ultimate tensile strength)

$$TS = \frac{F_{max}}{A_o}$$

Ductility in Tensile Test

- Ability of a material to plastically strain without fracture
- Ductility measure = elongation *EL*

$$EL = \frac{L_f - L_o}{L_o}$$

where EL = elongation; L_f = specimen length at fracture; and L_o = original specimen length

L_f is measured as the distance between gage marks after two pieces of specimen are put back together

True Stress

- Stress value obtained by dividing the instantaneous area into applied load

$$\sigma = \frac{F}{A}$$

where σ = true stress; F = force; and A = actual (instantaneous) area resisting the load

True Strain

- Provides a more realistic assessment of "instantaneous" elongation per unit length

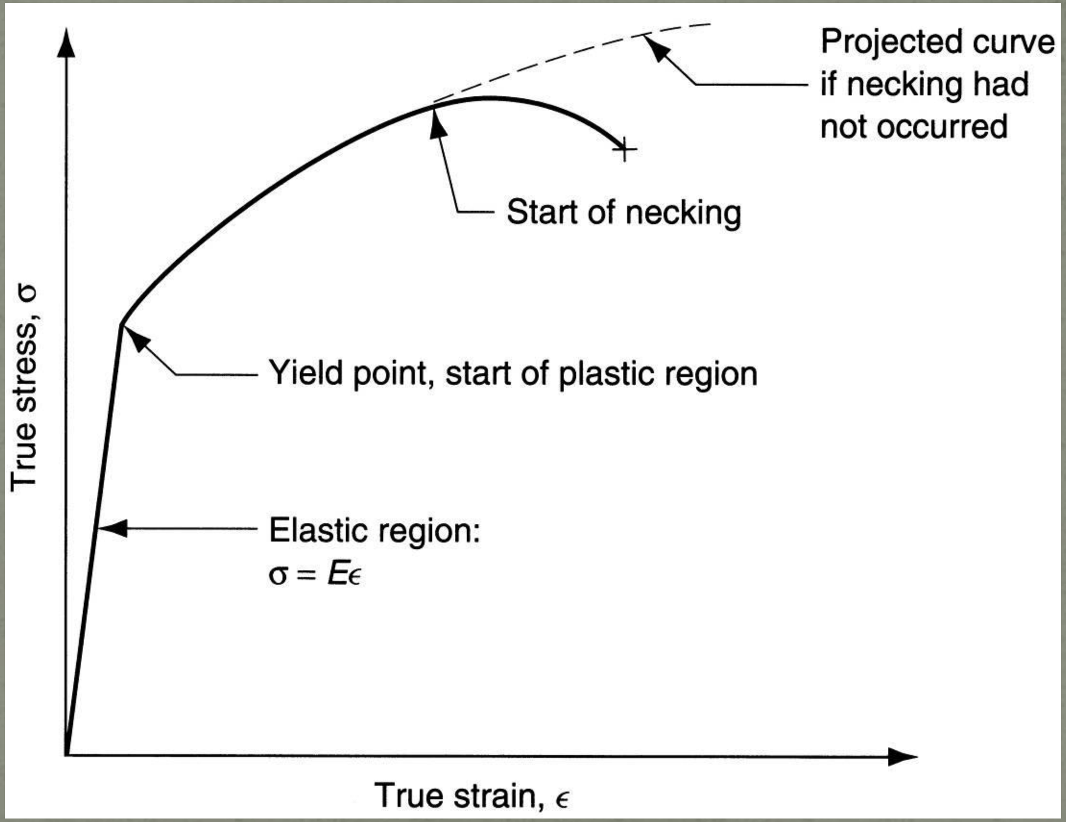
$$\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln \frac{L}{L_o}$$

Some example values for steels:

- mild steel:
- UTS = 60,000 psi = 410 Mpa; e = 35%
- medium-carbon steel:
- UTS = 85,000 psi = 590 MPa; e = 6%
- High-strength alloy steel:
- UTS = 180,000 psi = 1,240 MPa; e = 6%

True Stress-Strain Curve

Figure 3.4 - True stress-strain curve for the previous engineering stress-strain plot in Figure 3.3.



Strain Hardening in Stress-Strain Curve

- Note that true stress increases continuously in the plastic region until necking
  - In the engineering stress-strain curve, the significance of this was lost because stress was based on an incorrect area value
- It means that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening*

Strain Hardening

- The dislocation density in a metal increases with deformation or cold work. Consequently, the average distance of separation between dislocations decreases - the dislocations are positioned close together. On the average, dislocation - dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations. As the dislocation density increases, this resistance to dislocation motion by other dislocations becomes more pronounced. Thus, the imposed stress necessary to deform a metal increases with increasing cold work.
- Strain hardening is often utilized commercially to enhance the mechanical properties of metals during fabrication procedures.

True Stress-Strain in Log-Log Plot

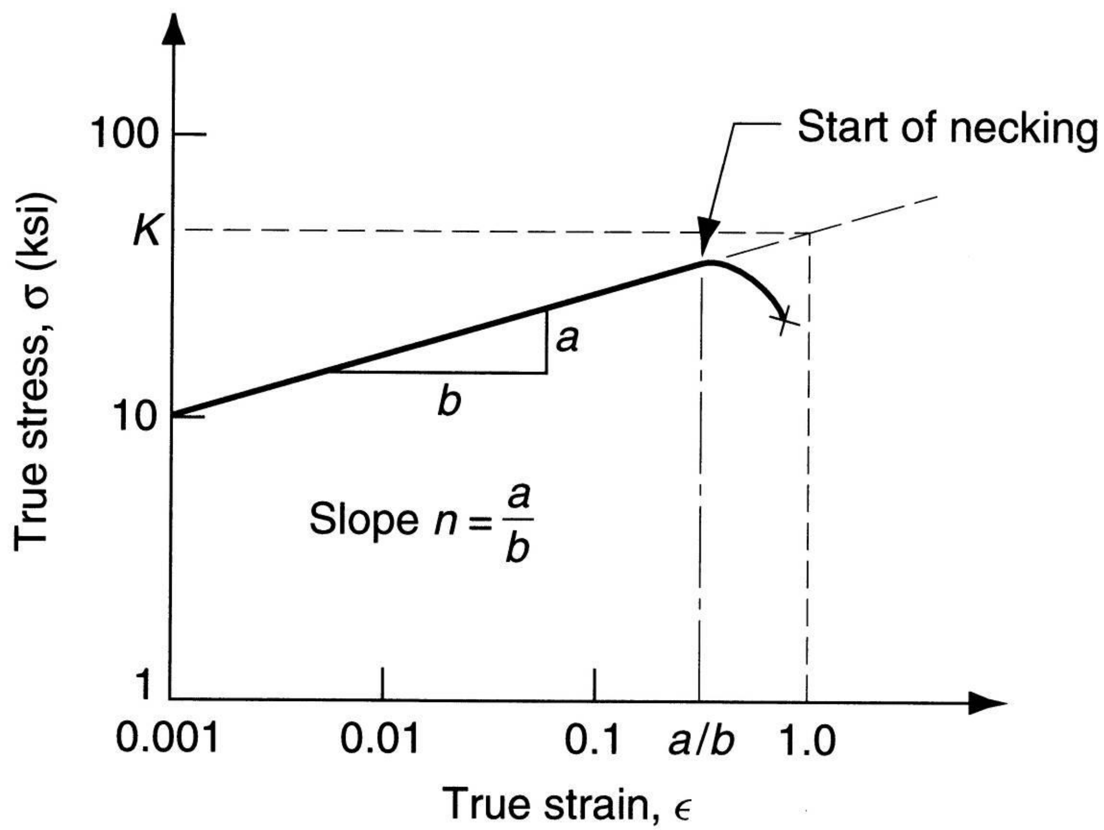


Figure 3.5 True stress-strain curve plotted on log-log scale.

Flow Curve

- Because it is a straight line in a log-log plot, the relationship between true stress and true strain in the plastic region is

$$\sigma = K\varepsilon^{n}$$

where *K* = *strength coefficient;* and *n = strain hardening exponent*

Categories of Stress-Strain Relationship

- Perfectly elastic
- Elastic and perfectly plastic
- Elastic and strain hardening

Perfectly Elastic

- Behavior is defined completely by modulus of elasticity *E*
- Fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers

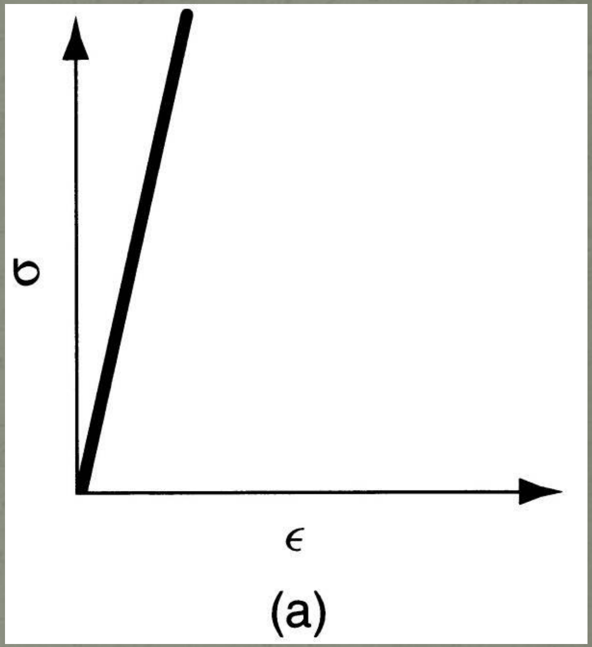


Figure 3.6 Three categories of stress-strain relationship:

(a) perfectly elastic.

Elastic and Perfectly Plastic

- Stiffness defined by *E*
- Once *Y* reached, deforms plastically at same stress level
- Flow curve: $K = Y$, $n = 0$
- Metals behave like this when heated to sufficiently high temperatures (above recrystallization)

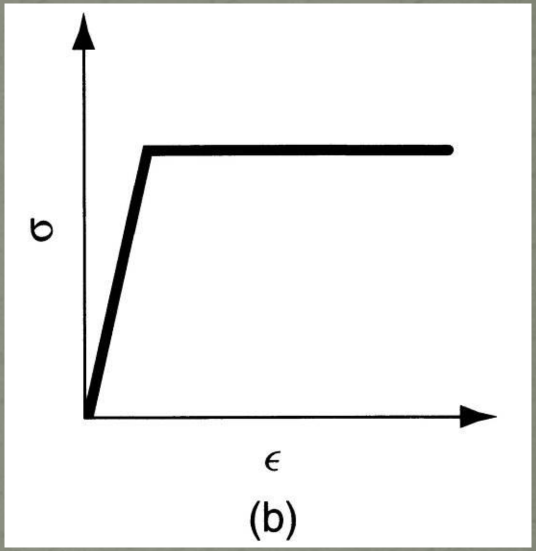


Figure 3.6 Three categories of stress-strain relationship: (b) elastic and perfectly plastic.

Elastic and Strain Hardening

- Hooke's Law in elastic region, yields at Y
- Flow curve: $K > Y$, $n > 0$
- Most ductile metals behave this way when cold worked

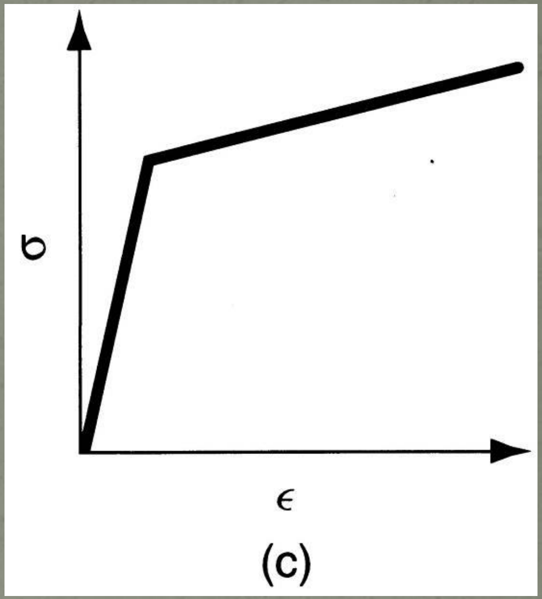


Figure 3.6 Three categories of stress-strain relationship: (c) elastic and strain hardening.

Compression Test

- Applies a load that squeezes the ends of a cylindrical specimen between two platens

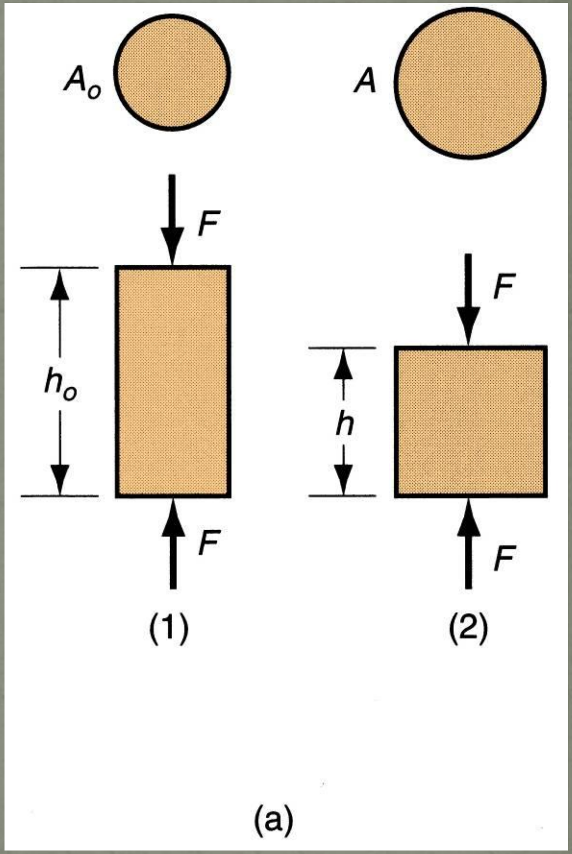
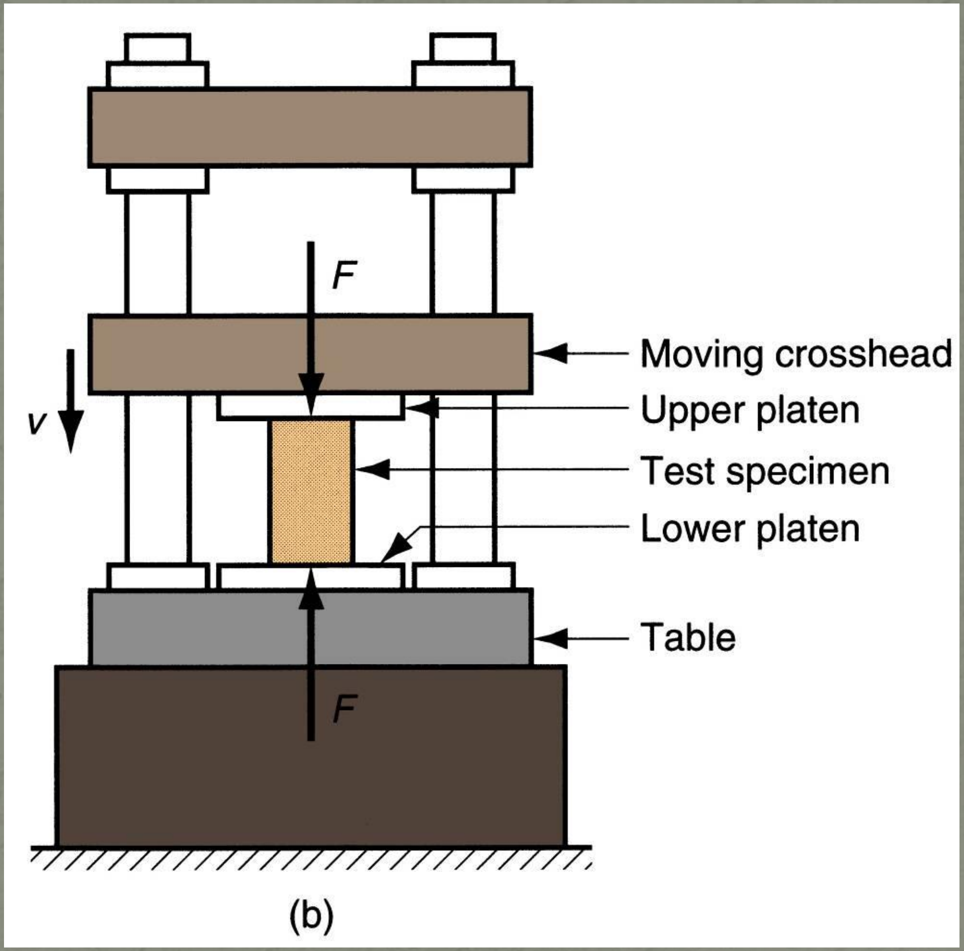


Figure 3.7 Compression test:

(a) compression force applied to test piece in (1) and (2) resulting change in height.

Compression Test Setup



Engineering Stress in Compression

- As the specimen is compressed, its height is reduced and cross-sectional area is increased

- $$\sigma_e = -\frac{F}{A_o}$$

where A_o = original area of the specimen

Engineering Strain in Compression

- Engineering strain is defined

$$e = \frac{h - h_o}{h_o}$$

Since height is reduced during compression, value of *e* is negative (the negative sign is usually ignored when expressing compression strain)

Stress-Strain Curve in Compression

- Shape of plastic region is different from tensile test because cross section increases
- Calculated value of engineering stress is higher

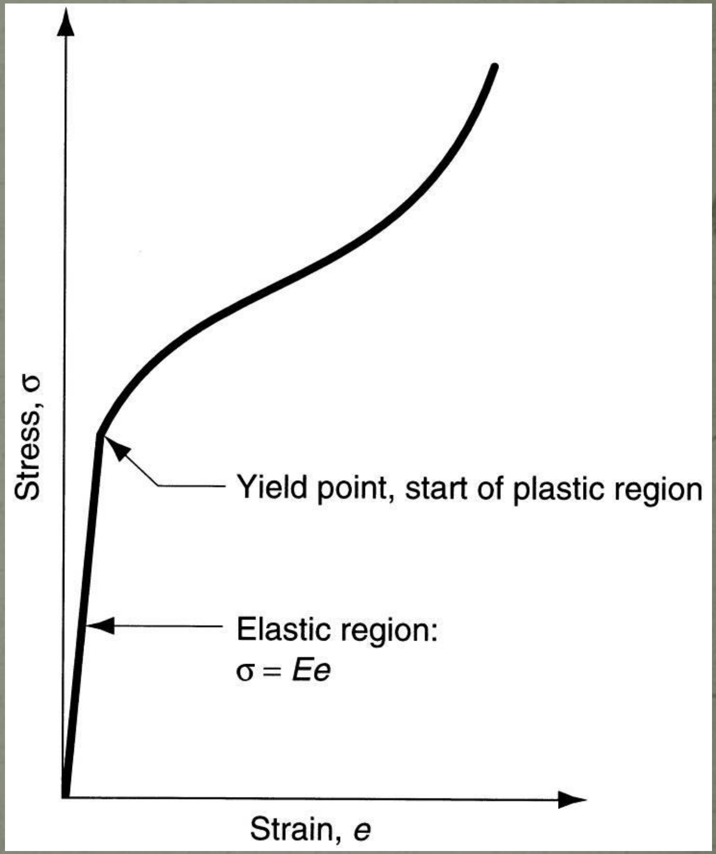


Figure 3.8 Typical engineering stress-strain curve for a compression test.

Tensile Test vs. Compression Test

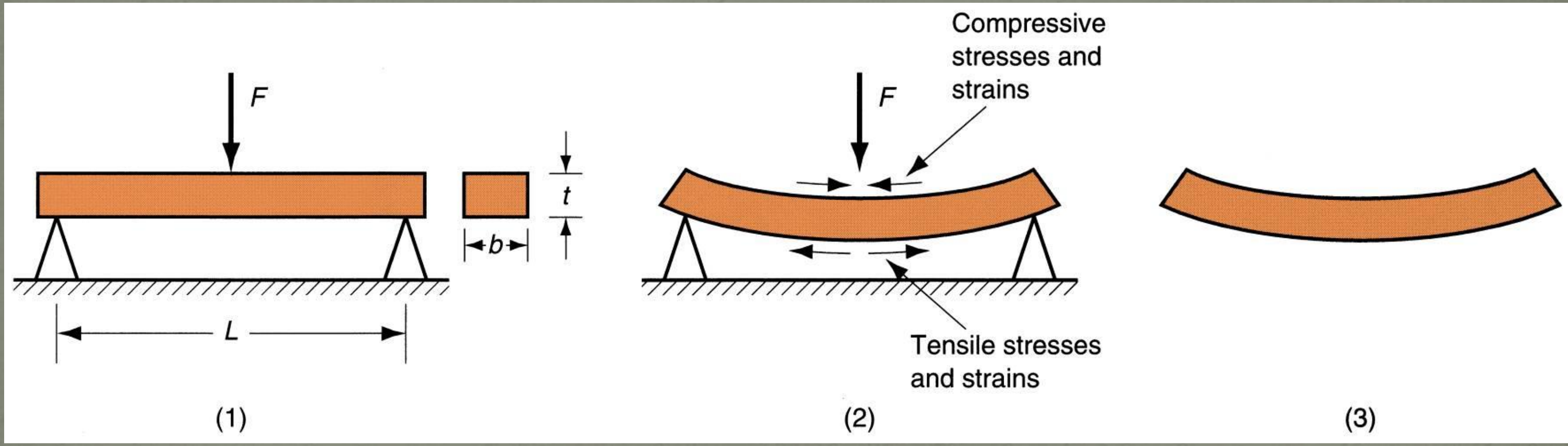
- Although differences exist between engineering stress-strain curves in tension and compression, the true stress-strain relationships are nearly identical
- Since tensile test results are more common, flow curve values (K and n) from tensile test data can be applied to compression operations
- When using tensile K and n data for compression, ignore necking, which is a phenomenon peculiar to straining induced by tensile stresses

Testing of Brittle Materials

- Hard brittle materials (e.g., ceramics) possess elasticity but little or no plasticity
- Often tested by a *bending test* (also called *flexure test*)
  - Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center

Bending Test

- Figure 3.10 Bending of a rectangular cross-section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part.



Testing of Brittle Materials

- Brittle materials do not flex
- They deform elastically until fracture
  - Failure occurs because tensile strength of outer fibers of specimen are exceeded
  - Failure type: *cleavage (الشقّ)* - common with ceramics and metals at low temperatures, in which separation rather than slip occurs along certain crystallographic planes

Transverse Rupture Strength

- The strength value derived from the bending test:

$$TRS = \frac{1.5FL}{bt^2}$$

where *TRS* = transverse rupture strength; *F* = applied load at fracture; *L* = length of specimen between supports; and *b* and *t* are dimensions of cross-section

Shear Properties

- Application of stresses in opposite directions on either side of a thin element

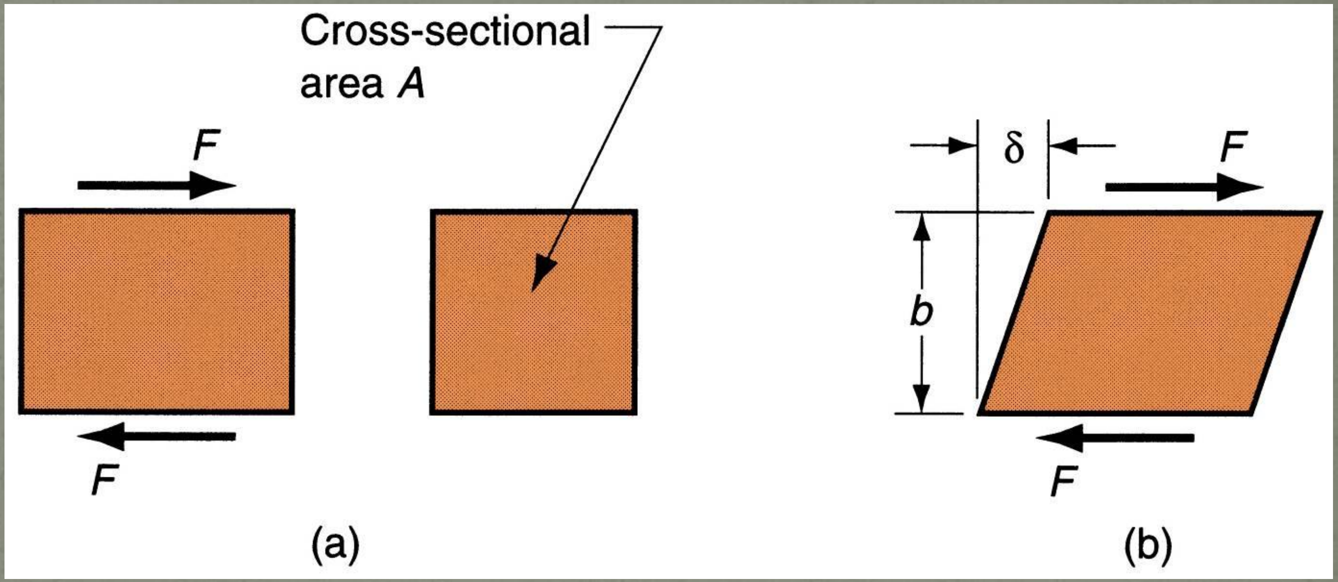


Figure 3.11 Shear (a) stress and (b) strain.

Shear Stress and Strain

- *Shear stress* defined as $\tau = \frac{F}{A}$

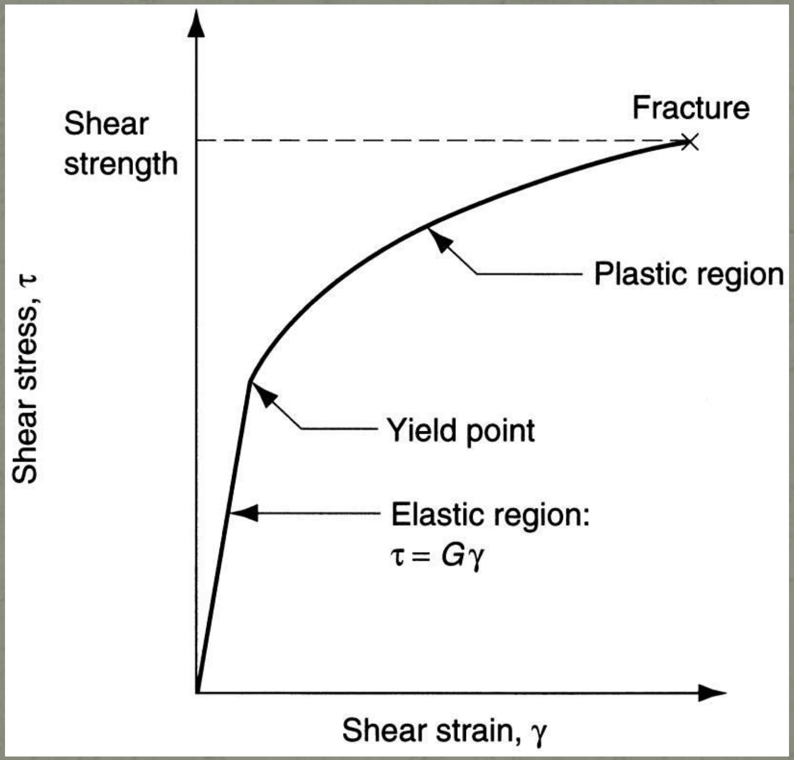
- where F = applied force; and A = area over which deflection occurs.

$$\gamma = \frac{\delta}{b}$$

- *Shear strain* defined as

- where δ = deflection element; and b = distance over which deflection occurs

Torsion Stress-Strain Curve



- Figure 3.13 Typical shear stress-strain curve from a torsion test.

Shear Elastic Stress-Strain Relationship

- In the elastic region, the relationship is defined as

$$\tau = G\gamma$$

where G = *shear modulus,* or *shear modulus of elasticity*

For most materials, $G \cong 0.4E$, where E = elastic modulus

Shear Plastic Stress-Strain Relationship

- Relationship similar to flow curve for a tensile test
- Shear stress at fracture = *shear strength S*
  - Shear strength can be estimated from tensile strength: $S \cong 0.7(TS)$
- Since cross-sectional area of test specimen in torsion test does not change as in tensile and compression, engineering stress-strain curve for shear ≅ true stress-strain curve

Hardness

- Resistance to permanent indentation
- Good hardness generally means material is resistant to scratching and wear
- Most tooling used in manufacturing must be hard for scratch and wear resistance

Hardness Tests

- Commonly used for assessing material properties because they are quick and convenient
- Variety of testing methods are appropriate due to differences in hardness among different materials
- Most well-known hardness tests are *Brinell* and *Rockwell*
- Other test methods are also available, such as Vickers, Knoop, Scleroscope, and durometer

Brinell Hardness Test

- Widely used for testing metals and nonmetals of low to medium hardness
- A hard ball is pressed into specimen surface with a load of 500, 1500, or 3000 kg

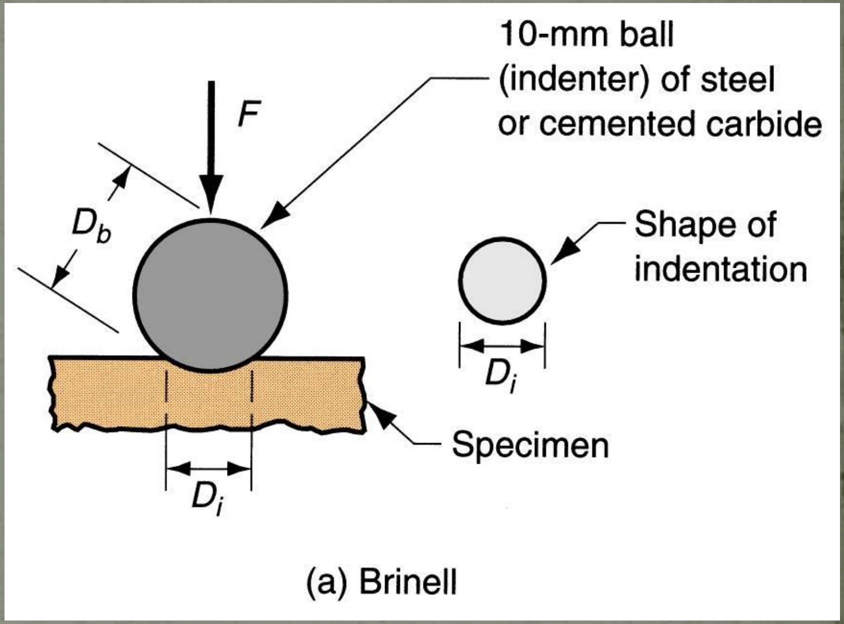


Figure 3.14 Hardness testing methods: (a) Brinell

Brinell Hardness Number

- Load divided into indentation area = Brinell Hardness Number (BHN)

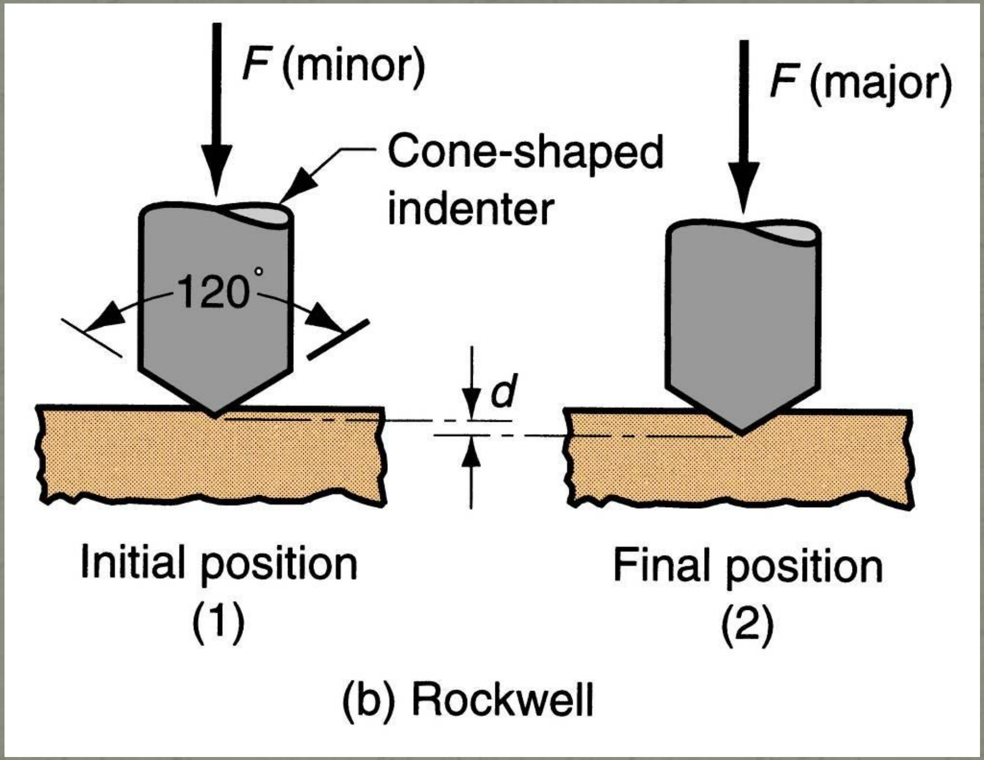
$$HB = \frac{2F}{\pi D_b (D_b - \sqrt{D_b^2 - D_i^2})}$$

where HB = Brinell Hardness Number (BHN), F = indentation load, kg; D_b = diameter of ball, mm, and D_i = diameter of indentation, mm

Rockwell Hardness Test

- Another widely used test
- A cone shaped indenter is pressed into specimen using a minor load of 10 kg, thus seating indenter in material
- Then, a major load of 150 kg is applied, causing indenter to penetrate beyond its initial position
- Additional penetration distance *d* is converted into a Rockwell hardness reading by the testing machine

Rockwell Hardness Test



- Figure 3.14 Hardness testing methods: (b) Rockwell:
- (1) initial minor load and (2) major load.

Examples

Brinell test
Mild steel: 120
Medium-carbon steel: 165
Cast iron: 150-200

Comparison of Hardness Numbers

BHN (10 mm ball, 3000 kg force)	Rockwell *C* (diamond cone, 150 kg force)	Rockwell *B* (1/16 in. ball, 100 kg force)	*UTS* of steel (ksi)	*UTS* of steel (MPa)
	68			
	65			
653	60			
563	55			
483	50		300	2070
422	45		215	1484
371	40		182	1256
336	35		157	1083
285	30		138	952
258	25		125	863
226	20	98	108	745
200		91	93	642
175		88	85	587
150		81	74	511
130		74	65	449
110		65	55	380

- Effect of Temperature on Properties

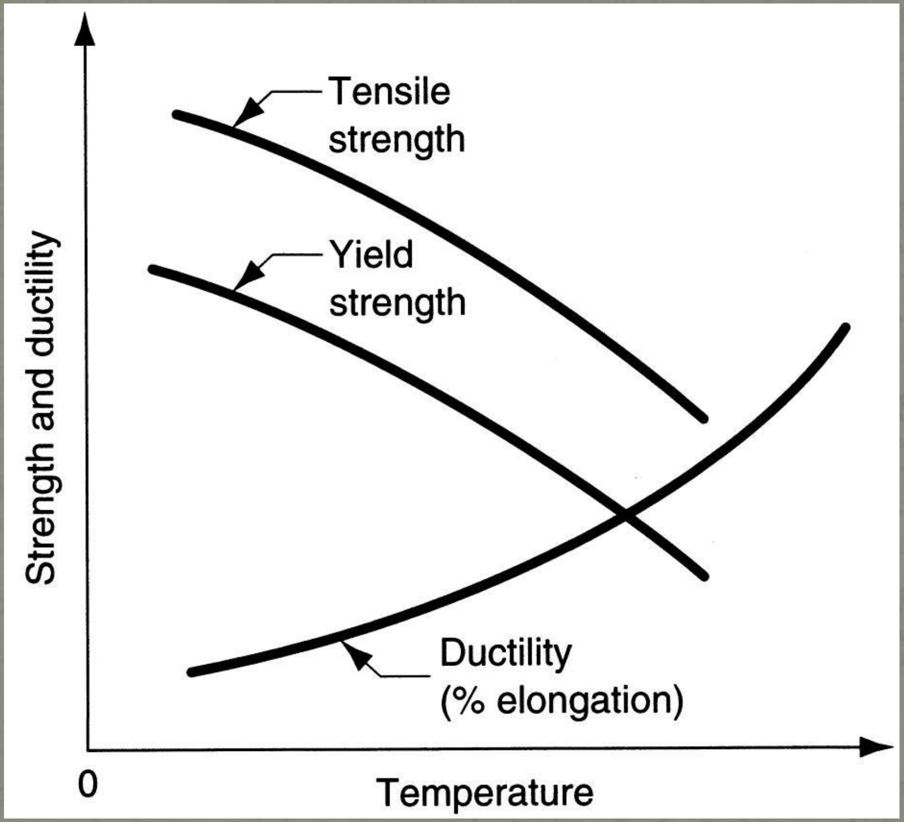
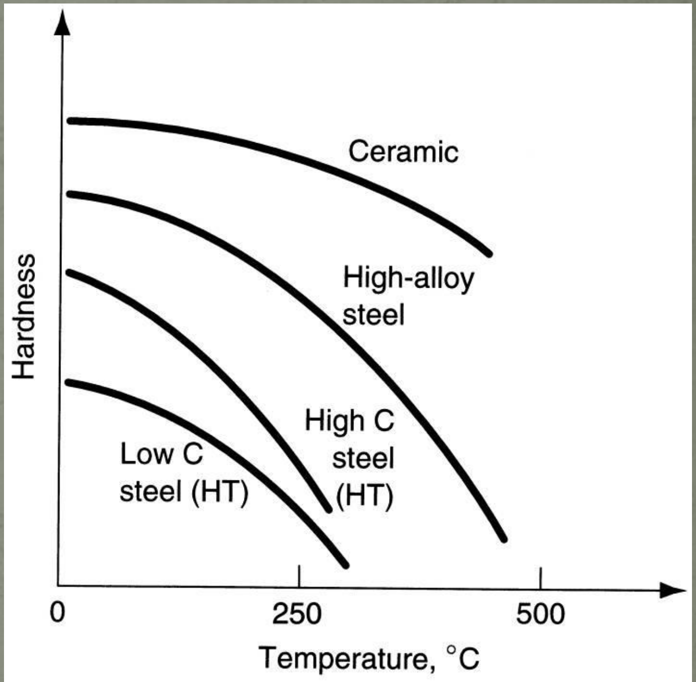


Figure 3.15 General effect of temperature on strength and ductility.

Hot Hardness

- Ability of a material to retain hardness at elevated temperatures



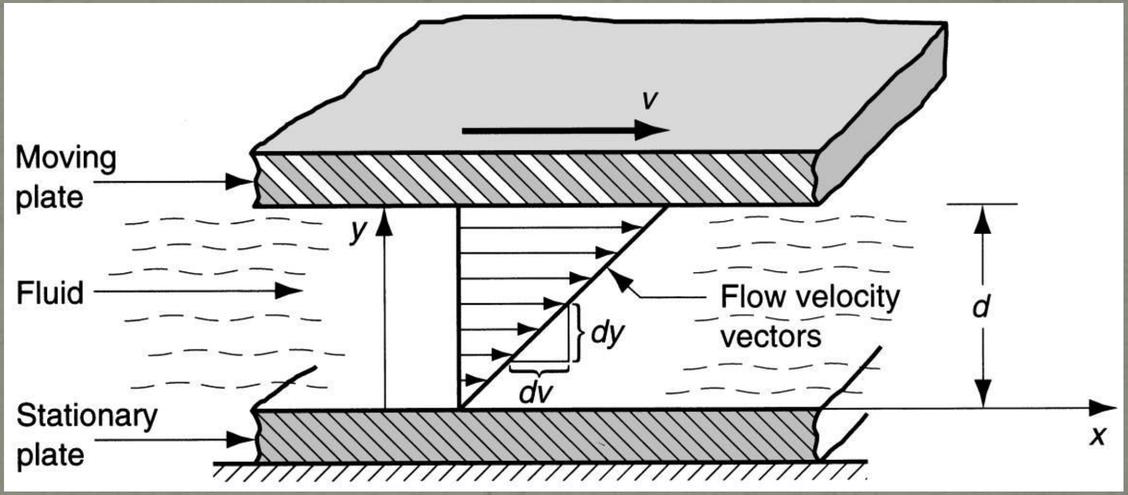
- Figure 3.16 Hot hardness - typical hardness as a function of temperature for several materials.

Viscosity in Fluids

- Viscosity is the resistance to flow that is characteristic of a given fluid
- Flow is a defining characteristic of fluids, but the tendency to flow varies for different fluids
- Viscosity is a measure of the internal friction when velocity gradients are present in the fluid
  - The more viscous the fluid, the higher the internal friction and the greater the resistance to flow
  - Reciprocal of viscosity is *fluidity* - the ease with which a fluid flows

Viscosity

- Viscosity can be defined using two parallel plates separated by a distance *d* and a fluid fills the space between the two plates



- Figure 3.17 Fluid flow between two parallel plates, one stationary and the other moving at velocity *v*

Shear Stress

- Shear stress is the frictional force exerted by the fluid per unit area
- Motion of the upper plate is resisted by a frictional force resulting from the shear viscosity of the fluid
- This force F can be reduced to a *shear stress* τ by dividing by plate area A

$$\tau = \frac{F}{A}$$

Shear Rate

- Shear stress is related to *shear rate*, defined as the change in velocity *dv* relative to *dy*

$$\dot{\gamma} = \frac{dv}{dy}$$

where $\dot{\gamma}$ = shear rate, 1/s; *dv* = change in velocity, m/s; and *dy* = change in distance *y*, m

Shear rate = velocity gradient perpendicular to flow direction

Shear Viscosity

- Shear viscosity is the fluid property that defines the relationship between F/A and *dv/dy*; that is,

$$\frac{F}{A} = \eta \frac{dv}{dy}$$

- or $\tau = \eta \dot{\gamma}$

  where η = a constant of proportionality called the *coefficient of viscosity*, Pa-s

  - For *Newtonian* fluids, viscosity is a constant
  - For non-Newtonian fluids, it is not

Coefficient of Viscosity

- Rearranging, coefficient of viscosity can be expressed:

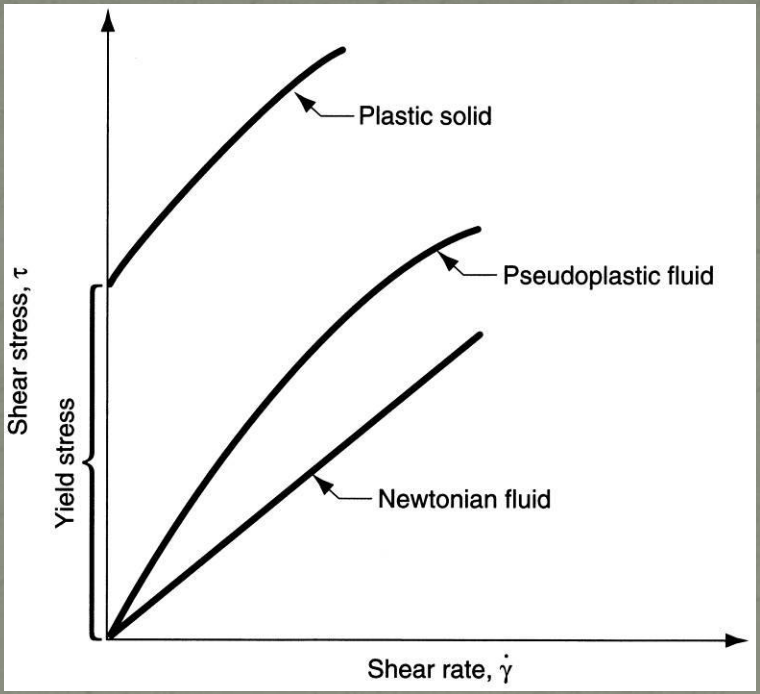
$$\eta = \frac{\tau}{\dot{\gamma}}$$

- Viscosity of a fluid is the ratio of shear stress to shear rate during flow

Viscosity of Polymers and Flow Rate

- Viscosity of a thermoplastic polymer melt is not constant
  - It is affected by flow rate
  - Its behavior is non-Newtonian
- A fluid that exhibits this decreasing viscosity with increasing shear rate is called *pseudoplastic*
- This complicates analysis of polymer shaping processes such as injection molding

Newtonian versus Pseudoplastic Fluids

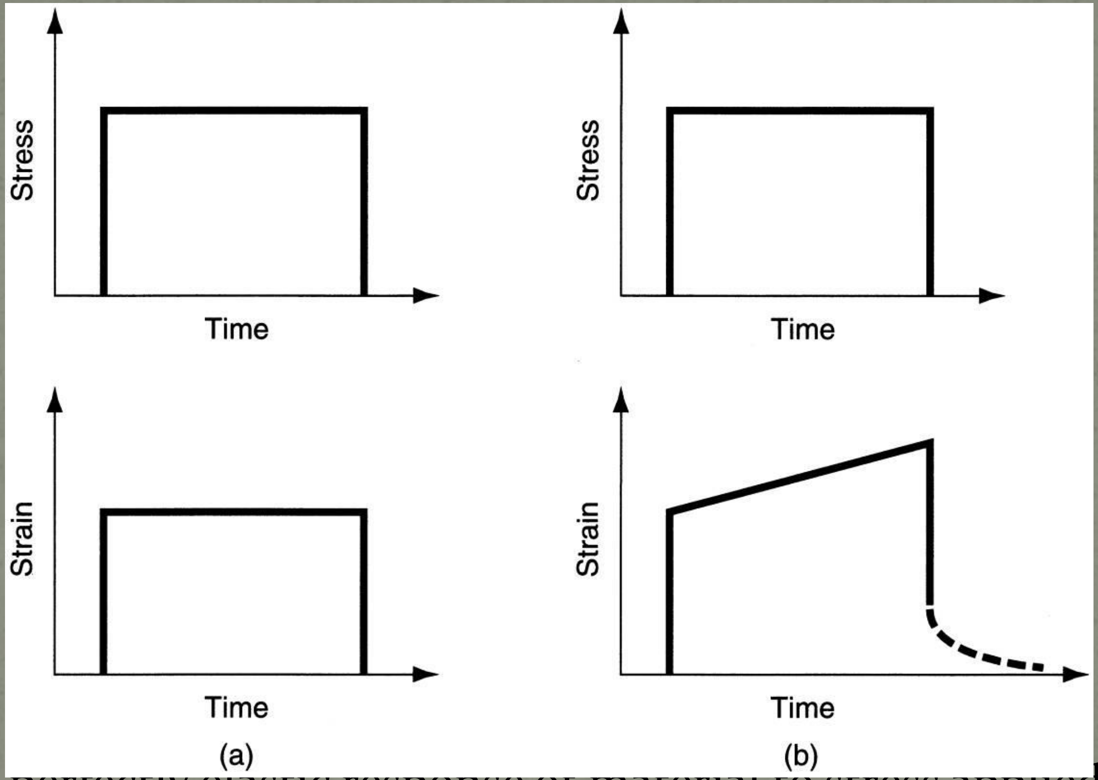


- Figure 3.18 Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.

Viscoelastic Behavior

- Material property that determines the strain that the material experiences when subjected to combinations of stress and temperature over time
- Combination of viscosity and elasticity

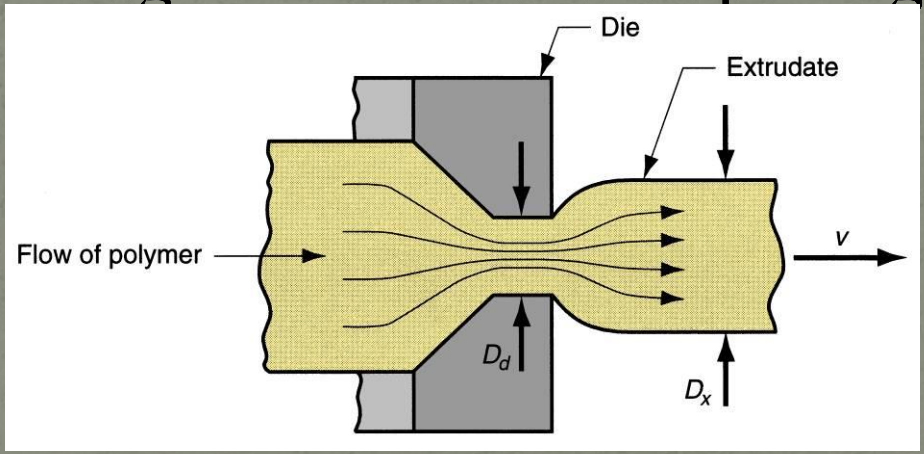
Elastic versus Viscoelastic Behavior



- Figure 3.19 (a) perfectly elastic response of material to stress applied over time; and (b) response of a viscoelastic material under same conditions. The material in (b) takes a strain that is a function of time and temperature.

Viscoelastic Behavior of Polymers: Shape Memory

- A problem in extrusion of polymers is *die swell*, in which the profile of extruded material grows in size, reflecting its tendency to return to its previously larger cross section in the extruder barrel immediately before being squeezed through the smaller die opening



Main Forming Processes

1. **Bulk deformation**
   - Rolling
   - Forging
   - Extrusion
   - Wire and bar drawing
2. **Sheet metalworking**
   - Bending
   - Deep drawing
   - Cutting
   - Miscellaneous processes

Rolling

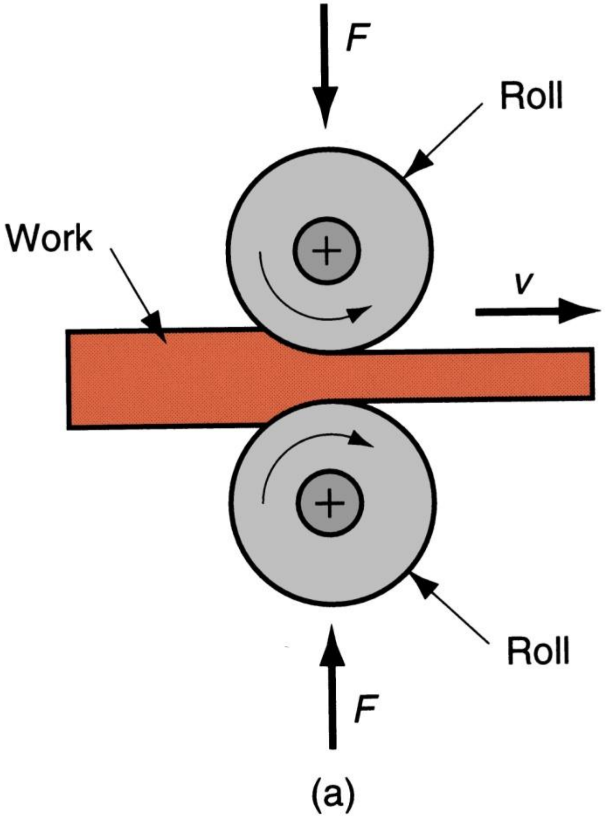


Figure 18.2 Basic bulk deformation processes: (a) rolling

Forging

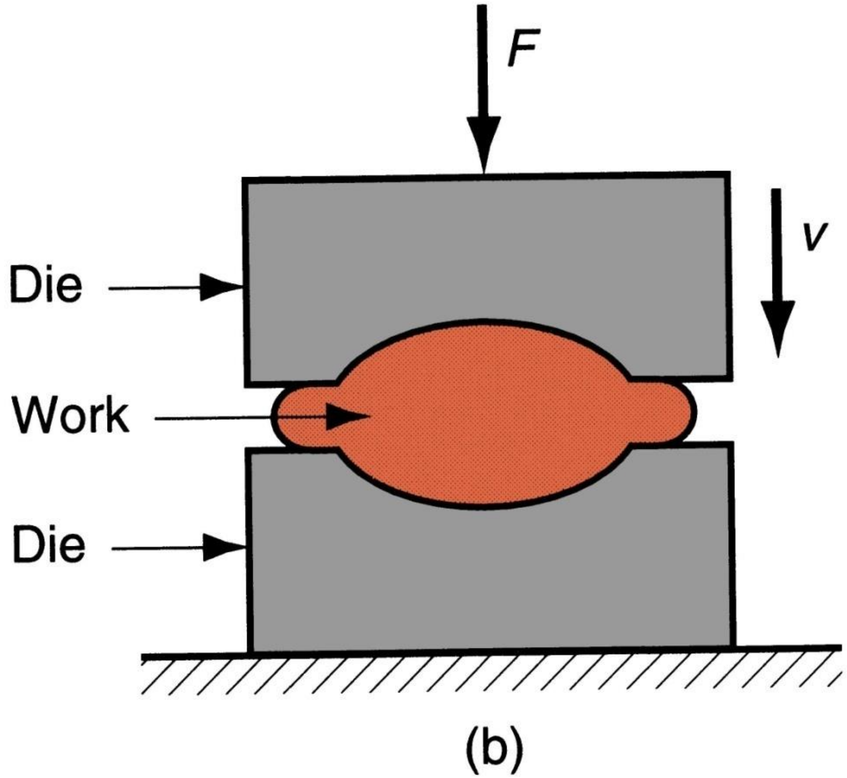


Figure 18.2 Basic bulk deformation processes: (b) forging

Extrusion

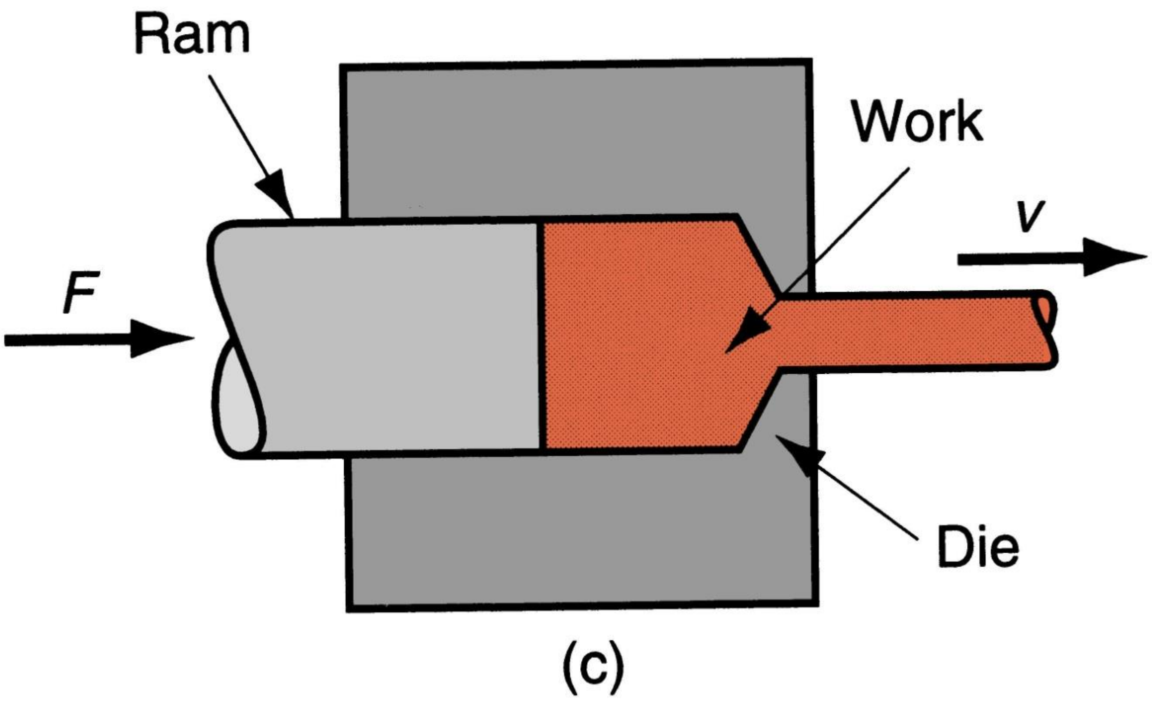


Figure 18.2 Basic bulk deformation processes: (c) extrusion

Wire and Bar Drawing

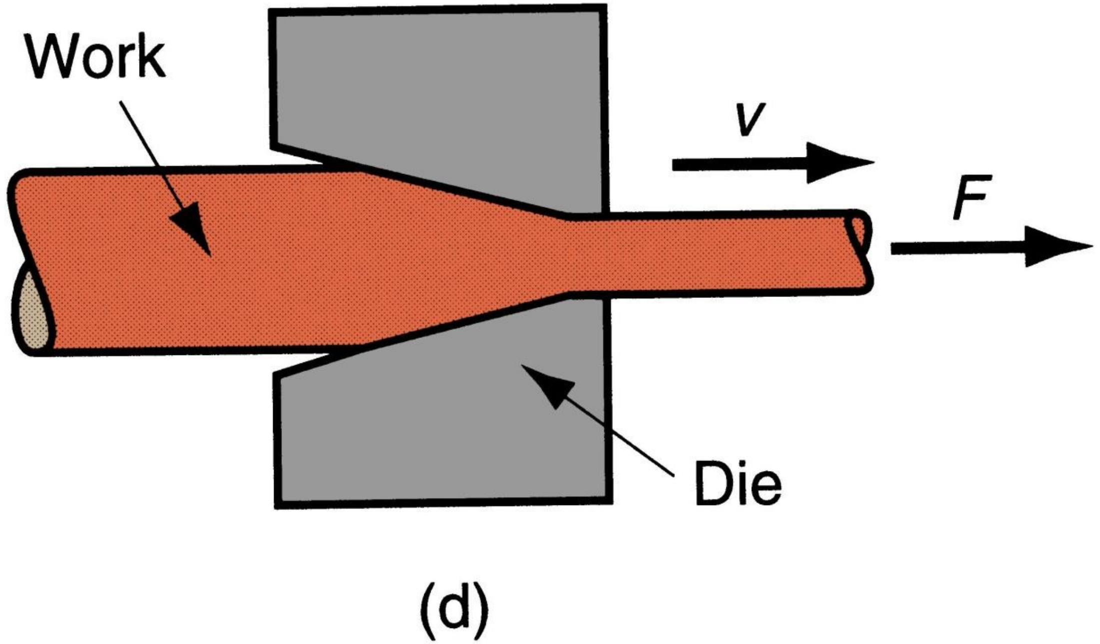


Figure 18.2 Basic bulk deformation processes: (d) drawing

- Forming and related operations performed on metal sheets, strips, and coils
- High surface area-to-volume ratio of starting metal, which distinguishes these from bulk deformation
- Often called *pressworking* because presses perform these operations
  - Parts are called *stampings*
  - Usual tooling: *punch* and *die*

Sheet Metal Bending

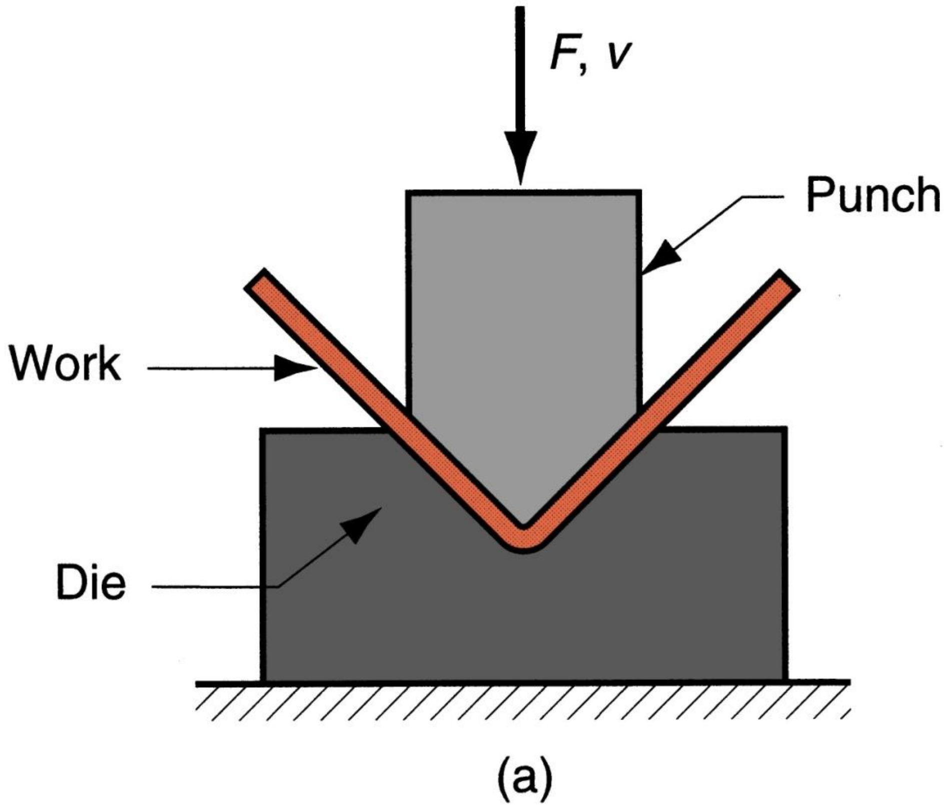


Figure 18.3 Basic sheet metalworking operations: (a) bending

Deep Drawing

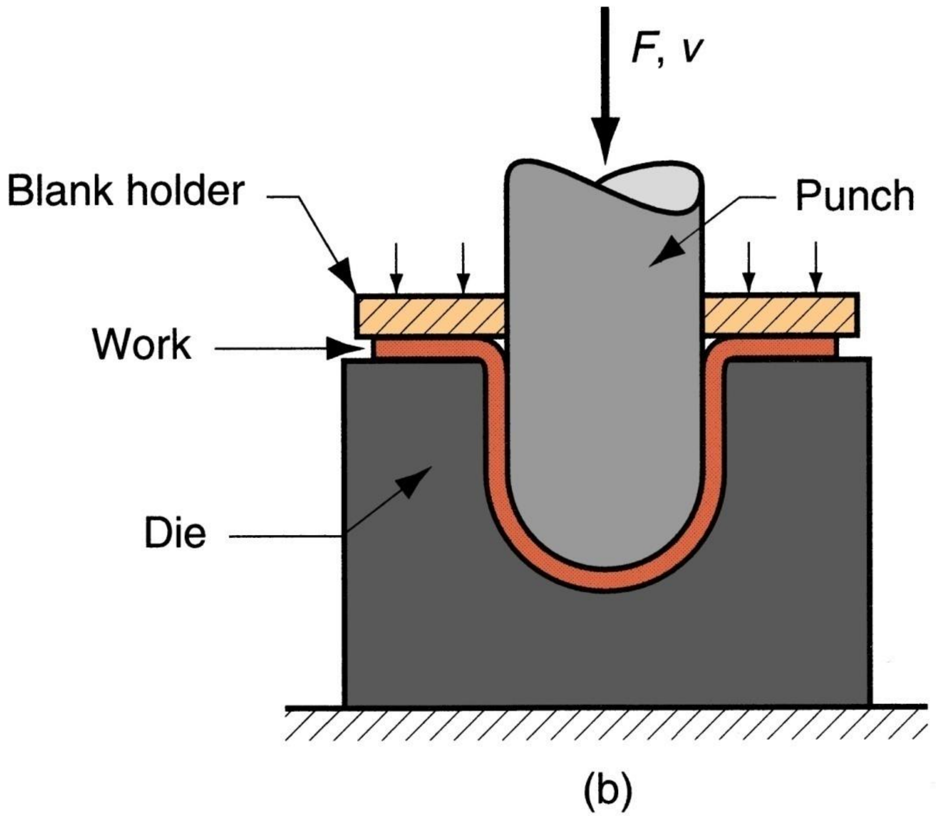


Figure 18.3 Basic sheet metalworking operations: (b) drawing

Shearing of Sheet Metal

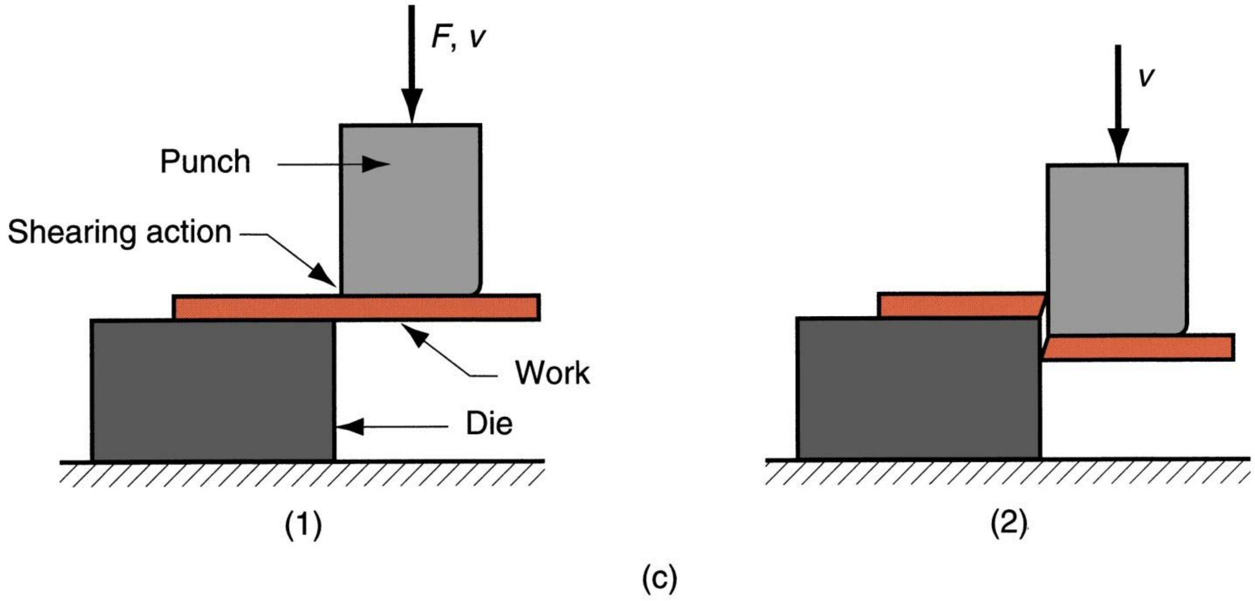


Figure 18.3 Basic sheet metalworking operations: (c) shearing

- Plastic region of stress-strain curve is primary interest because material is plastically deformed
- In plastic region, metal's behavior is expressed by the flow curve:

$$\sigma = K\varepsilon^n$$

where K = strength coefficient; and n = strain hardening exponent

- Flow curve based on true stress and true strain

- For most metals at room temperature, strength increases when deformed due to strain hardening
- *Flow stress* = instantaneous value of stress required to continue deforming the material

$$Y_f = K\varepsilon^n$$

where Y_f = flow stress, that is, the yield strength as a function of strain

- Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

where $\bar{Y}_f$ = average flow stress; and ε = maximum strain during deformation process

- For any metal, *K* and *n* in the flow curve depend on temperature
  - Both strength (*K*) and strain hardening (*n*) are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures

Temperature ranges in metal forming

(*Types of working based on temperature*)

- Any deformation operation can be accomplished with lower forces and power at elevated temperature
- Three temperature ranges in metal forming:
  - Cold working
  - Warm working
  - Hot working

Cold Working

- Performed at room temperature or slightly above
- Many cold forming processes are important mass production operations
- Minimum or no machining usually required
  - These operations are *near net shape* or *net shape* processes

Advantages of Cold Forming

- Better accuracy, closer tolerances
- Better surface finish
- Strain hardening increases strength and hardness
- Grain flow during deformation can cause desirable directional properties in product
- No heating of work required

Disadvantages of Cold Forming

- Higher forces and power required in the deformation operation
- Surfaces of starting workpiece must be free of scale and dirt
- Ductility and strain hardening limit the amount of forming that can be done
  - In some cases, metal must be annealed to allow further deformation
  - In other cases, metal is simply not ductile enough to be cold worked

Warm Working

- Performed at temperatures above room temperature but below recrystallization temperature
- Dividing line between cold working and warm working often expressed in terms of melting point:
  - $0.3T_m$, where T_m = melting point (absolute temperature) for metal

Advantages of Warm Working

- Lower forces and power than in cold working
- More intricate work geometries possible
- Need for annealing may be reduced or eliminated

Hot Working

- Deformation at temperatures above the *recrystallization temperature*
- Recrystallization temperature = about one-half of melting point on absolute scale
  - In practice, hot working usually performed somewhat above $0.5\,T_m$
  - Metal continues to soften as temperature increases above $0.5\,T_m$, enhancing advantage of hot working above this level

video

Why Hot Working?

Capability for substantial plastic deformation of the metal - far more than possible with cold working or warm working

- Why?
  - Strength coefficient (*K*) is substantially less than at room temperature
  - Strain hardening exponent (*n*) is zero (theoretically)
  - Ductility is significantly increased

Advantages of Hot Working

- Workpart shape can be significantly altered
- Lower forces and power required but?
- Metals that usually fracture in cold working can be hot formed
- Strength properties of product are generally isotropic
- No strengthening of part occurs from work hardening
  - Advantageous in cases when part is to be subsequently processed by cold forming

Disadvantages of Hot Working

- Lower dimensional accuracy
- Higher total energy required (due to the thermal energy to heat the workpiece)
- Work surface oxidation (scale), poorer surface finish
- Shorter tool life

Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent $n = 0$
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures: Strain rate sensitivity

What is Strain Rate?

- Strain rate in forming is directly related to speed of deformation *v*
- Deformation speed *v* = velocity of the ram or other movement of the equipment
- *Strain rate* is defined:

$$\dot{\varepsilon} = \frac{v}{h}$$

where:

$\dot{\varepsilon}$ = true strain rate; and

h = instantaneous height of workpiece being deformed

Evaluation of Strain Rate

- In most practical operations, valuation of strain rate is complicated by
  - Workpart geometry
  - Variations in strain rate in different regions of the part
- Strain rate can reach 1000 s^{-1} or more for some metal forming operations.

Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature
- At hot working temperatures, flow stress also depends on strain rate
  - As strain rate increases, resistance to deformation increases
  - This effect is known as strain-rate sensitivity

Strain Rate Sensitivity

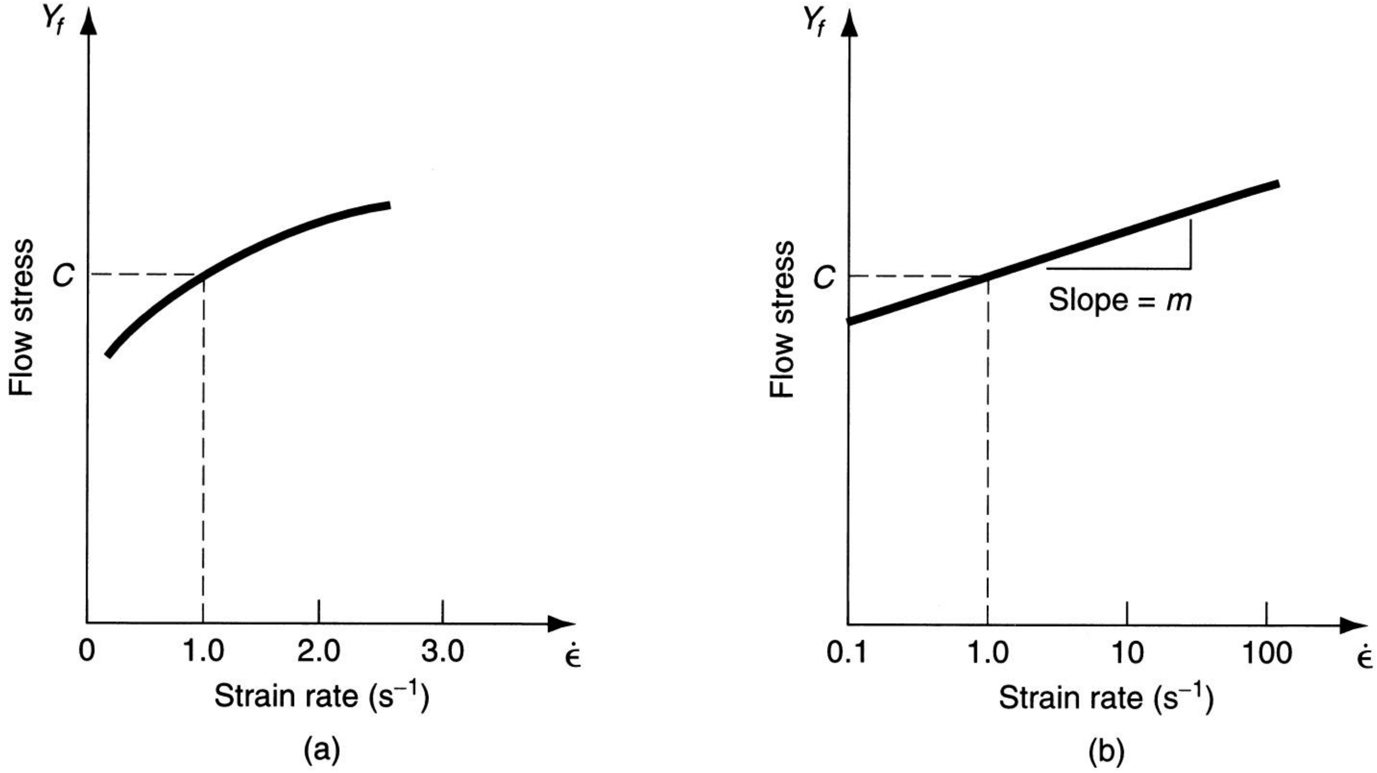


Figure 18.5 (a) Effect of strain rate on flow stress at an elevated work temperature. (b) Same relationship plotted on log-log coordinates.

Strain Rate Sensitivity Equation

$$Y_f = C\dot{\varepsilon}^m$$

where C = strength constant (similar but not equal to strength coefficient in flow curve equation), and m = strain-rate sensitivity exponent

Effect of Temperature on Flow Stress

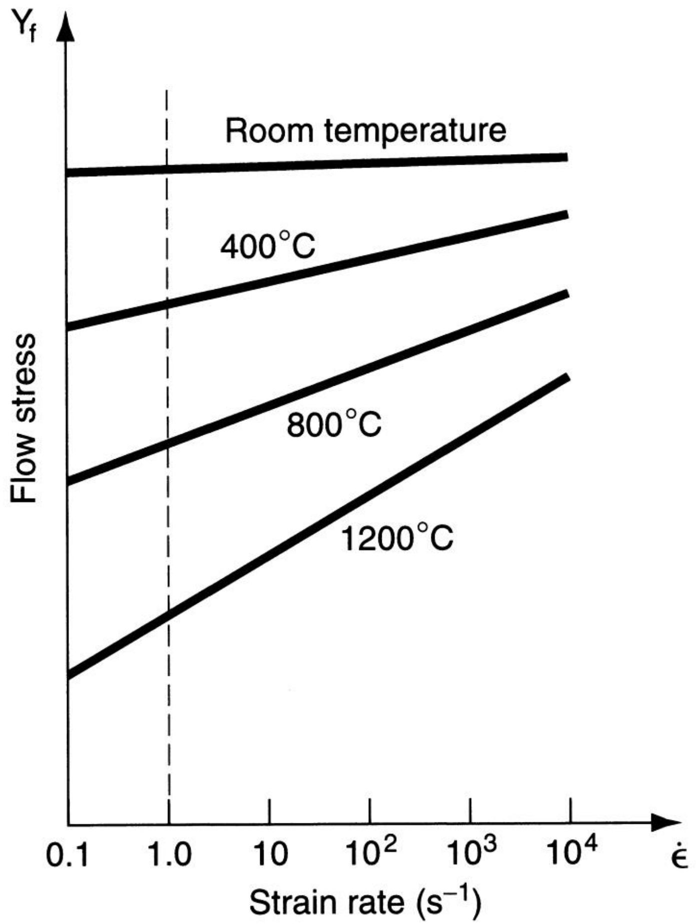


Figure 18.6 Effect of temperature on flow stress for a typical metal. The constant *C*, as indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and *m* (slope of each plot) increases with increasing temperature.

Observations about Strain Rate Sensitivity

- Increasing temperature decreases *C* and increases *m*
  - At room temperature, effect of strain rate is almost negligible
    - Flow curve is a good representation of material behavior
  - As temperature increases, strain rate becomes increasingly important in determining flow stress

Friction in Metal Forming

- In most metal forming processes, friction is undesirable:
  - Metal flow is retarded
  - Forces and power are increased
  - Tooling wears faster
- Friction and tool wear are more severe in hot working

Lubrication in Metal Forming

- Metalworking lubricants are applied to tool-work interface in many forming operations to reduce harmful effects of friction
- Benefits:
  - Reduced sticking, forces, power, tool wear
  - Better surface finish
  - Removes heat from the tooling

Considerations in Choosing a Lubricant

- Type of forming process (rolling, forging, sheet metal drawing, etc.)
- Hot working or cold working
- Work material
- Chemical reactivity with tool and work metals
- Ease of application
- Cost

BULK DEFORMATION PROCESSES IN METALWORKING

1. Rolling
2. Other Deformation Processes Related to Rolling
3. Forging
4. Other Deformation Processes Related to Forging
5. Extrusion
6. Wire and Bar Drawing
7. Deep Drawing

Bulk Deformation

Metal forming operations which cause significant shape change by deforming metal parts whose initial form is bulk rather than sheet

- Starting forms:
  - Cylindrical bars and billets,
  - Rectangular billets and slabs, and similar shapes
- These processes stress metal sufficiently to cause plastic flow into desired shape
- Performed as cold, warm, and hot working operations

Importance of Bulk Deformation

- In hot working, significant shape change can be accomplished
- In cold working, strength is increased during shape change
- Little or no waste - some operations are *near net shape* or *net shape* processes
  - The parts require little or no subsequent machining

Four Basic Bulk Deformation Processes

1. Rolling – slab or plate is squeezed between opposing rolls
2. Forging – work is squeezed and shaped between opposing dies
3. Extrusion – work is squeezed through a die opening, thereby taking the shape of the opening
4. Wire and bar drawing – diameter of wire or bar is reduced by pulling it through a die opening

Rolling

Deformation process in which work thickness is reduced by compressive forces exerted by two opposing rolls

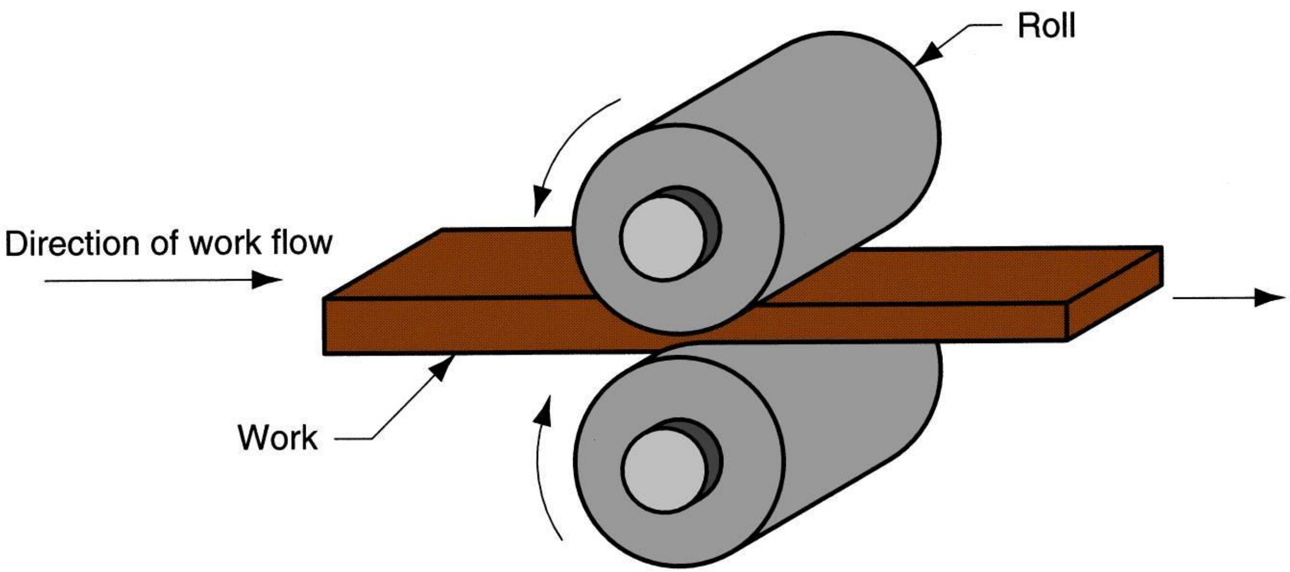


Figure 19.1 The rolling process (specifically, flat rolling).

The Rolls

Rotating rolls perform two main functions:

- Pull the work into the gap between them by friction between workpart and rolls
- Simultaneously squeeze the work to reduce its cross section

Types of Rolling

- Based on workpiece geometry :
  - Flat rolling - used to reduce thickness of a rectangular cross section
  - Shape rolling - square cross section is formed into a shape such as an I-beam
- Based on work temperature :
  - Hot Rolling – most common due to the large amount of deformation required
  - Cold rolling – produces finished sheet and plate stock

Rolled Products Made of Steel

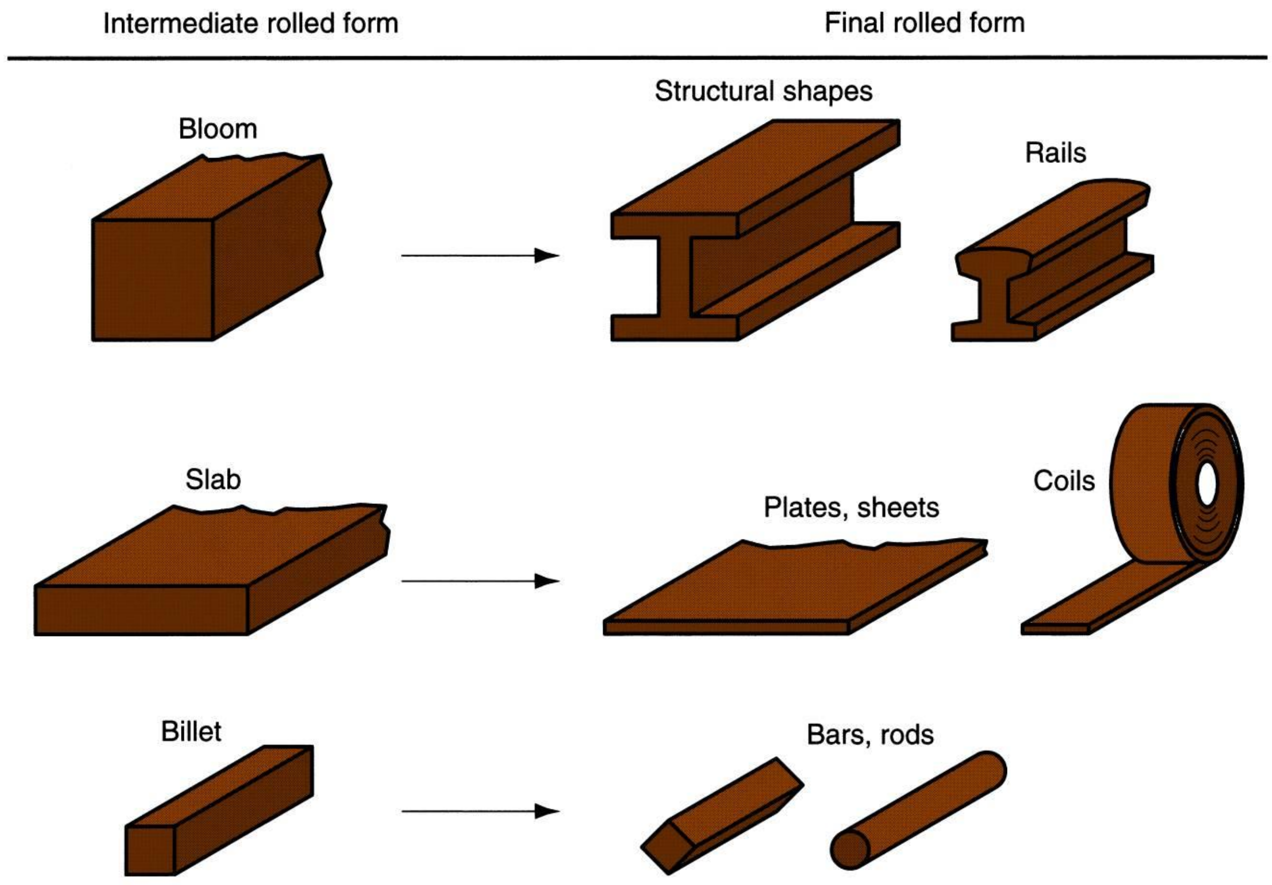


Figure 19.2 Some of the steel products made in a rolling mill.

Diagram of Flat Rolling

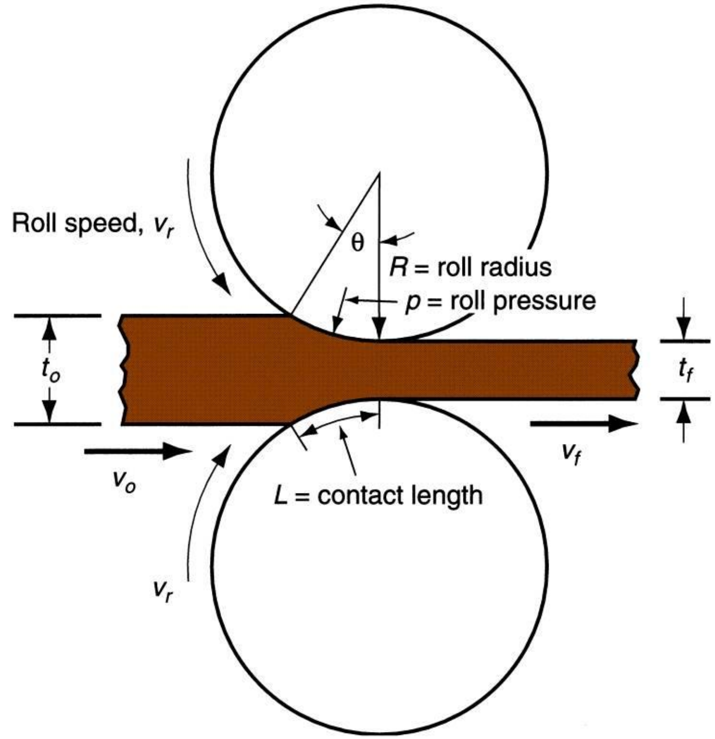


Figure 19.3 Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features.

Flat Rolling Terminology

Draft = amount of thickness reduction

$$d = t_o - t_f$$

where d = draft; t_o = starting thickness; and t_f = final thickness

Flat Rolling Terminology

Reduction = draft expressed as a fraction of starting stock thickness:

$$r = \frac{d}{t_o}$$

where r = reduction

Shape Rolling

Work is deformed into a contoured cross section rather than flat (rectangular)

- Accomplished by passing work through rolls that have the reverse of desired shape
- Products include:
  - Construction shapes such as I-beams, L-beams, and U-channels
  - Rails for railroad tracks
  - Round and square bars and rods

A rolling mill for hot flat rolling. The steel plate is seen as the glowing strip in lower left corner (photo courtesy of Bethlehem Steel).

Rolling Mills

- Equipment is massive and expensive
- Rolling mill configurations:
  - Two-high – two opposing rolls
  - Three-high – work passes through rolls in both directions
  - Four-high – backing rolls support smaller work rolls
  - Cluster mill – multiple backing rolls on smaller rolls
  - Tandem rolling mill – sequence of two-high mills

Two-High Rolling Mill

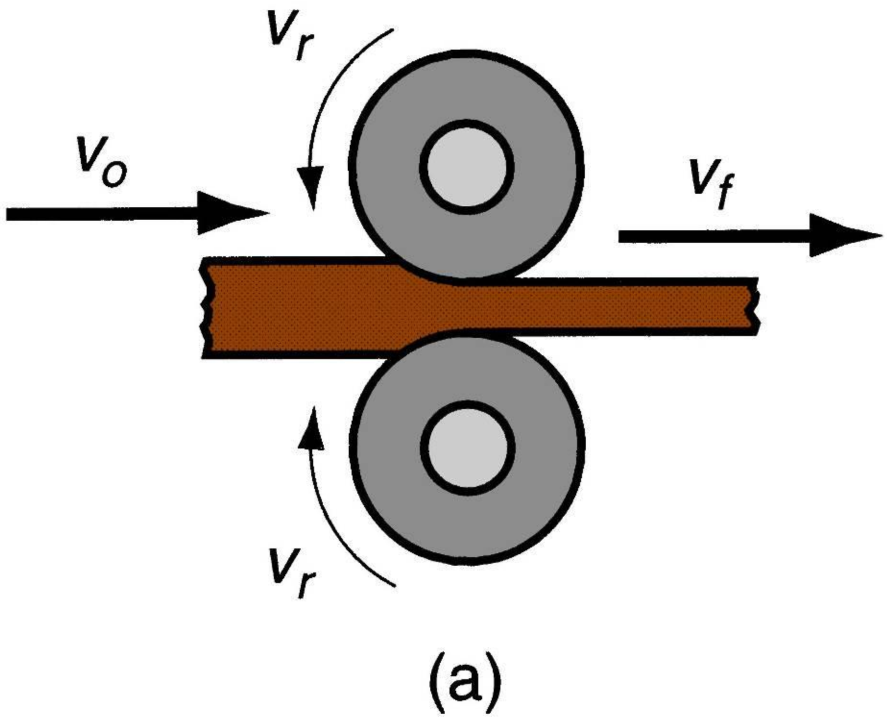


Figure 19.5 Various configurations of rolling mills: (a) 2-high rolling mill.

Three-High Rolling Mill

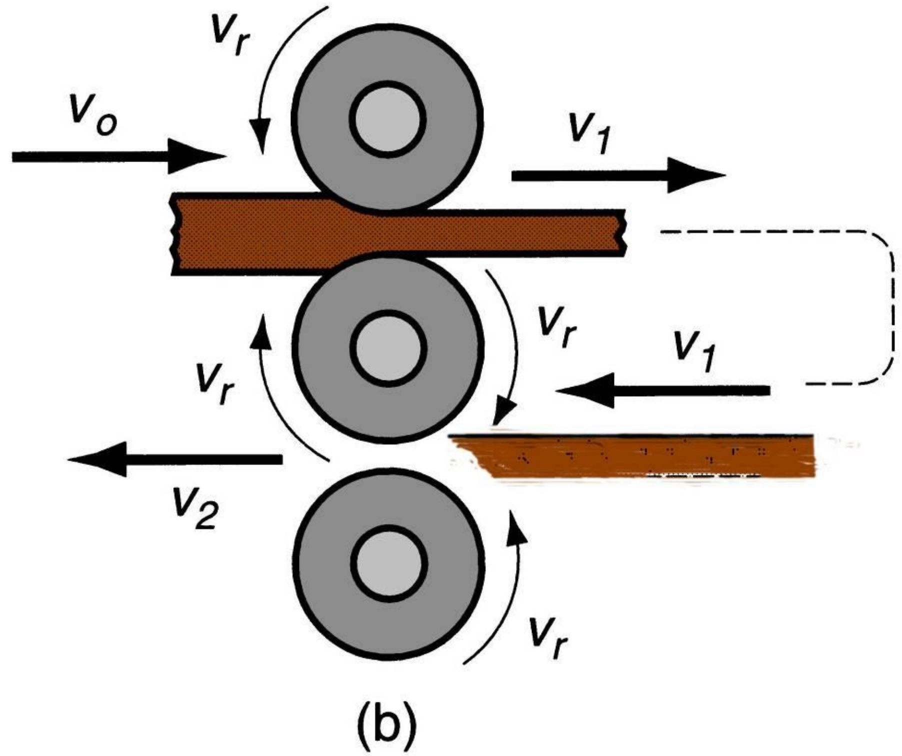


Figure 19.5 Various configurations of rolling mills: (b) 3-high rolling mill.

Four-High Rolling Mill

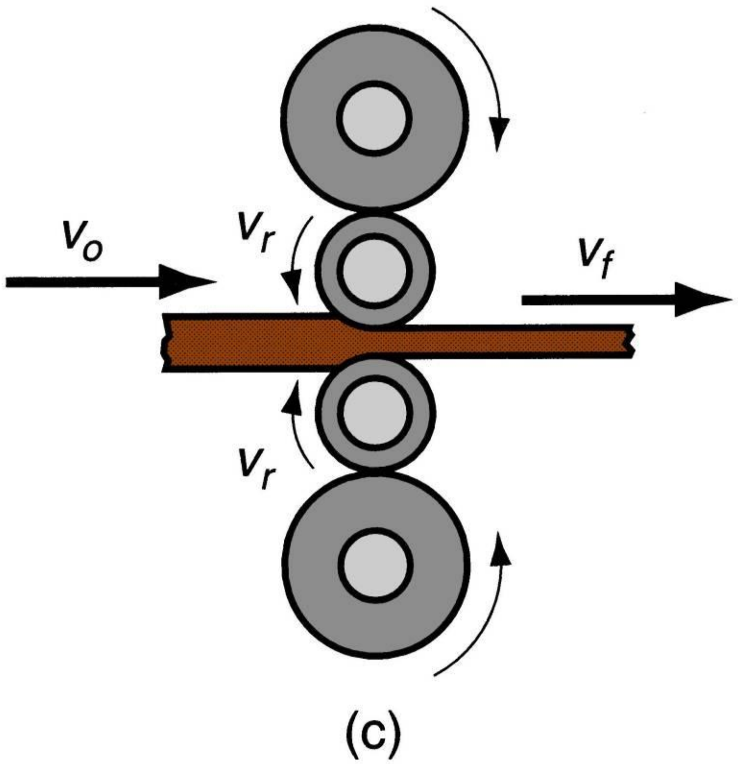


Figure 19.5 Various configurations of rolling mills: (c) four-high rolling mill.

Cluster Mill

Multiple backing rolls allow even smaller roll diameters

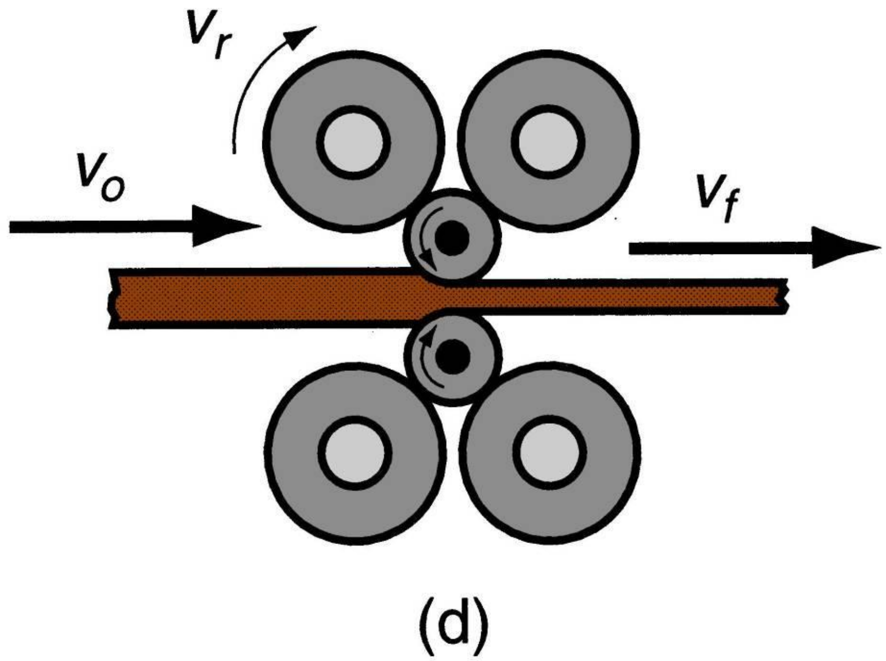


Figure 19.5 Various configurations of rolling mills: (d) cluster mill

Tandem Rolling Mill

A series of rolling stands in sequence

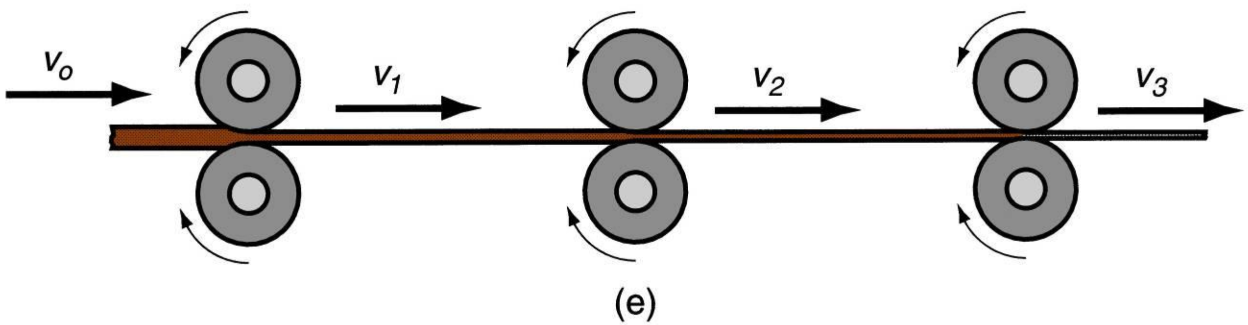


Figure 19.5 Various configurations of rolling mills: (e) tandem rolling mill.

Thread Rolling

Bulk deformation process used to form threads on cylindrical parts by rolling them between two dies

- Important commercial process for mass producing bolts and screws
- Performed by cold working in thread rolling machines
- Advantages over thread cutting (machining):
    - Higher production rates
    - Better material utilization
    - Stronger threads and better fatigue resistance due to work hardening

Thread Rolling

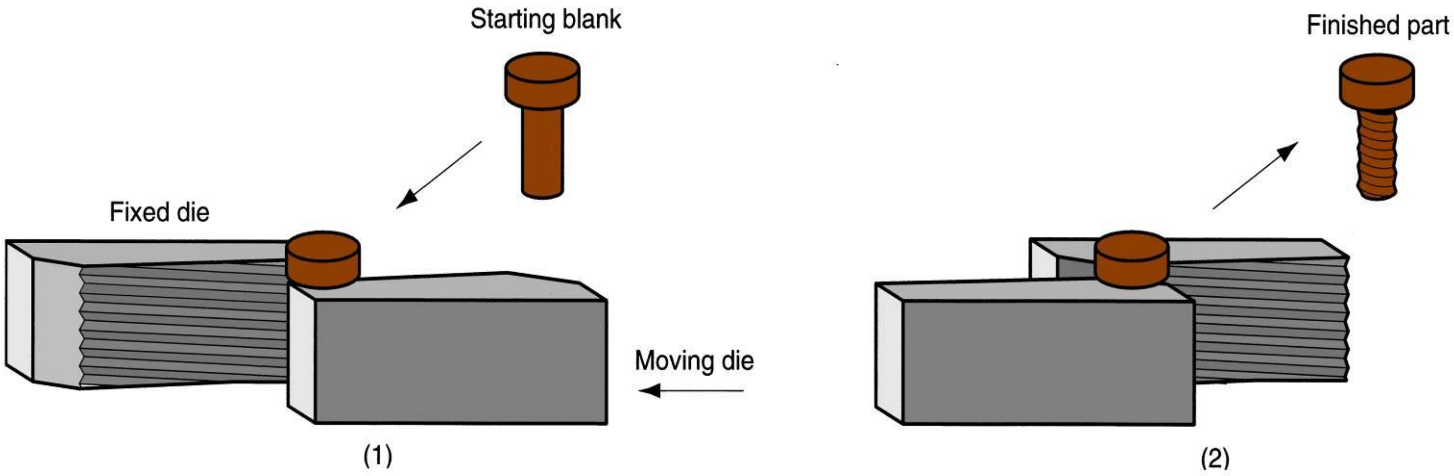


Figure 19.6 Thread rolling with flat dies: (1) start of cycle, and (2) end of cycle.

Ring Rolling

Deformation process in which a thick-walled ring of smaller diameter is rolled into a thin-walled ring of larger diameter

- As thick-walled ring is compressed, deformed metal elongates, causing diameter of ring to be enlarged
- Hot working process for large rings and cold working process for smaller rings
- Applications: ball and roller bearing races, steel tires for railroad wheels, and rings for pipes, pressure vessels, and rotating machinery
- Advantages: material savings, ideal grain orientation, strengthening through cold working

Ring Rolling

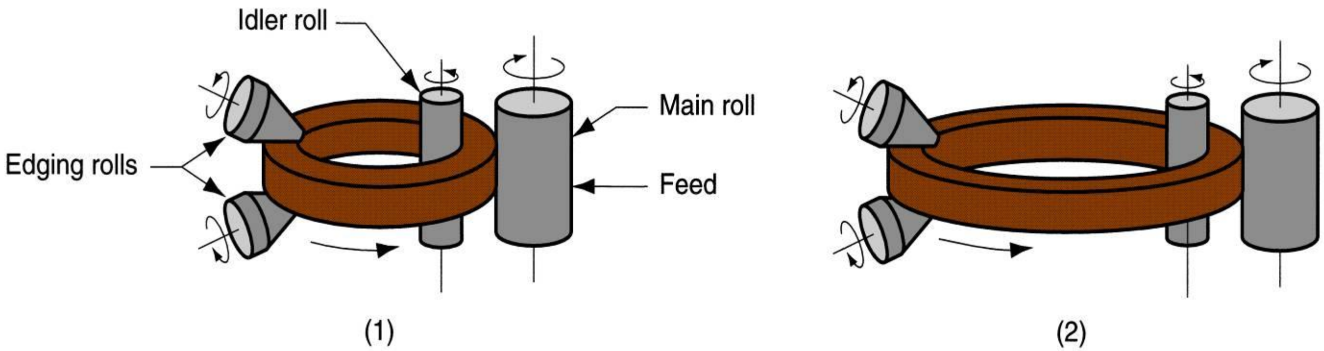


Figure 19.7 Ring rolling used to reduce the wall thickness and increase the diameter of a ring: (1) start, and (2) completion of process.

Forging

Deformation process in which work is compressed between two dies

- Oldest of the metal forming operations, dating from about 5000 B C
- Components: engine crankshafts, connecting rods, gears, aircraft structural components, jet engine turbine parts
- Also, basic metals industries use forging to establish basic form of large parts that are subsequently machined to final shape and size

Classification of Forging Operations

- Cold vs. hot forging:
  - Hot or warm forging – most common, due to the significant deformation and the need to reduce strength and increase ductility of work metal
  - Cold forging – advantage: increased strength that results from strain hardening
- Impact vs. press forging:
  - Forge hammer - applies an impact load
  - Forge press - applies gradual pressure

Types of Forging Dies

- Open-die forging - work is compressed between two flat dies, allowing metal to flow laterally with minimum constraint
- Impression-die forging - die contains cavity or impression that is imparted to workpart
  - Metal flow is constrained so that flash is created
- Flashless forging - workpart is completely constrained in die
  - No excess flash is created

Open-Die Forging

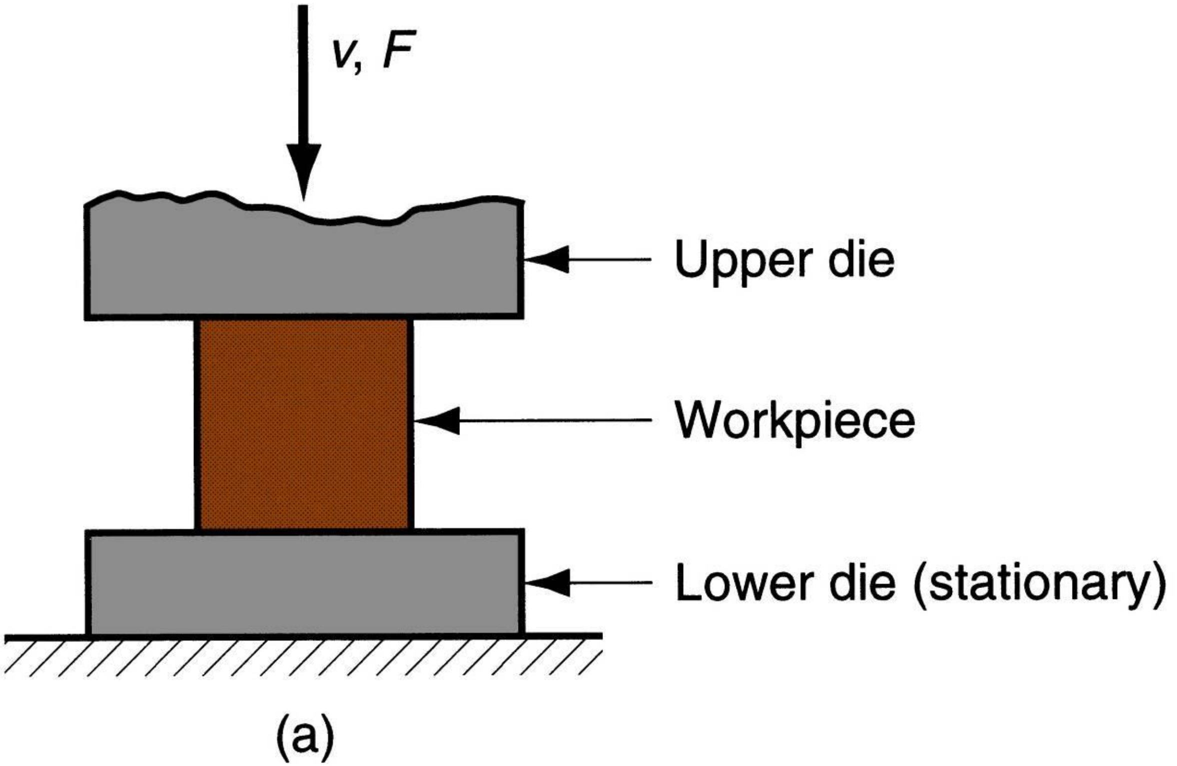


Figure 19.9 Three types of forging: (a) open-die forging.

Impression-Die Forging

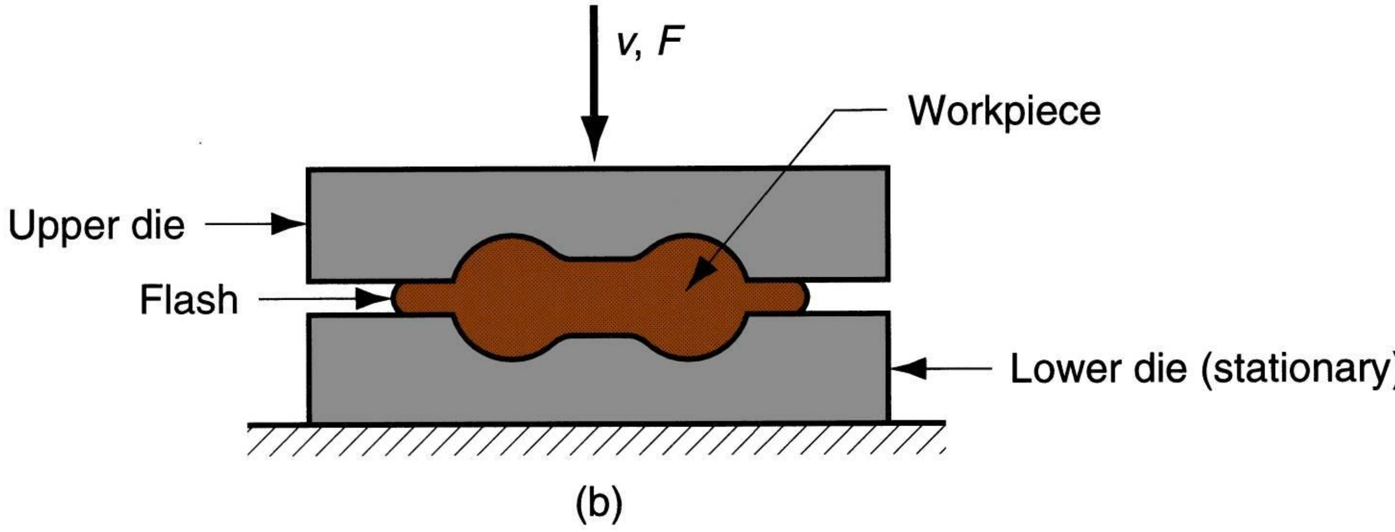


Figure 19.9 Three types of forging: (b) impression-die forging.

Flashless Forging

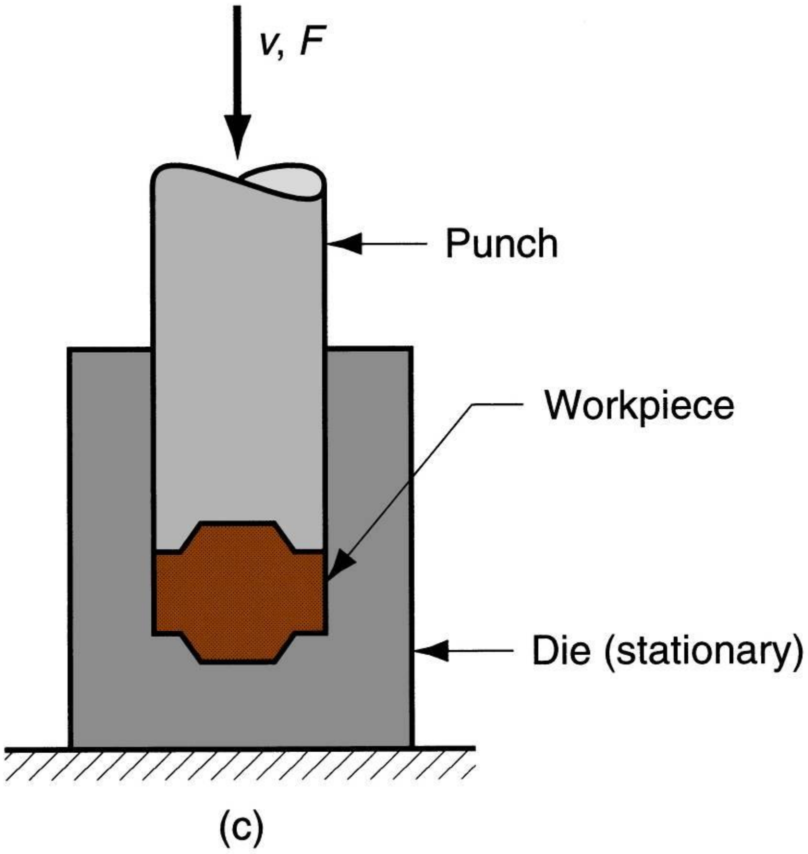


Figure 19.9 Three types of forging (c) flashless forging.

Open-Die Forging

Compression of workpart between two flat dies

- Similar to compression test when workpart has cylindrical cross section and is compressed along its axis
  - Deformation operation reduces height and increases diameter of work
  - Common names include *upsetting* or *upset forging*

Open-Die Forging with No Friction

If no friction occurs between work and die surfaces, then homogeneous deformation occurs, so that radial flow is uniform throughout workpart height and true strain is given by:

$$\varepsilon = \ln \frac{h_o}{h}$$

where h_o = starting height; and h = height at some point during compression

- At h = final value h_f, true strain is maximum value

Open-Die Forging with No Friction

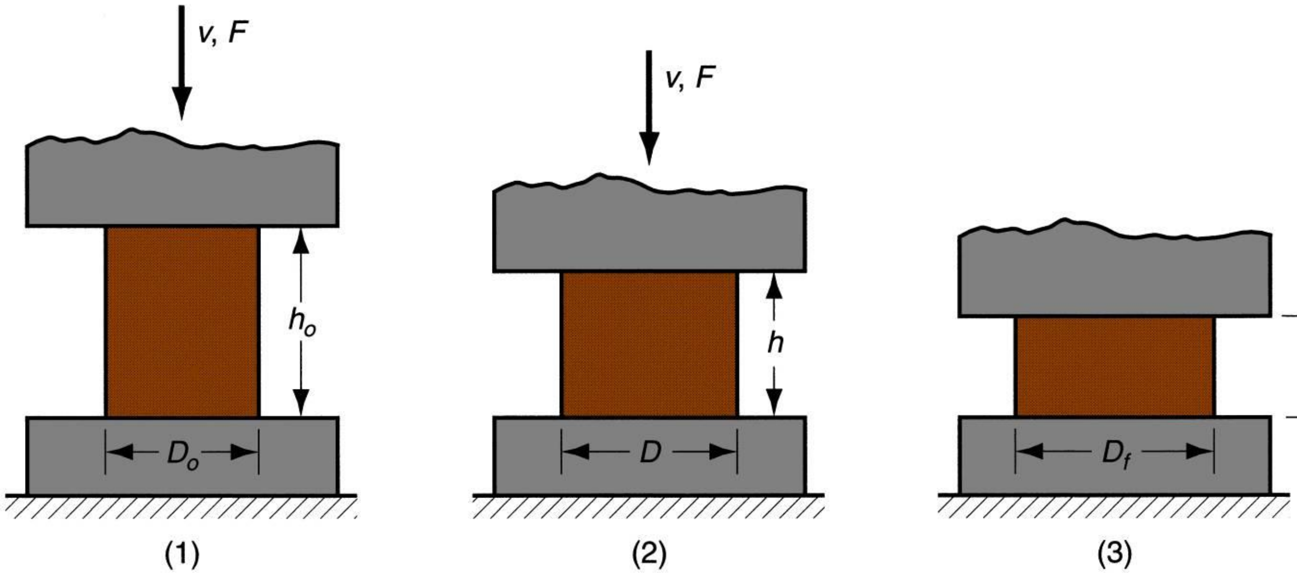


Figure 19.10 Homogeneous deformation of a cylindrical workpart under ideal conditions in an open-die forging operation: (1) start of process with workpiece at its original length and diameter, (2) partial compression, and (3) final size.

Open-Die Forging with Friction

- Friction between work and die surfaces constrains lateral flow of work, resulting in barreling effect
- In hot open-die forging, effect is even more pronounced due to heat transfer at and near die surfaces, which cools the metal and increases its resistance to deformation

Open-Die Forging with Friction

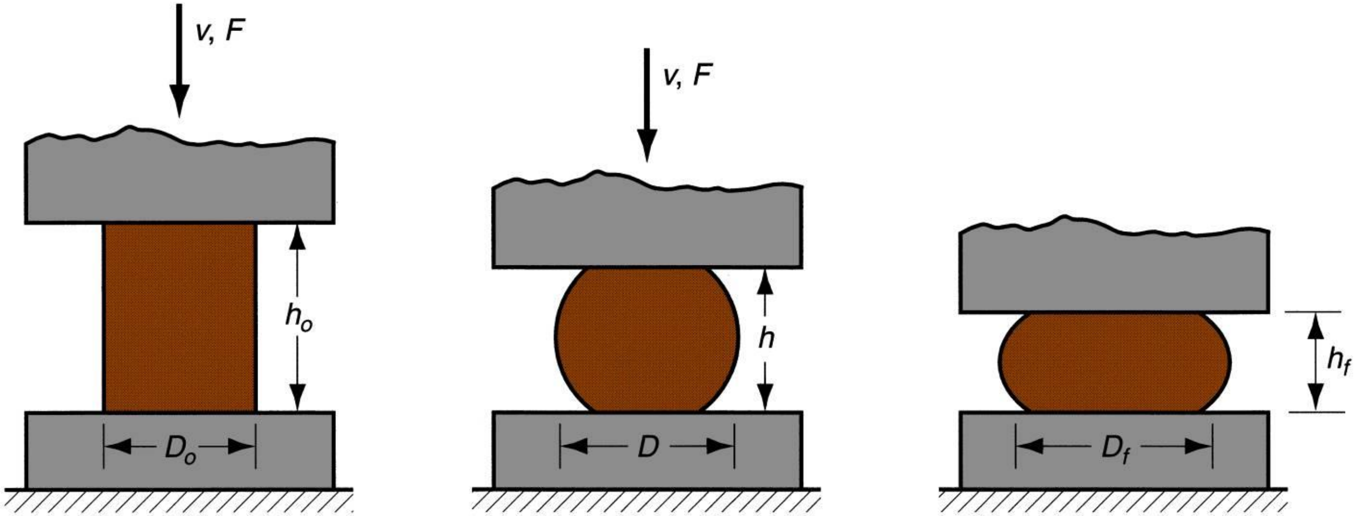


Figure 19.11 Actual deformation of a cylindrical workpart in open-die forging, showing pronounced *barreling*: (1) start of process, (2) partial deformation, and (3) final shape.

Impression-Die Forging

Compression of workpart by dies with inverse of desired part shape

- Flash is formed by metal that flows beyond die cavity into small gap between die plates
- Flash must be later trimmed, but it serves an important function during compression:
  - As flash forms, friction resists continued metal flow into gap, constraining material to fill die cavity
  - In hot forging, metal flow is further restricted by cooling against die plates

Impression-Die Forging

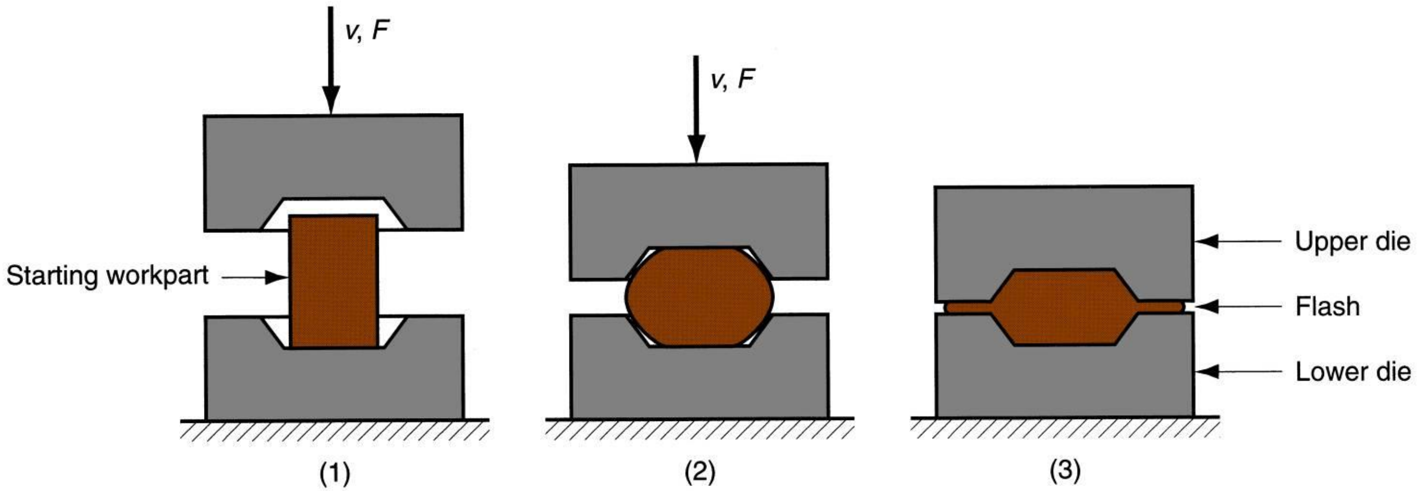


Figure 19.14 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

Impression-Die Forging Practice

- Several forming steps often required, with separate die cavities for each step
  - Beginning steps redistribute metal for more uniform deformation and desired metallurgical structure in subsequent steps
  - Final steps bring the part to final geometry
- Impression-die forging is often performed manually by skilled operator under adverse conditions

Advantages and Limitations

- Advantages of impression-die forging compared to machining from solid stock:
  - Higher production rates
  - Less waste of metal
  - Greater strength
  - Favorable grain orientation in the metal
- Limitations:
  - Not capable of close tolerances
  - Machining often required to achieve accuracies and features needed

Flashless Forging

Compression of work in punch and die tooling whose cavity does not allow for flash

- Starting workpart volume must equal die cavity volume within very close tolerance
- Process control more demanding than impression-die forging
- Best suited to part geometries that are simple and symmetrical
- Often classified as a *precision forging* process

Flashless Forging

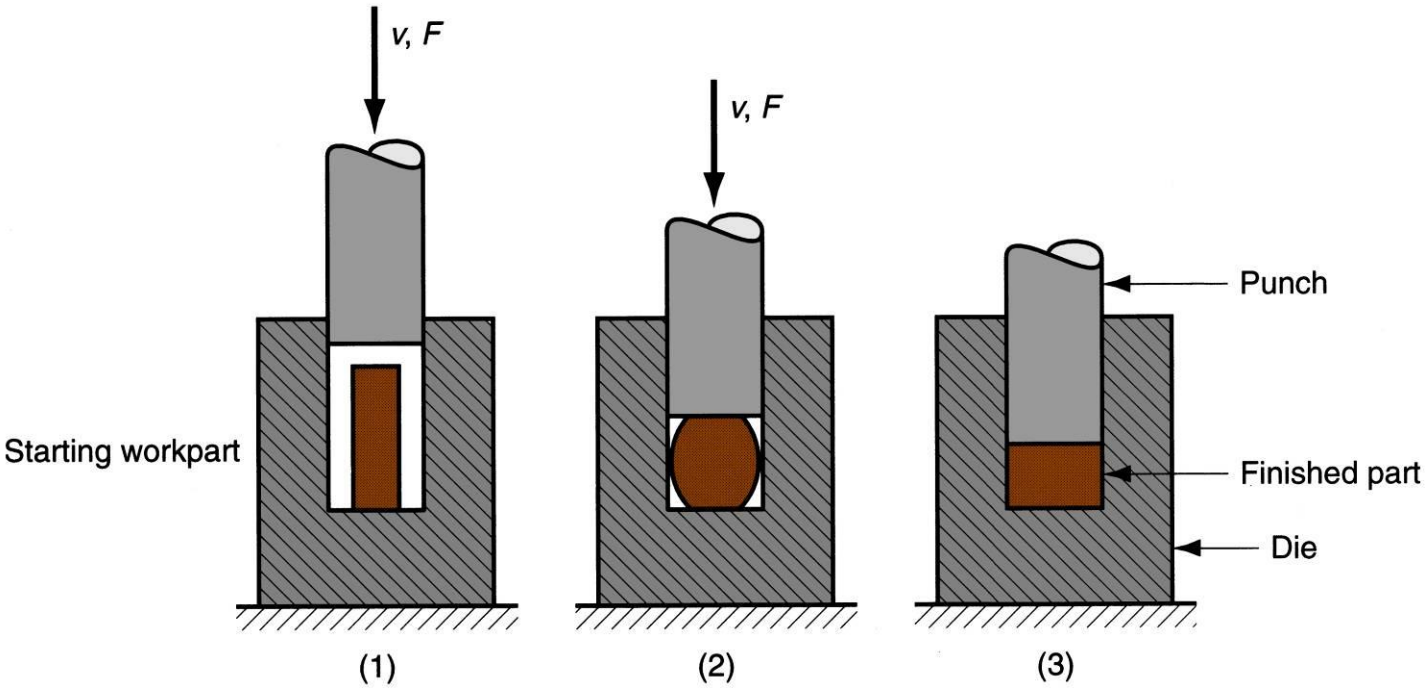


Figure 19.17 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure.

Forging Hammers (Drop Hammers)

Apply impact load against workpart

- Two types:
  - Gravity drop hammers - impact energy from falling weight of a heavy ram
  - Power drop hammers - accelerate the ram by pressurized air or steam
- Disadvantage: impact energy transmitted through anvil into floor of building
- Commonly used for impression-die forging

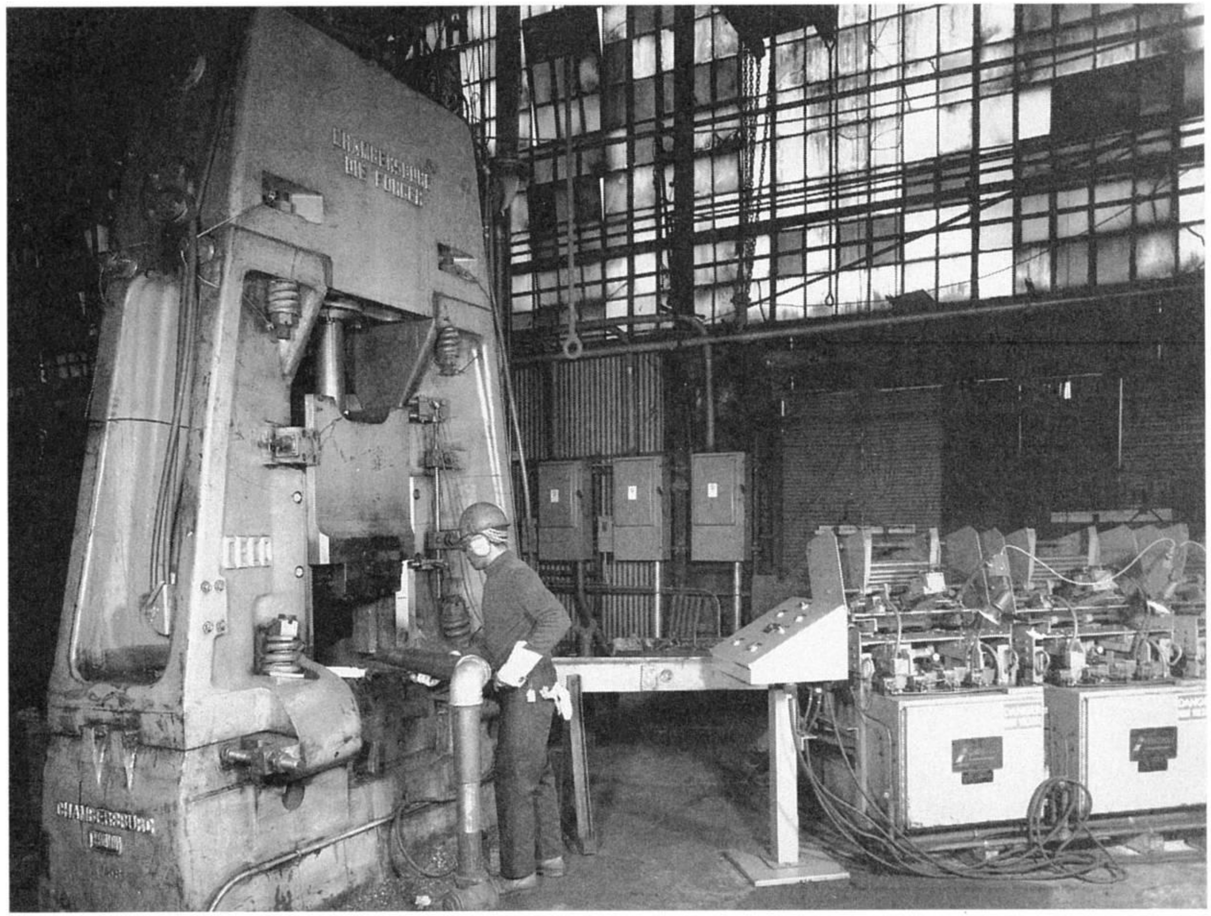


Figure 19.19 Drop forging hammer, fed by conveyor and heating units at the right of the scene (photo courtesy of Chambersburg Engineering Company).

Drop Hammer Details

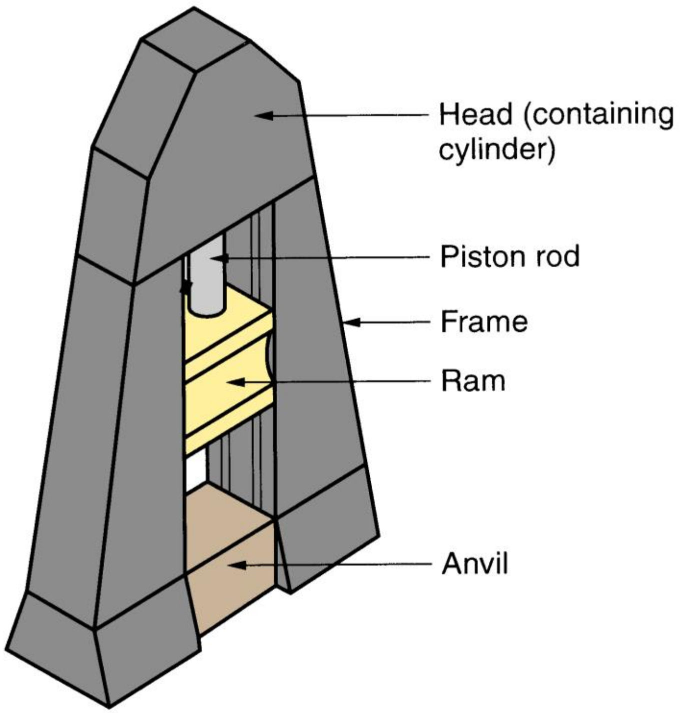


Figure 19.20 Diagram showing details of a drop hammer for impression-die forging.

Forging Presses

- Apply gradual pressure to accomplish compression operation
- Types:
  - Mechanical press - converts rotation of drive motor into linear motion of ram
  - Hydraulic press - hydraulic piston actuates ram
  - Screw press - screw mechanism drives ram

Upsetting and Heading

Forging process used to form heads on nails, bolts, and similar hardware products

- More parts produced by upsetting than any other forging operation
- Performed cold, warm, or hot on machines called *headers* or *formers*
- Wire or bar stock is fed into machine, end is headed, then piece is cut to length
- For bolts and screws, thread rolling is then used to form threads

Upset Forging

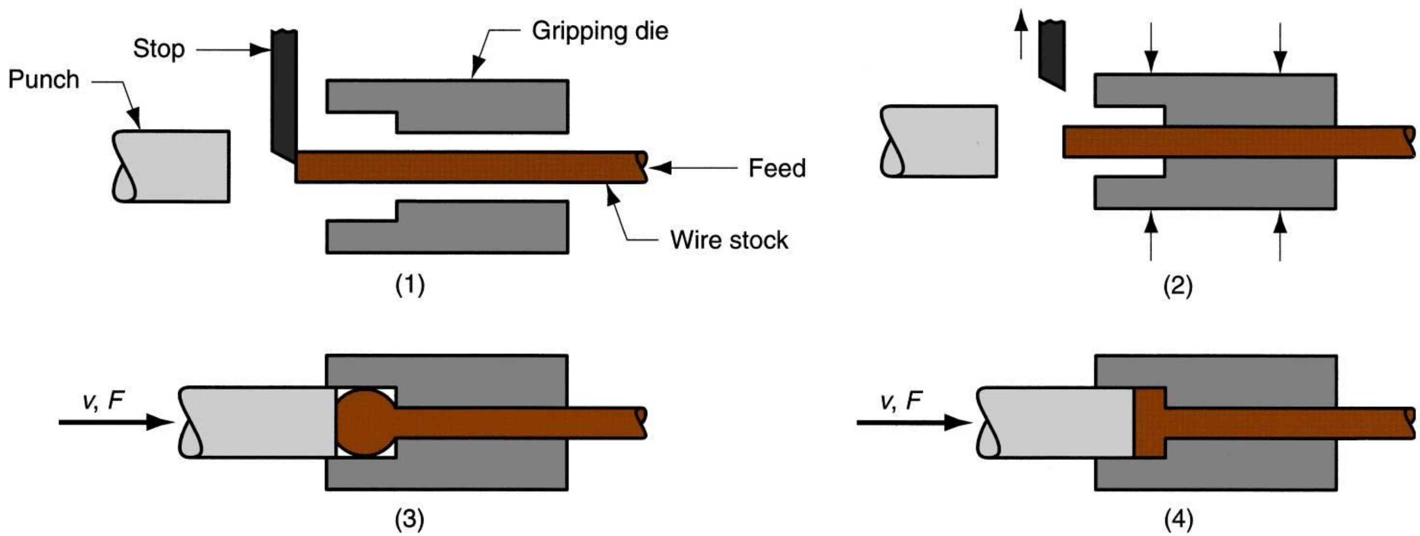


Figure 19.22 An upset forging operation to form a head on a bolt or similar hardware item The cycle consists of: (1) wire stock is fed to the stop, (2) gripping dies close on the stock and the stop is retracted, (3) punch moves forward, (4) bottoms to form the head.

Heading (Upset Forging)

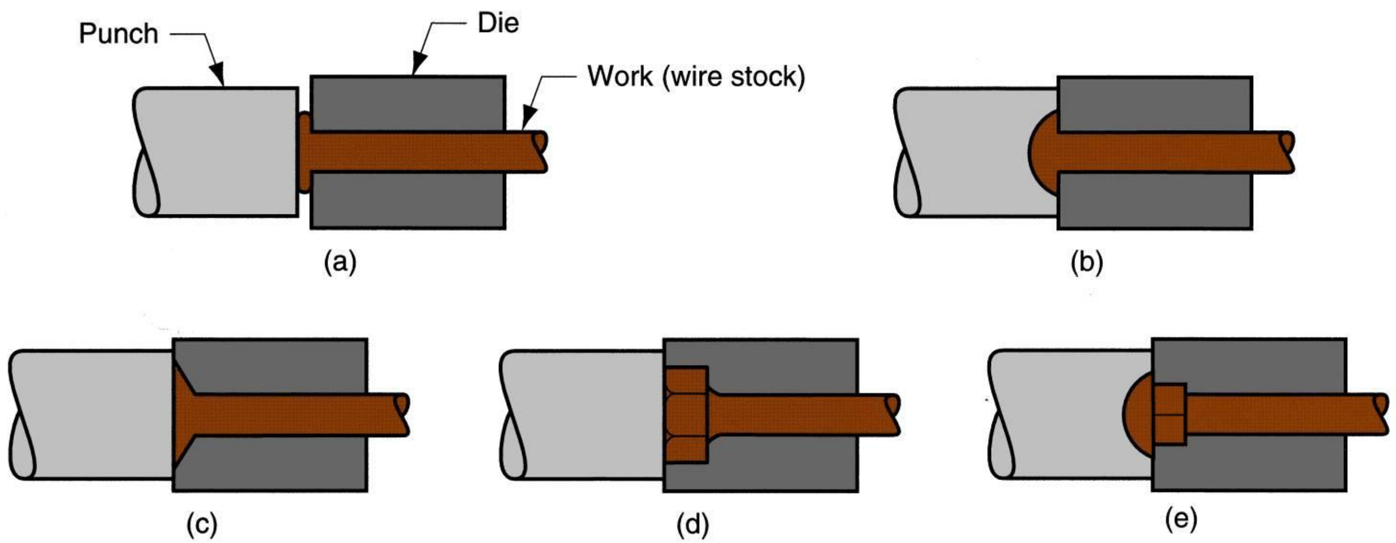


Figure 19.23 Examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c) and (d) two common head styles for screws formed by die, (e) carriage bolt head formed by punch and die.

Swaging

Accomplished by rotating dies that hammer a workpiece radially inward to taper it as the piece is fed into the dies

- Used to reduce diameter of tube or solid rod stock
- Mandrel sometimes required to control shape and size of internal diameter of tubular parts

Swaging

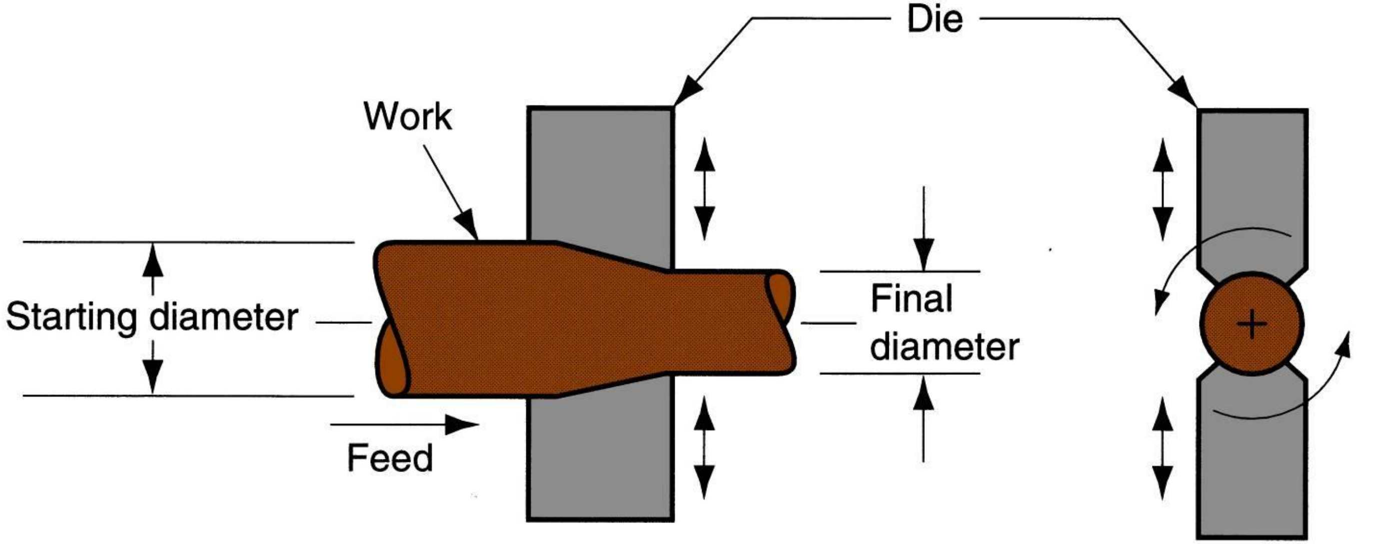


Figure 19.24 Swaging process to reduce solid rod stock; the dies rotate as they hammer the work In radial forging, the workpiece rotates while the dies remain in a fixed orientation as they hammer the work.

Trimming

Cutting operation to remove flash from workpart in impression-die forging

- Usually done while work is still hot, so a separate trimming press is included at the forging station
- Trimming can also be done by alternative methods, such as grinding or sawing

Trimming After Impression-Die Forging

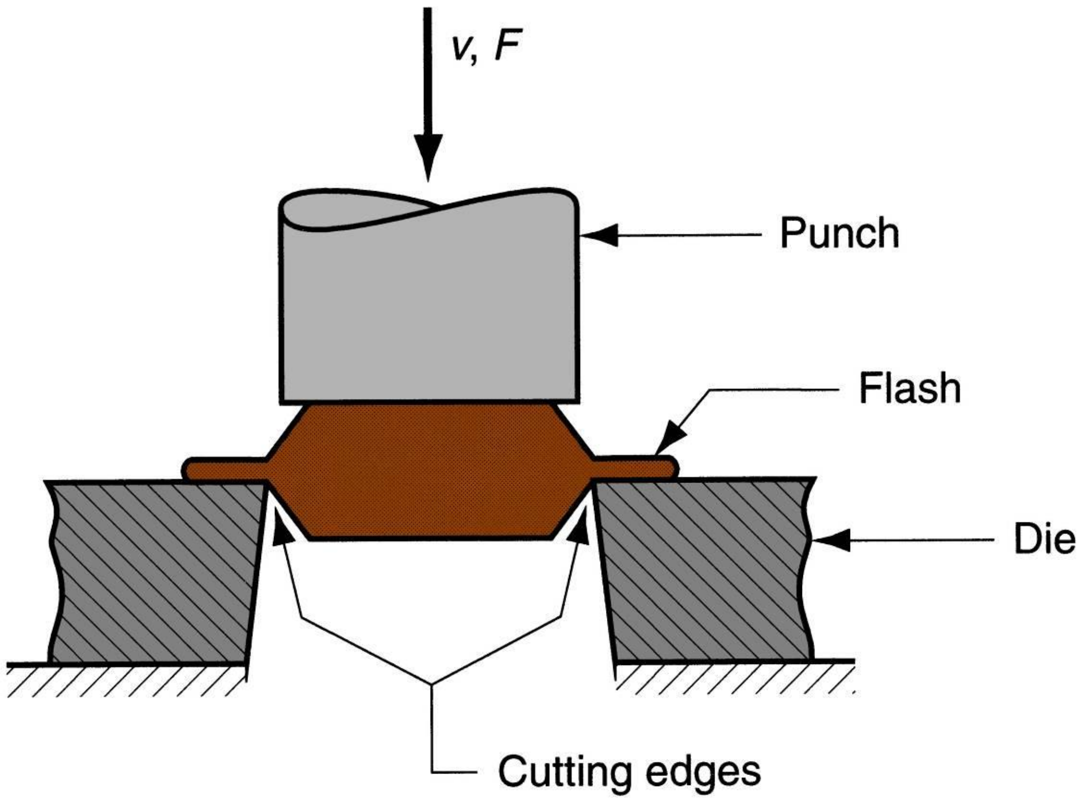


Figure 19.29 Trimming operation (shearing process) to remove the flash after impression-die forging.

Extrusion

Compression forming process in which work metal is forced to flow through a die opening to produce a desired cross-sectional shape

- Process is similar to squeezing toothpaste out of a toothpaste tube
- In general, extrusion is used to produce long parts of uniform cross sections
- Two basic types:
  - Direct extrusion
  - Indirect extrusion

Direct Extrusion

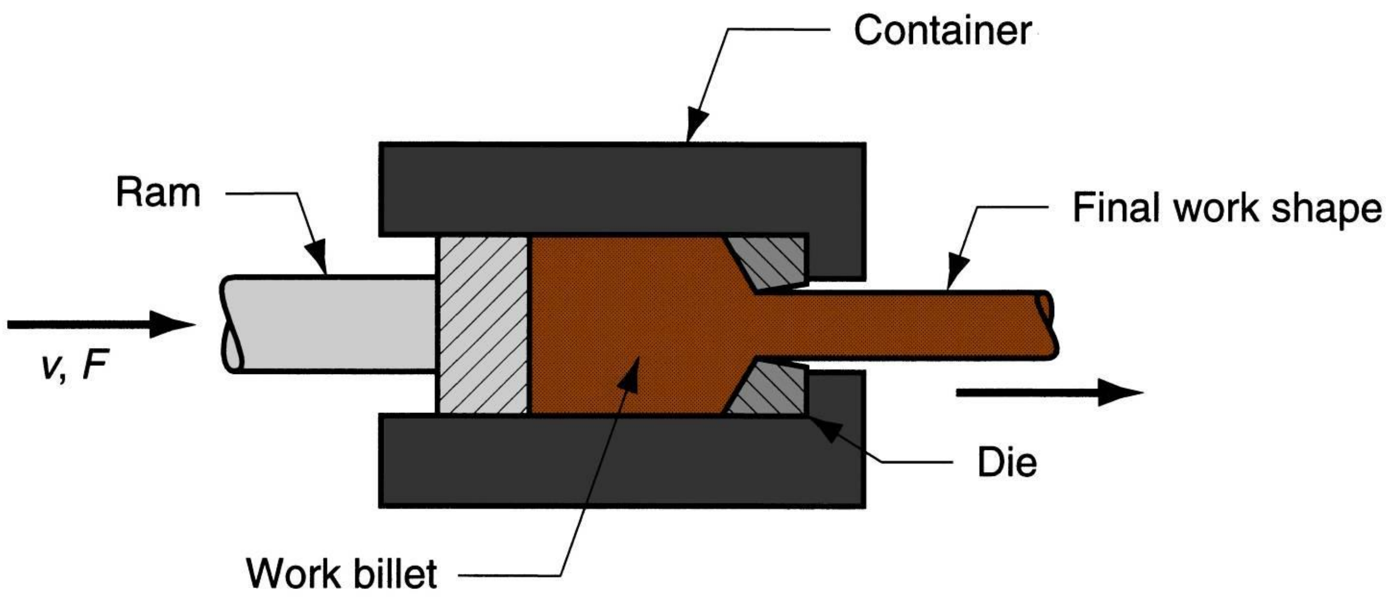


Figure 19.30 Direct extrusion.

Comments on Direct Extrusion

- Also called *forward extrusion*
- As ram approaches die opening, a small portion of billet remains that cannot be forced through die opening
- This extra portion, called the *butt*, must be separated from *extrudate* by cutting it just beyond the die exit
- Starting billet cross section usually round
- Final shape of extrudate is determined by die opening

Hollow and Semi-Hollow Shapes

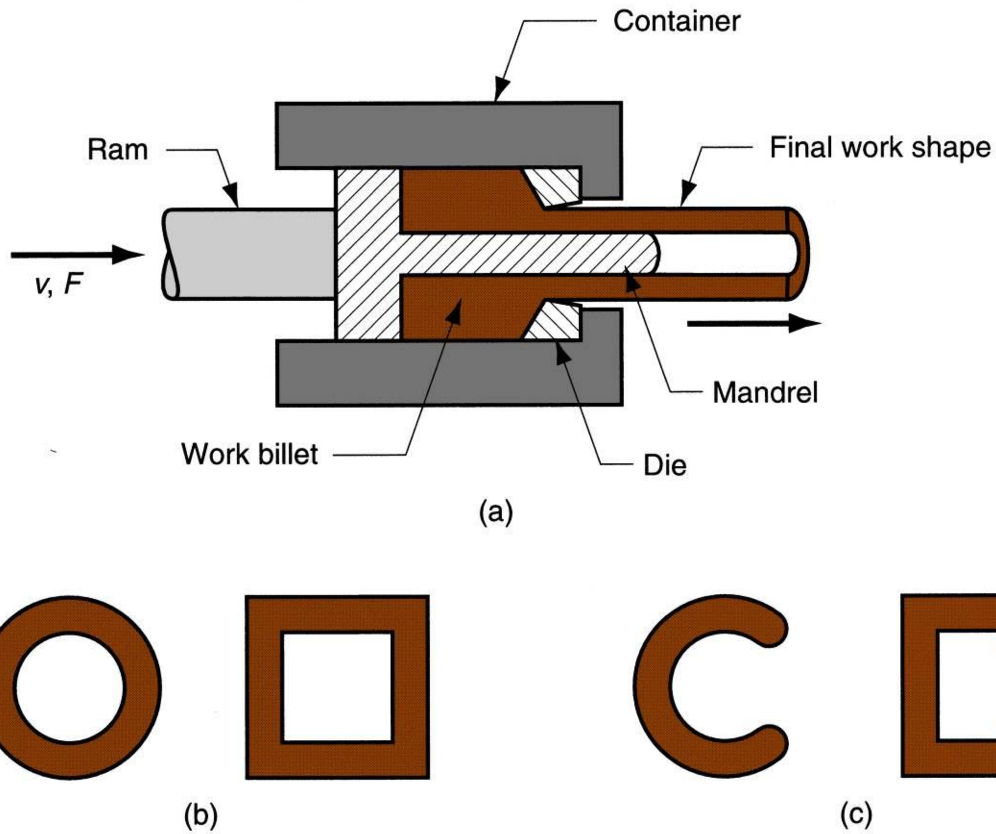


Figure 19.31 (a) Direct extrusion to produce a hollow or semi-hollow cross sections; (b) hollow and (c) semi-hollow cross sections.

Indirect Extrusion

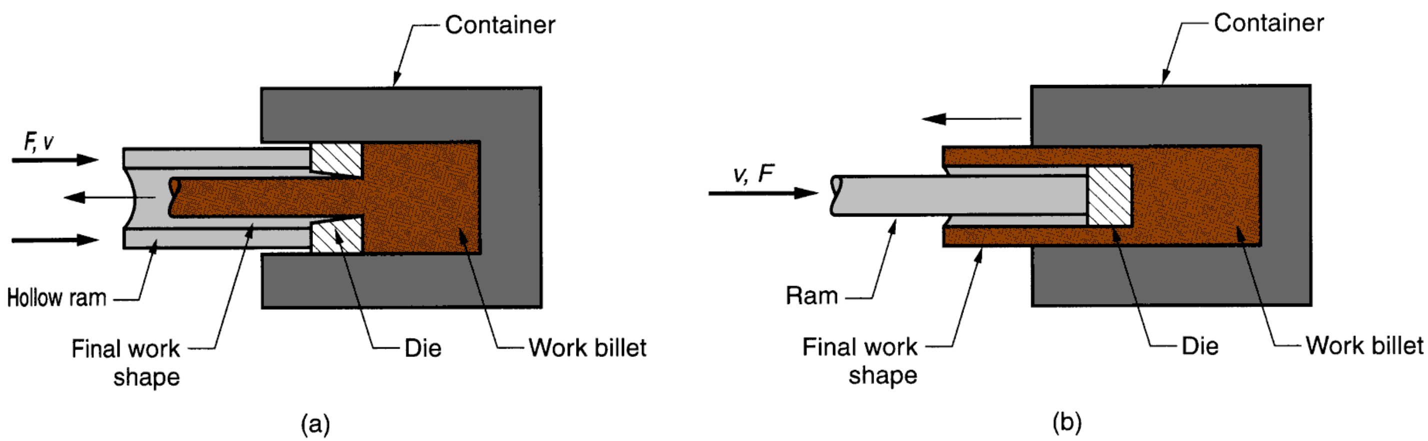


Figure 19.32 Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section.

Comments on Indirect Extrusion

- Also called *backward extrusion* and *reverse extrusion*
- Limitations of indirect extrusion are imposed by
  - Lower rigidity of hollow ram
  - Difficulty in supporting extruded product as it exits die

Advantages of Extrusion

- Variety of shapes possible, especially in hot extrusion
  - Limitation: part cross section must be uniform throughout length
- Grain structure and strength enhanced in cold and warm extrusion
- Close tolerances possible, especially in cold extrusion
- In some operations, little or no waste of material

Hot vs. Cold Extrusion

- Hot extrusion - prior heating of billet to above its recrystallization temperature
  - Reduces strength and increases ductility of the metal, permitting more size reductions and more complex shapes
- Cold extrusion - generally used to produce discrete parts
  - The term impact extrusion is used to indicate high speed cold extrusion

Extrusion Ratio

Also called the *reduction ratio*, it is defined as

$$r_x = \frac{A_o}{A_f}$$

where r_x = extrusion ratio; A_o = cross-sectional area of the starting billet; and A_f = final cross-sectional area of the extruded section

- Applies to both direct and indirect extrusion

Extrusion Die Features

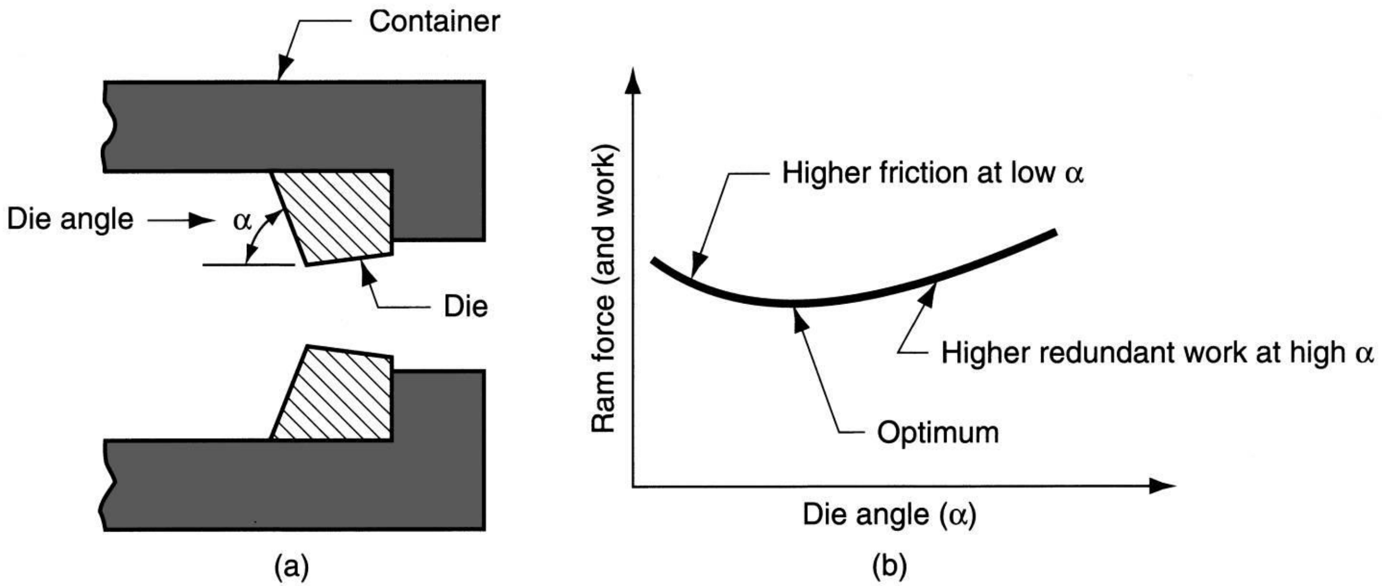


Figure 19.35 (a) Definition of die angle in direct extrusion; (b) effect of die angle on ram force.

Comments on Die Angle

- Low die angle - surface area is large, which increases friction at die-billet interface
  - Higher friction results in larger ram force
- Large die angle - more turbulence in metal flow during reduction
  - Turbulence increases ram force required
- Optimum angle depends on work material, billet temperature, and lubrication

Orifice Shape of Extrusion Die

- Simplest cross section shape is circular die orifice
- Shape of die orifice affects ram pressure
- As cross section becomes more complex, higher pressure and greater force are required
- Effect of cross-sectional shape on pressure can be assessed by means the die *shape factor* K_x

Complex Cross Section

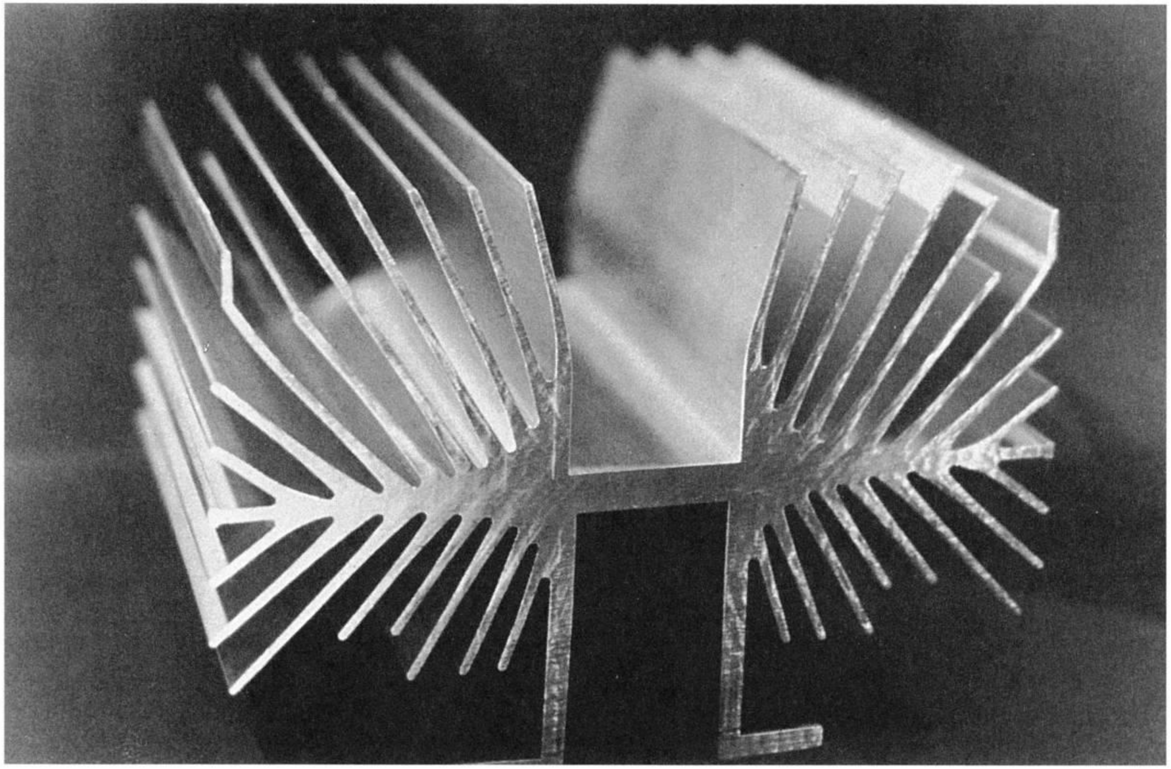


Figure 19.36 A complex extruded cross section for a heat sink (photo courtesy of Aluminum Company of America)

Extrusion Presses

- Either horizontal or vertical
  - Horizontal more common
- Extrusion presses - usually hydraulically driven, which is especially suited to semi-continuous direct extrusion of long sections
- Mechanical drives - often used for cold extrusion of individual parts

Wire and Bar Drawing

Cross-section of a bar, rod, or wire is reduced by pulling it through a die opening

- Similar to extrusion except work is *pulled* through die in drawing (it is *pushed* through in extrusion)
- Although drawing applies tensile stress, compression also plays a significant role since metal is squeezed as it passes through die opening

Wire and Bar Drawing

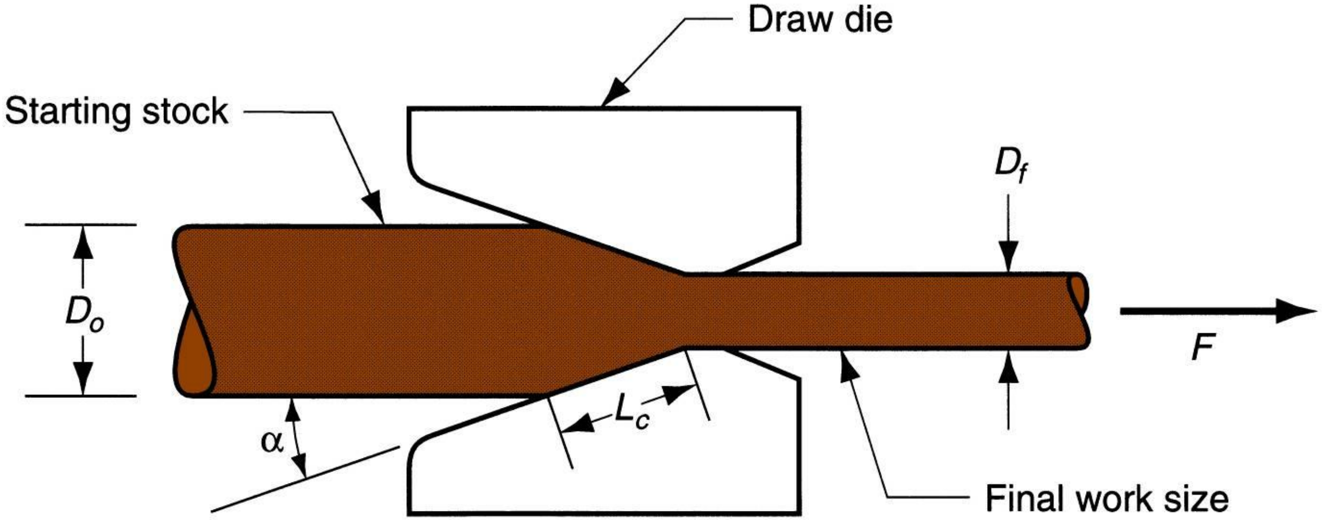


Figure 19.40 Drawing of bar, rod, or wire.

Area Reduction in Drawing

Change in size of work is usually given by area reduction:

$$r = \frac{A_o - A_f}{A_o}$$

where r = area reduction in drawing; A_o = original area of work; and A_r = final work

Wire Drawing vs. Bar Drawing

- Difference between bar drawing and wire drawing is stock size
  - Bar drawing - large diameter bar and rod stock
  - Wire drawing - small diameter stock - wire sizes down to 0.03 mm (0.001 in.) are possible
- Although the mechanics are the same, the methods, equipment, and even terminology are different

Drawing Practice and Products

- Drawing practice:
  - Usually performed as cold working
  - Most frequently used for round cross sections
- Products:
  - Wire: electrical wire; wire stock for fences, coat hangers, and shopping carts
  - Rod stock for nails, screws, rivets, and springs
  - Bar stock: metal bars for machining, forging, and other processes

Bar Drawing

- Accomplished as a *single-draft* operation - the stock is pulled through one die opening
- Beginning stock has large diameter and is a straight cylinder
- Requires a batch type operation

Bar Drawing Bench

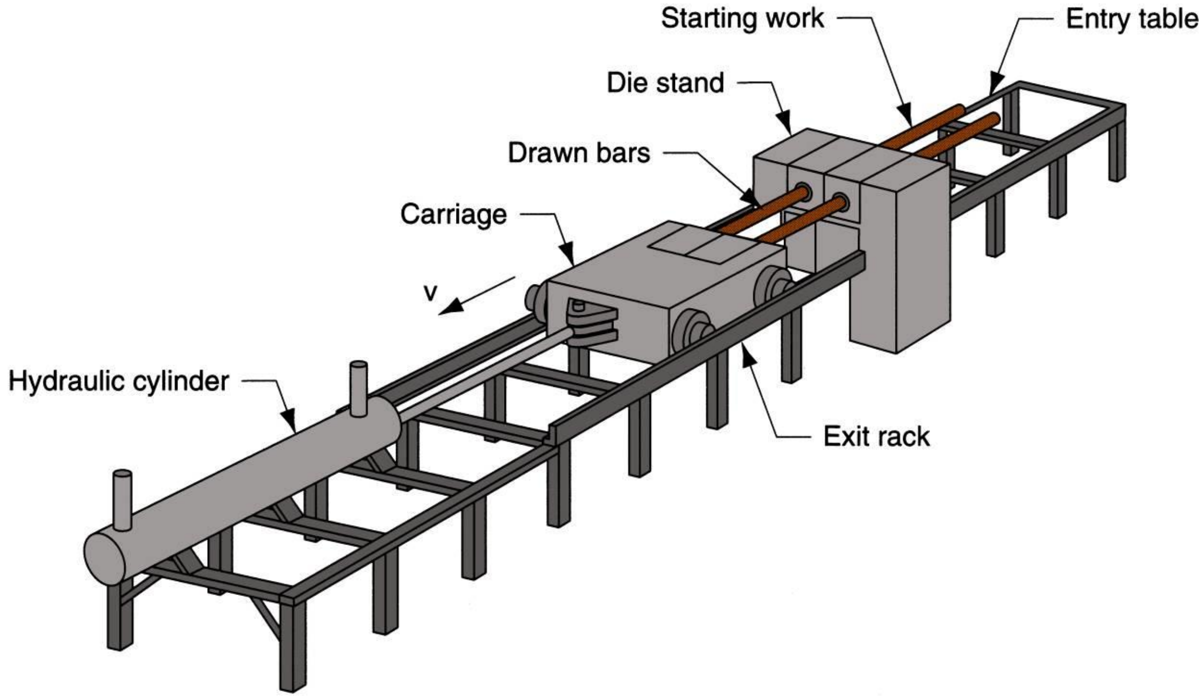


Figure 19.41 Hydraulically operated draw bench for drawing metal bars.

Wire Drawing

- Continuous drawing machines consisting of multiple draw dies (typically 4 to 12) separated by accumulating drums
  - Each drum (*capstan*) provides proper force to draw wire stock through upstream die
  - Each die provides a small reduction, so desired total reduction is achieved by the series
  - Annealing sometimes required between dies to relieve work hardening

Continuous Wire Drawing

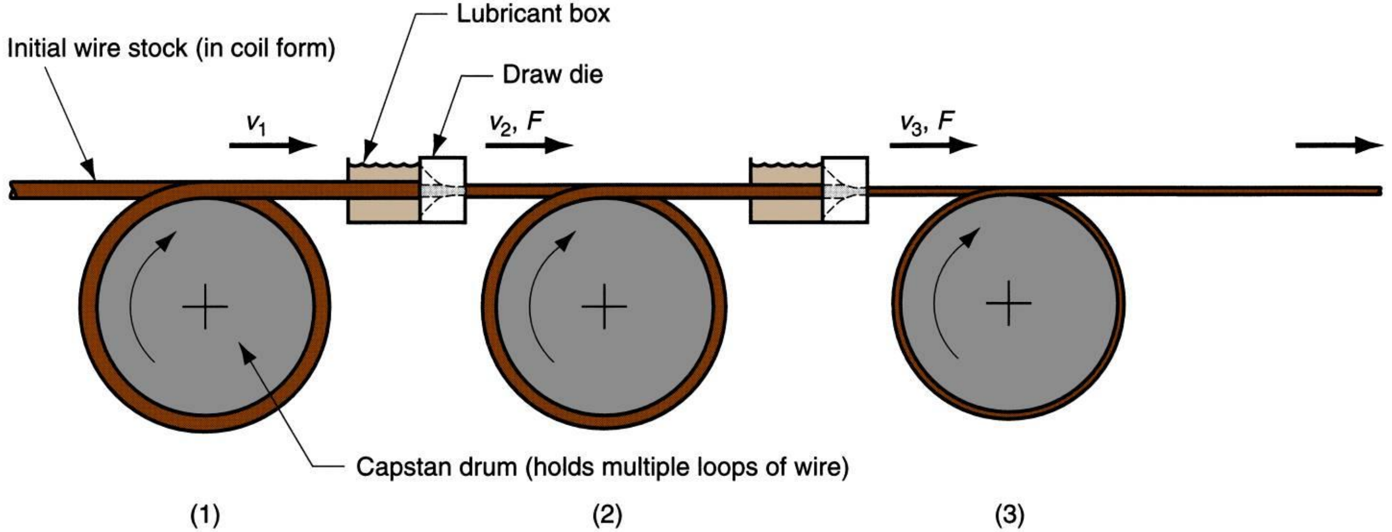


Figure 19.42 Continuous drawing of wire.

Features of a Draw Die

- Entry region - funnels lubricant into the die to prevent scoring of work and die
- Approach - cone-shaped region where drawing occurs
- Bearing surface - determines final stock size
- Back relief - exit zone - provided with a back relief angle (half-angle) of about 30°
- Die materials: tool steels or cemented carbides

Draw Die Details

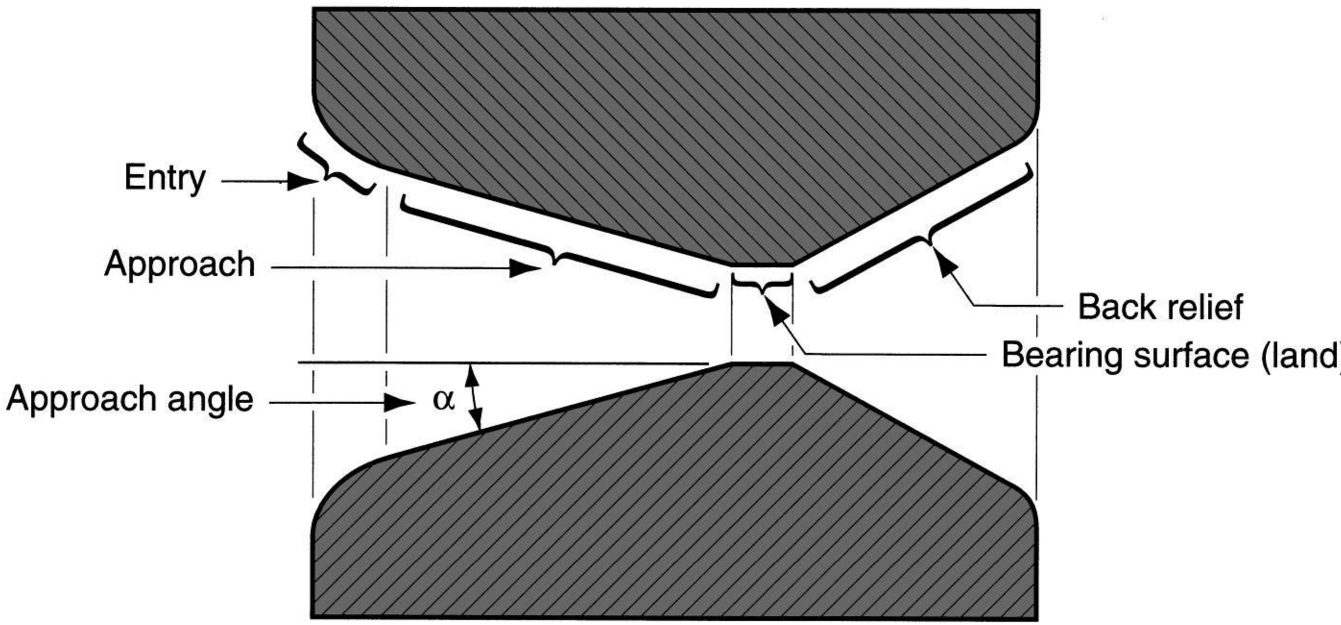


Figure 19.43 Draw die for drawing of round rod or wire.

Preparation of Work for Drawing

- Annealing – to increase ductility of stock
- Cleaning - to prevent damage to work surface and draw die
- Pointing – to reduce diameter of starting end to allow insertion through draw die

Deep Drawing

One of the more important types of sheet metal forming is called

Deep Drawing.

Deep drawing has three important elements:

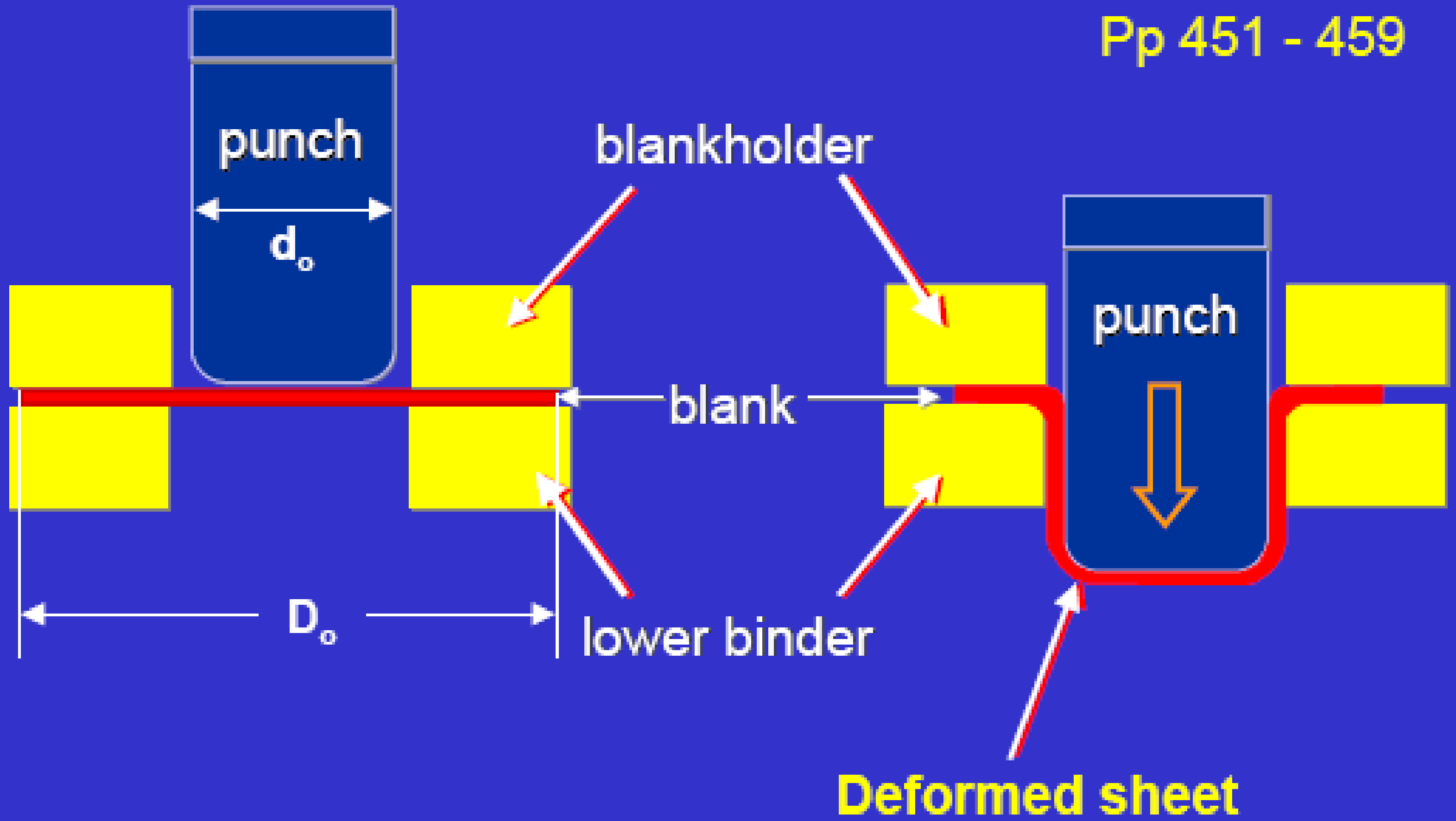
A **blank** - the sheet metal,

A **blankholder** - a device to hold the blank,

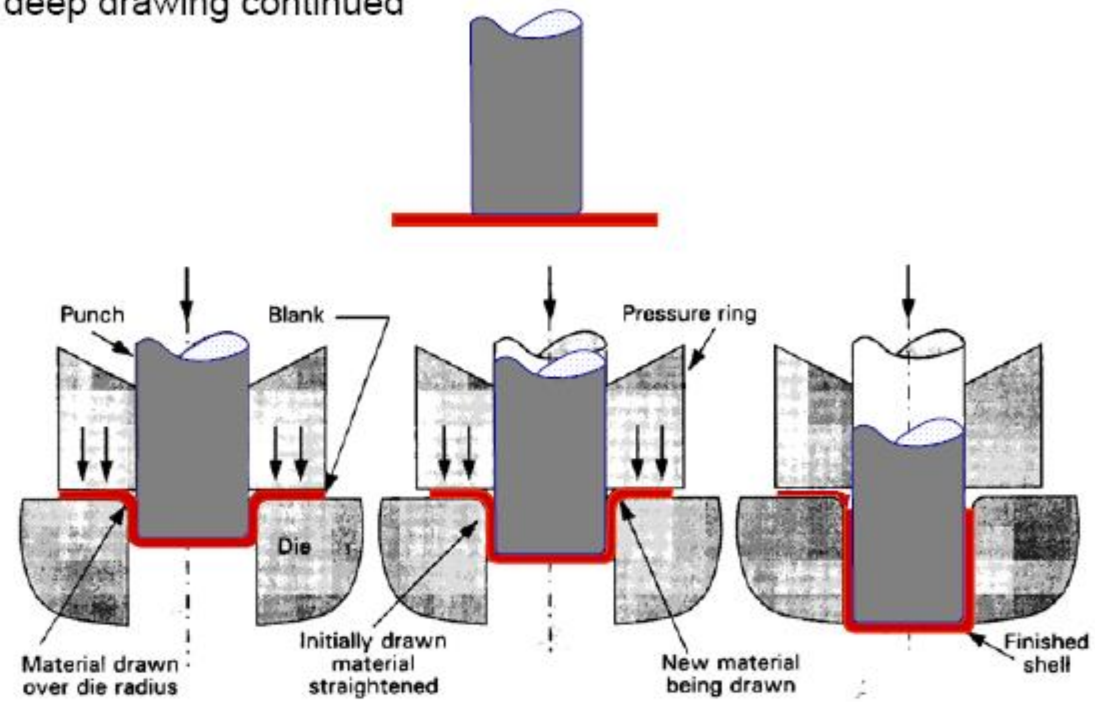
A **punch** – tool to deform the sheet to a specific shape.

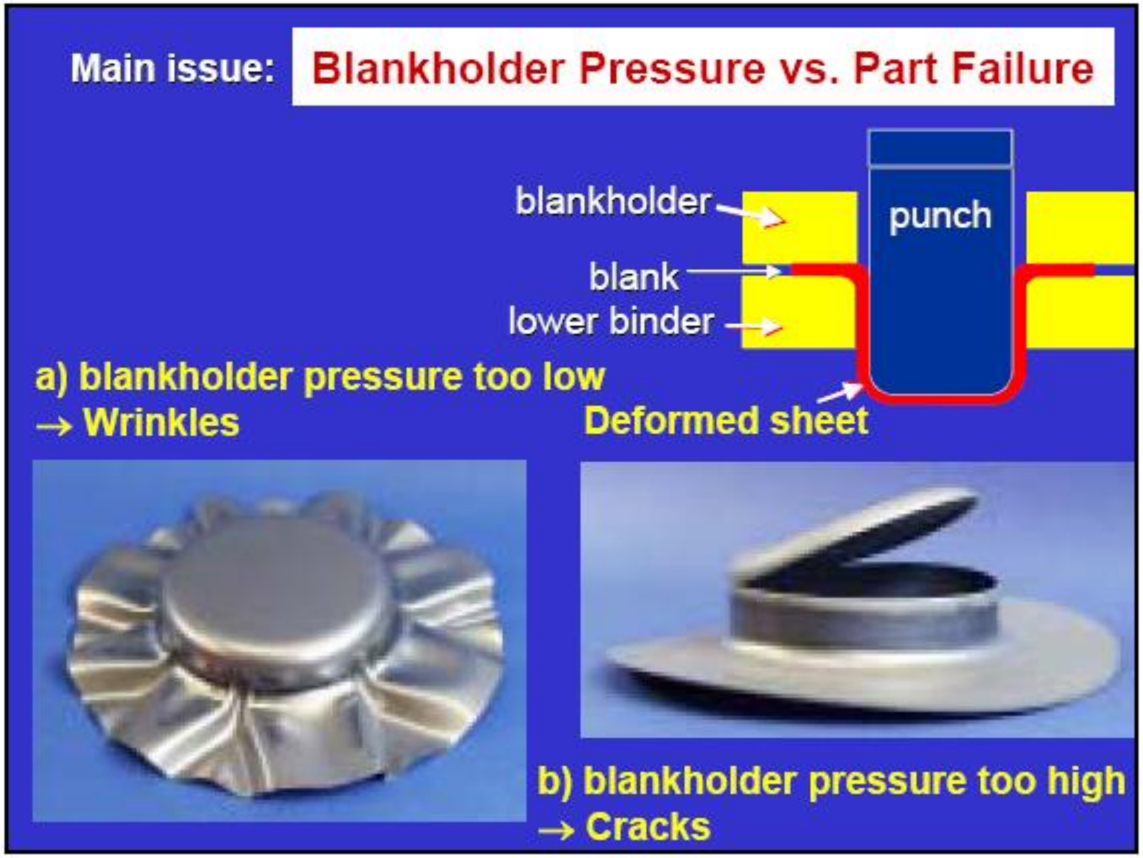
Conventional Deep-Drawing

Pp 451 - 459



deep drawing continued

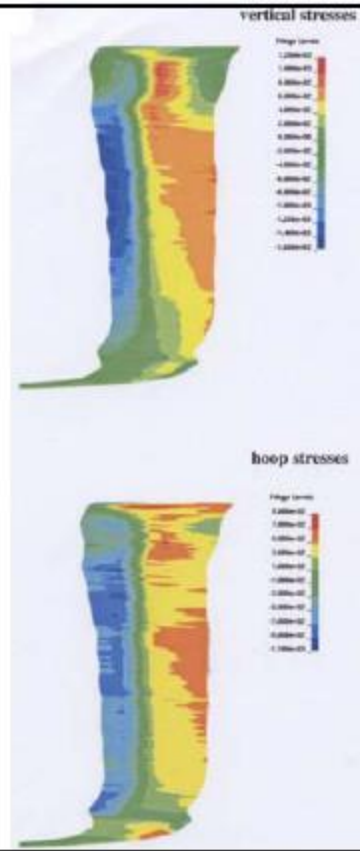




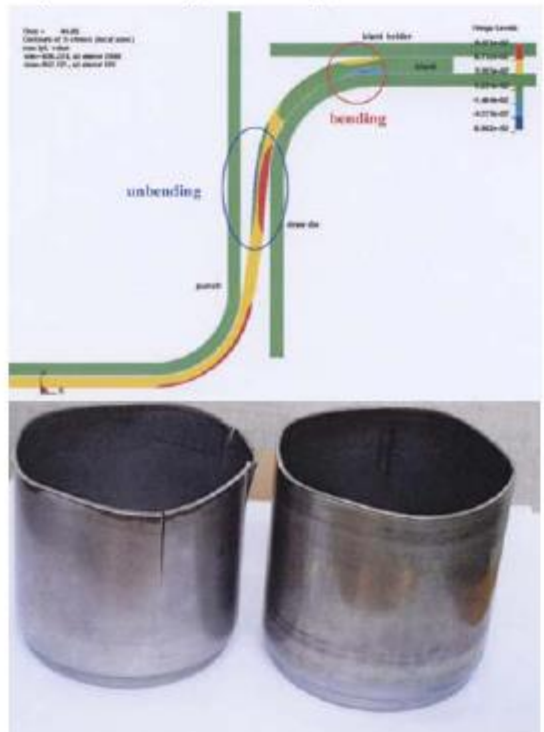
Main issue:
Blankholder Pressure vs. Part Failure
blankholder
punch
blank
lower binder
a) blankholder pressure too low
→ Wrinkles
Deformed sheet
b) blankholder pressure too high
→ Cracks

FEM example of deep drawn cup.

Deep drawn cup made form meta-stable austenitic stainless steel. A number of cracks are after the deep drawing formed in the upper part of the cup due to residual stresses in the cup wall.



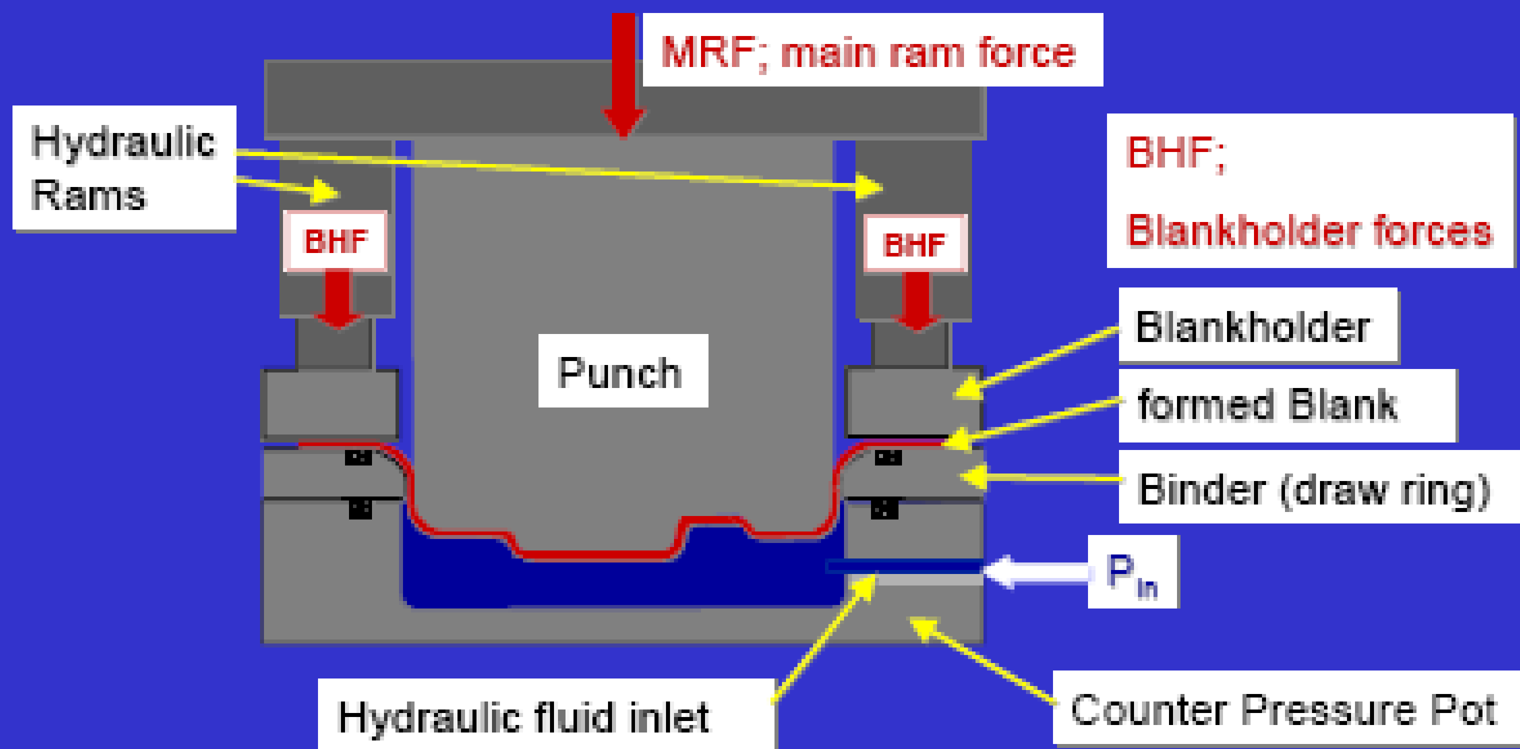
Solving the problem by altering the die corner:



Cup drawn conventionally (the left) and using the elliptically shaped profile in the second stage (right)

There are several ways of doing deep drawing, one of these is:

Hydromechanical Deep-Drawing



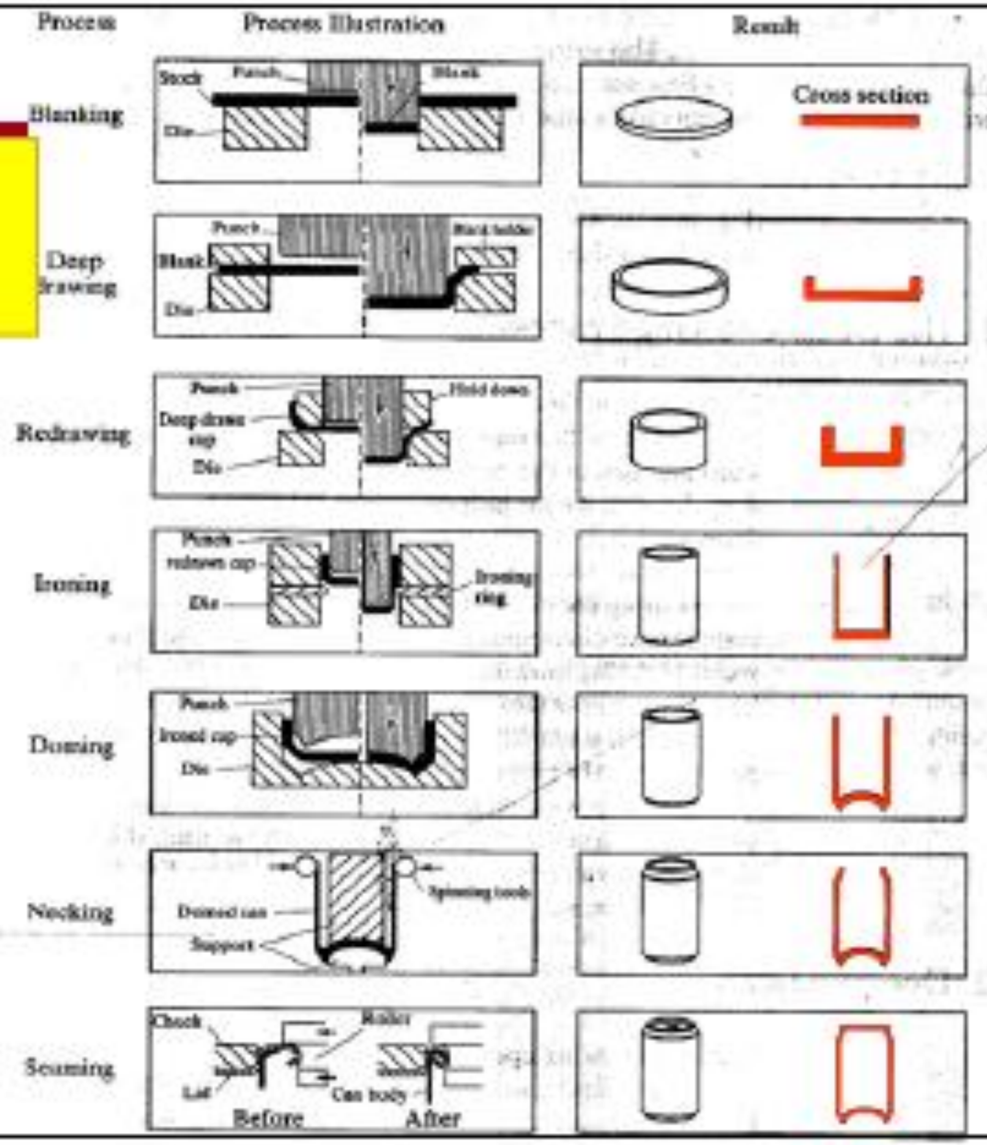
Automotive example

Hydromechanical Deep-Drawn Lower Tank Tray with Failures

Example 2

Forming steps used in making beverage cans

See figure 16.31



More Deep Drawing:

Example of combined bulk- and sheet-metal forming of a workpiece (production of a flange). (*Courtesy of* Daimler Benz.)

Shear - Spinning and Tube - Spinning

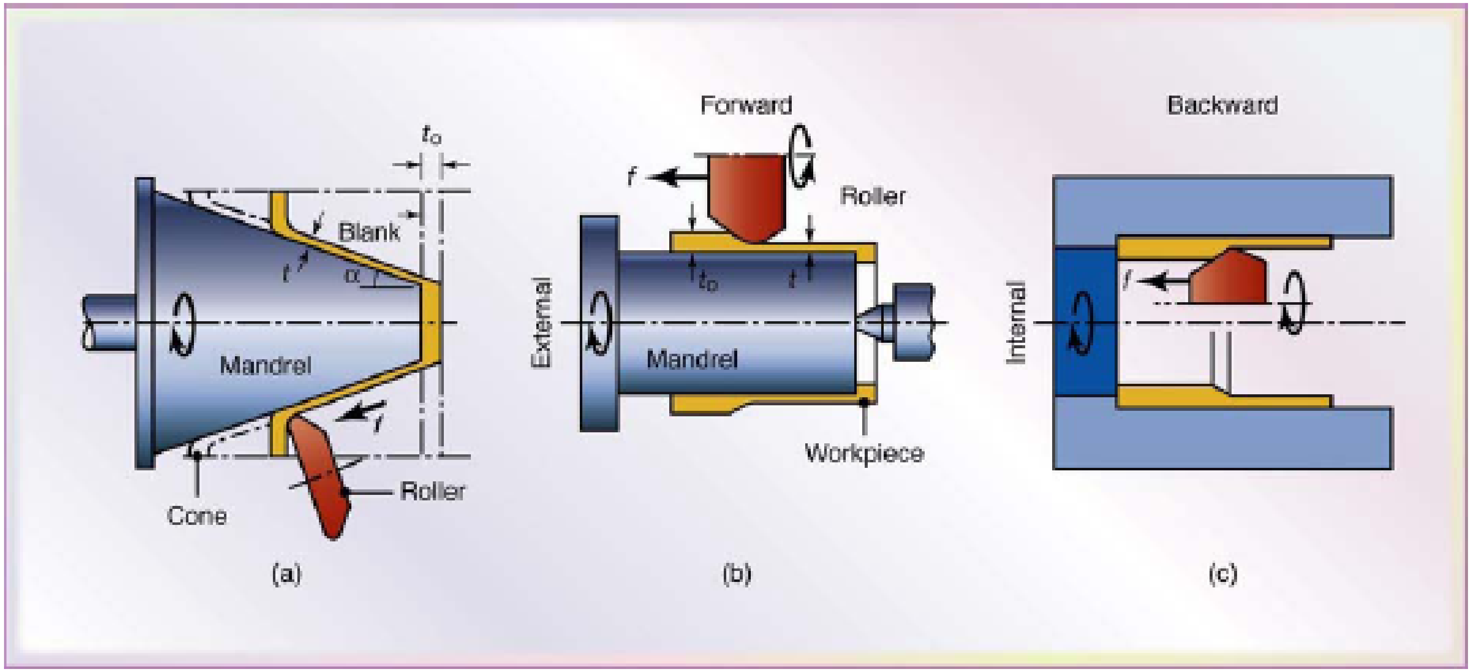
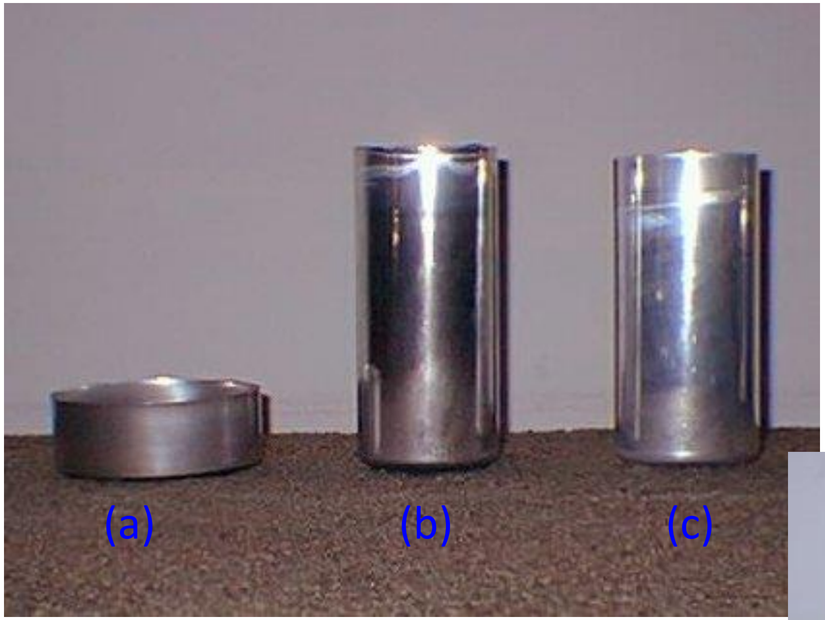


Figure 16.43 (a) Schematic illustration of the shear-spinning process for making conical parts. The mandrel can be shaped so that curvilinear parts can be spun. (b) and (c) Schematic illustrations of the tube-spinning process

Hydromechanical Press
600 ton capacity, University of Stuttgart

Deep Drawing of Cans

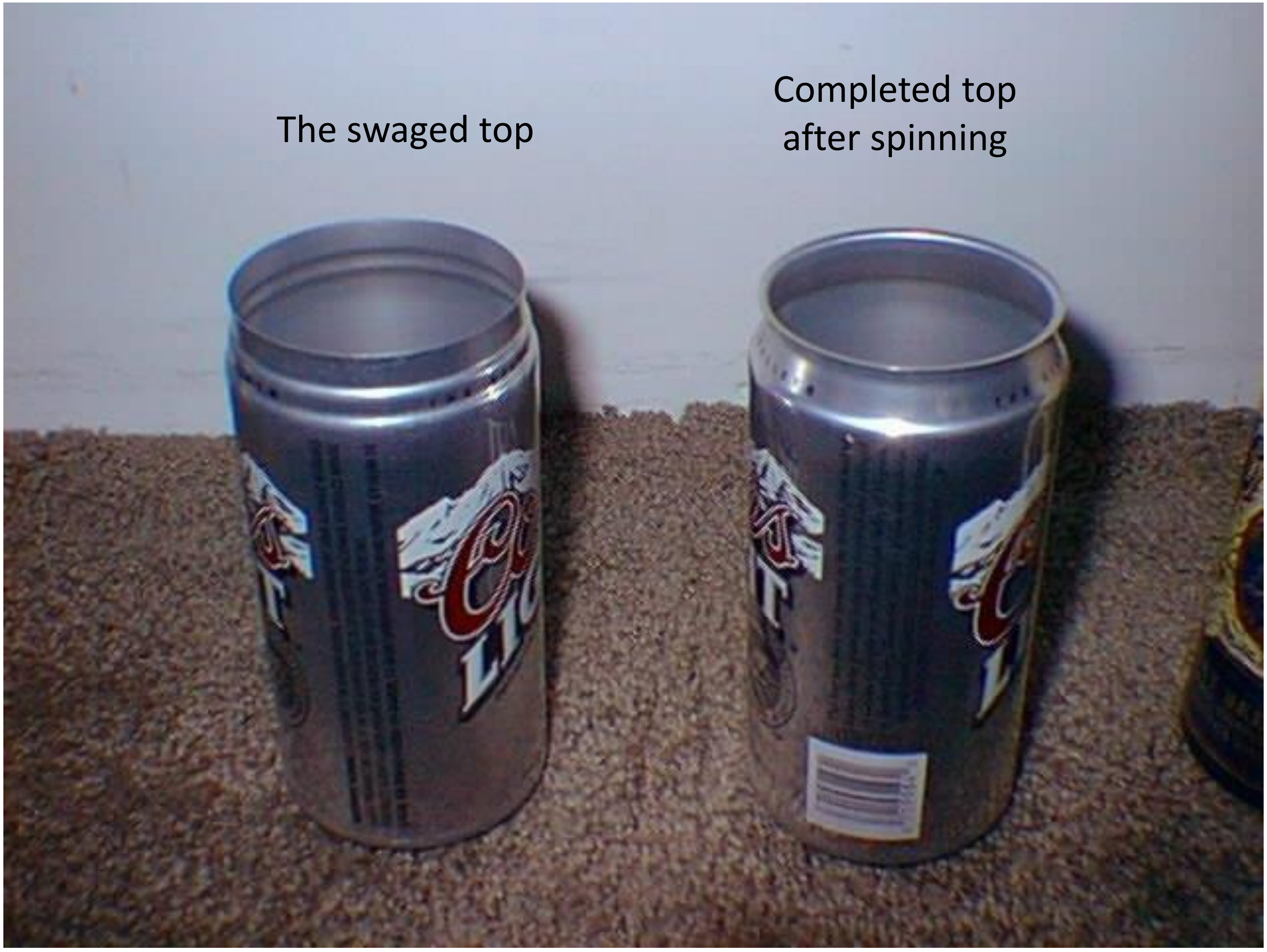


a) drawing of shallow cup from flat, round blank.
b) reverse deep drawing of can to final diameter.
c) trimming of top lip.

d) swaging the top.
e) spinning the neck and flange.
f) filling the can and forming the seam with the lid.

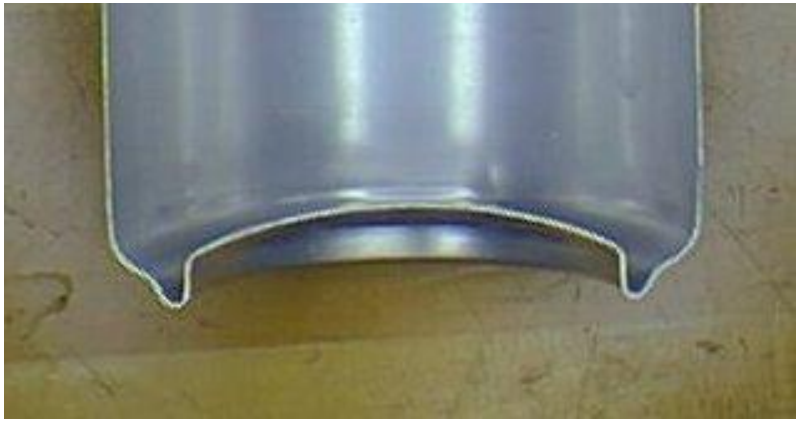
Trimming the Top

Strengthening of the Neck

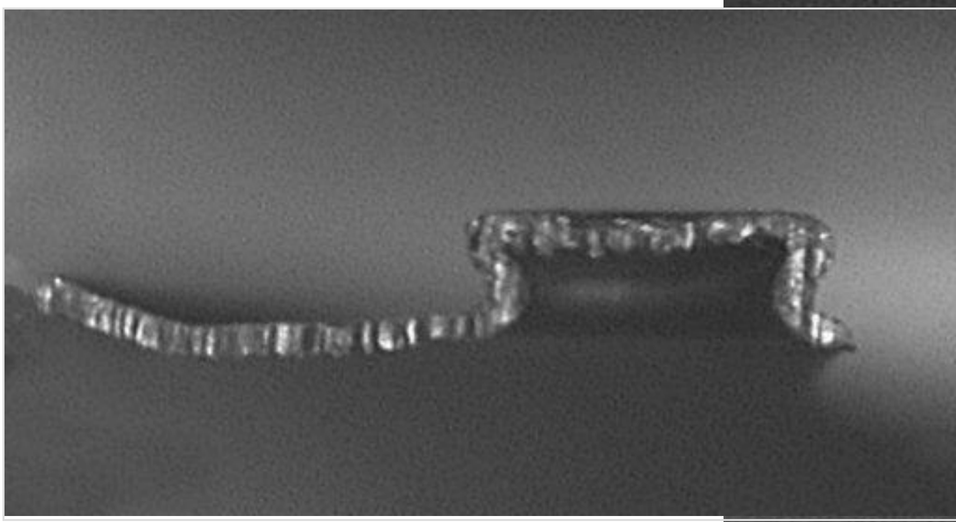


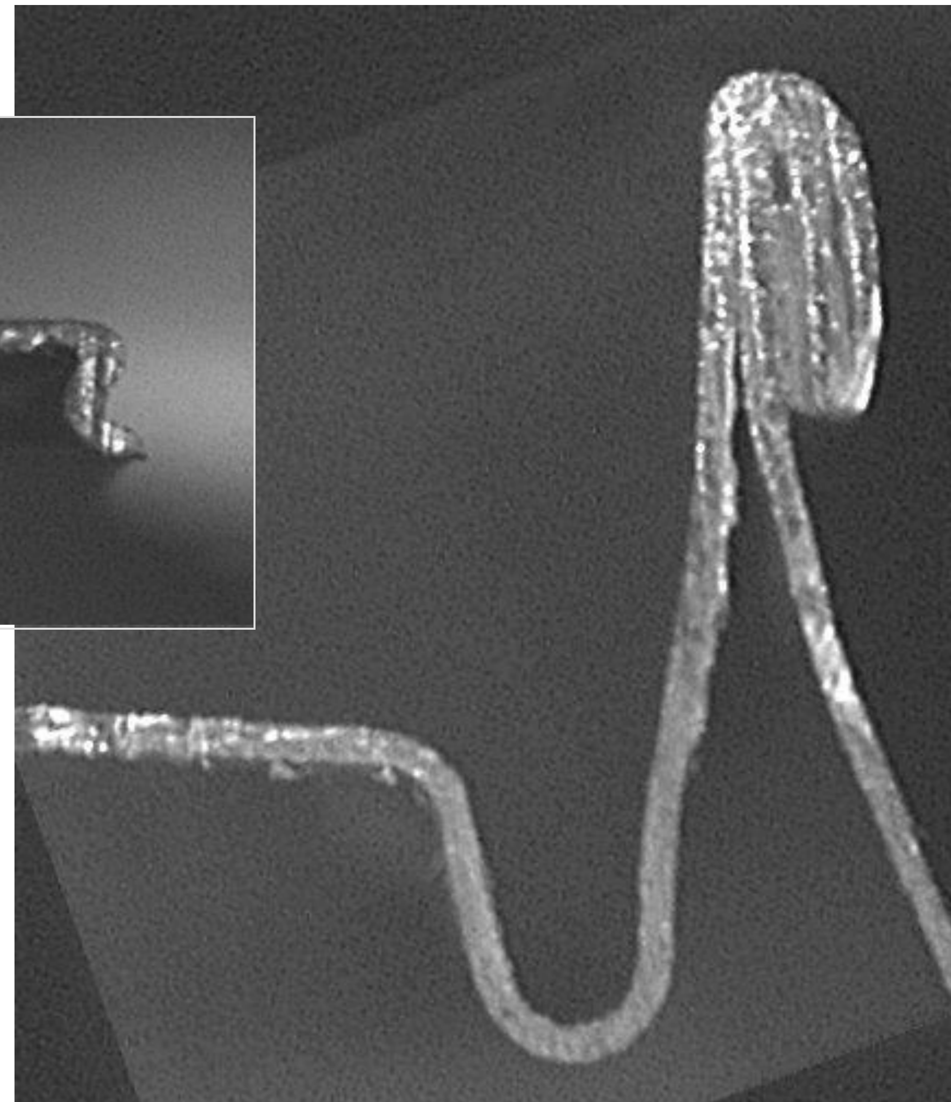
A Sectioned Two-piece Can

Wall thickness varies: bottom is thicker than the wall



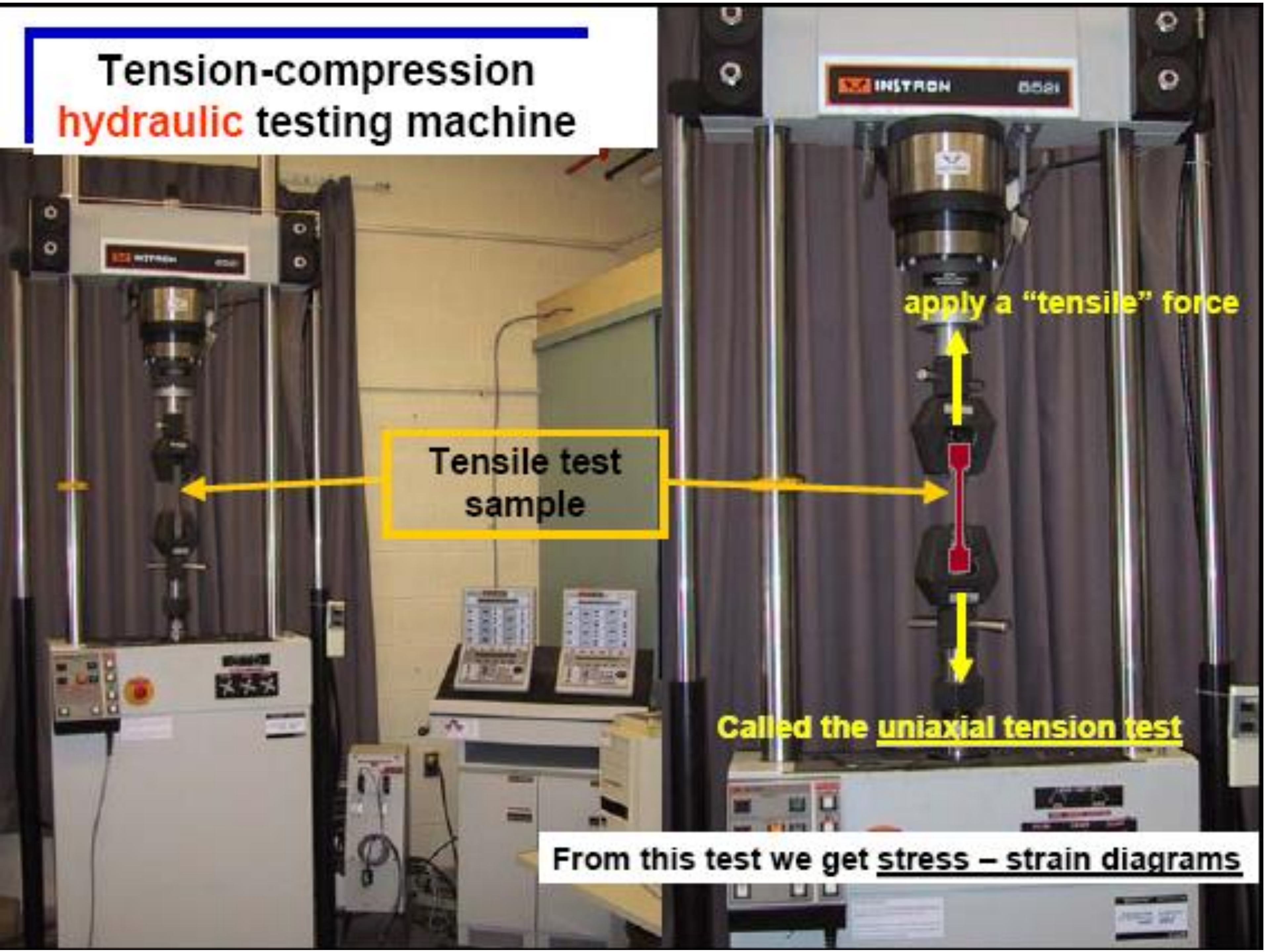
Two-piece Can, Details





Notice the double fold (right) and the integrated rivet (top) to hold the tab on the lid

Tension-compression hydraulic testing machine



- Engineering Stress is based upon the original cross-sectional area A_o.

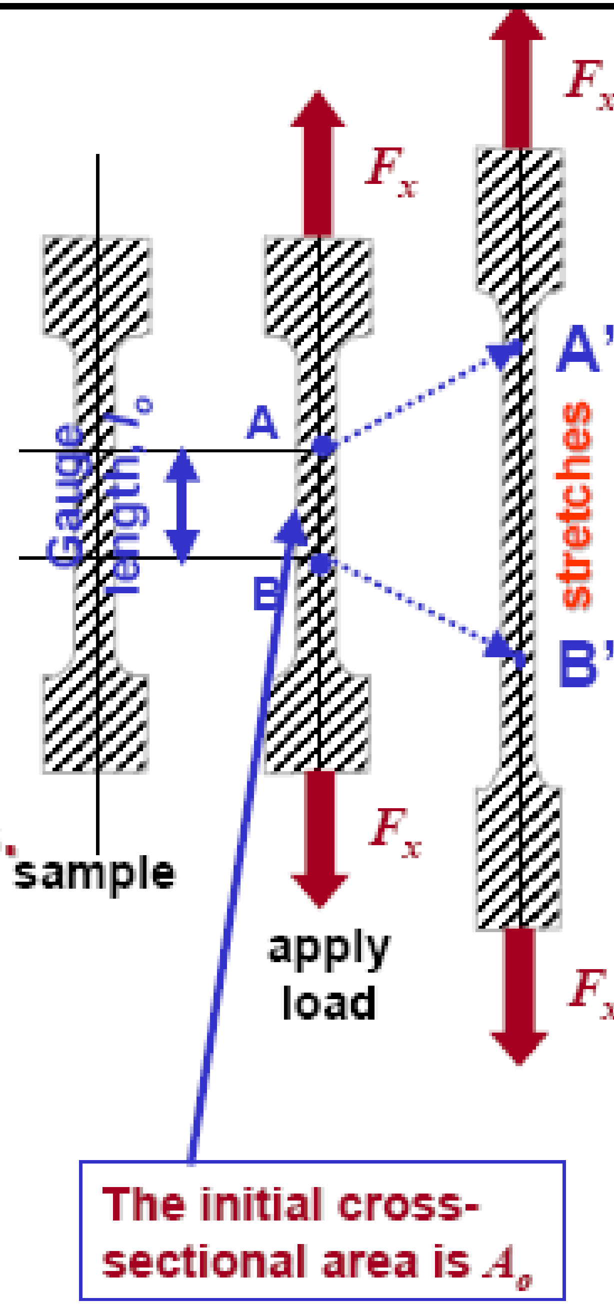
$$\sigma_{engineering} = \frac{F}{A_o}$$

But, in a tensile test, the sample cross-sectional area becomes smaller as it stretches [elongates].

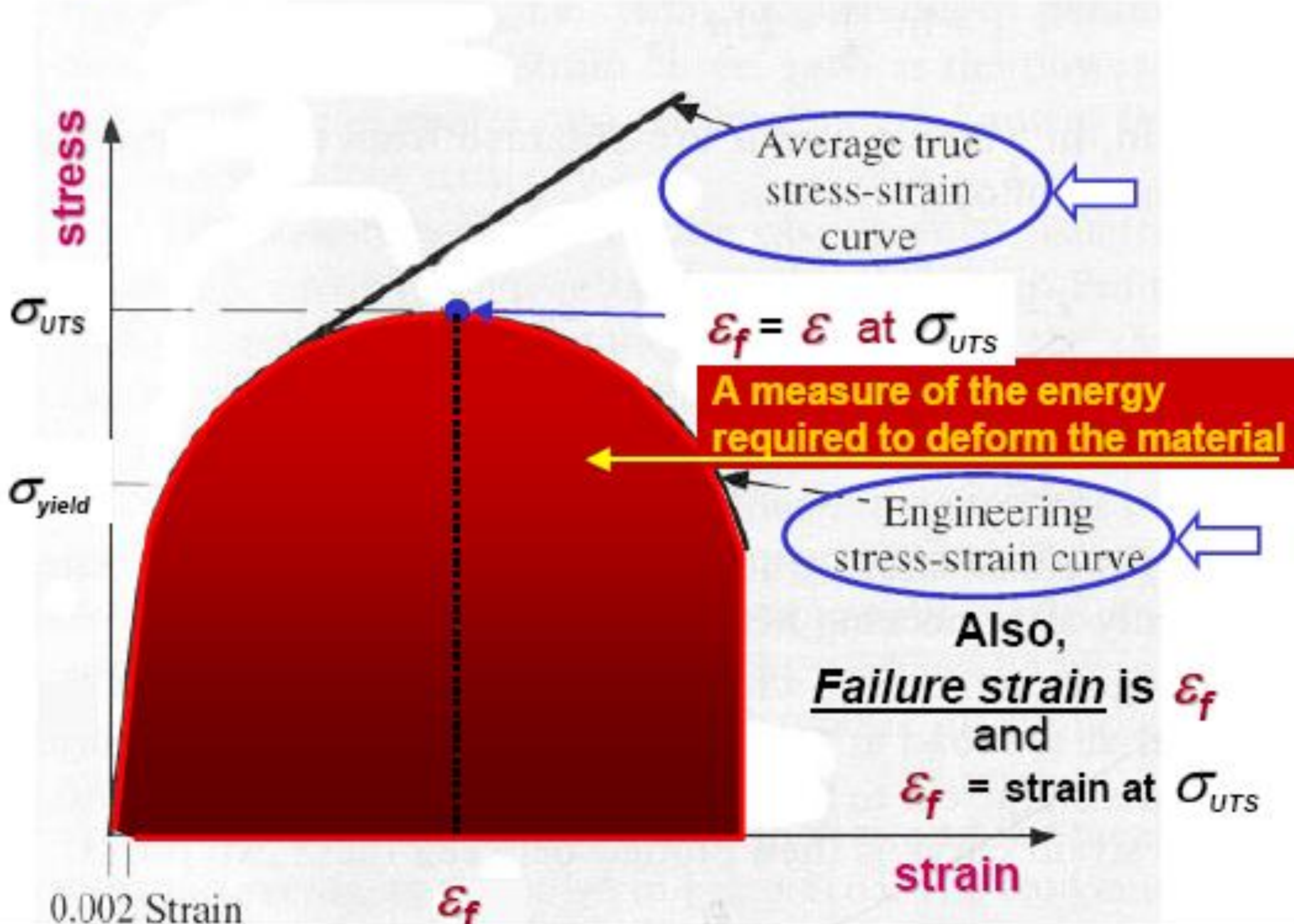
The Engineering Stress does not represent the ***actual Stress,*** because instantaneous area, A, **changes.**

The Actual Stress or ***TRUE STRESS***, is the ratio of the current load, F_x, **divided by** the current cross-sectional area, A.

$$\sigma_{true} = \frac{F}{A}$$



A comparison of Stress – Strain curves



The linear, elastic part of the stress-strain curve is modeled by:

$$\sigma = \varepsilon E$$

The plastic part of the true stress-strain curve is often modeled by:

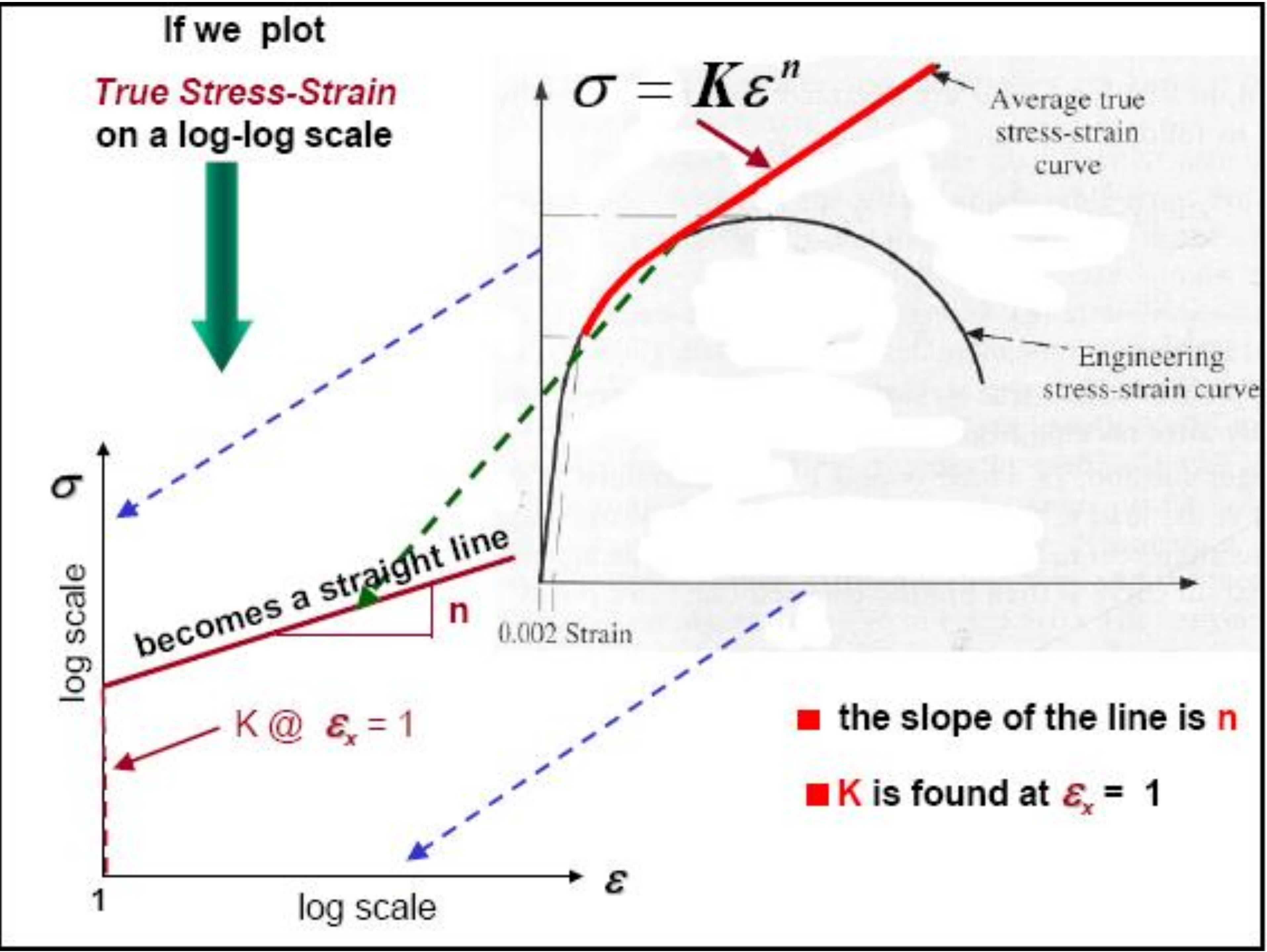
$$\sigma = K\varepsilon^n$$

where K = strength coefficient

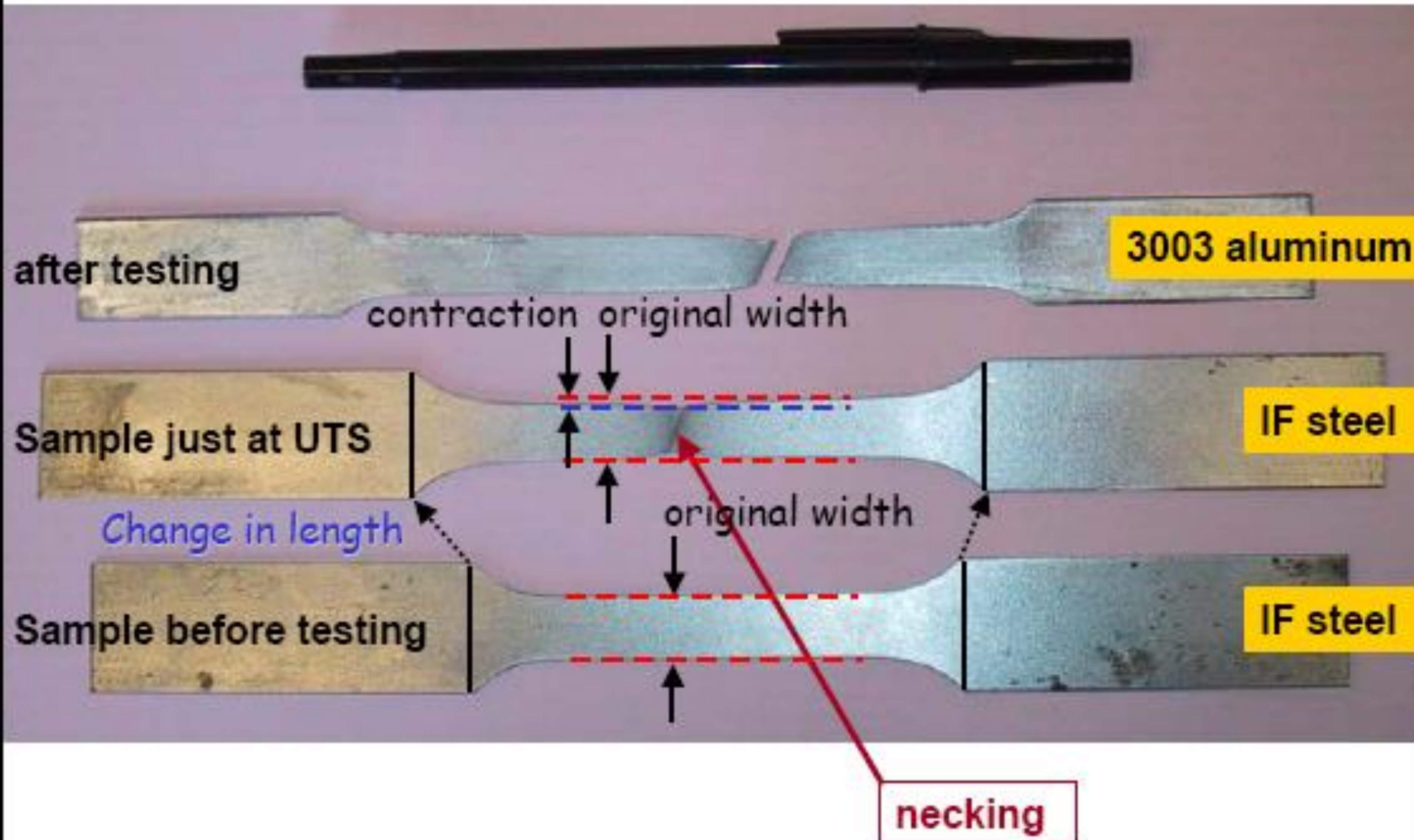
n = strain-hardening, or work-hardening exponent

ε_f: strain at σ_{UTS}

$\varepsilon_f = n$ at σ_{UTS}


If we plot
True Stress-Strain
on a log-log scale
$\sigma = K\varepsilon^n$
Average true stress-strain curve
Engineering stress-strain curve
0.002 Strain
σ
log scale
becomes a straight line
n
K @ $\varepsilon_x = 1$
1
log scale
ε
the slope of the line is n
K is found at $\varepsilon_x = 1$

Stretching and contraction can be seen in an actual Tensile Test



First Compare Engineering Strain and True Strain

For **Engineering Strain**: $e = (l - l_o)/l_o = \delta/l_o$

For **True Strain**:

instantaneous change in length is used: $\varepsilon = ln(l/l_o)$

A comparison of e and •,•*at a strain of 0.1 and 1*

@ $e_x = 0.1$, $\varepsilon_x = 0.095$ ← values are close

and

@ $e_x = 1.0$, $\varepsilon_x = 0.69$ ← values are not close

One may also make the observation that:

True Strain <u>is additive</u> and **Engineering Strain <u>is not</u>**.

Engineering strain, e, and True strain, ε, are related:

$$\varepsilon = \int_{l_o}^{l} \frac{dl}{l} = \ln \frac{l}{l_o}$$ **Eqn 2.7**

true strain

and $l = l_o + \delta l$ — engineering strain

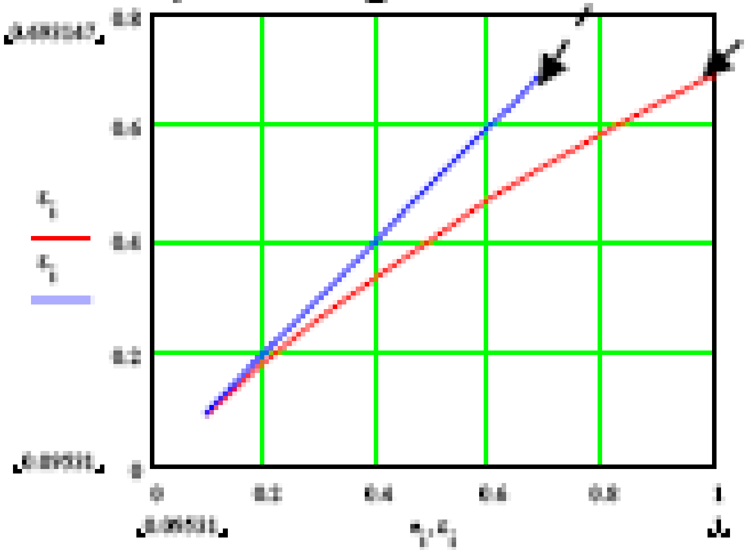
then $\varepsilon = \ln\left(\frac{l_o + \delta l}{l_o}\right)$ *and* $\varepsilon = \ln(1+e)$

The relation between true strain and engineering strain

Calculating values gives:

e_i	ε_i
0.1	0.095
0.2	0.182
0.3	0.262
0.4	0.336
0.5	0.405
0.6	0.47
0.7	0.531
0.8	0.588
0.9	0.642
1	0.693

plotting:



Once again Equation 2.7 gives $\varepsilon = \int_{l_o}^{l} \frac{dl}{l} = \ln \frac{l}{l_o}$

Constant volume requires $A_o l_o = Al$ or $\frac{l}{l_o} = \frac{A_o}{A}$

Then strain in terms of changing area is: $\varepsilon = \ln \frac{A_o}{A}$

or $\frac{A_o}{A} = e^{\varepsilon}$

since True Strain can also be calculated in terms of area: $\varepsilon = \ln \frac{A_o}{A}$

then at necking: $\varepsilon_f = \ln[A_o/A_f]$

So one can find true strain at necking from engineering strain at necking $\varepsilon_f = \ln(1+e_f)$,

and then find true area at necking from true strain at necking, $\varepsilon_f = \ln[A_o/A_f]$.

SUMMARY

- **Stress** and **strain**: *These are size-independent measures of load and displacement, respectively*.
- **Elastic** behavior: *This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).*
- **Plastic** behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σy.
- **Toughness**: *The energy needed to break a unit volume of material*.
- **Ductility**: *The plastic strain at failure*.

Relationships between Engineering stress & True stress, and Engineering strain and and True strain

True Stress (σ_T)

True stress is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area

True stress is related to engineering stress:

Assuming material volume remains constant

$$A_o \ell_o = A \ell$$

$$\sigma_T = \frac{P}{A} = \frac{P}{A} * \frac{A_o}{A_o} = \frac{P}{A_o} * \frac{A_o}{A}$$

$$\frac{A_o}{A} = \frac{\ell}{\ell_o} = \frac{\delta + \ell_o}{\ell_o} = \frac{\delta}{\ell_o} + 1 = (1 + \varepsilon)$$

$$\sigma_T = \frac{P}{A_o}(1+\varepsilon) = \sigma(1+\varepsilon)$$

True Strain (ε_T)

The rate of instantaneous increase in the instantaneous gauge length.

$$\varepsilon_T = \int \frac{d\ell}{\ell} = \ln\left(\frac{\ell}{\ell_o}\right)$$

$$\varepsilon_T = \ln\left(\frac{\ell_o + \Delta\ell}{\ell_o}\right) \Rightarrow \ln\left(\frac{\ell_o}{\ell_o} + \frac{\Delta\ell}{\ell_o}\right)$$

$$\varepsilon_T = \ln(1 + \varepsilon)$$

The main relationships to determine the mechanical characteristics from curves can be summerized as follows:

Engineering stress	$\sigma = P/A_0$
Engineering strain	$\varepsilon = \delta / l_0 = (l_f - l_0) / l_0$
Young's modulus or stiffness	$E = \sigma / \varepsilon$
for nonlinear elastic behavior	$Esec = d\sigma/d\varepsilon$
Modulus of resilience	$u = \sigma^2_{yield} / 2E$
Modulus of toughness	$u_T = \int_0^{\varepsilon r} \sigma \, d\varepsilon$
True stress	$\sigma_T = P/A$
True strain	$\varepsilon_T = ln(\delta / l_0) = ln[(l_f - l_0) / l_0]$

The relationship between Engineering (nominal) stress and true stress:

$$\sigma_T = \sigma (1+\varepsilon)$$

The relationship between Engineering (nominal) strain and true strain:

$$\varepsilon_T = ln\,(1+\varepsilon)$$

Sometimes the curve after yield strength can be approximated by determining the constants of equation: $\sigma_T = k\,(\varepsilon_T)^n$

Percent élongation	$EL\% = [(l_f - l_0) / l_0]^* \, 100\%$
Percent reduction in area	$AR\% = [(- A_f + A_0) / A_0]^* \, 100\%)$

POLYMERS

1. Fundamentals of Polymer Technology
2. Thermoplastic Polymers
3. Thermosetting Polymers
4. Elastomers
5. Guide to the Processing of Polymers

Polymer: A compound consisting of long-chain molecules, each molecule made up of repeating units connected together

- There may be thousands, even millions of units in a single polymer molecule
- The word *polymer* is derived from the Greek words *poly*, meaning many, and *meros* (reduced to *mer*), meaning part
- Most polymers are based on carbon and are therefore considered organic chemicals

Types of Polymers

- Polymers can be separated into plastics and rubbers
- As engineering materials, it is appropriate to divide them into the following three categories:

1. Thermoplastic polymers
2. Thermosetting polymers
3. Elastomers

where (1) and (2) are plastics and (3) are rubbers

Thermoplastic Polymers - Thermoplastics

Solid materials at room temperature but viscous liquids when heated to temperatures of only a few hundred degrees

- This characteristic allows them to be easily and economically shaped into products
- They can be subjected to heating and cooling cycles repeatedly without significant degradation
- Symbolized by TP

Thermosetting Polymers - Thermosets

- Cannot tolerate repeated heating cycles as thermoplastics can
  - When initially heated, they soften and flow for molding
  - Elevated temperatures also produce a chemical reaction that hardens the material into an infusible solid
  - If reheated, thermosets degrade and char rather than soften
- Symbolized by TS

Elastomers (Rubbers)

Polymers that exhibit extreme elastic extensibility when subjected to relatively low mechanical stress

- Some elastomers can be stretched by a factor of 10 and yet completely recover to their original shape
- Although their properties are quite different from thermosets, they share a similar molecular structure that is different from the thermoplastics

Market Shares

- Thermoplastics are commercially the most important of the three types
  - About 70% of the tonnage of all synthetic polymers produced
  - Thermosets and elastomers share the remaining 30% about evenly, with a slight edge for the former
- On a volumetric basis, current annual usage of polymers exceeds that of metals

Examples of Polymers

- **Thermoplastics:**

Polyethylene, polyvinylchloride, polypropylene, polystyrene, and nylon

- **Thermosets:**

Phenolics, epoxies, and certain polyesters

- **Elastomers:**

Natural rubber (vulcanized),

Synthetic rubbers, which exceed the tonnage of natural rubber

Reasons Why Polymers are Important:

- **Plastics** can be molded into intricate part shapes, usually with no further processing
  - Very compatible with *net shape* processing
- **On a volumetric basis, polymers:**
  - Are cost competitive with metals
  - Generally require less energy to produce than metals
- **Certain plastics** are translucent and/or transparent, which makes them competitive with glass in some applications

General Properties of Polymers

- Low density relative to metals and ceramics
- Good strength-to-weight ratios for certain (but not all) polymers
- High corrosion resistance
- Low electrical and thermal conductivity

Limitations of Polymers

- Low strength relative to metals and ceramics
- Low modulus of elasticity (stiffness)
- Service temperatures are limited to only a few hundred degrees
- Viscoelastic properties, which can be a distinct limitation in load bearing applications
- Some polymers degrade when subjected to sunlight and other forms of radiation

Synthesis of Polymers

- Nearly all polymers used in engineering are synthetic
  - They are made by chemical processing
- Polymers are synthesized by joining many small molecules together into very large molecules, called *macromolecules*, that possess a chain-like structure
- The small units, called *monomers*, are generally simple unsaturated organic molecules such as ethylene C_2H_4

Polyethylene

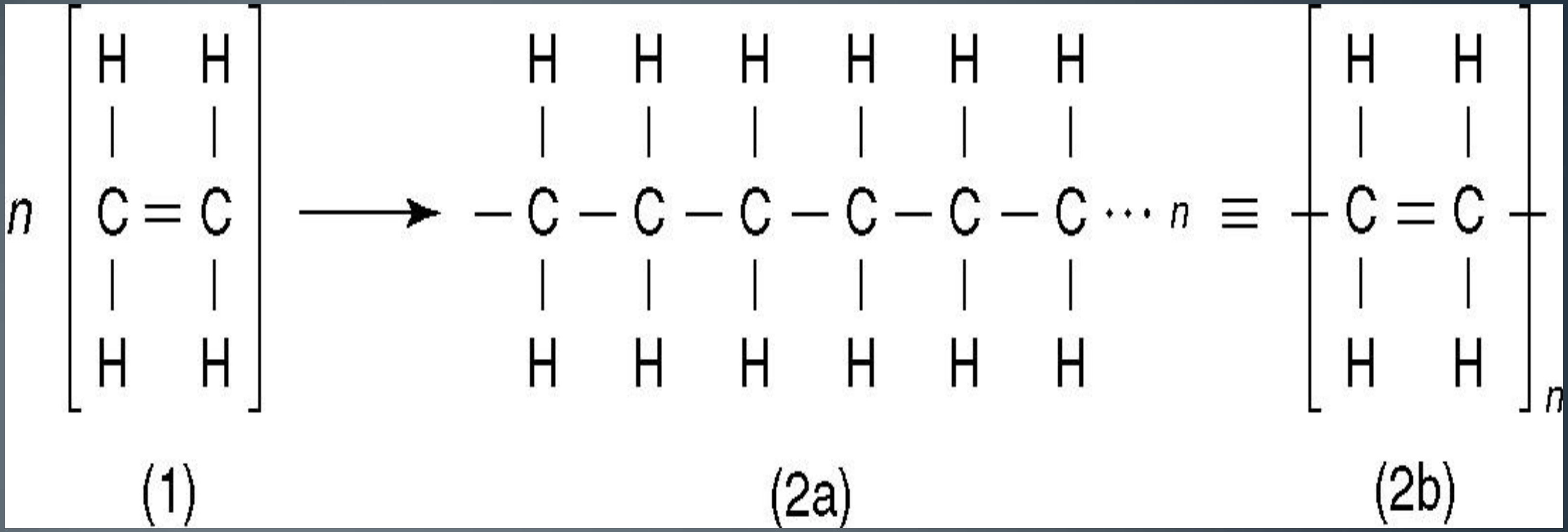


Figure 8.1 Synthesis of polyethylene from ethylene monomers: (1) n ethylene monomers yields, (2a) polyethylene of chain length *n*; (2b) concise notation for depicting the polymer structure of chain length *n*.

Polymerization

- As a chemical process, the synthesis of polymers can occur by either of two methods:
  1. Addition polymerization
  2. Step polymerization
- Production of a given polymer is generally associated with one method or the other

Addition Polymerization

- In this process, exemplified by polyethylene, the double bonds between carbon atoms in the ethylene monomers are induced to open up so that they join with other monomer molecules
- The connections occur on both ends of the expanding macromolecule, developing long chains of repeating mers
- It is initiated using a chemical catalyst (called an *initiator*) to open the carbon double bond in some of the monomers

Addition Polymerization

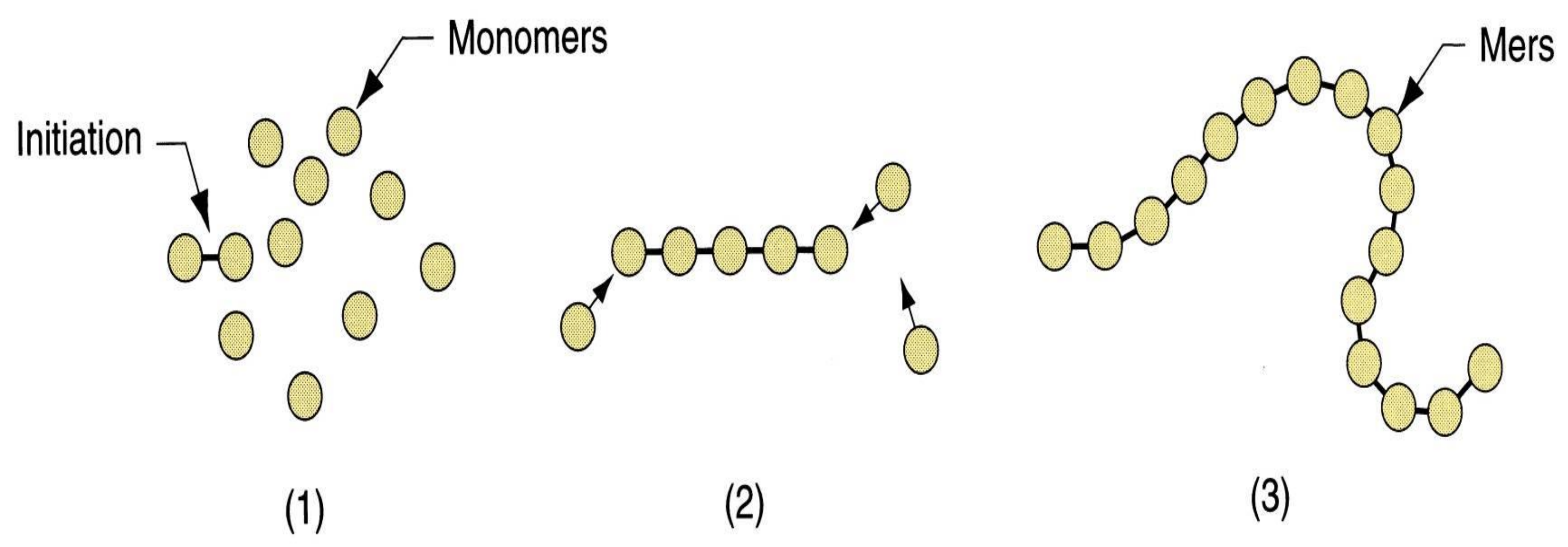


Figure 8.2 Model of addition (chain) polymerization: (1) initiation, (2) rapid addition of monomers, and (3) resulting long chain polymer molecule with *n* mers at termination of reaction.

Step Polymerization

- In this form of polymerization, two reacting monomers are brought together to form a new molecule of the desired compound
- As reaction continues, more reactant molecules combine with the molecules first synthesized to form polymers of length $n = 2$, then polymers of length $n = 3$, and so on
- In addition, polymers of length n_1 and n_2 also combine to form molecules of length $n = n_1 + n_2$, so that two types of reactions are proceeding simultaneously

Step Polymerization

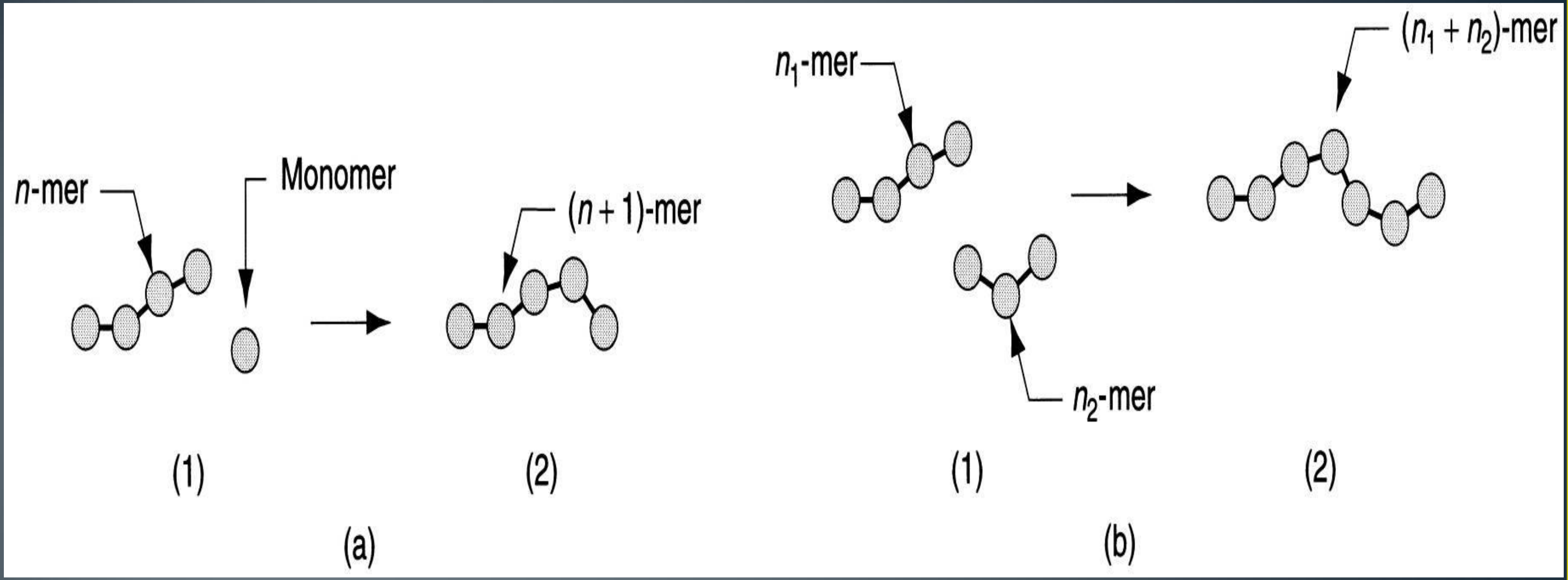


Figure 8.4 Model of step polymerization showing the two types of reactions occurring: (a) n-mer attaching a single monomer to form a $(n+1)$-mer; and (b) n_1-mer combining with n_2-mer to form a (n_1+n_2)-mer. Sequence is shown by (1) and (2).

Some Examples

- **Polymers produced by *addition* polymerization:**
  - **Polyethylene, polypropylene, polyvinylchloride, polyisoprene**
- **Polymers produced by *step* polymerization:**
  - **Nylon, polycarbonate, phenol formaldehyde**

Degree of Polymerization

- Since molecules in a given batch of polymerized material vary in length, *n* for the batch is an average
  - Its statistical distribution is normal
- The mean value of *n* is called the *degree of polymerization* (DP) for the batch
- DP affects properties of the polymer
  - Higher DP increases mechanical strength but also increases viscosity in the fluid state, which makes processing more difficult

Molecular Weight

- *Molecular weight* (MW) of a polymer is the sum of the molecular weights of the mers in the molecule
  - MW = *n* times the molecular weight of each repeating unit
  - Since *n* varies for different molecules in a batch, the molecule weight must be interpreted as an average

Typical Values of DP and MW

Polymer	DP(*n*)	MW
Polyethylene	10,000	300,000
Polyvinylchloride	1,500	100,000
Nylon	120	15,000
Polycarbonate	200	40,000

Polymer Molecular Structures

- Linear structure – chain-like structure
  - Characteristic of thermoplastic polymers
- Branched structure – chain-like but with side branches
  - Also found in thermoplastic polymers
- Cross-linked structure
  - Loosely cross-linked, characteristic of elastomers
  - Tightly cross-linked, characteristic of thermosets

Linear Structure

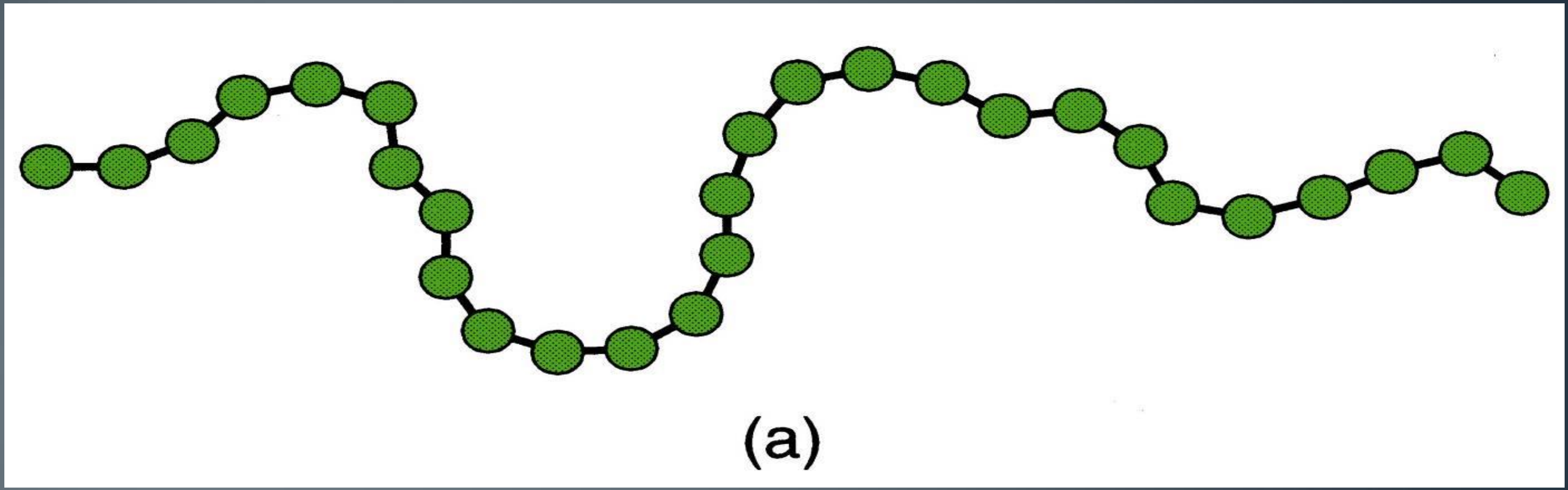
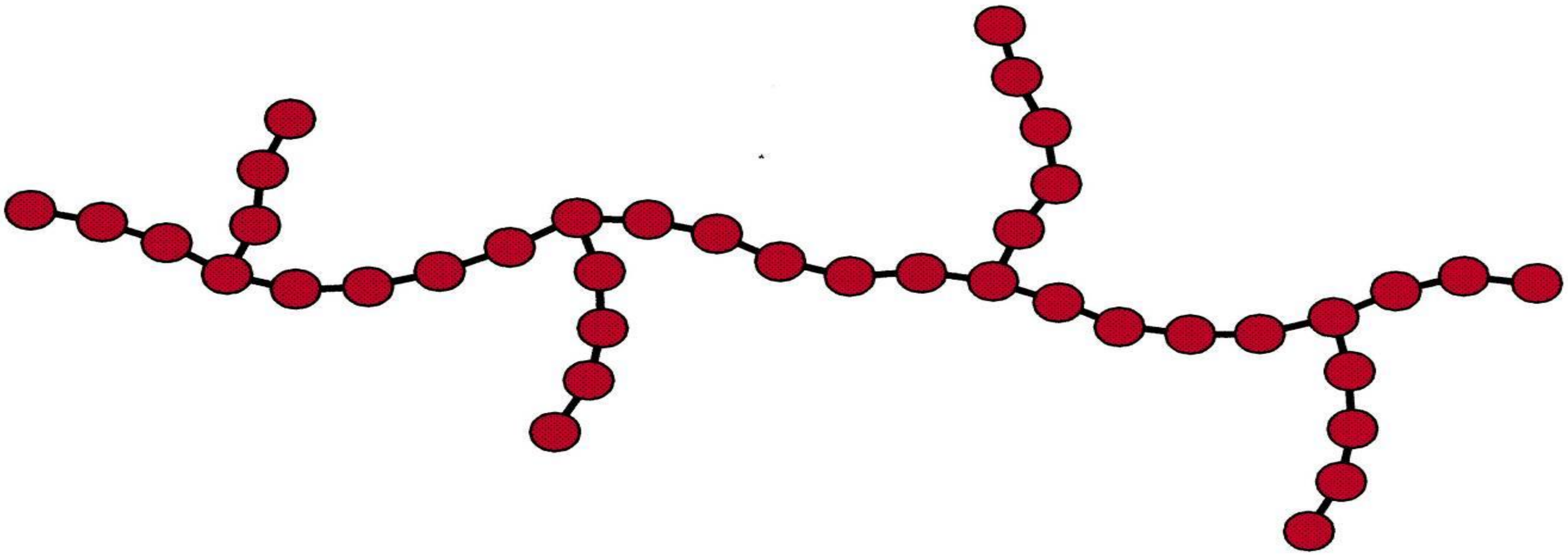


Figure 8.7 Various structures of polymer molecules: (a) linear, characteristic of thermoplastics.

Branched Structure



(b)

Figure 8.7 Various structures of polymer molecules: (b) branched, also characteristic of thermoplastics.

Loosely Cross-linked Structure

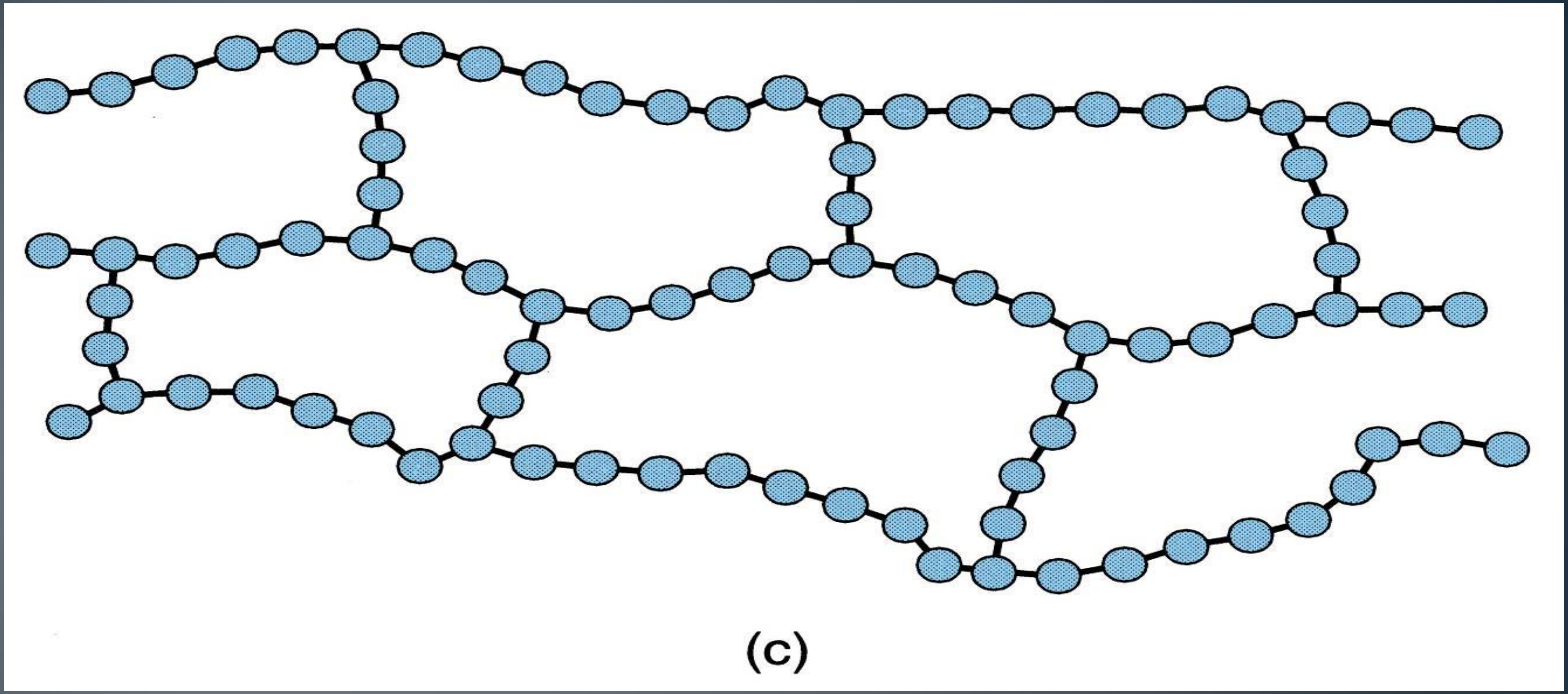


Figure 8.7 Various structures of polymer molecules: (c) loosely cross-linked characteristic of an elastomer.

Tightly Cross-linked Structure

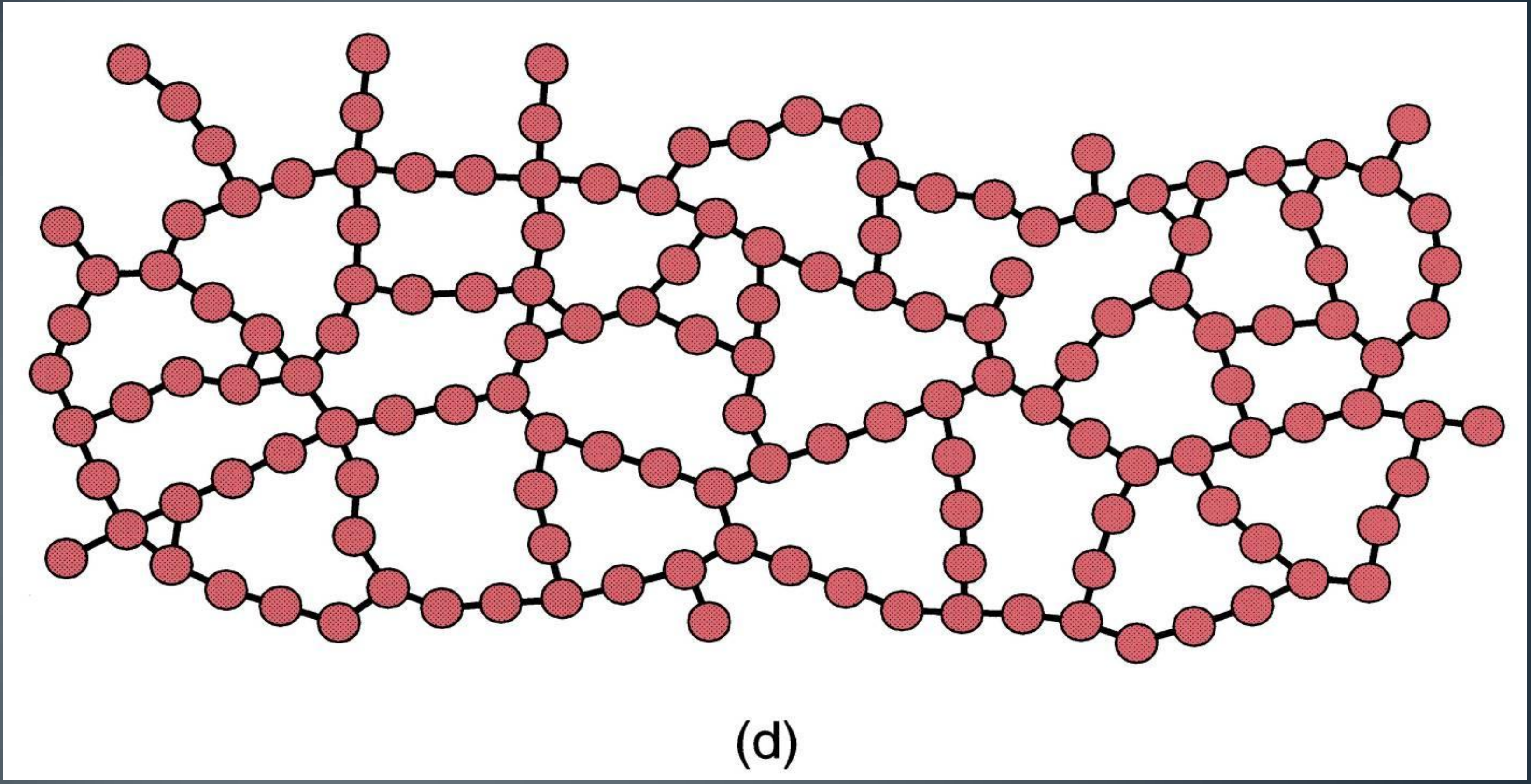


Figure 8.7 Various structures of polymer molecules: (d) tightly cross-linked or networked structure as in a thermoset.

Effect of Branching on Properties

- Thermoplastic polymers always possess linear or branched structures, or a mixture of the two
- Branches increase entanglement among the molecules, which makes the polymer
  - Stronger in the solid state
  - More viscous at a given temperature in the plastic or liquid state

Effect of Cross-Linking on Properties

- Thermosets possess a high degree of cross-linking, while elastomers possess a low degree of cross-linking
- Thermosets are hard and brittle, while elastomers are elastic and resilient
- Cross-linking causes the polymer to become chemically set
  - The reaction cannot be reversed
  - The polymer structure is permanently changed; if heated, it degrades or burns rather than melt

Crystallinity in Polymers

- Both amorphous and crystalline structures are possible, although the tendency to crystallize is much less than for metals or non-glass ceramics
- Not all polymers can form crystals
- For those that can, the *degree of crystallinity* (the proportion of crystallized material in the mass) is always less than 100%

Crystalline Polymer Structure

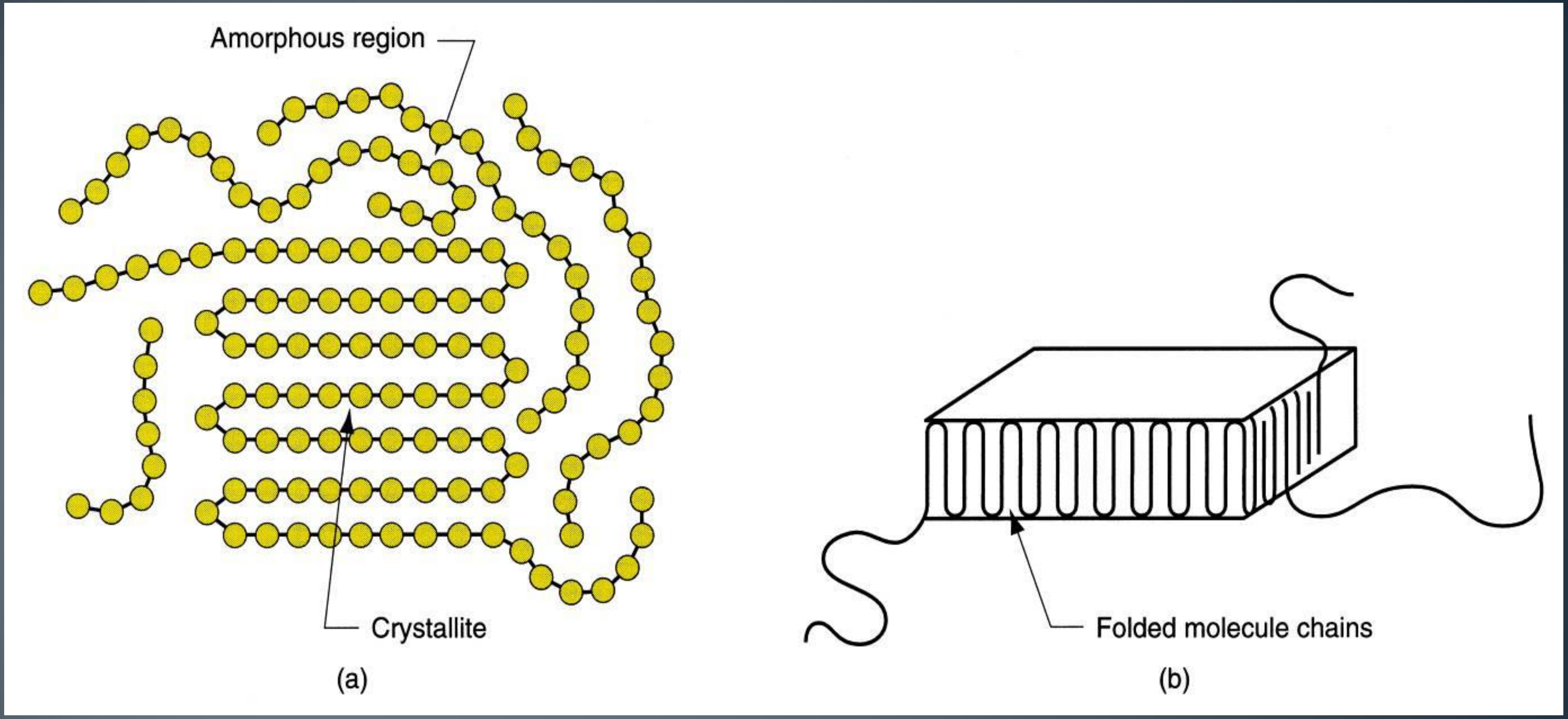


Figure 8.9 Crystallized regions in a polymer: (a) long molecules forming crystals randomly mixed in with the amorphous material; and (b) folded chain lamella, the typical form of a crystallized region.

Crystallinity and Properties

- As crystallinity is increased in a polymer
  - Density increases
  - Stiffness, strength, and toughness increases
  - Heat resistance increases
  - If the polymer is transparent in the amorphous state, it becomes opaque when partially crystallized

Low Density & High Density Polyethylene

Polyethylene type	Low density	High density
Degree of crystallinity	55%	92%
Specific gravity	0.92	0.96
Modulus of elasticity	140 MPa (20,000 lb/in^2)	700 MPa (100,000 lb/in^2)
Melting temperature	115°C (239°F)	135°C (275°F)

Some Observations About Crystallization

- Linear polymers consist of long molecules with thousands of repeated mers
  - Crystallization involves folding back and forth of the long chains upon themselves to achieve a very regular arrangement
- The crystallized regions are called *crystallites*
- Crystallites take the form of lamellae randomly mixed in with amorphous material
  - A polymer that crystallizes is a two-phase system - crystallites interspersed throughout an amorphous matrix

Factors for Crystallization

- Slower cooling promotes crystal formation and growth
- Mechanical deformation, as in the stretching of a heated thermoplastic, tends to align the structure and increase crystallization
- Plasticizers (chemicals added to a polymer to soften it) reduce the degree of crystallinity

Additives

- Properties of a polymer can often be beneficially changed by combining it with additives
- Additives either alter the molecular structure or
- Add a second phase, in effect transforming the polymer into a composite material

Types of Additives by Function

- Fillers – to strengthen polymer or reduce cost
- Plasticizers – to soften polymer and improve flow
- Colorants – pigments or dyes
- Lubricants – to reduce friction and improve flow
- Flame retardents – to reduce flammability of polymer
- Cross-linking agents – for thermosets and elastomers
- Ultraviolet light absorbers – to reduce degradation from sunlight
- Antioxidants – to reduce oxidation damage

Thermoplastic Polymers (TP)

- A thermoplastic polymer can be heated from a solid state to a viscous liquid state and then cooled back down to solid
  - Heating and cooling can be repeated many times without degrading the polymer
  - The reason is that TP polymers consist of linear (and/or branched) macromolecules that do not cross-link upon heating
- By contrast, thermosets and elastomers change chemically when heated, which cross-links their molecules and permanently sets these polymers

Mechanical Properties of Thermoplastics

- Low modulus of elasticity (stiffness)
  - *E* is two or three orders of magnitude lower than metals and ceramics
- Low tensile strength
  - *TS* is about 10% of the metal
- Much lower hardness than metals or ceramics
- Greater ductility on average
  - Tremendous range of values, from 1% elongation for polystyrene to 500% or more for polypropylene

Strength vs. Temperature

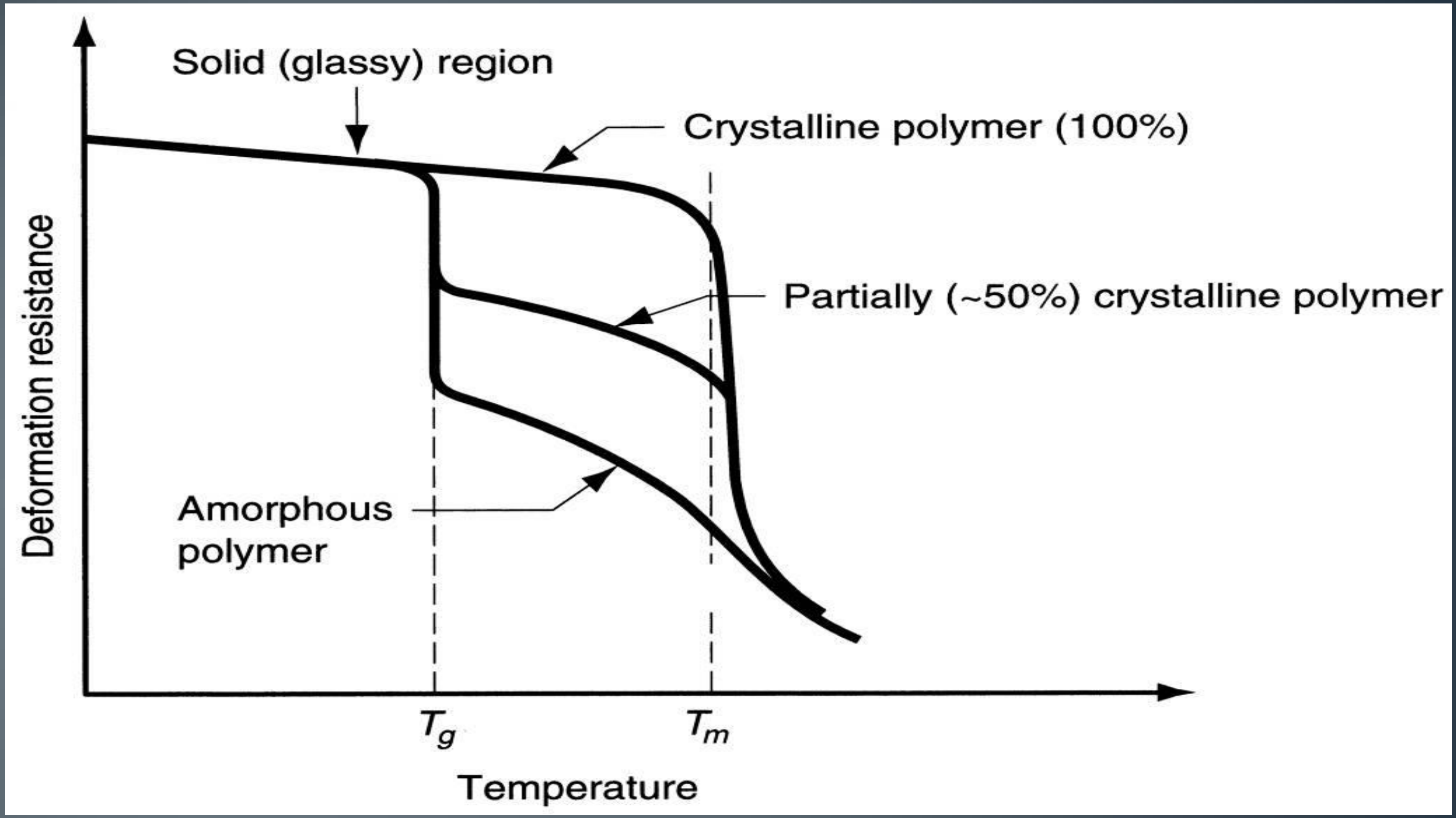


Figure 8.11 Relationship of mechanical properties, portrayed as deformation resistance, as a function of temperature for an amorphous thermoplastic, a 100% crystalline (theoretical) thermoplastic, and a partially crystallized thermoplastic.

Physical Properties of Thermoplastics

- Lower densities than metals or ceramics
  - Typical specific gravity for polymers are ~1.2
  - Ceramics specific gravity = ~2.5
  - Metals specific gravity = ~7.0
- Much higher coefficient of thermal expansion
  - Roughly five times the value for metals and 10 times the value for ceramics
- Much lower melting temperatures
- Insulating electrical properties
- Higher specific heats than metals and ceramics

Commercial Thermoplastic Products and Raw Materials

- Thermoplastic products include
  - Molded and extruded items
  - Fibers and filaments
  - Films and sheets
  - Packaging materials
  - Paints and varnishes
- The starting plastic materials are normally supplied to the fabricator in the form of powders or pellets in bags, drums, or larger loads by truck or rail car

Thermosetting Polymers (TS)

- TS polymers are distinguished by their highly cross-linked three-dimensional, covalently-bonded structure
- Chemical reactions associated with cross-linking are called *curing* or *setting*
- In effect, the formed part (e.g., pot handle, electrical switch cover, etc.) becomes one large macromolecule
- Always amorphous and exhibits no glass transition temperature

General Properties of Thermosets

- Rigid - modulus of elasticity is two to three times greater than thermoplastics
- Brittle, virtually no ductility
- Less soluble in common solvents than thermoplastics
- Capable of higher service temperatures than thermoplastics
- Cannot be remelted - instead they degrade or burn

Cross-Linking in TS Polymers

- Three categories:
  1. Temperature-activated systems
  2. Catalyst-activated systems
  3. Mixing-activated systems
- Curing is accomplished at the fabrication plants that make the parts rather than the chemical plants that supply the starting materials to the fabricator

Temperature-Activated Systems

Curing caused by heat supplied during part shaping operation (e.g., molding)

- Starting material is a linear polymer in granular form supplied by the chemical plant
  - As heat is added, material softens for molding, but continued heating causes cross-linking
- Most common TS systems
  - The term “thermoset" applies best to these polymers

Catalyst-Activated Systems

Cross-linking occurs when small amounts of a catalyst are added to the polymer, which is in liquid form

- Without the catalyst, the polymer remains stable and liquid
- Once combined with the catalyst it cures and changes into solid form

Mixing-Activated Systems

Mixing of two chemicals results in a reaction that forms a cross-linked solid polymer

- Elevated temperatures are sometimes used to accelerate the reactions
- Most epoxies are examples of these systems

TS vs. TP Polymers

- TS plastics are not as widely used as the TP
  - One reason is the added processing costs and complications involved in curing
- Largest market share of TS = phenolic resins with ~ 6% of the total plastics market
  - Compare polyethylene with ~ 35% market share
- TS Products: countertops, plywood adhesives, paints, molded parts, printed circuit boards and other fiber reinforced plastics

Elastomers

Polymers capable of large elastic deformation when subjected to relatively low stresses

- Some can be extended 500% or more and still return to their original shape
- Two categories:
  1. Natural rubber - derived from biological plants
  2. Synthetic polymers - produced by polymerization processes similar to those used for thermoplastic and thermosetting polymers

Characteristics of Elastomers

- Elastomers consist of long-chain molecules that are cross-linked (like thermosetting polymers)
- They owe their impressive elastic properties to two features:

1. Molecules are tightly kinked when unstretched
2. Degree of cross-linking is substantially less than thermosets

Elastomer Molecules

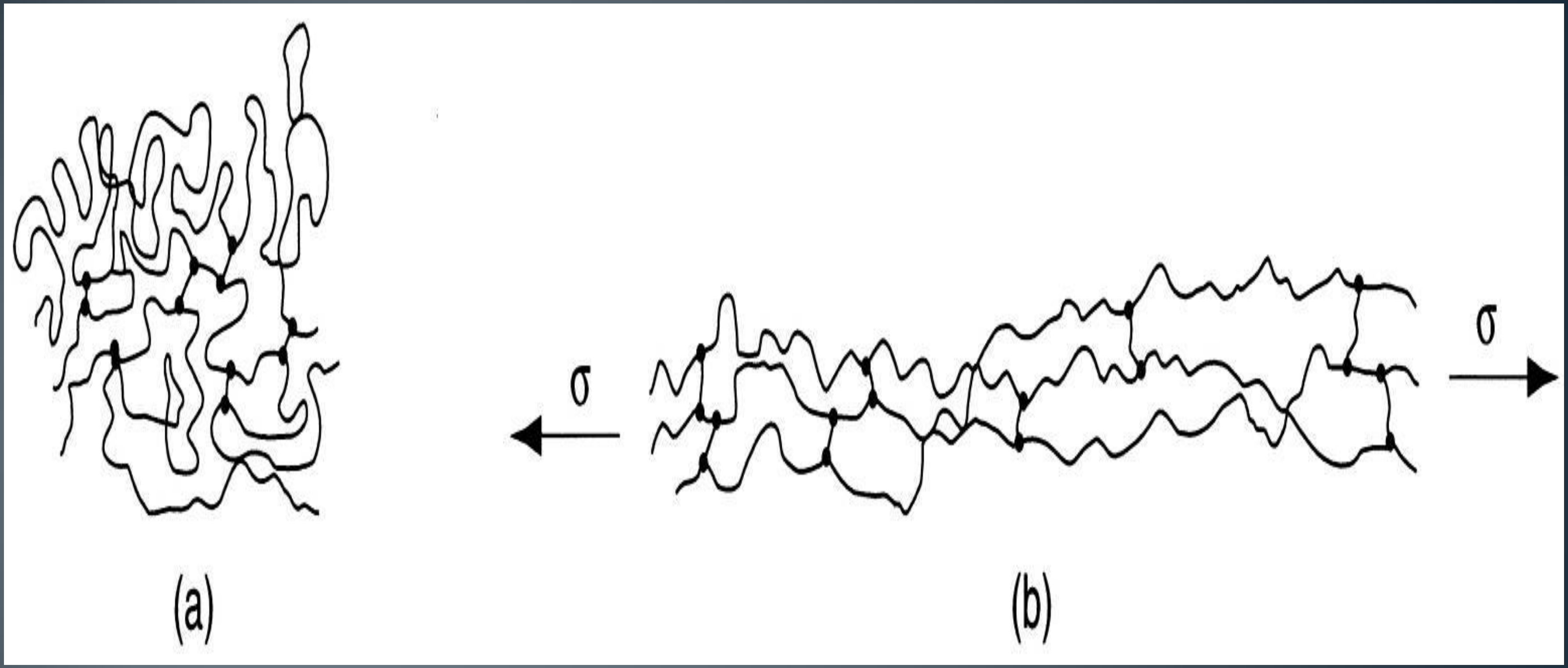


Figure 8.12 Model of long elastomer molecules, with low degree of cross-linking: (a) unstretched, and (b) under tensile stress.

Elastic Behavior of Elastomer Molecule

- When stretched, the molecules are forced to uncoil and straighten
- Natural resistance to uncoiling provides the initial elastic modulus of the aggregate material
- Under further strain, the covalent bonds of the cross-linked molecules begin to play an increasing role in the modulus, and stiffness increases
- With greater cross-linking, the elastomer becomes stiffer and its modulus of elasticity is more linear

Stiffness of Rubber

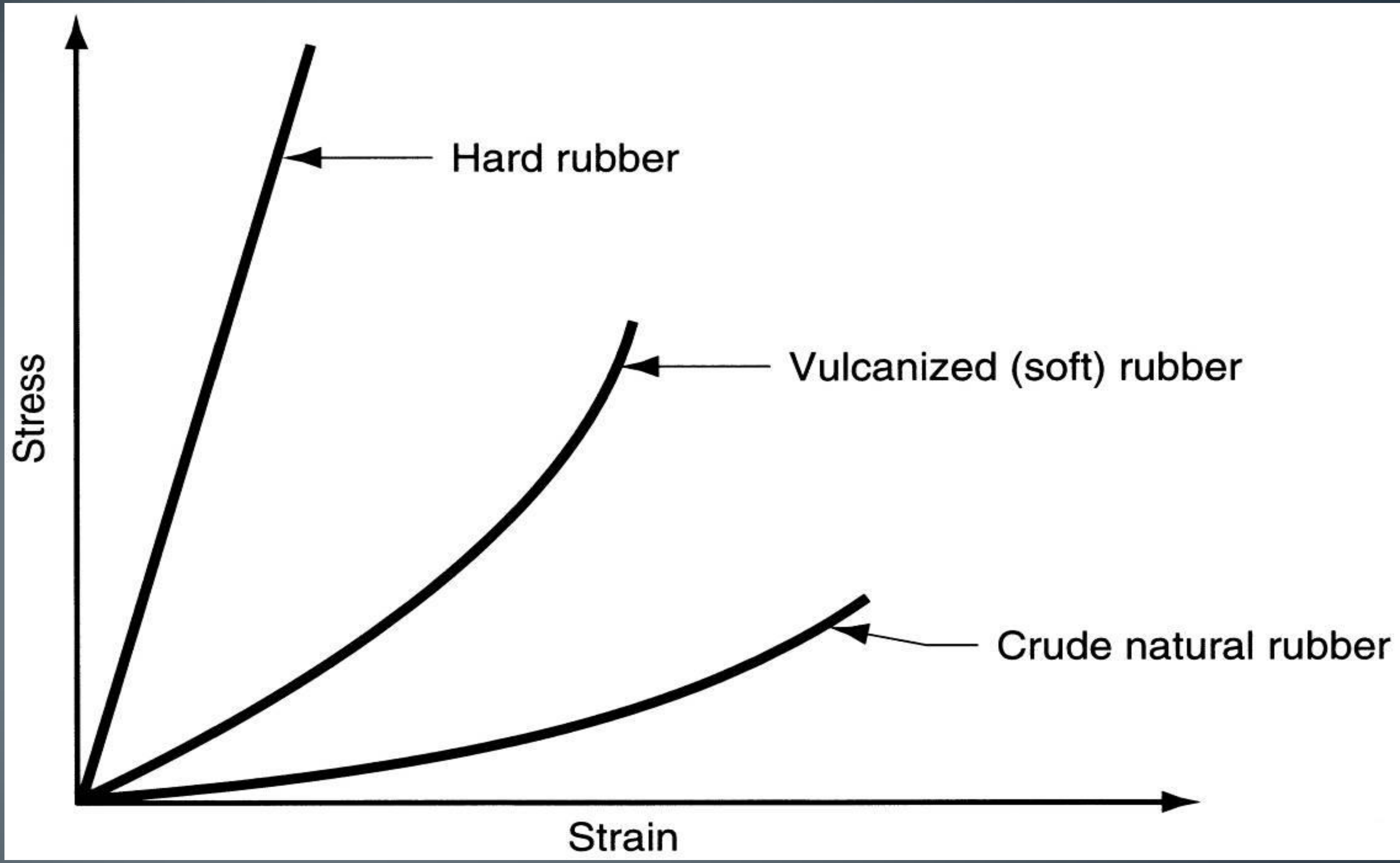


Figure 8.13 Increase in stiffness as a function of strain for three grades of rubber: natural rubber, vulcanized rubber, and hard rubber.

Vulcanization

Curing to cross-link most elastomers

- *Vulcanization* = the term for curing in the context of natural rubber (and certain synthetic rubbers)
- Typical cross-linking in rubber is one to ten links per hundred carbon atoms in the linear polymer chain, depending on degree of stiffness desired
  - Considerable less than cross-linking in thermosets

Natural Rubber (NR)

- NR consists primarily of polyisoprene, a high molecular-weight polymer of isoprene (C_5H_8)
- It is derived from *latex*, a milky substance produced by various plants, most important of which is the rubber tree that grows in tropical climates
- Latex is a water emulsion of polyisoprene (about 1/3 by weight), plus various other ingredients
- Rubber is extracted from latex by various methods that remove the water

Vulcanized Natural Rubber

- Properties: noted among elastomers for high tensile strength, tear strength, resilience (capacity to recover shape), and resistance to wear and fatigue
- Weaknesses: degrades when subjected to heat, sunlight, oxygen, ozone, and oil
  - Some of these limitations can be reduced by additives
- Market share of NR ~ 22% of total rubber volume (natural plus synthetic)
  - Total rubber volume ~ 15% of total polymer market

Natural Rubber Products

- Largest single market for NR is automotive tires
- Other products: shoe soles, bushings, seals, and shock absorbing components
- In tires, *carbon black* is an important additive; it reinforces the rubber, serving to increase tensile strength and resistance to tear and abrasion
- Other additives: clay, kaolin, silica, talc, and calcium carbonate, as well as chemicals that accelerate and promote vulcanization

Synthetic Rubbers

- Development of synthetic rubbers was motivated largely by world wars when NR was difficult to obtain
- Today, tonnage of synthetic rubbers is more than three times that of NR
- The most important synthetic rubber is styrene-butadiene rubber (SBR), a copolymer of butadiene (C_4H_6) and styrene (C_8H_8)
- As with most other polymers, the main raw material for synthetic rubbers is petroleum

Thermoplastic Elastomers (TPE)

A thermoplastic that behaves like an elastomer

- Elastomeric properties not from chemical cross-links, but from physical connections between soft and hard phases in the material
- Cannot match conventional elastomers in elevated temperature strength and creep resistance
- Products: footwear; rubber bands; extruded tubing, wire coating; molded automotive parts, but no tires

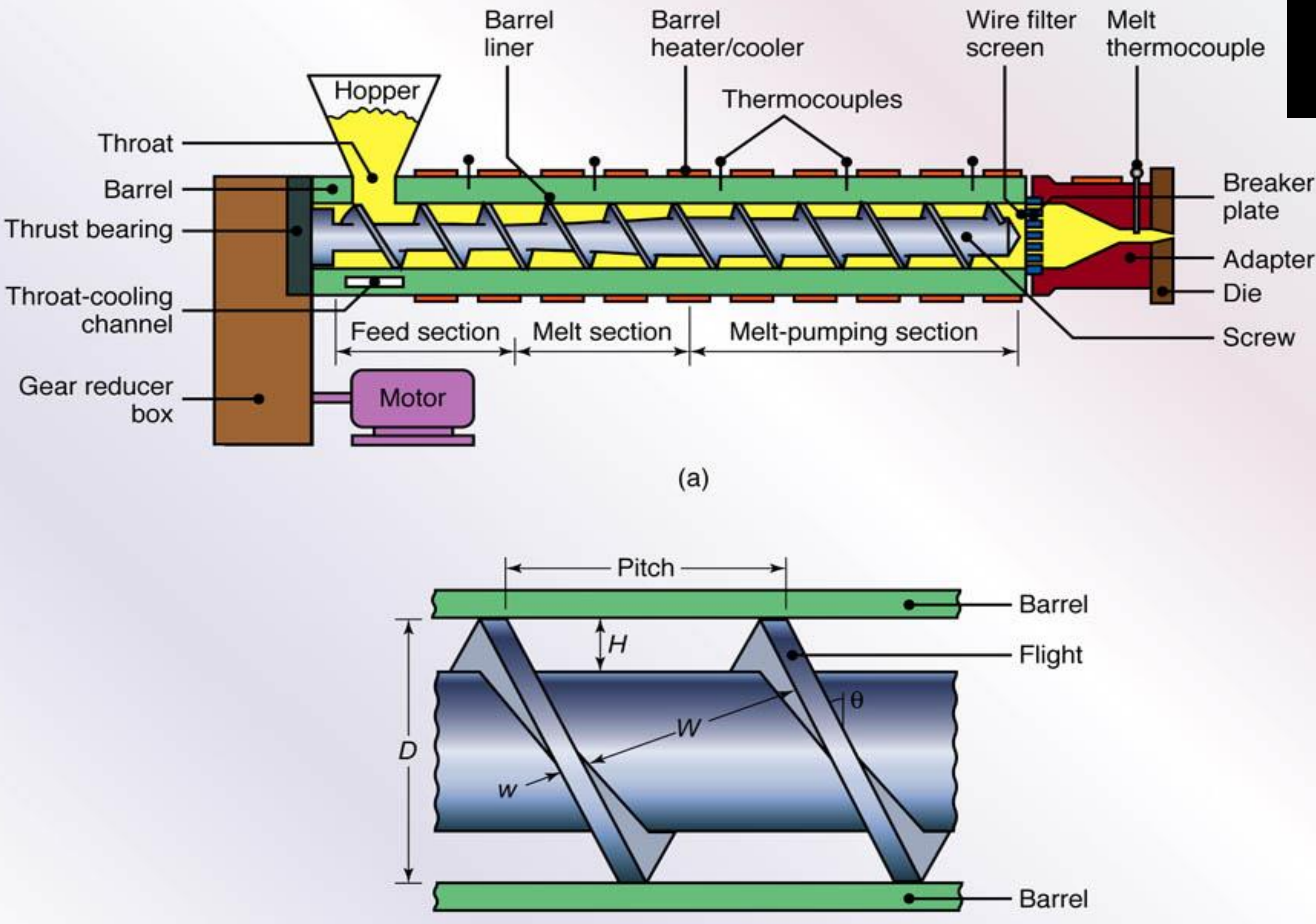
Guide to the Processing of Polymers

- Polymers are nearly always shaped in a heated, highly plastic state
- Common operations are extrusion and molding
- Molding of thermosets is more complicated because of cross-linking
- Thermoplastics are easier to mold and a greater variety of molding operations are available
- Rubber processing has a longer history than plastics, and rubber industries are traditionally separated from plastics industry, even though processing is similar

Extrusion

MFG 355

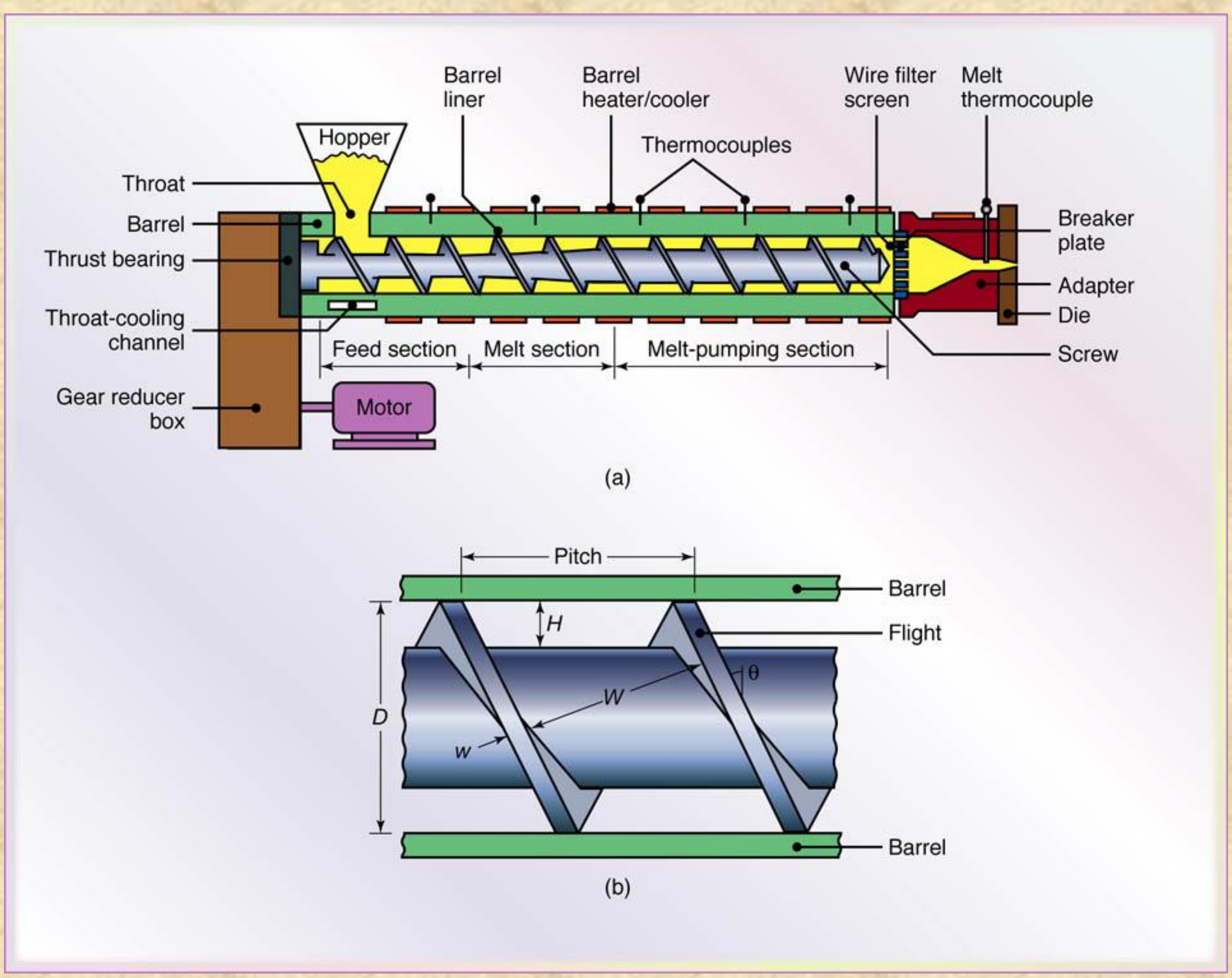
[redacted]



Barrel liner
Barrel heater/cooler
Wire filter screen
Melt thermocouple
Hopper
Thermocouples
Throat
Barrel
Thrust bearing
Throat-cooling channel
Gear reducer box
Motor
Feed section
Melt section
Melt-pumping section
Breaker plate
Adapter
Die
Screw
Pitch
H
D
W
w
θ
Barrel
Flight
Barrel

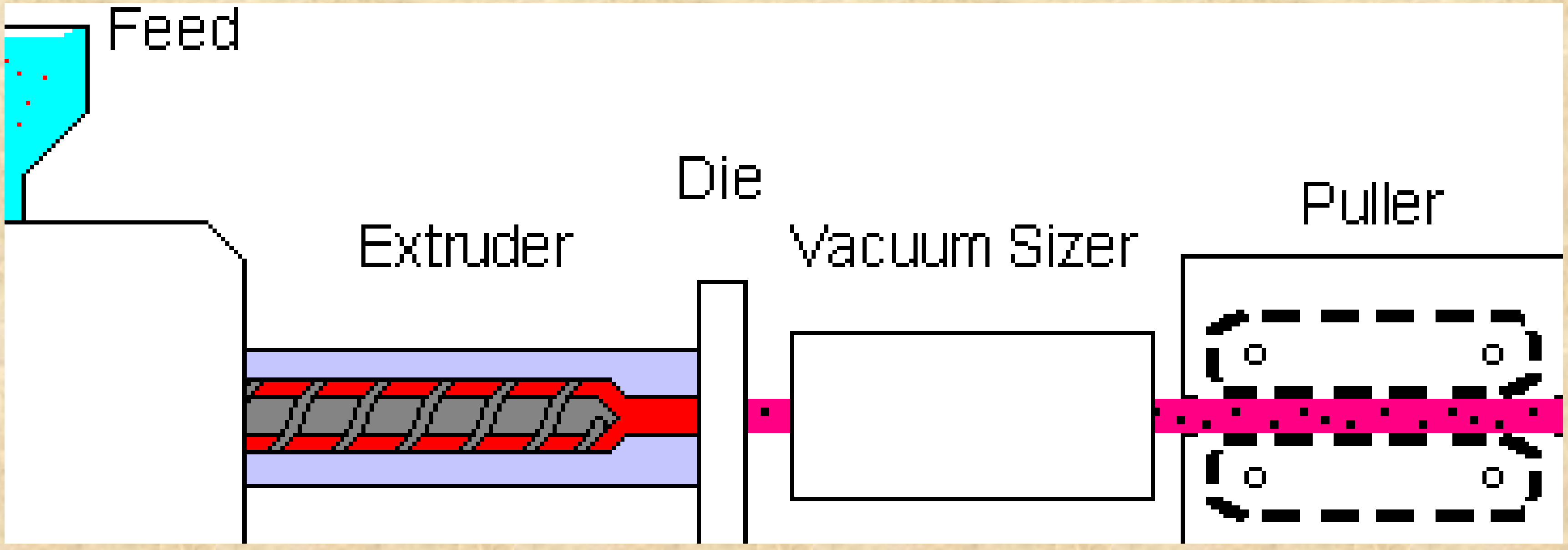
(a) (b)

Extruder Schematic

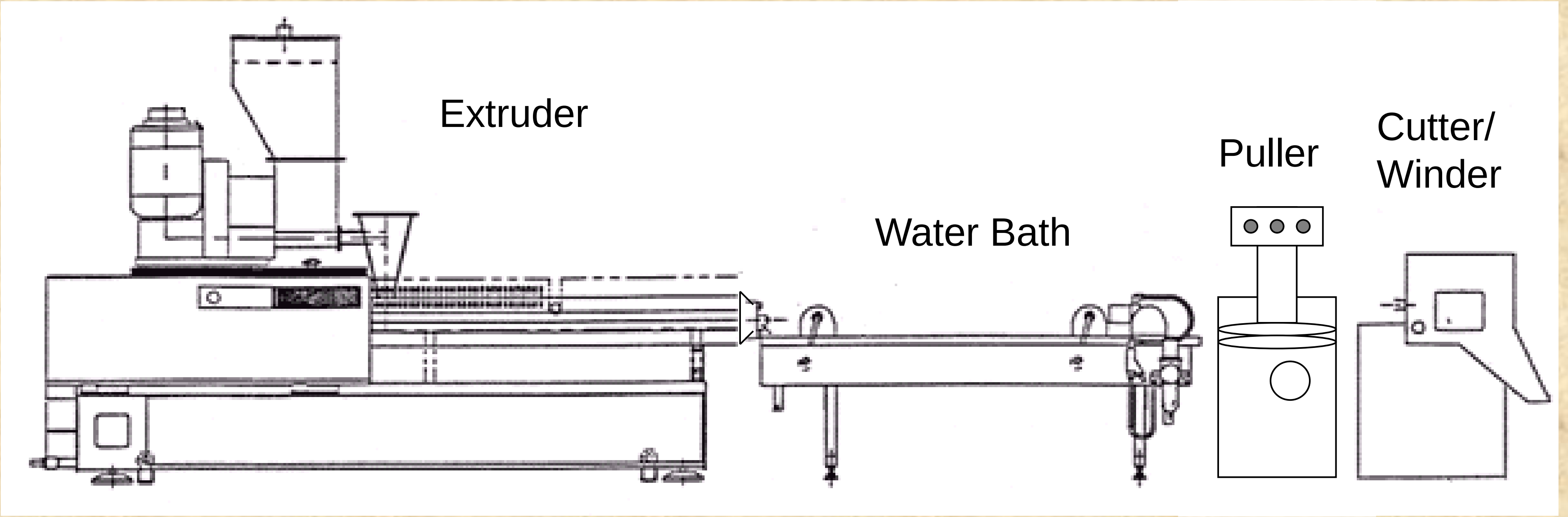


Schematic illustration of a typical screw extruder. (b) Geometry of an extruder screw. Complex shapes can be extruded with relatively simple and inexpensive dies.

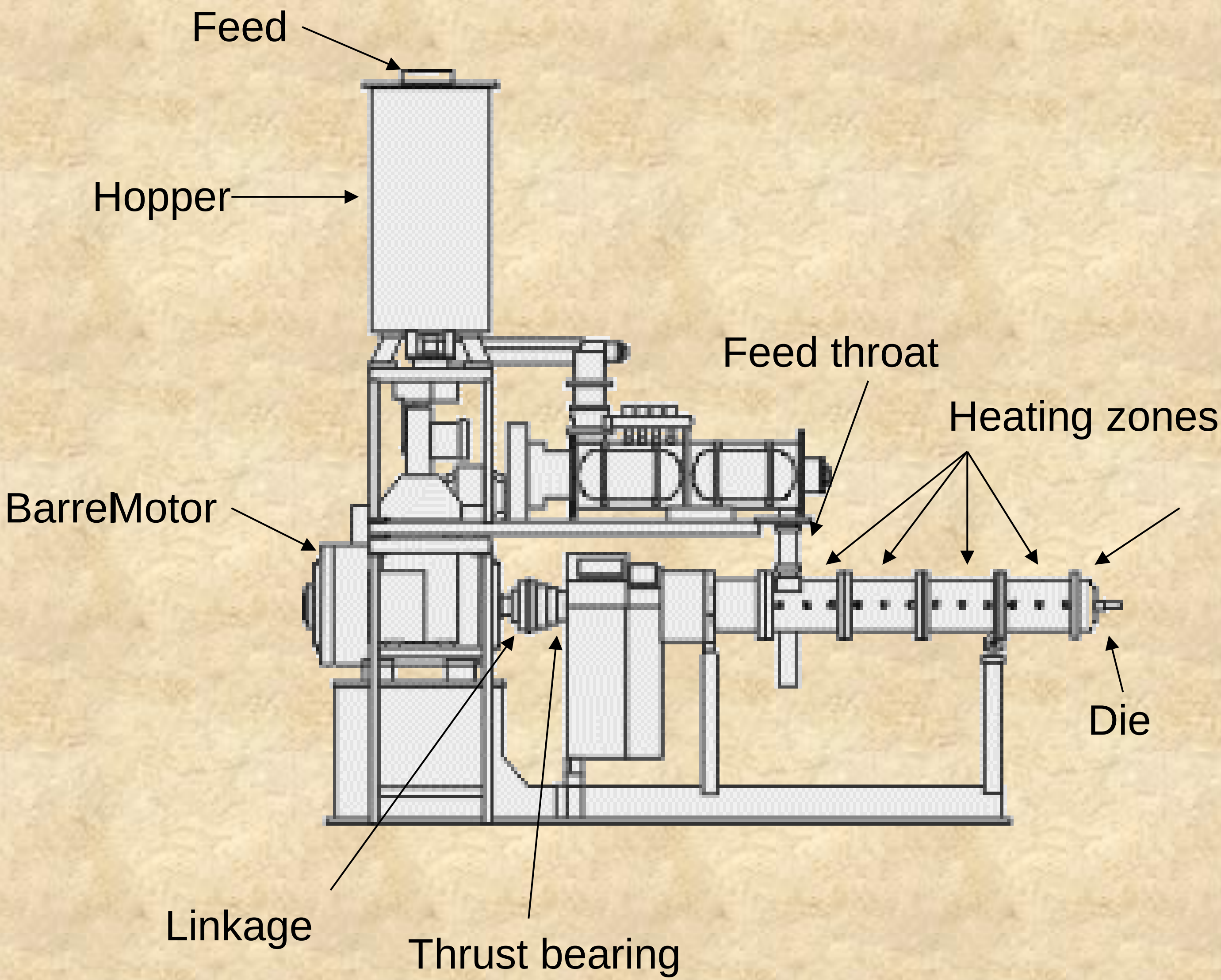
Extrusion



Extrusion System



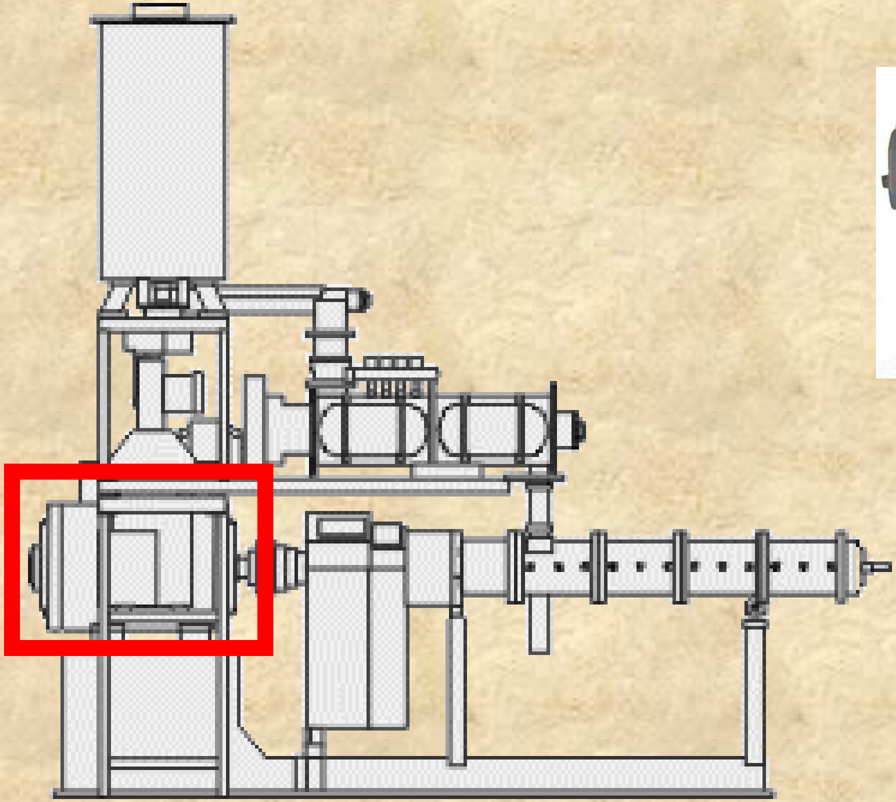
Extruder


Feed
Hopper
Feed throat
Heating zones
BarrelMotor
Die
Linkage
Thrust bearing

Extruder

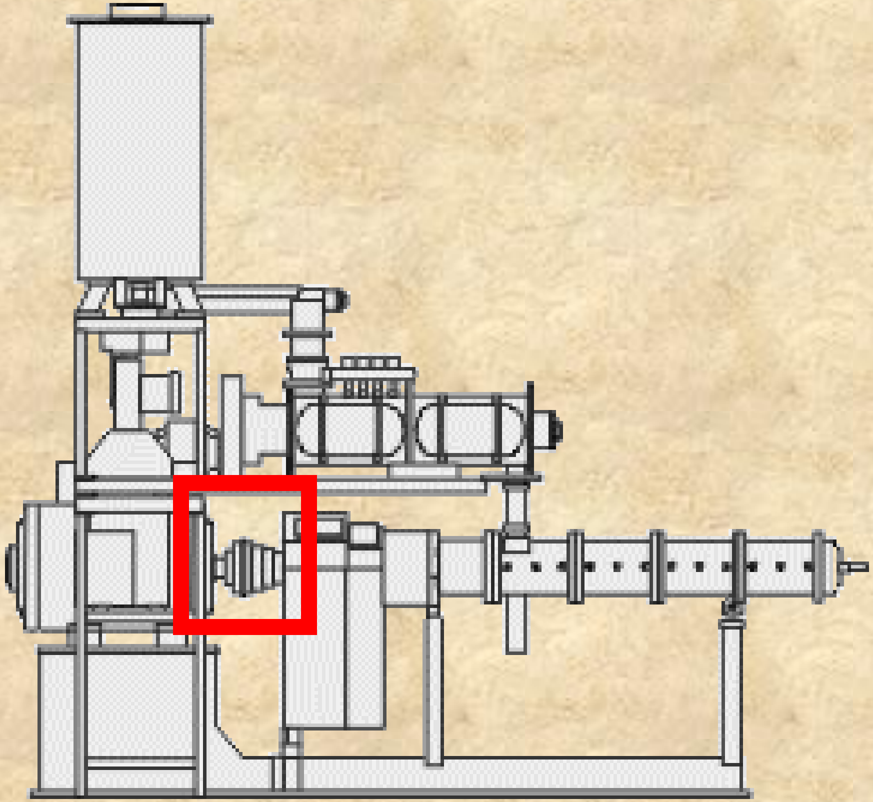
Drive Motor

- Turns the Screw
- Provides power for the process



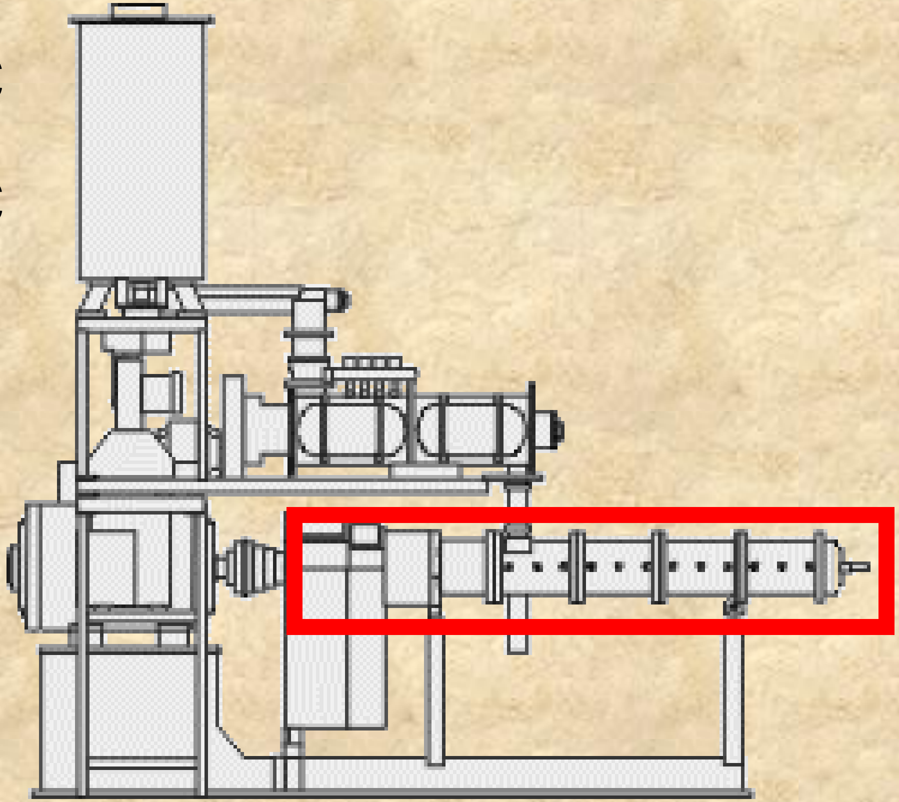
Thrust Bearing

- Prevents the screw from moving backward
- Seals off the end of the barrel

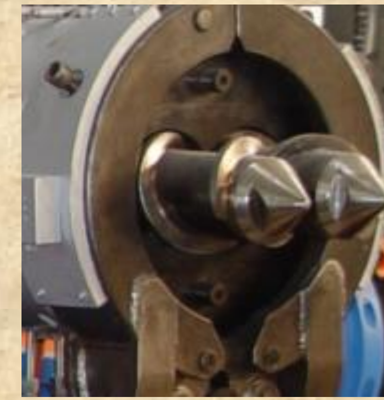


Extruder Screw

- Connected to drive linkage
- Inside barrel
- Grinds the plastic
- Moves the plastic

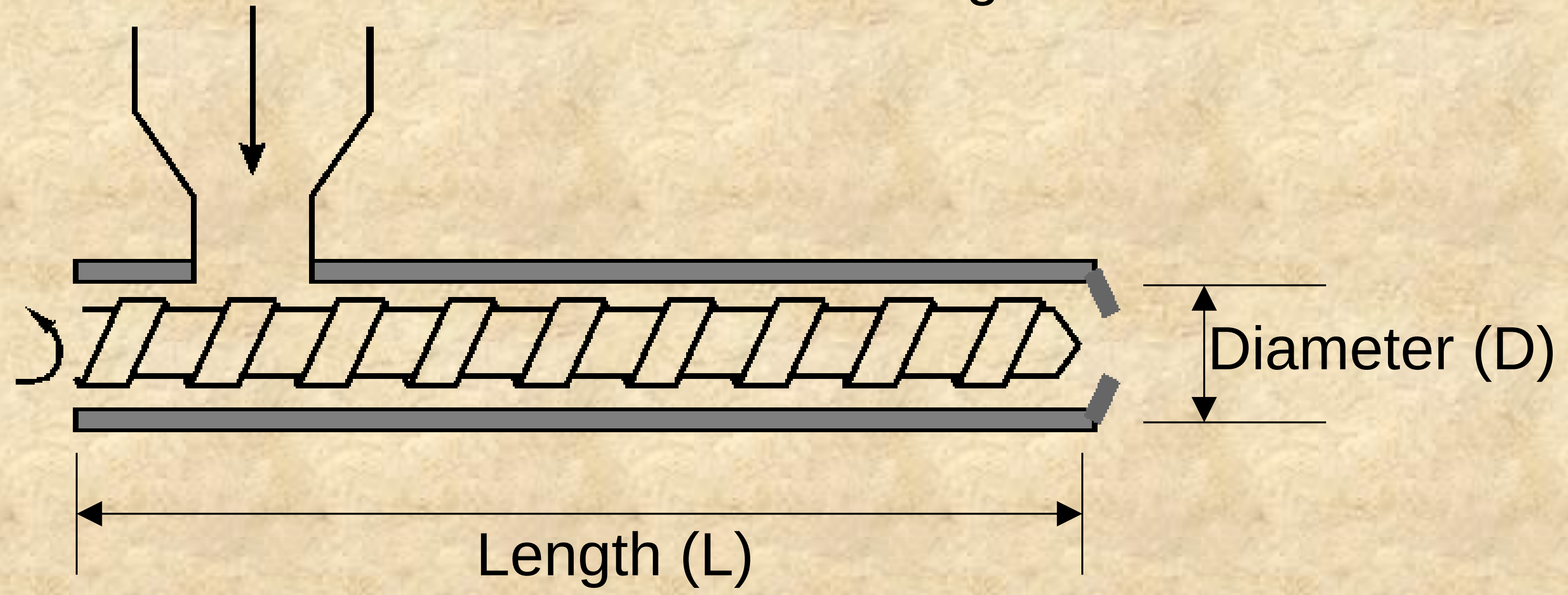


Extrusion Screws

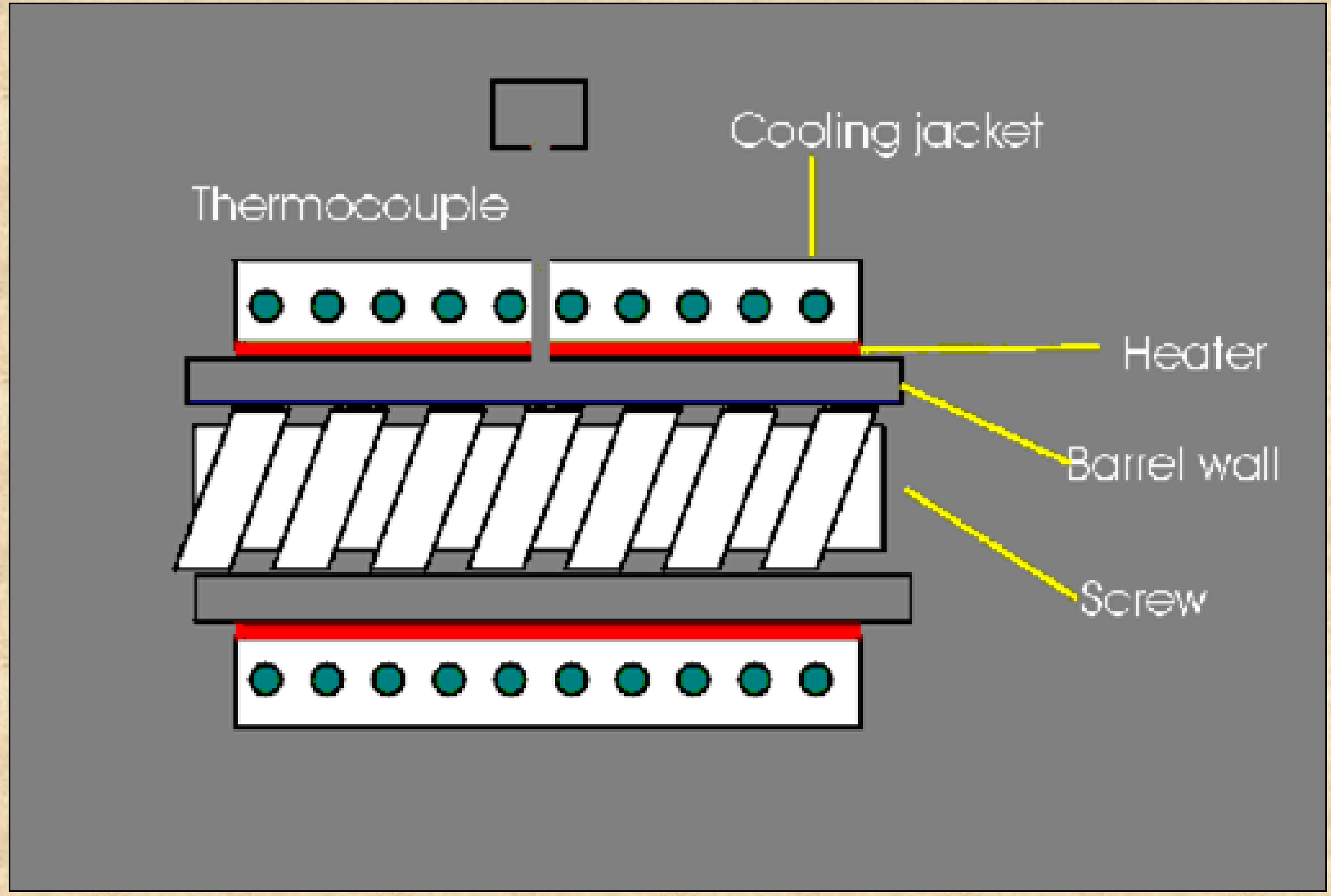


Extrusion Screws

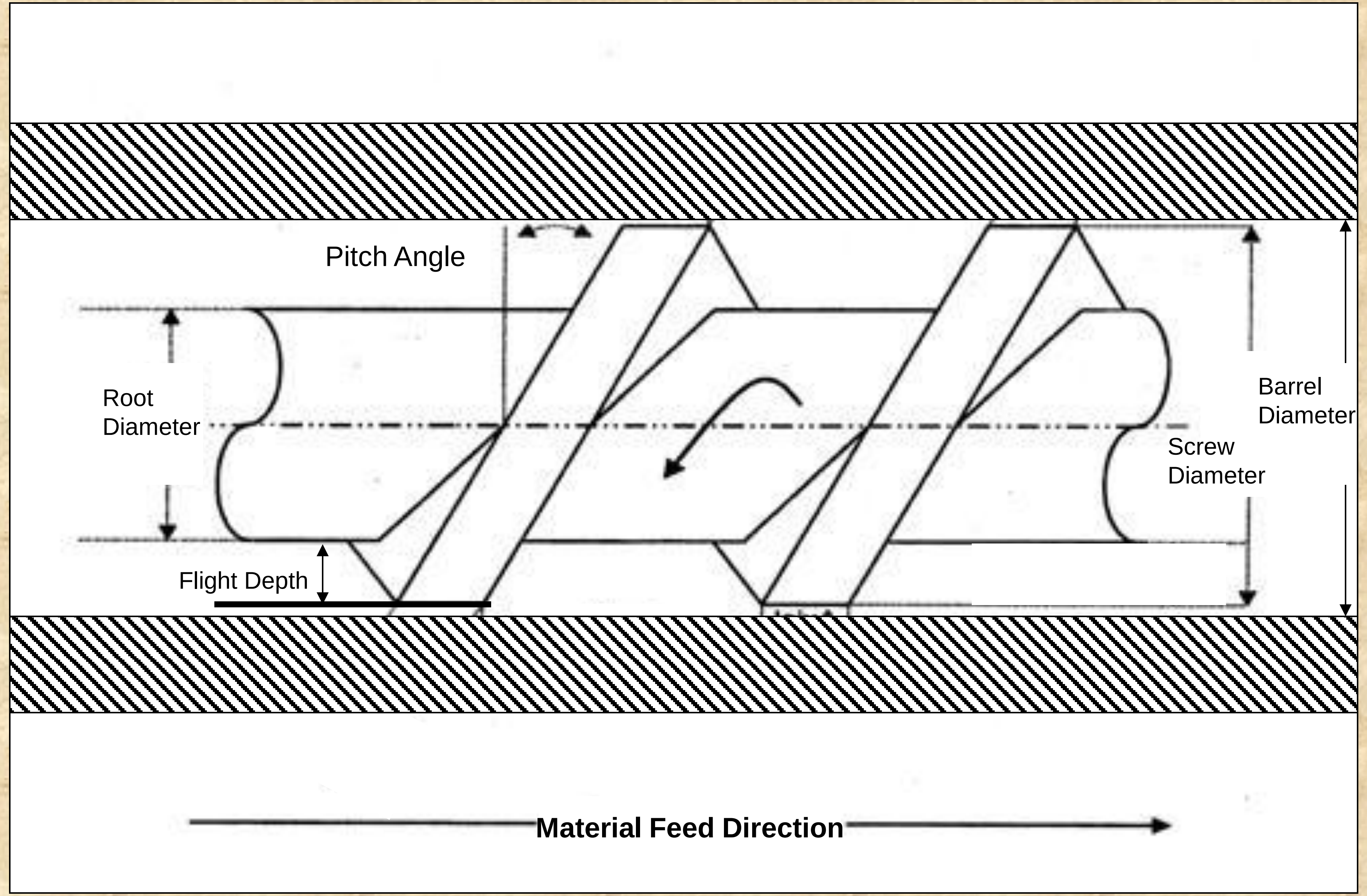
- L/D ratio
  - Relates directly to the extruder's ability to mix
  - Typical L/D ratio is 16:1 up to 32:1
    - Newer machines tend to have higher ratios



Extrusion Screws

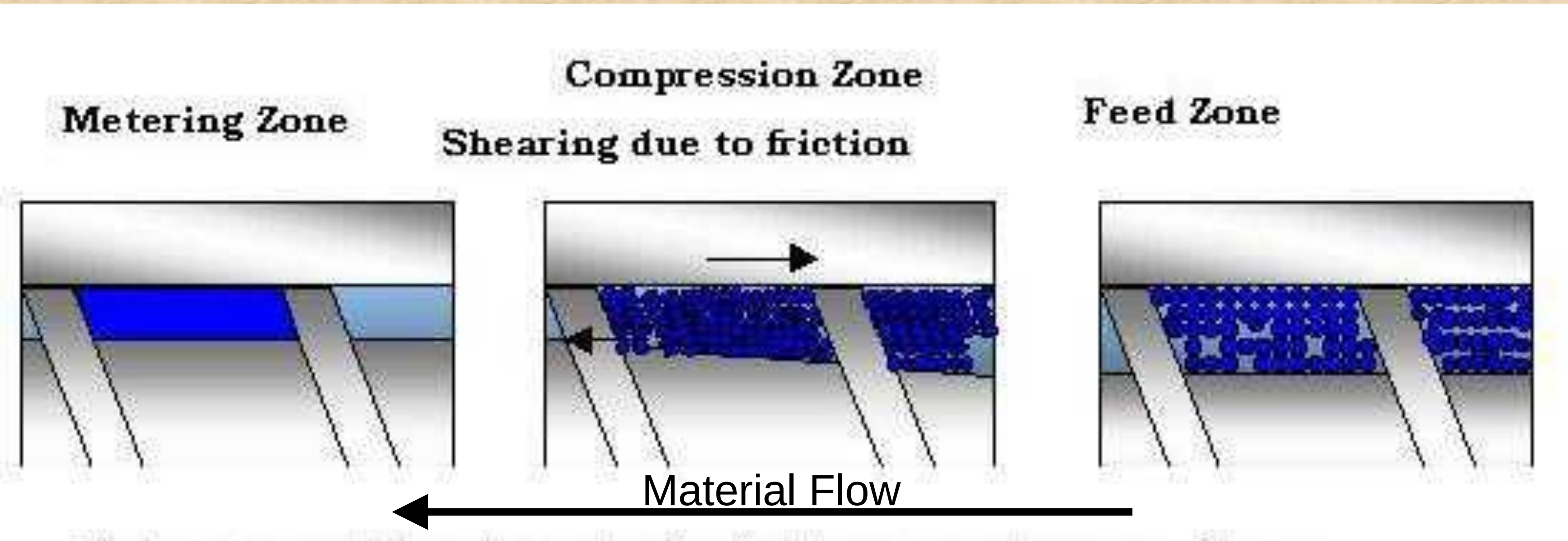


Extrusion Screws



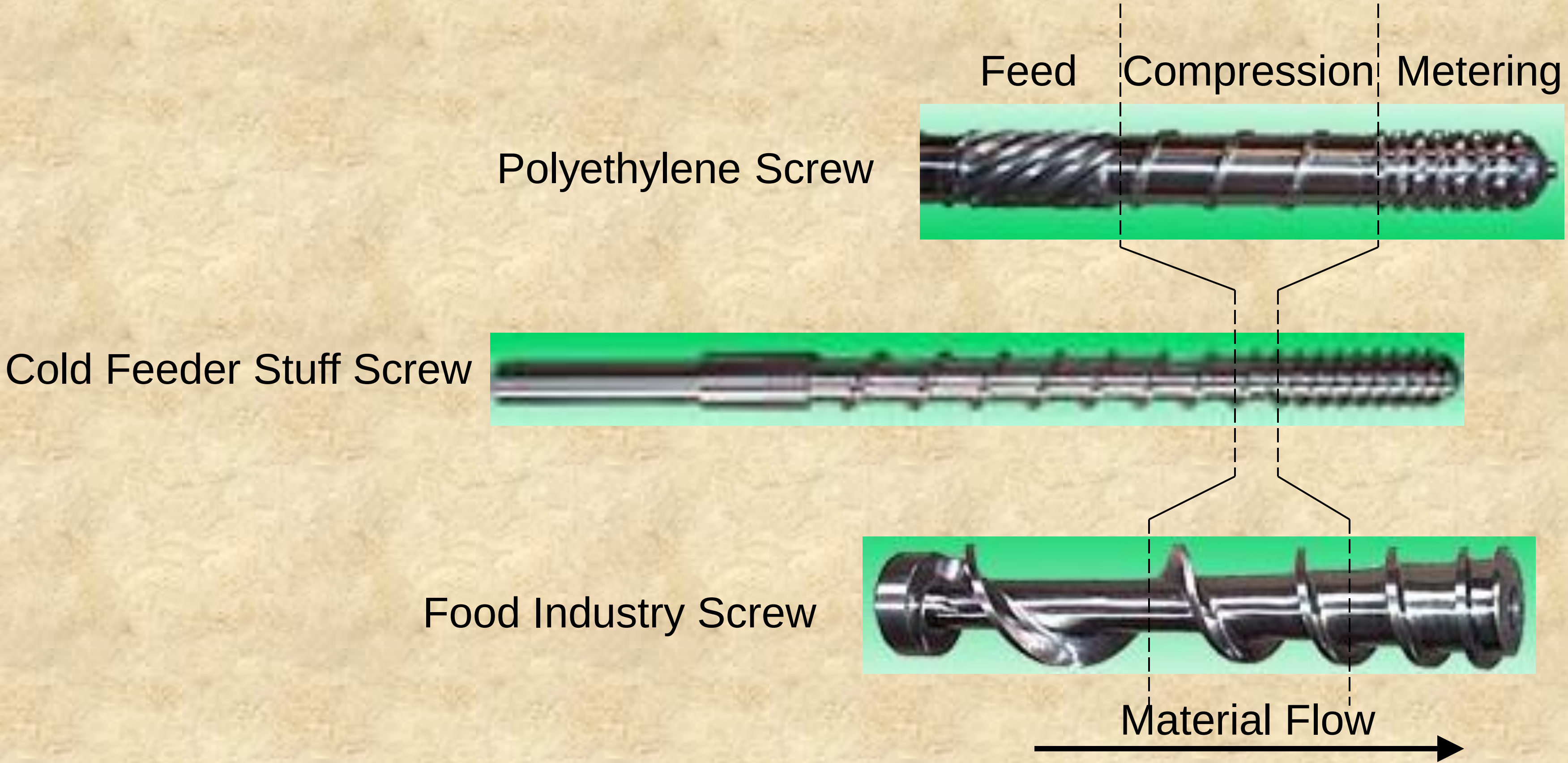
Extrusion Screws

- Zones



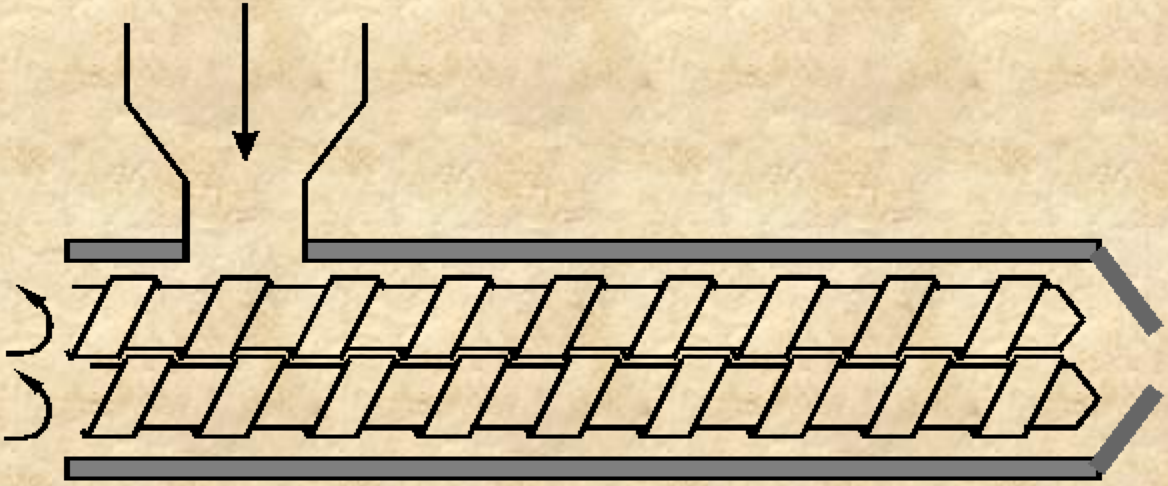
Extrusion Screws

- Varying screws for different resins/applications



Multi-Screw and Multi-Barrel

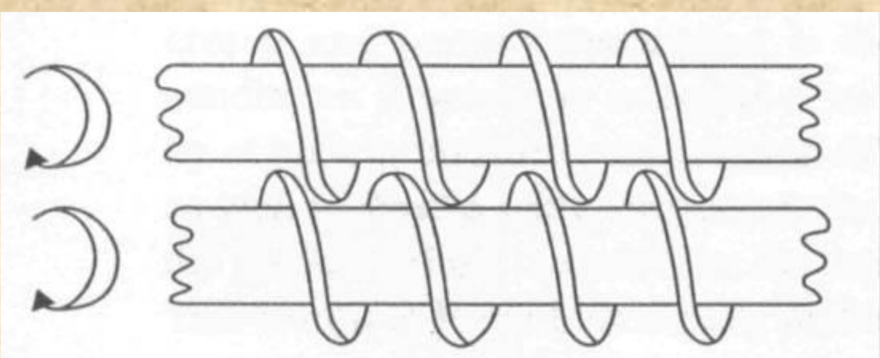
- Valuable in heat sensitive material processing (PVC)
- Increases efficiency in moving material
- More positive pumping action



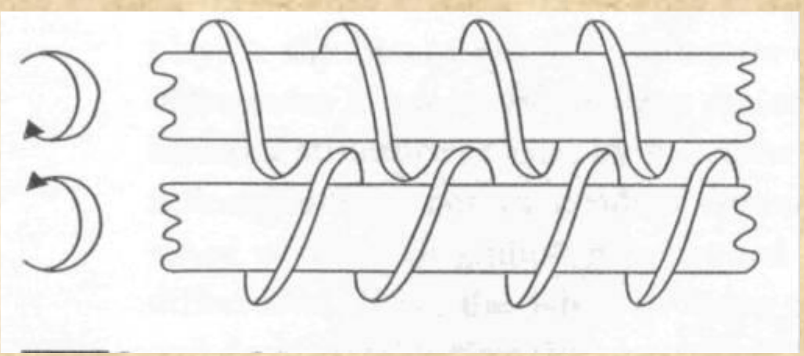
Multi-Screw and Multi-Barrel

- Co-Rotating Screws
- Counter-Rotating Screws
- Advantages and Disadvantages

Co-Rotating Screws

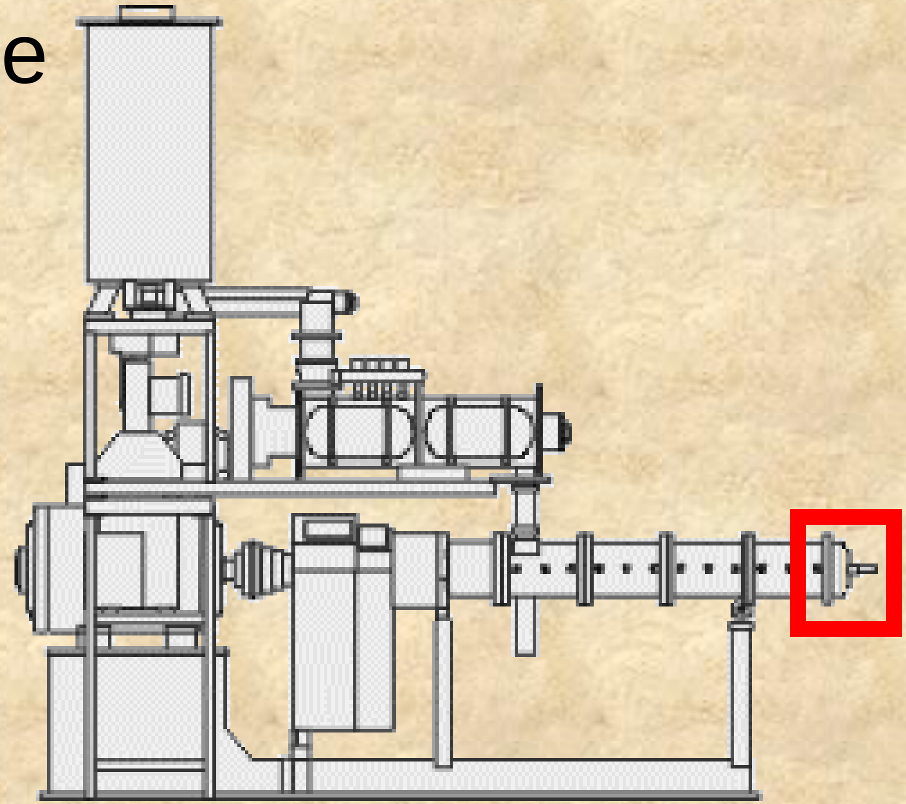


Counter-Rotating Screws

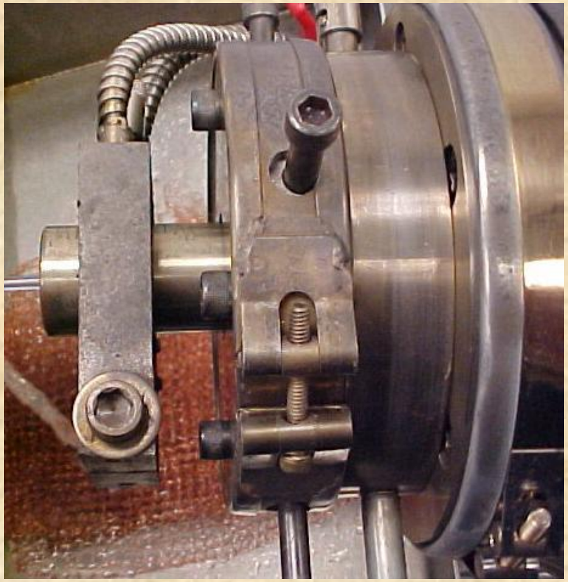
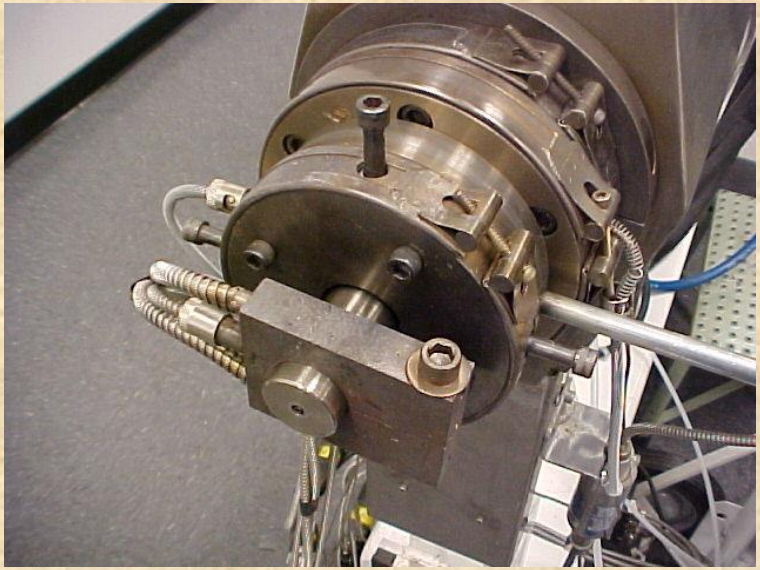


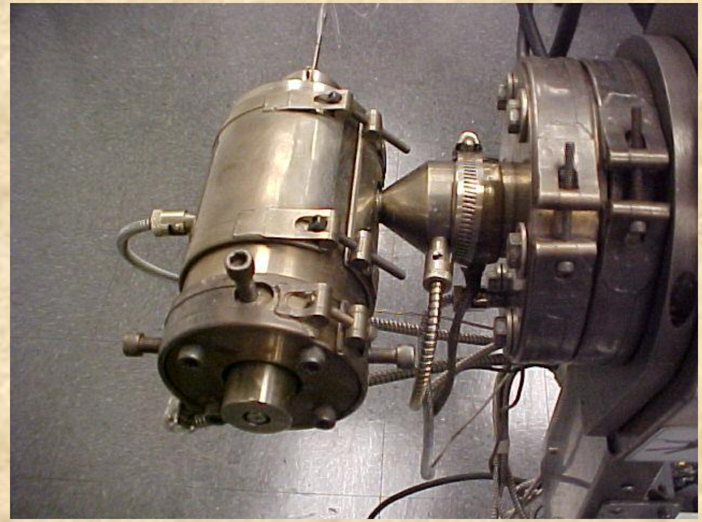
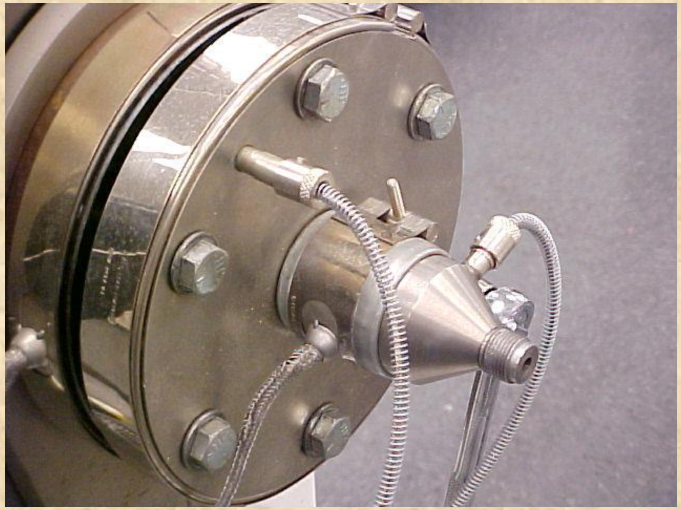
Head Zone

- The portion of the machine at the end of the barrel
- Holds/contains the die



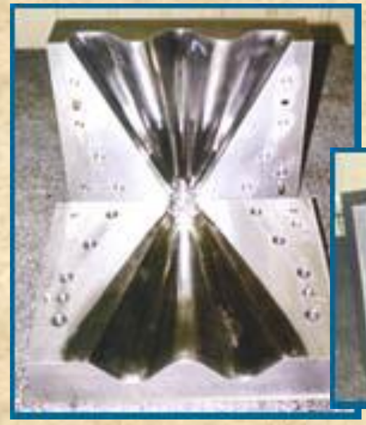
Head Zone

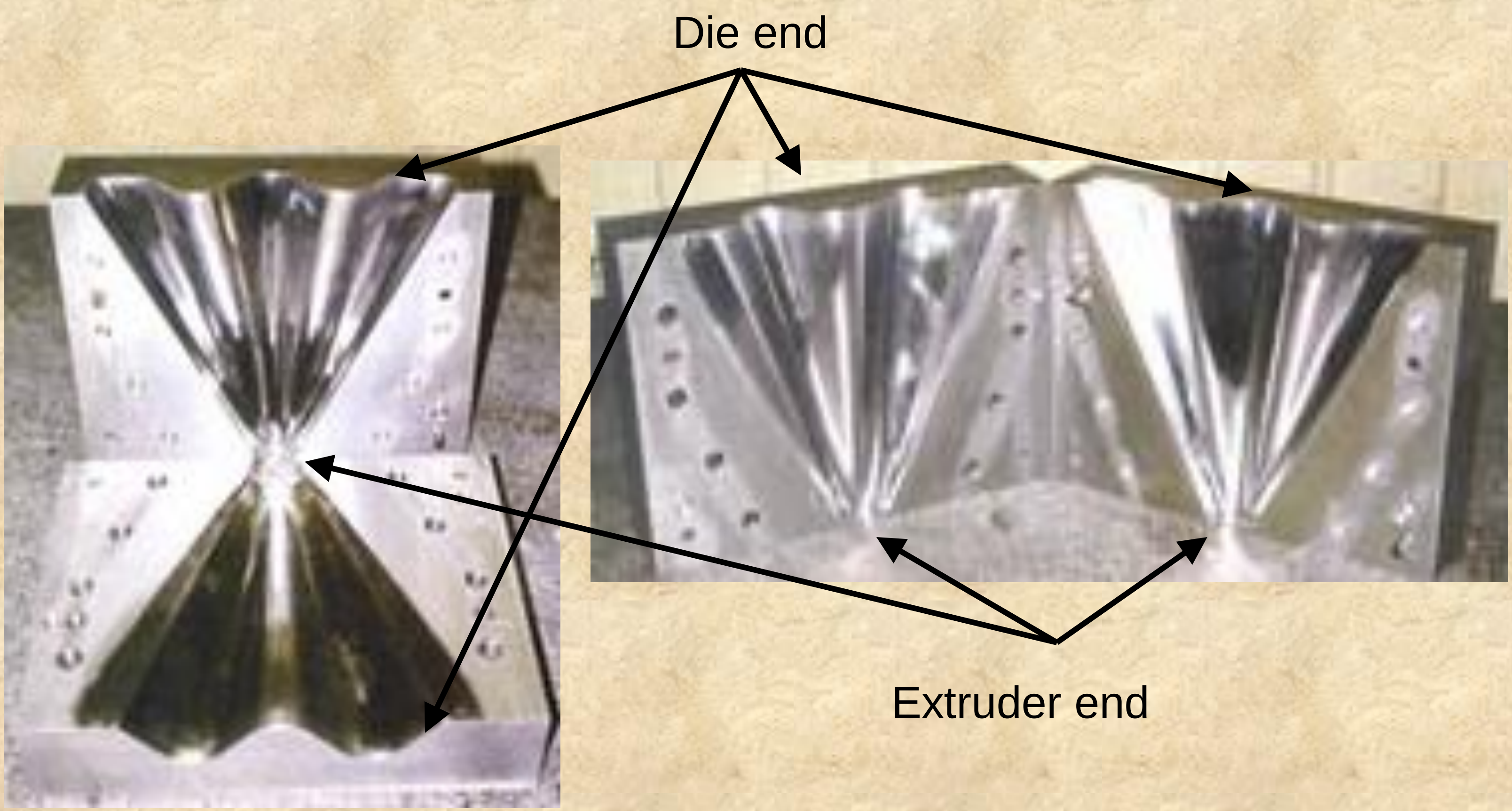
Head Zone

- Breaker plate
  - Screens
  - Filters
- Adaptor
  - Die mount



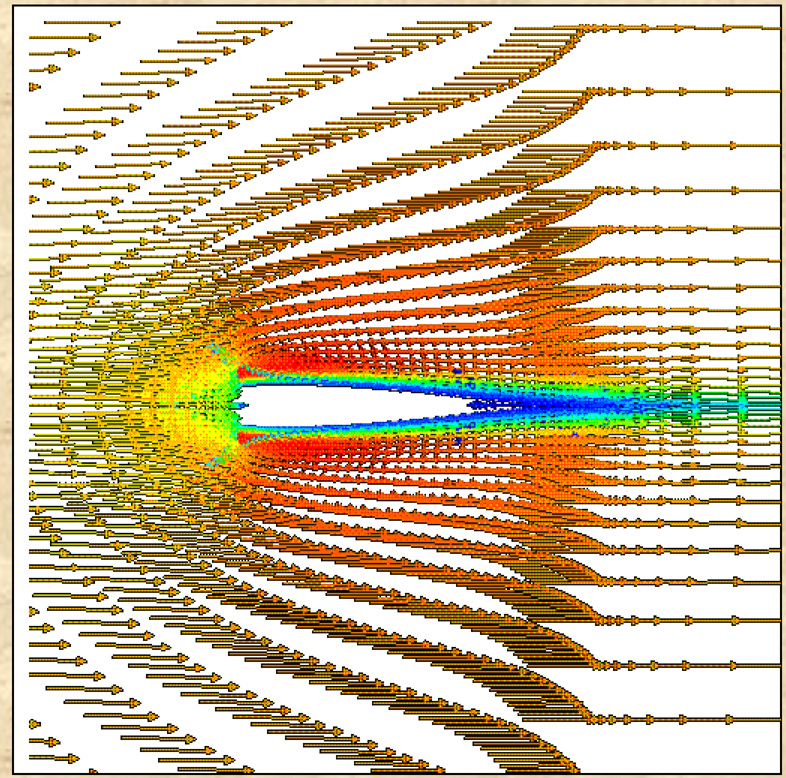
Adaptor

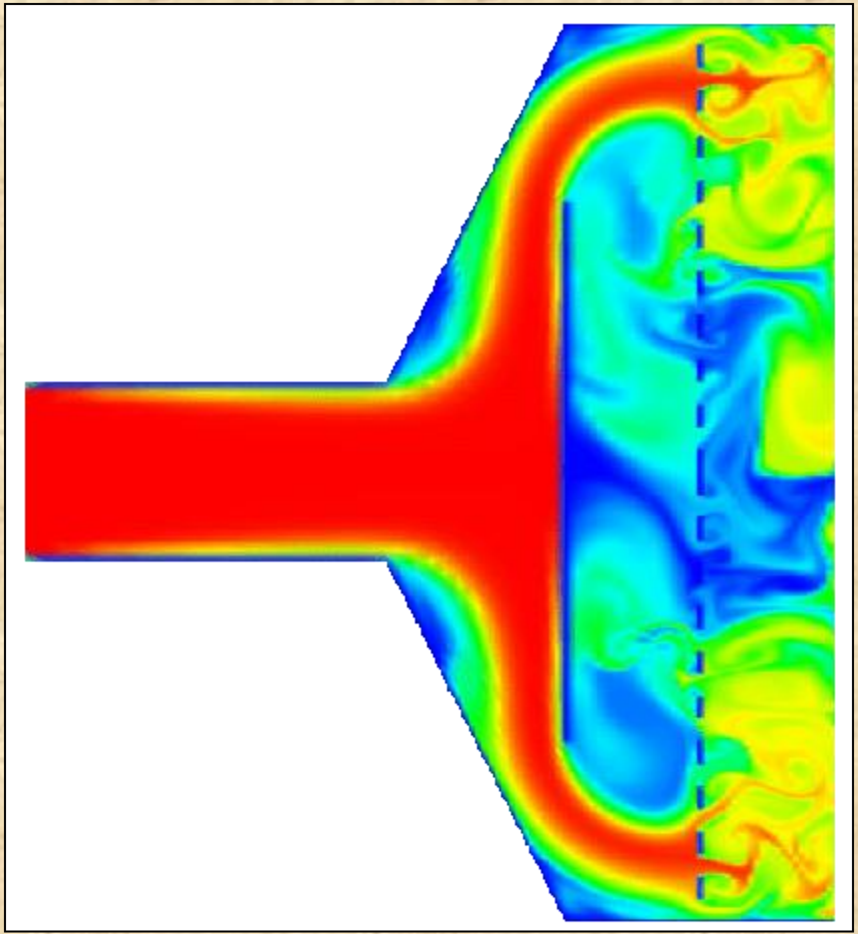
- Laminar flow or turbulent flow



Adaptor

- Laminar flow or turbulent flow

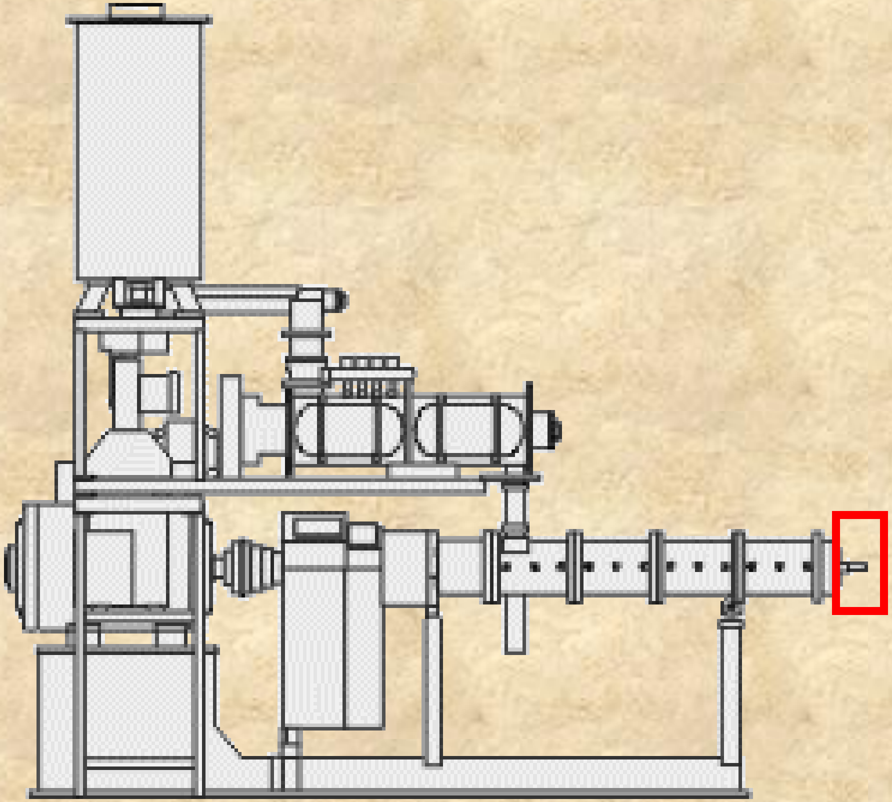




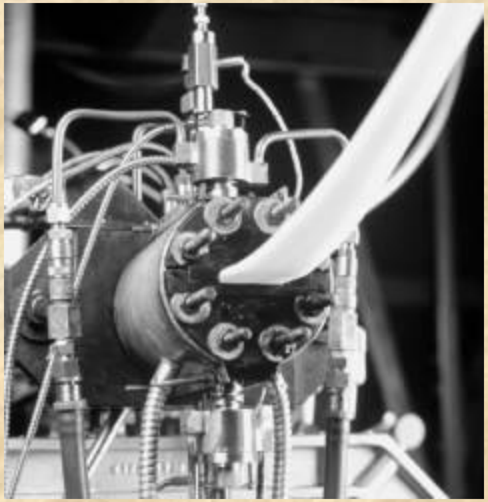
Material Flow

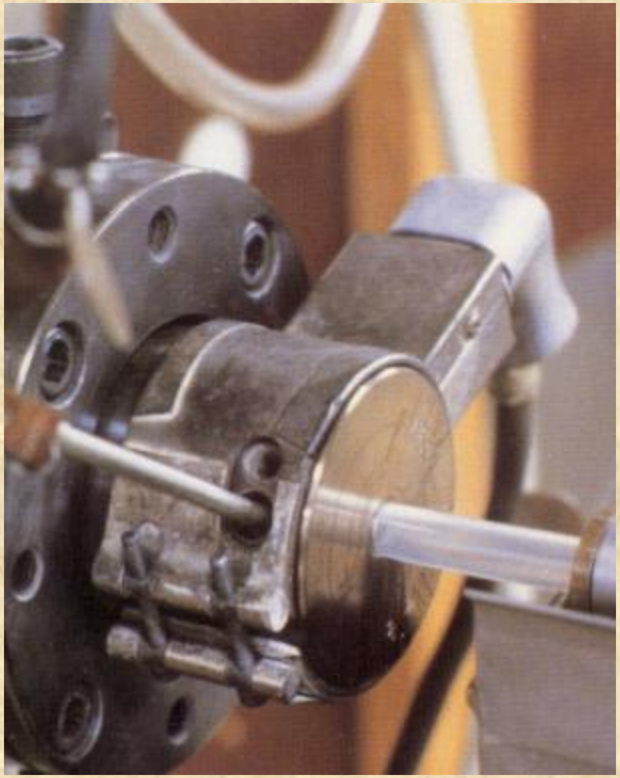
Die

- The “mold” for the extrusion process



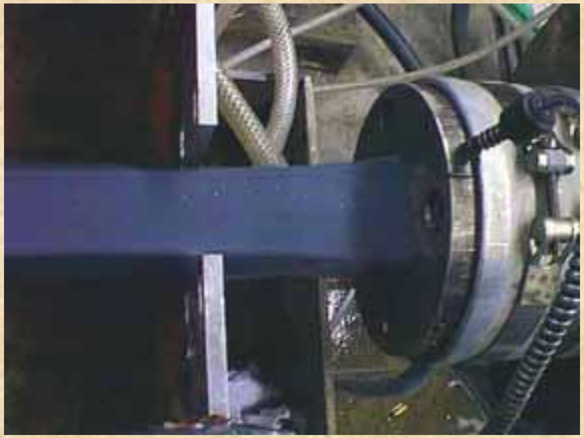
Die





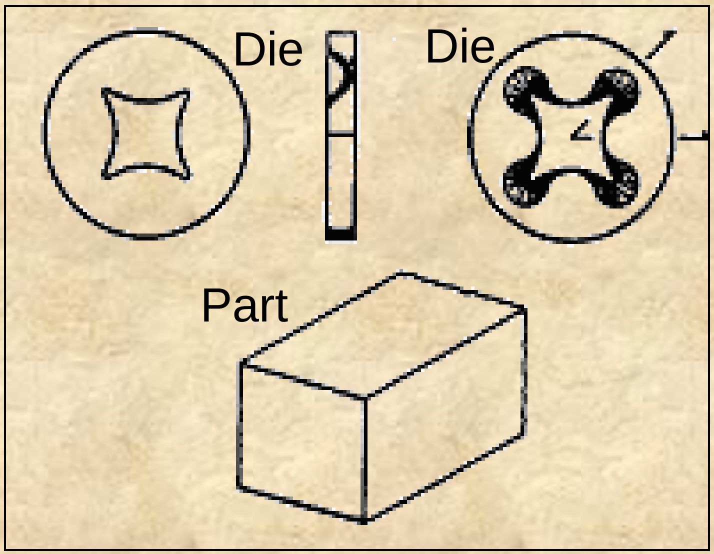
Input (machine) side

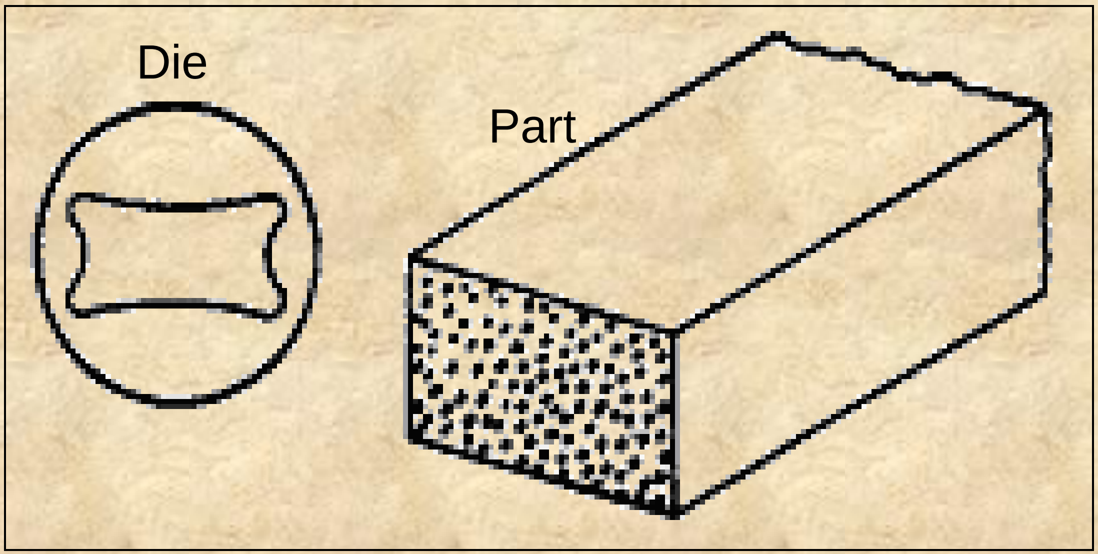
Output side



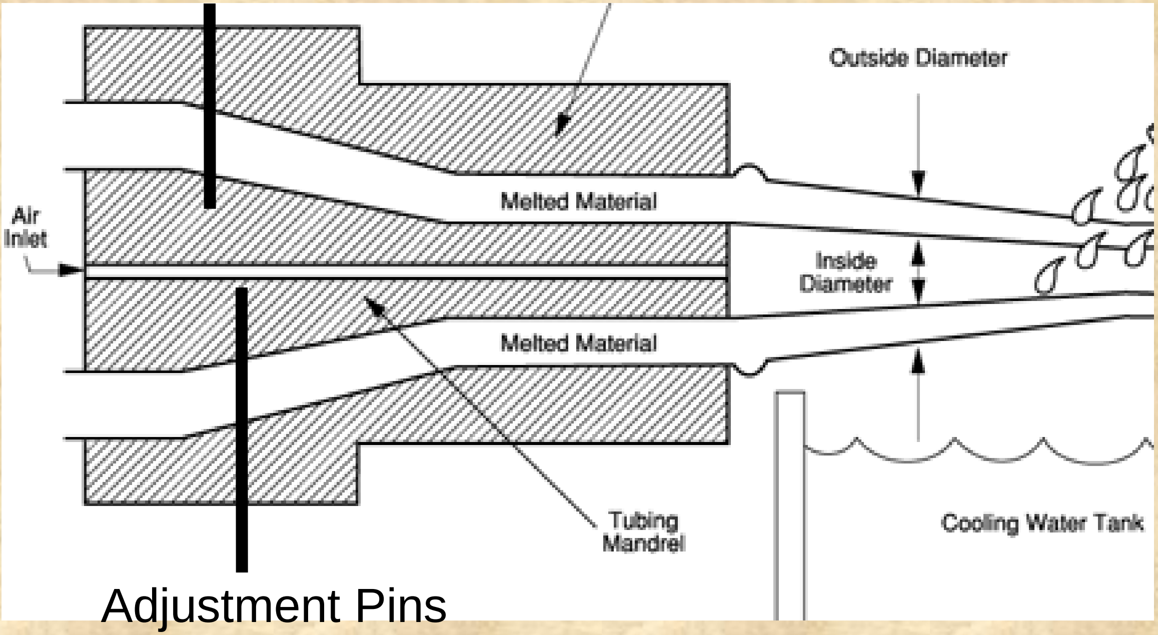
Die

- Dies are cut to produce a certain profile
- Cutout will probably not match the finished product



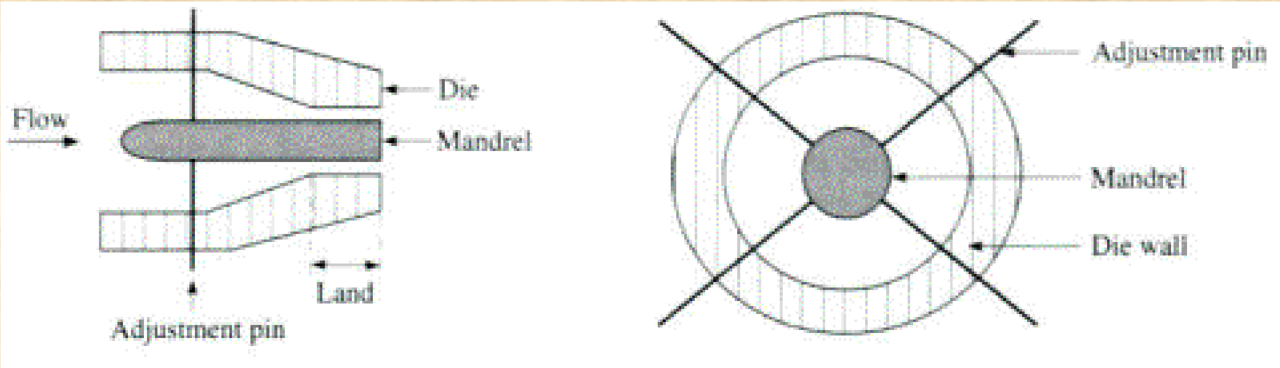


Spider Die



Adjustment Pins

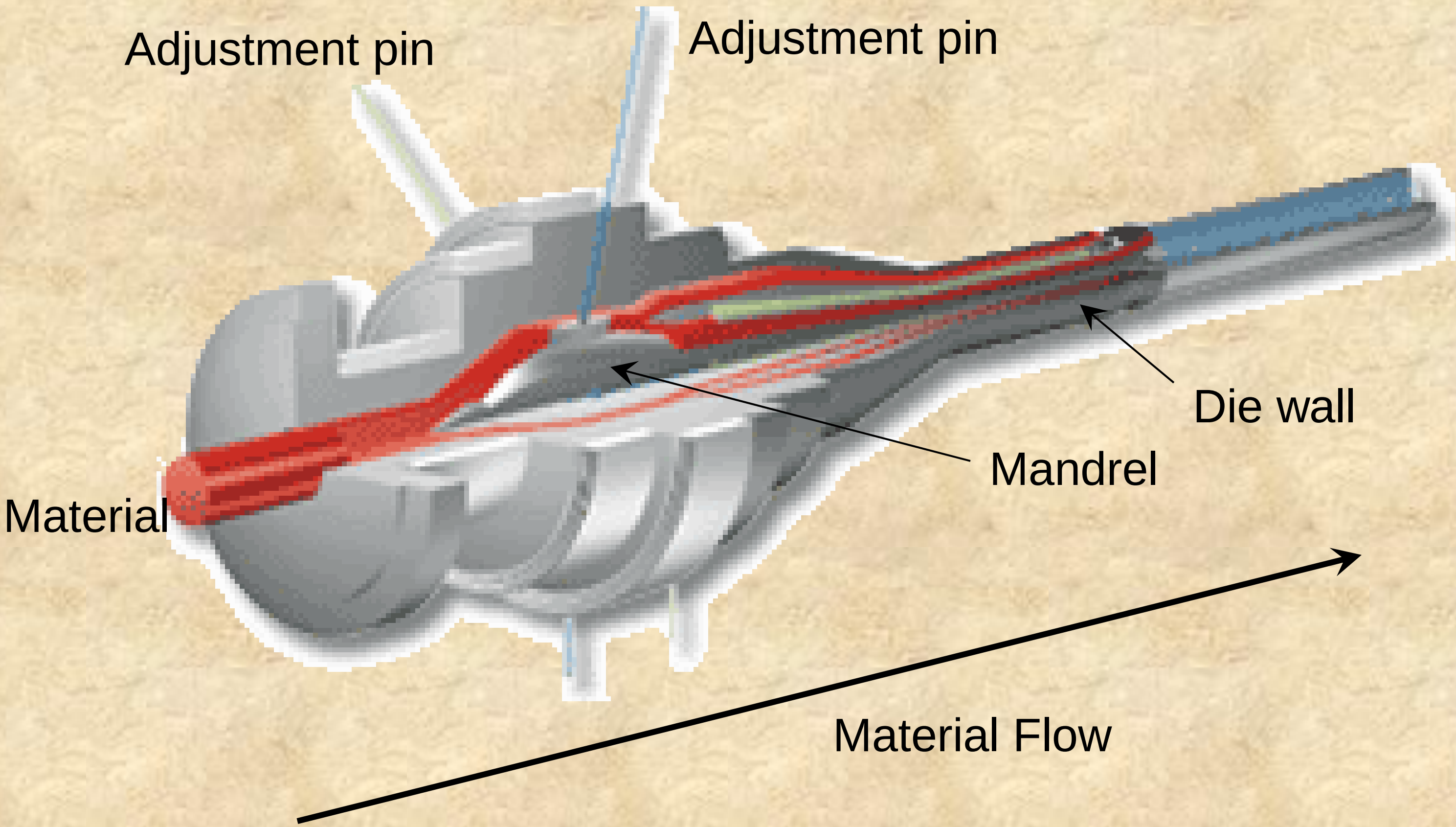
Material Flow



(a) Spider die

(b) Spider die, rear view

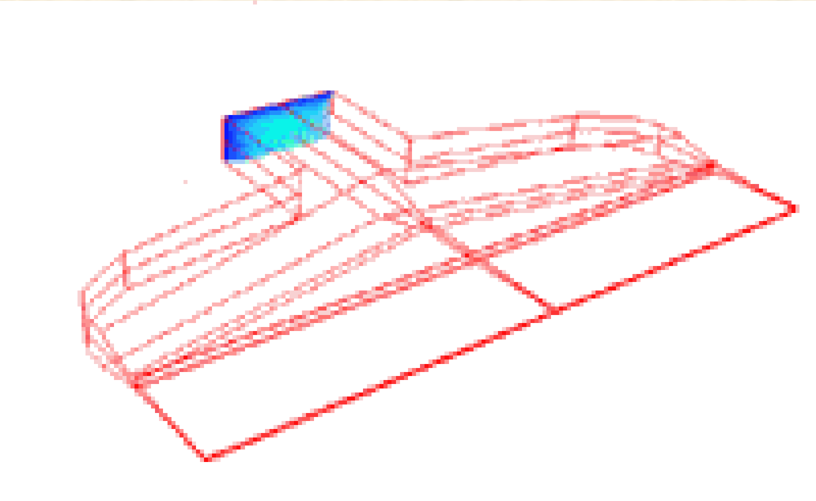
Spider Die


Adjustment pin
Adjustment pin
Die wall
Mandrel
Material
Material Flow

Spider Dies

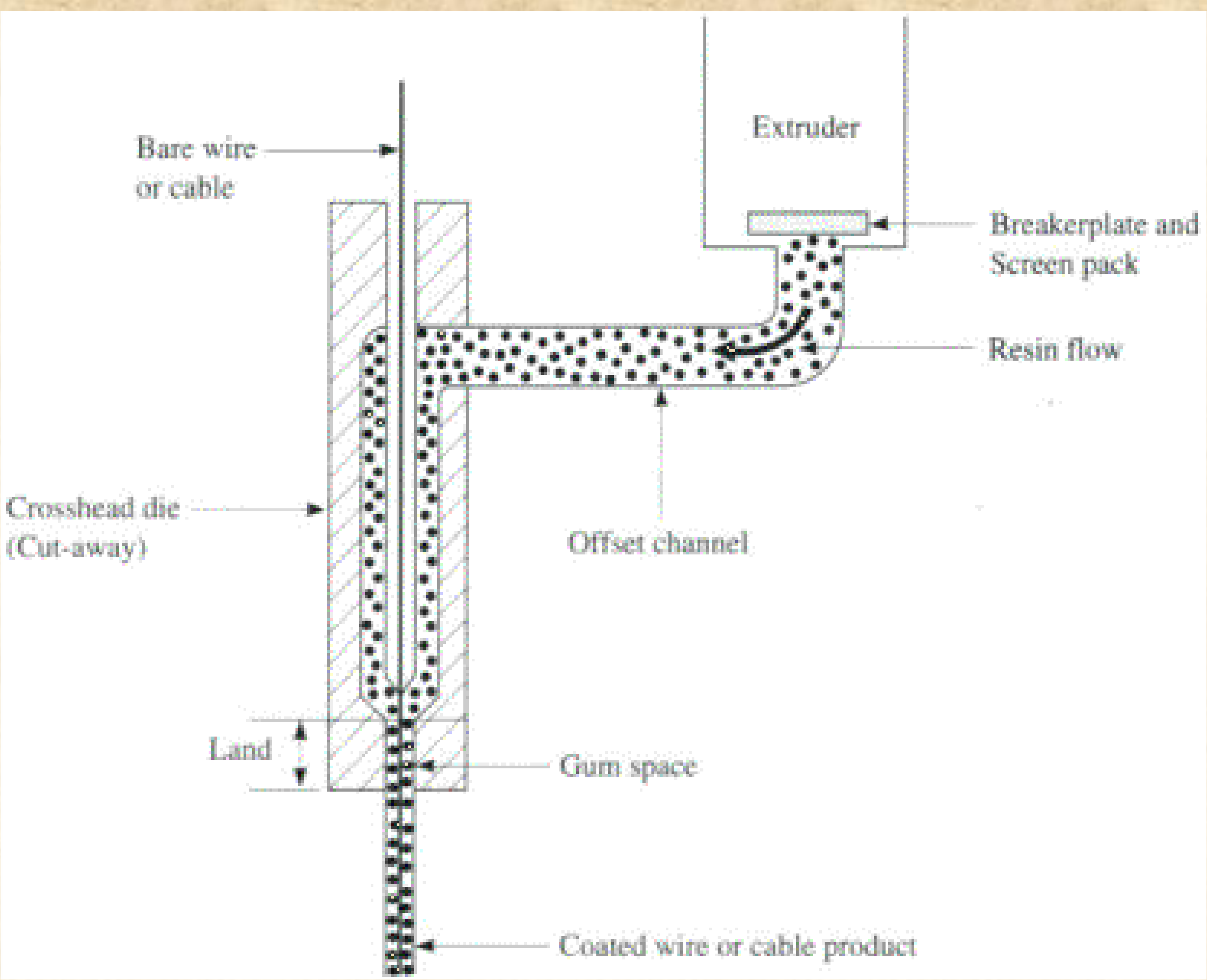
Coat Hanger Dies

- Correct flow
  - Velocity
  - Distribution

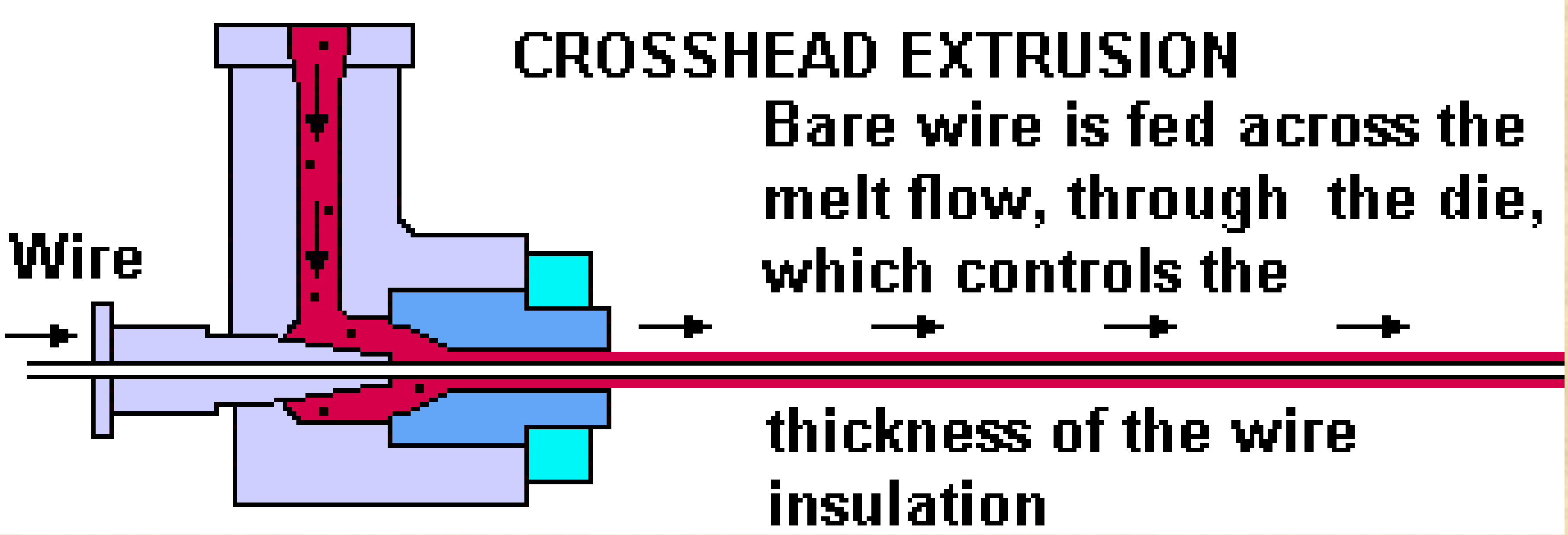


U Velocity Component

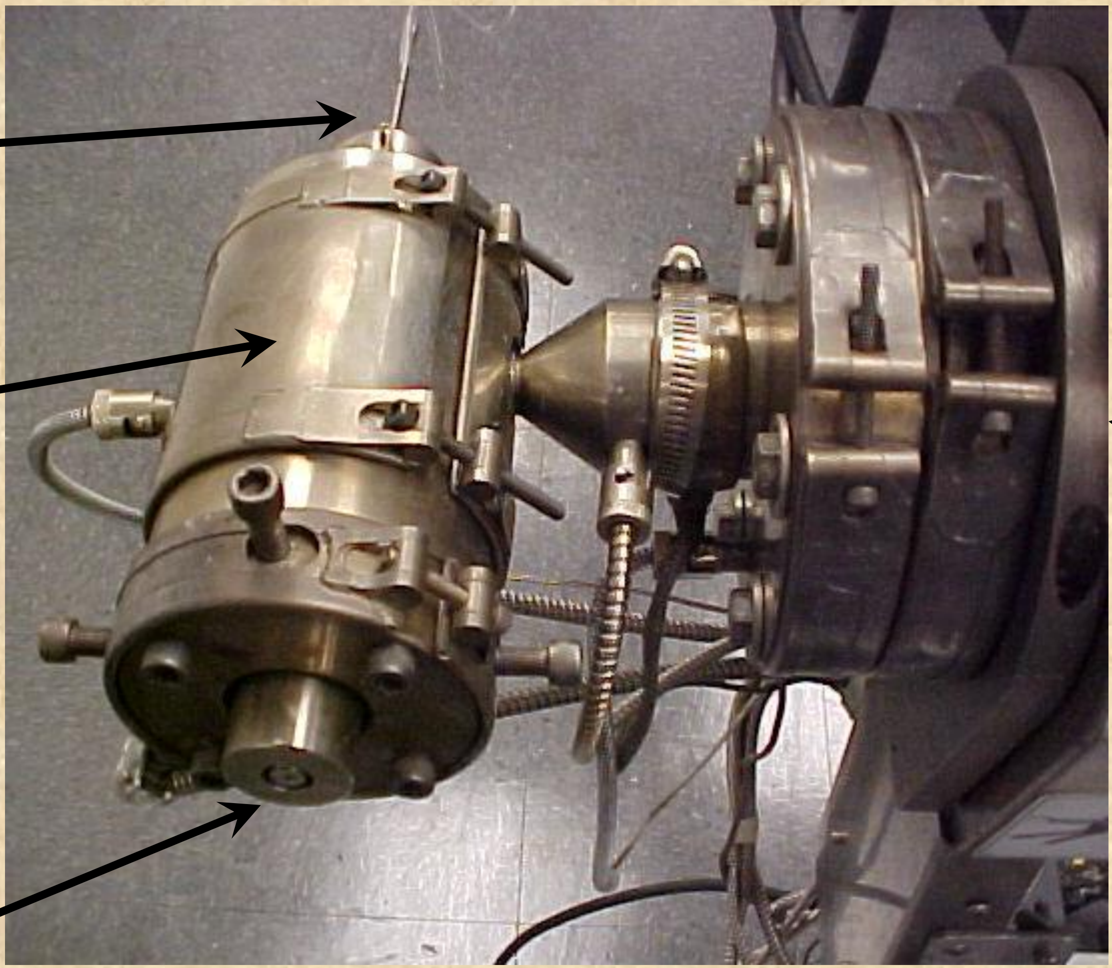
Wire Coating Dies



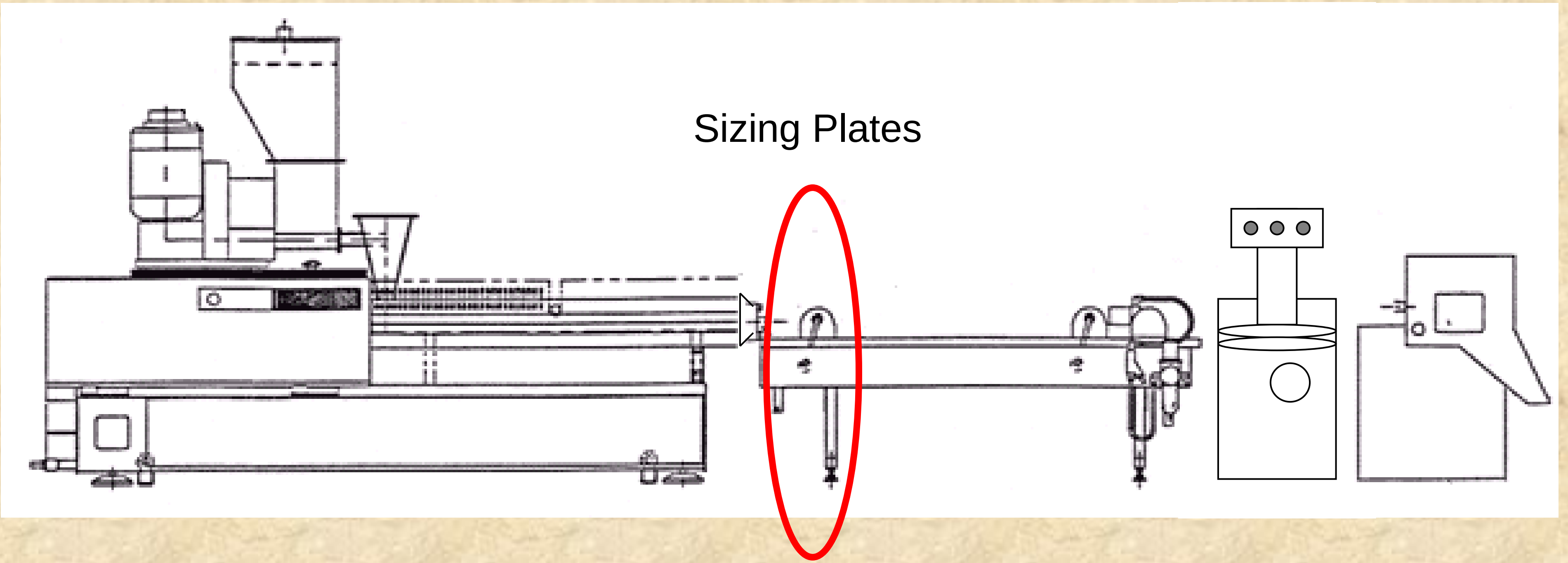
Wire Coating Dies



Wire Coating Dies



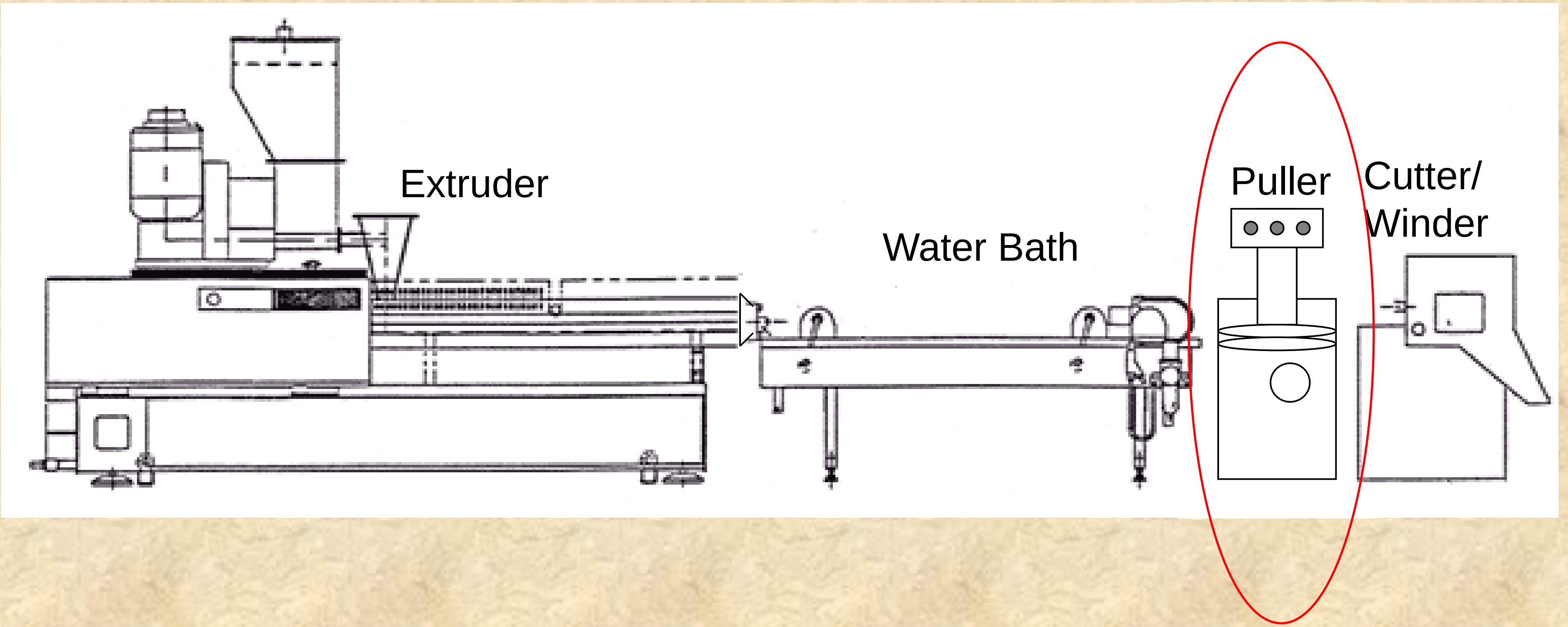
Dimensional Control



Part Dimension Control

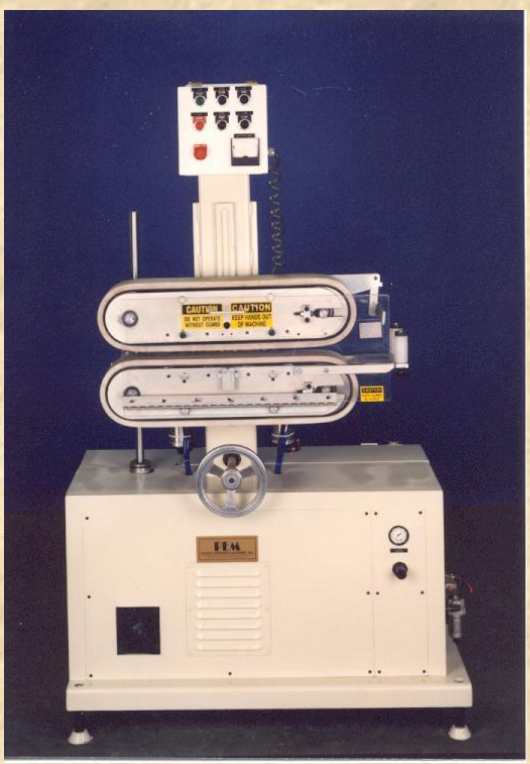
- Die
- Sizing plate
- Air pressure
- Cooling (shrinkage)
- Speed of pull

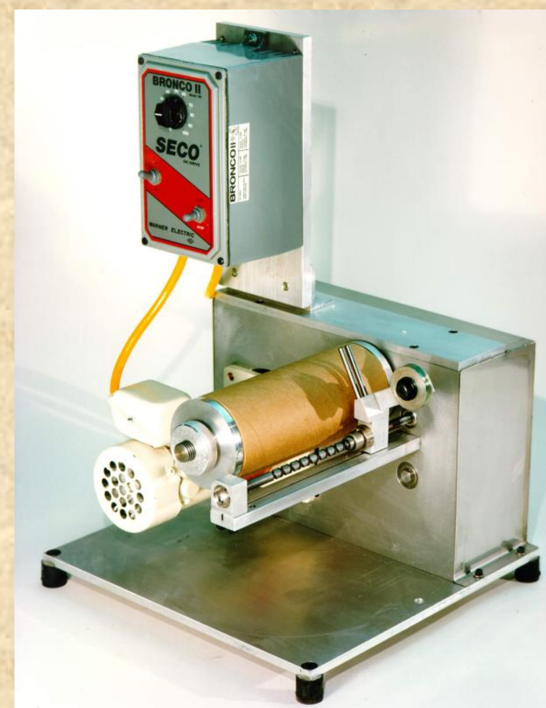
Pullers



Pullers

- Pullers are in contact with cooled material
- Pulling quicker will decrease the cross-sectional area of the extrudate

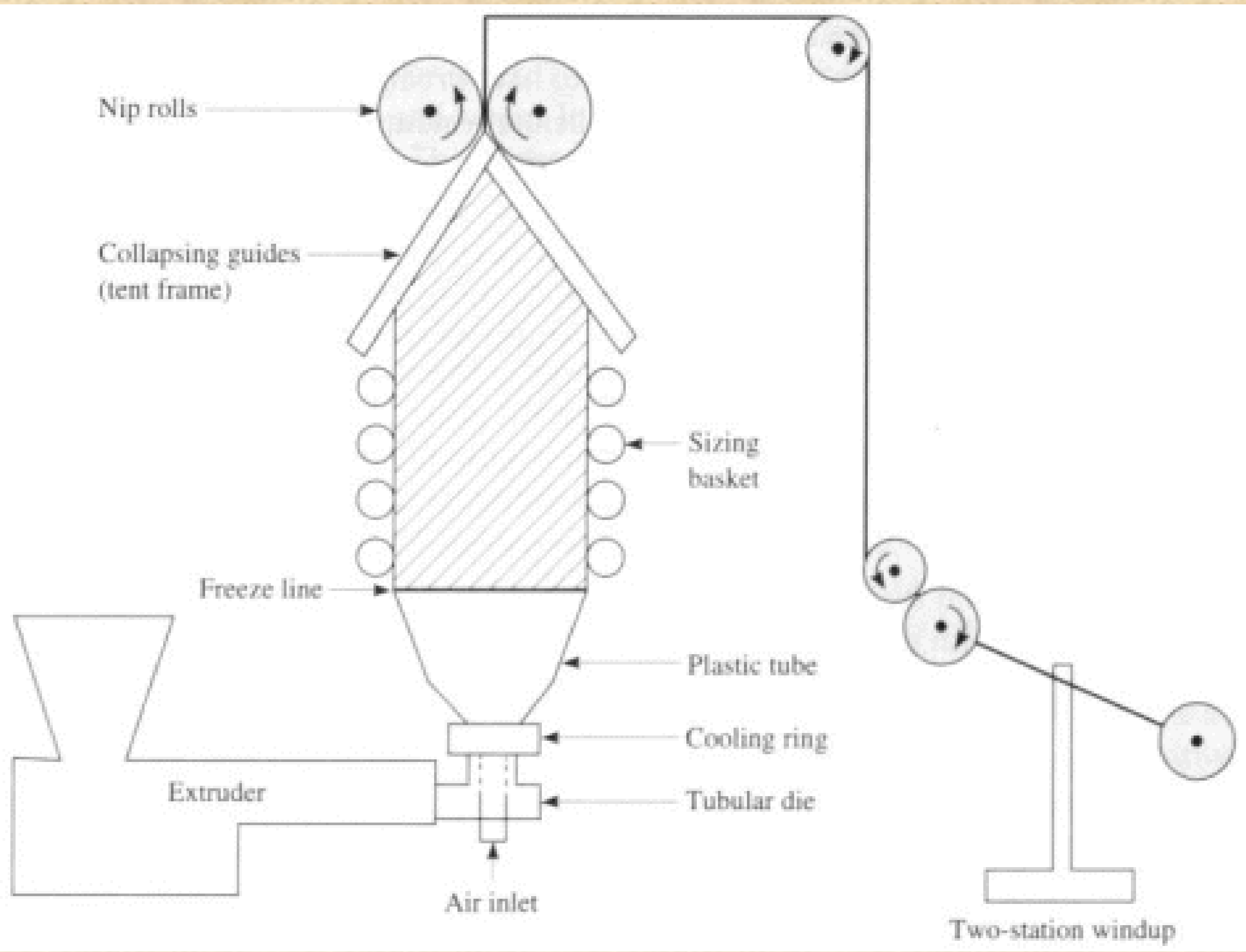


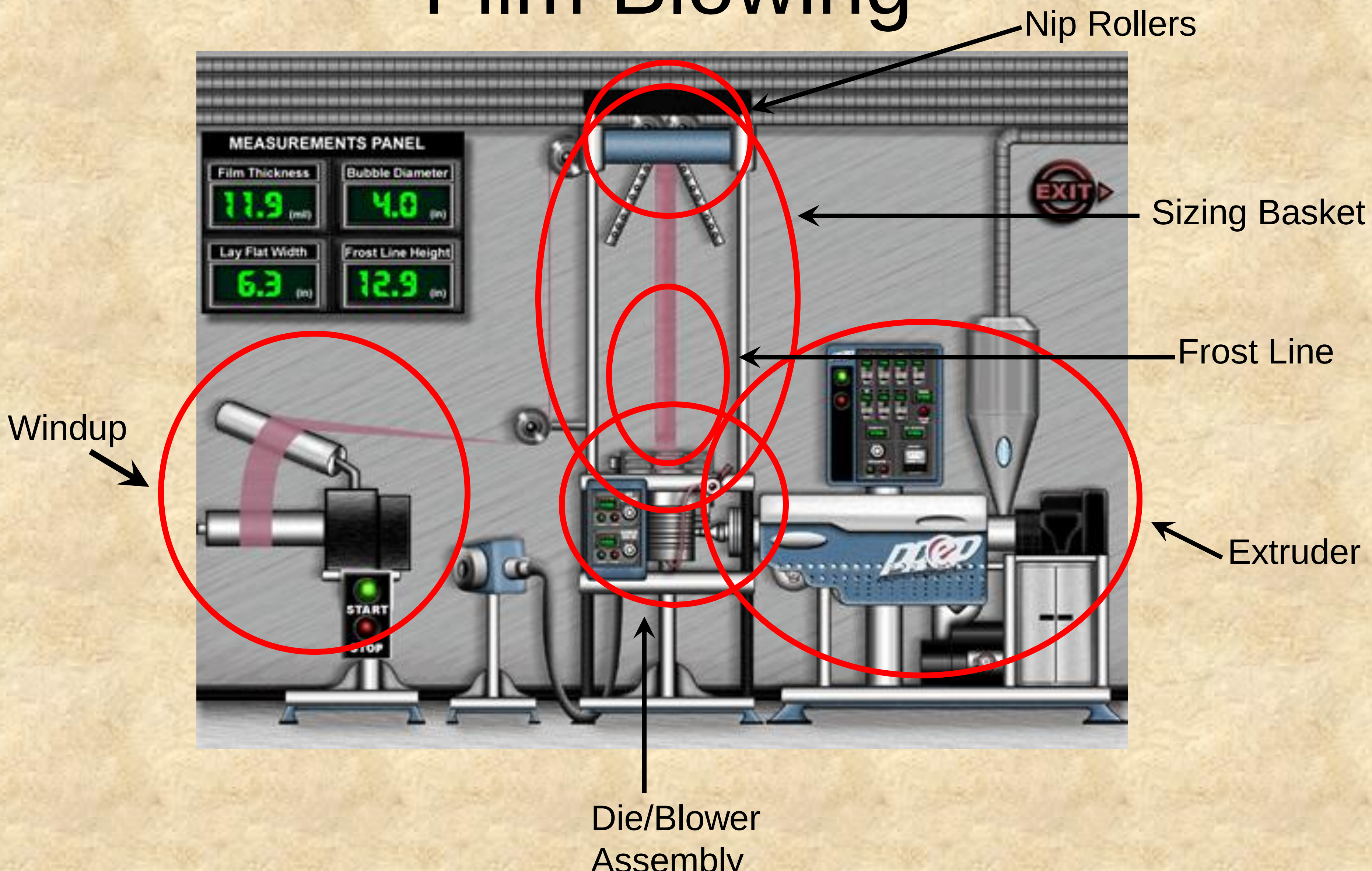
Film Blowing

- Extrude a “tube” upwards through vertical die
- Inflate “tube” till it becomes a film
- Collect film and process as needed

Film Blowing



Film Blowing



Film Blowing

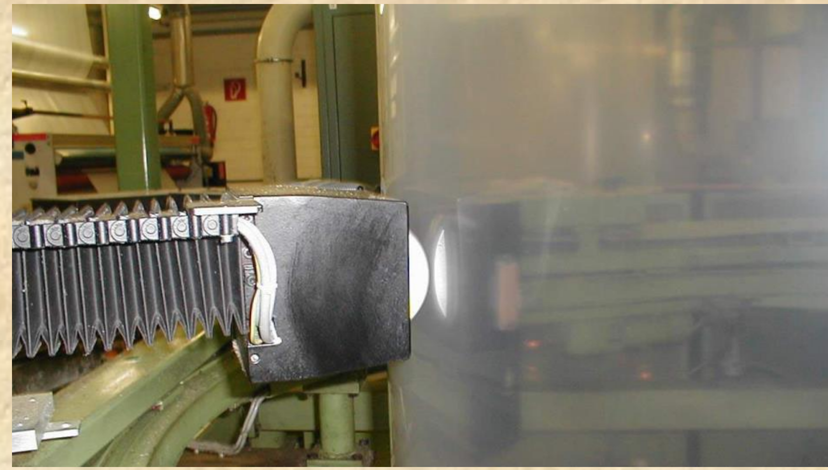
- Film Blowing Systems

Film Blowing

Extruder and Blower

Film Blowing

- Dies



Envelope Sensor

Film Blowing

- Printing/Cutting/Sorting

Film Blowing

Film Folders/Rollers

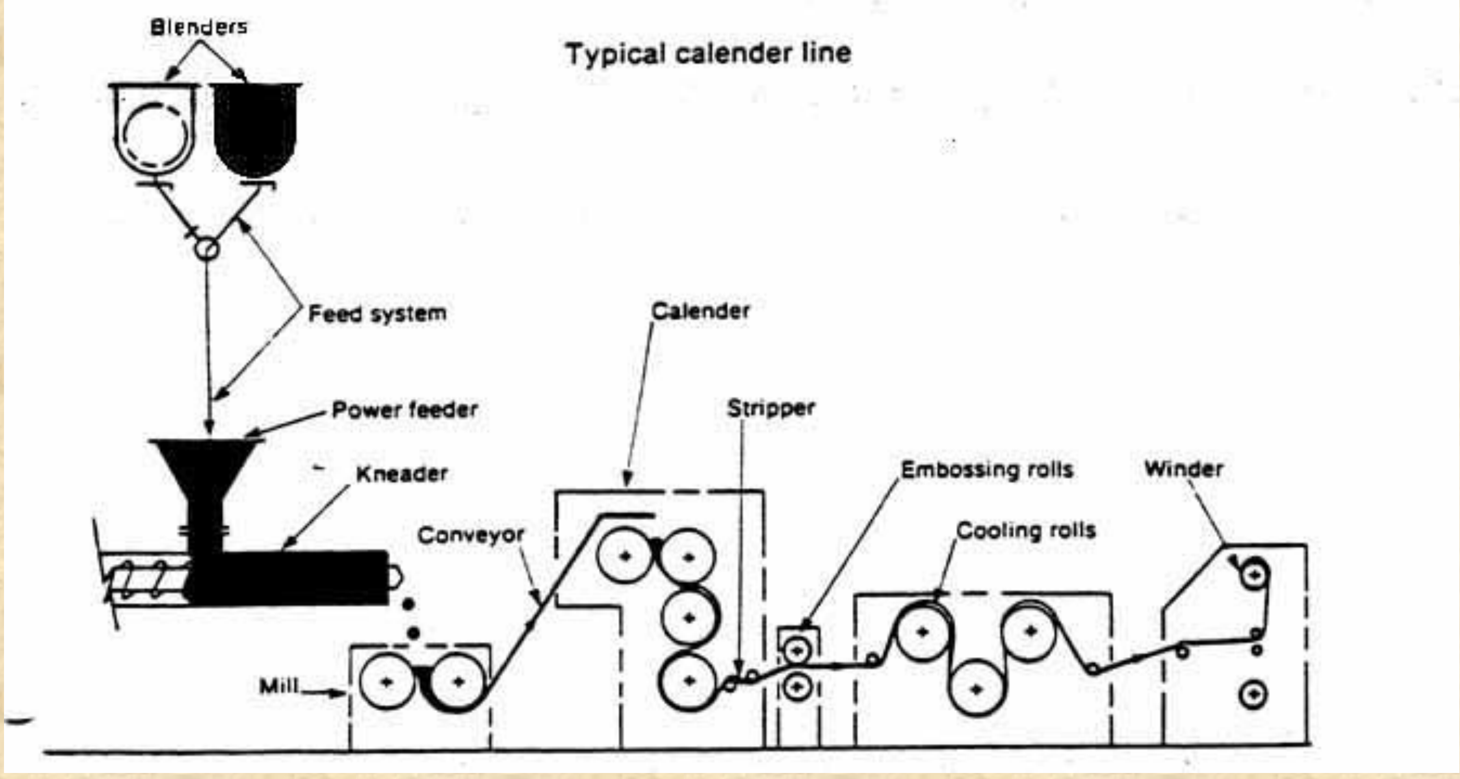
Coating of Paper and Fabric

- Extrude a film
- System of rollers to apply extruded film to paper/fabric
- Windup rollers take up coated paper/fabric



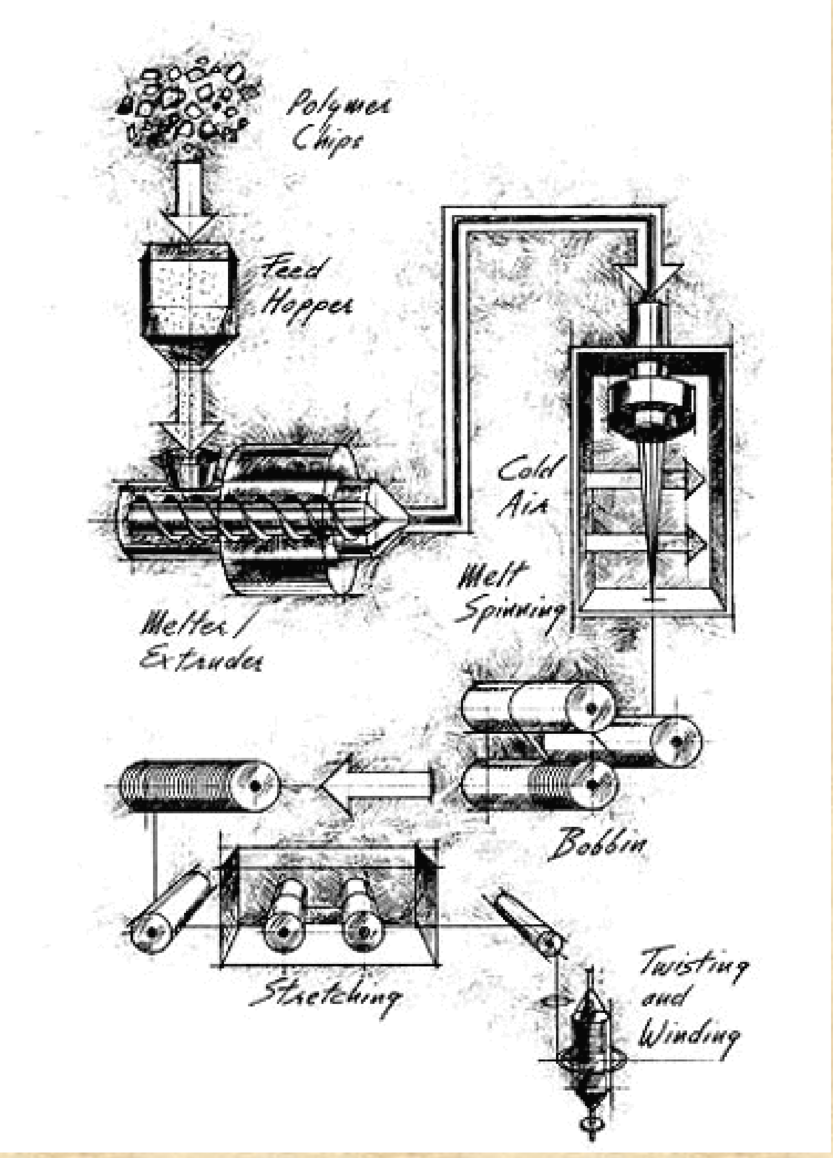
Calendering

- Extrude to a system of rollers
- Material is flattened/spread to desired specifications

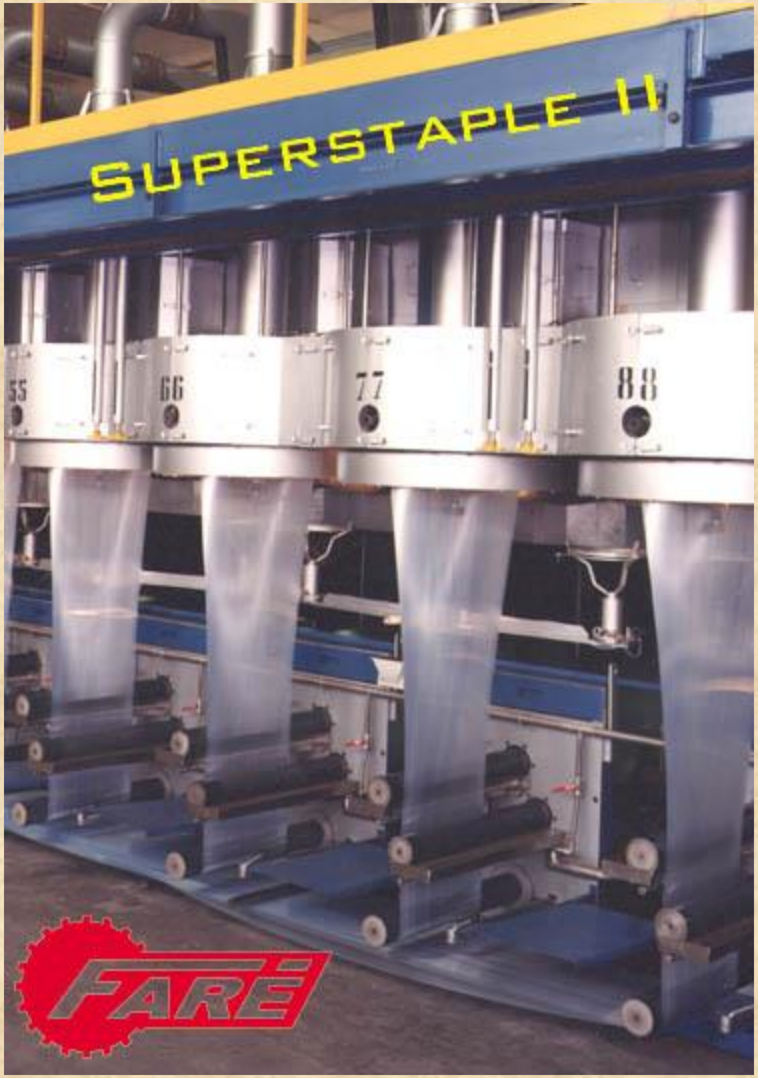


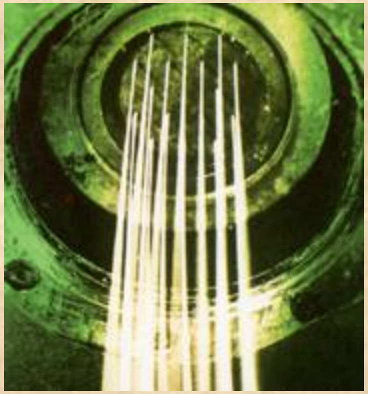
Fiber Extrusion

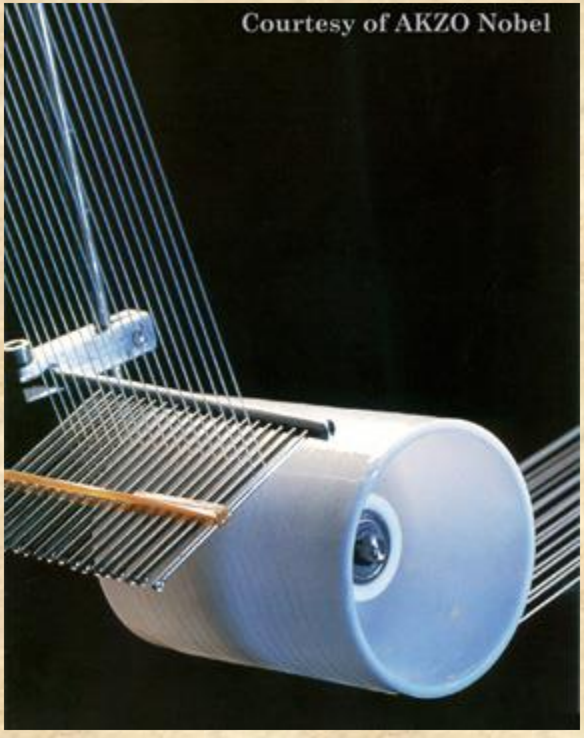
- Extrusion through an extruder
- Spun and stretched as filaments exit the die
- Twisted/wound and/or taken up on a roll



Fiber Extrusion





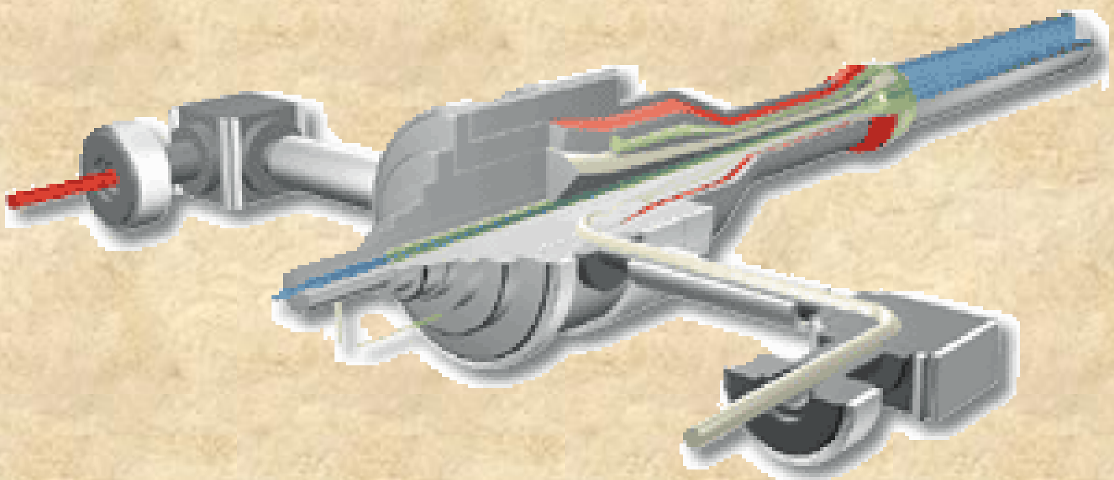

Courtesy of AKZO Nobel

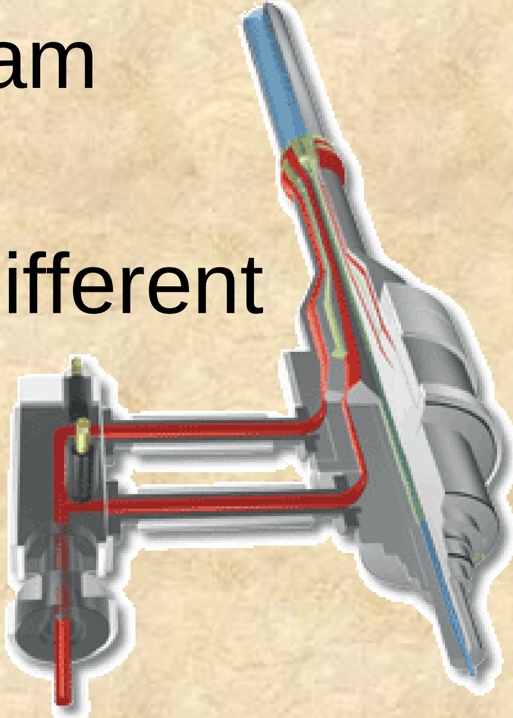
Post Extrusion Forming

- Corrugated pipe
- Perforated pipe
- Bell ended pipe

Coextrusion

- Join two streams of molten plastic into one
- Separate extruder for each stream (typically)
- Allows for multiple layers from different materials



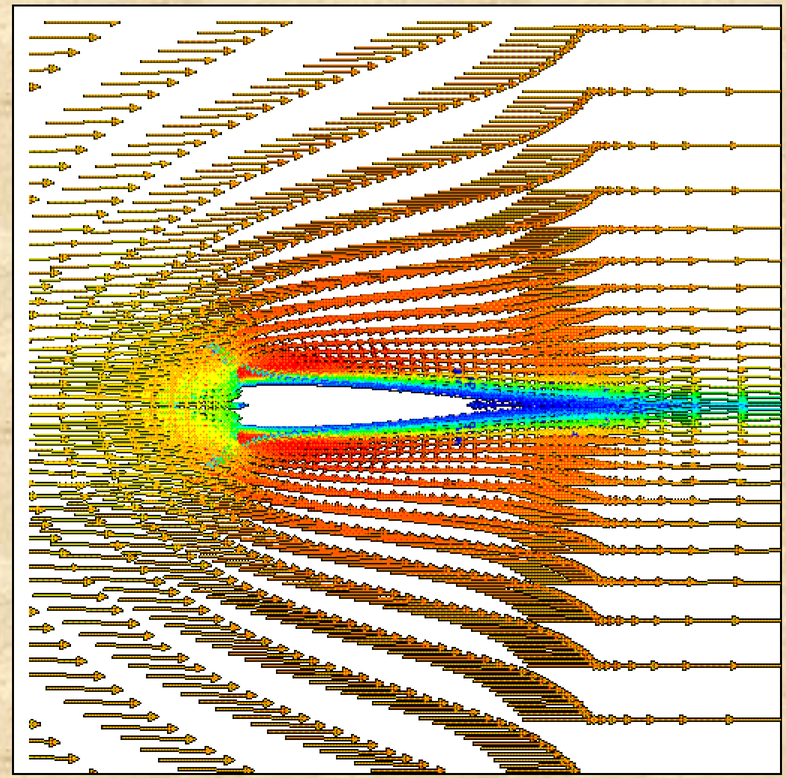


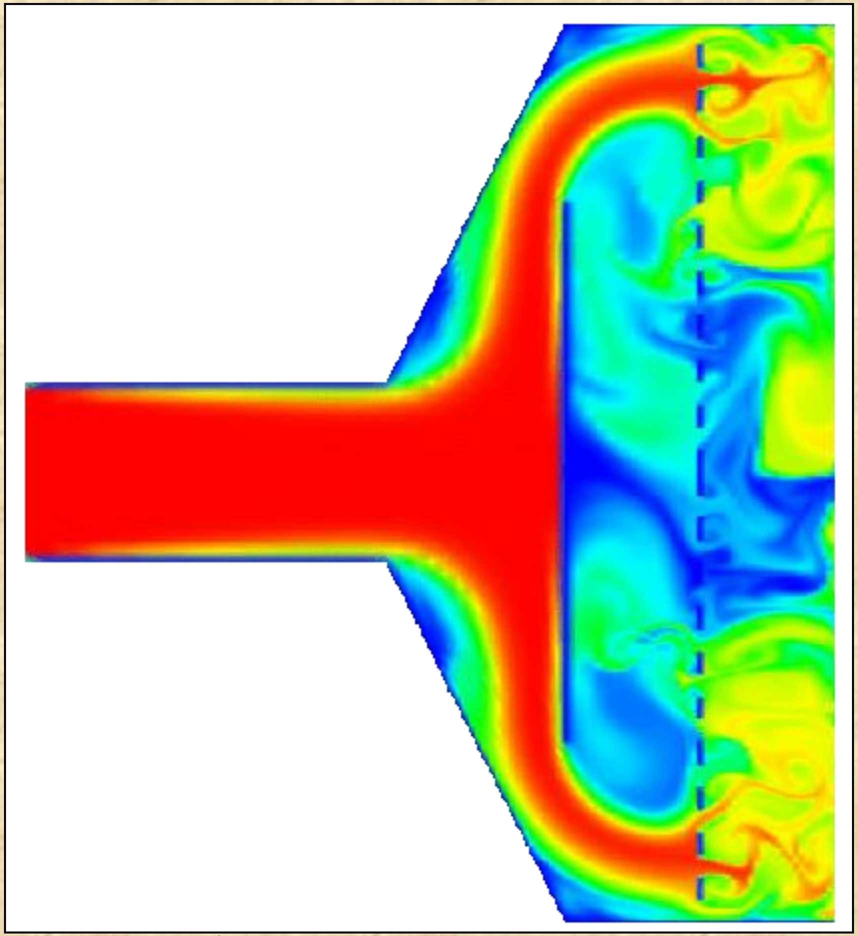
Extrusion Problems

- Melt fracture
- Sharkskin or alligator hide
- Uneven flow and surging
- Degradation
- Poor mixing
- Contamination
- Bubbles in extrudate

Melt Fracture

- Laminar flow or turbulent flow

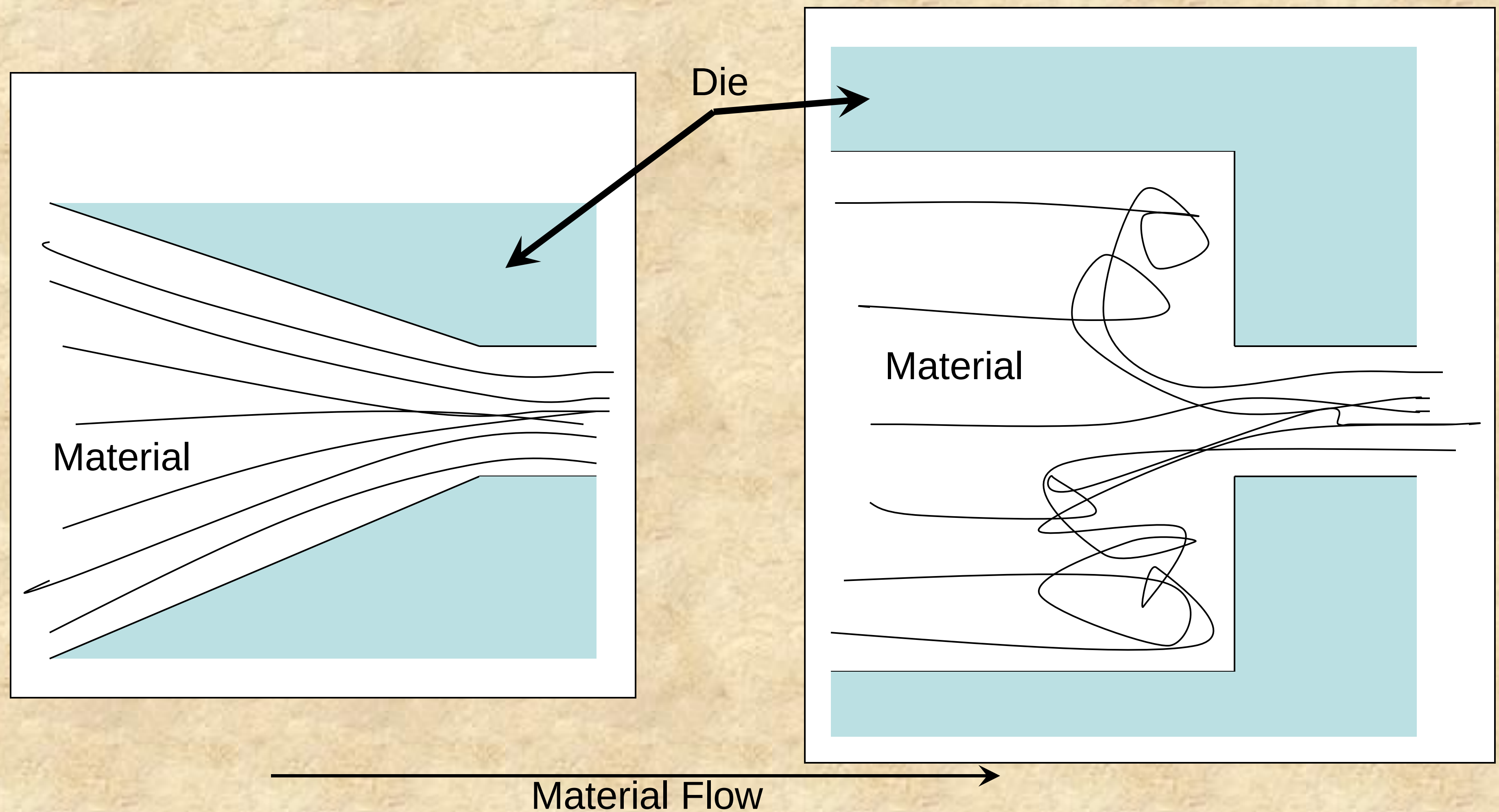




Material Flow

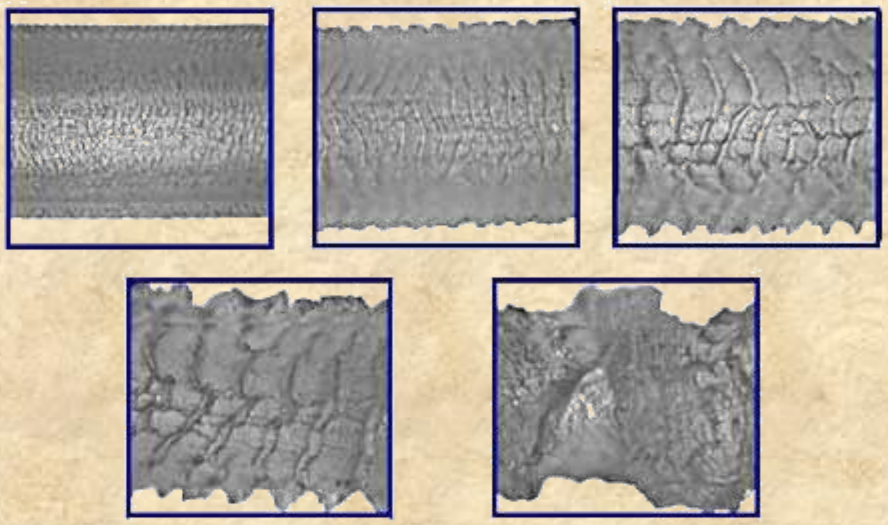
Melt Fracture

- Laminar flow or turbulent flow



Sharkskin or Alligator Hide

- Uneven or poor surface finish

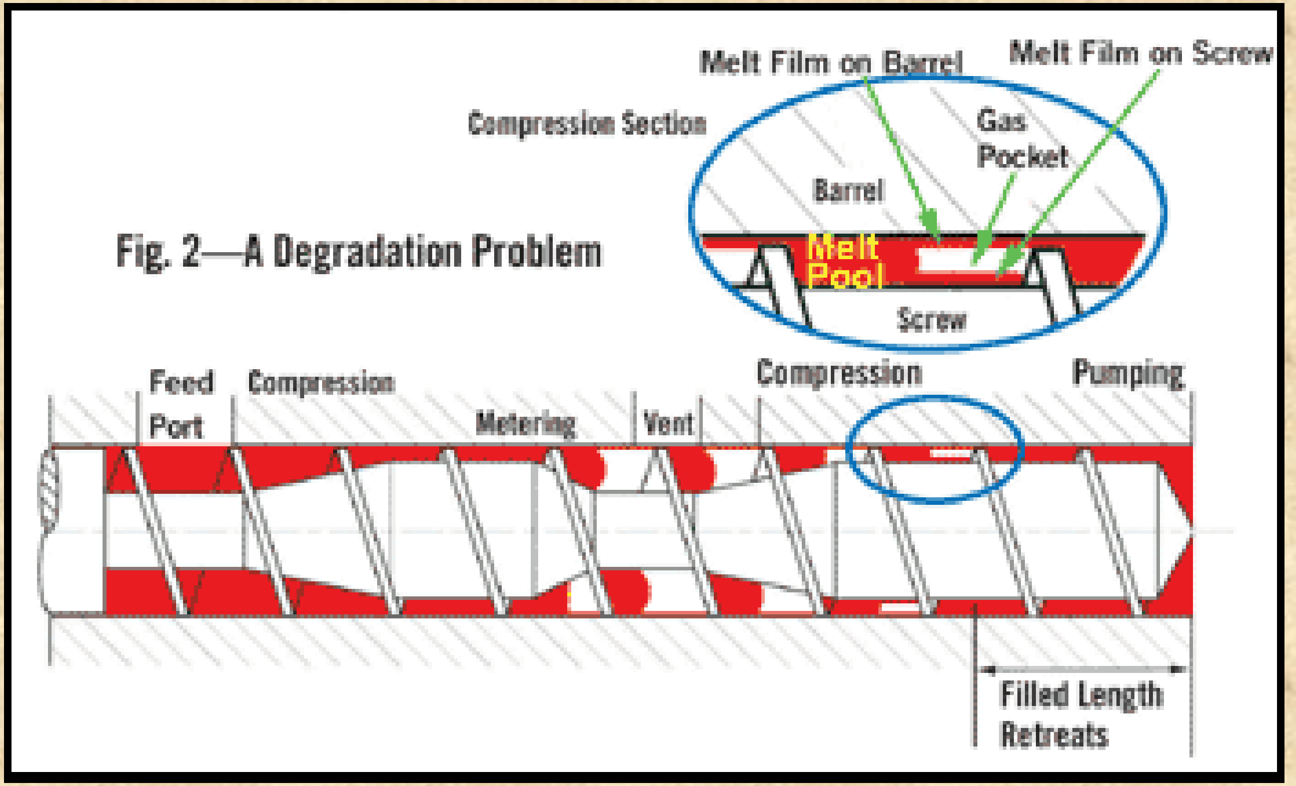


Uneven Flow and Surging

- Cause cross-sectional variation
- Cause wall thickness variation
- Depending on the parts this can cause premature failure

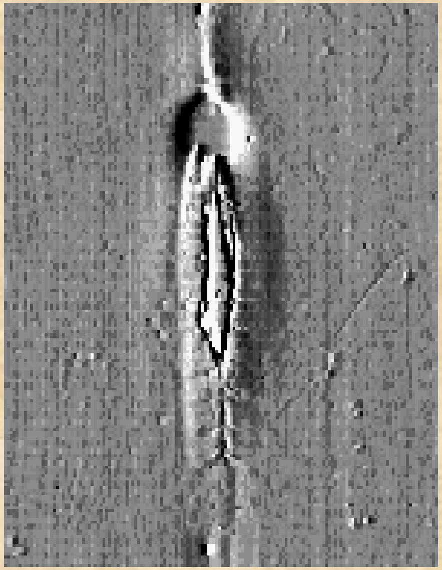
Degradation

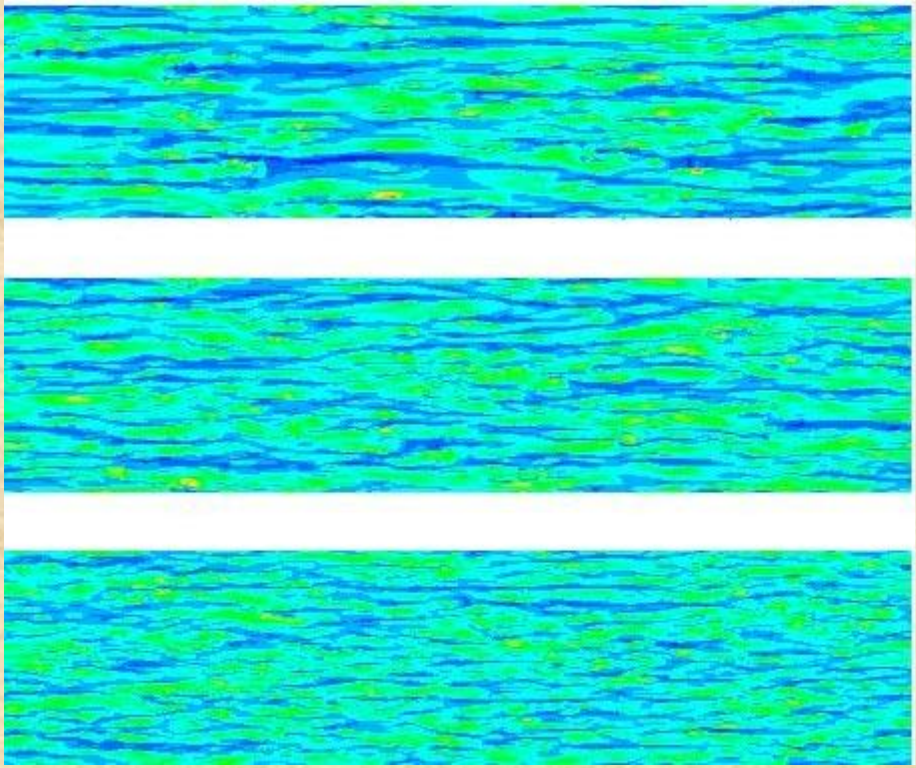
- Discoloration
- Weakening
- Speckling



Poor Mixing

- Streaks of coloration
- Particles



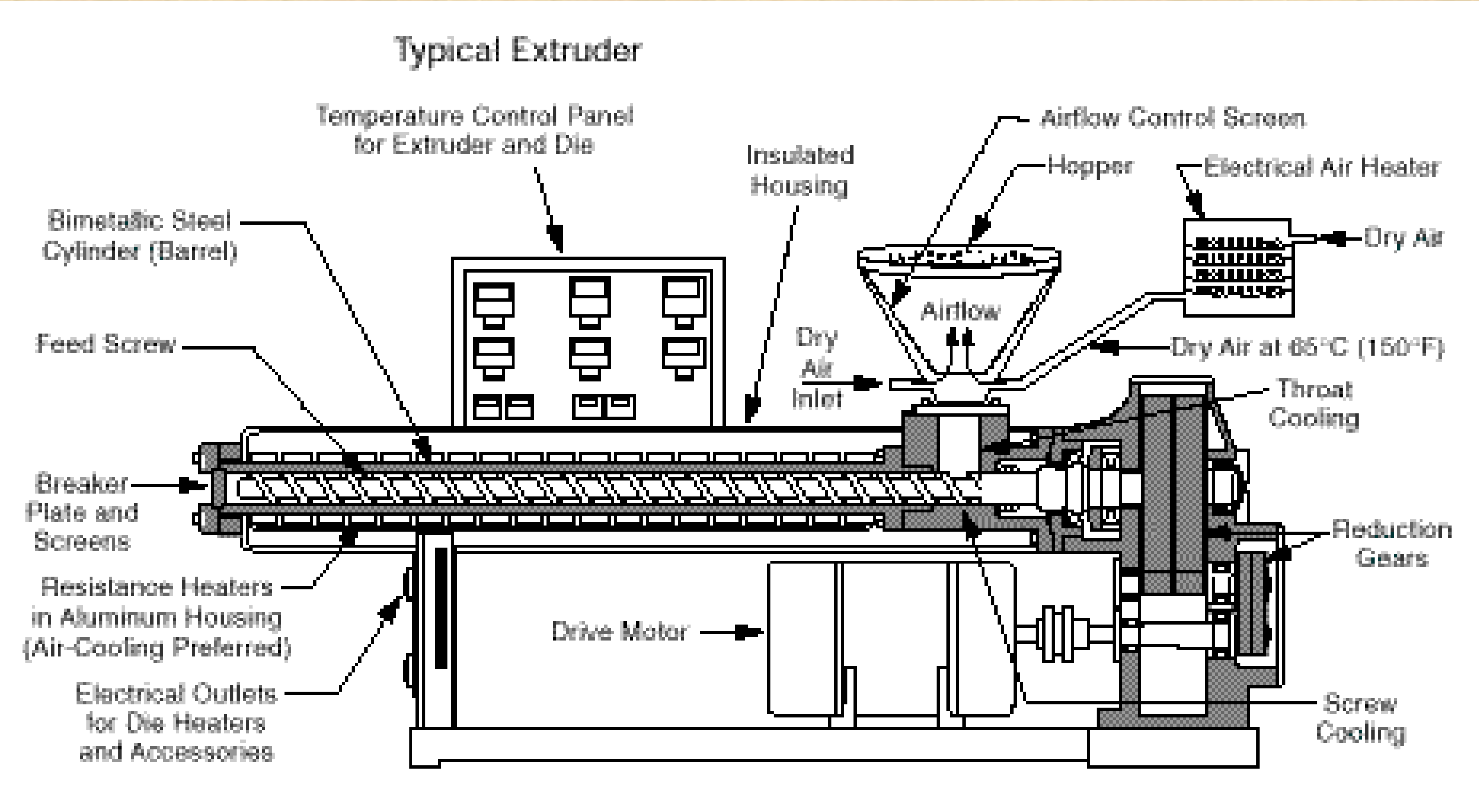


Bubbles in the Extrudate

- Excessive moisture
- Absorbed volatiles
- Severe degradation in the presence of moisture
  - PET, PC, Nylon
- Air entrapment

Thank You

Extruder



Typical Extruder
Temperature Control Panel for Extruder and Die
Insulated Housing
Airflow Control Screen
Hopper
Electrical Air Heater
Dry Air
Bimetallic Steel Cylinder (Barrel)
Airflow
Dry Air Inlet
Dry Air at 65°C (150°F)
Feed Screw
Throat Cooling
Breaker Plate and Screens
Reduction Gears
Resistance Heaters in Aluminum Housing (Air-Cooling Preferred)
Drive Motor
Electrical Outlets for Die Heaters and Accessories
Screw Cooling

POWDER METALLURGY

1. The Characterization of Engineering Powders
2. Production of Metallic Powders
3. Conventional Pressing and Sintering
4. Alternative Pressing and Sintering Techniques
5. Materials and Products for PM
6. Design Considerations in Powder Metallurgy

Powder Metallurgy (PM)

Metal processing technology in which parts are produced from metallic powders

- Usual PM production sequence:

1. Pressing – powders are compressed into desired shape to produce *green compact*
   - Accomplished in press using punch-and-die tooling designed for the part
2. Sintering – green compacts are heated to bond the particles into a hard, rigid mass
   - Performed at temperatures below the melting point of the metal

Why Powder Metallurgy is Important

- PM parts can be mass produced to *net shape* or *near net shape*, eliminating or reducing the need for subsequent machining
- PM process wastes very little material – ~ 97% of starting powders are converted to product
- PM parts can be made with a specified level of porosity, to produce porous metal parts
  - Examples: filters, oil-impregnated bearings and gears

More Reasons Why PM is Important

- Certain metals that are difficult to fabricate by other methods can be shaped by powder metallurgy
  - Tungsten filaments for incandescent lamp bulbs are made by PM
- Certain alloy combinations and cermets made by PM cannot be produced in other ways
- PM compares favorably to most casting processes in dimensional control
- PM production methods can be automated for economical production

Limitations and Disadvantages

- High tooling and equipment costs
- Metallic powders are expensive
- Problems in storing and handling metal powders
  - Degradation over time, fire hazards with certain metals
- Limitations on part geometry because metal powders do not readily flow laterally in the die during pressing
- Variations in density throughout part may be a problem, especially for complex geometries

PM Work Materials

- Largest tonnage of metals are alloys of iron, steel, and aluminum
- Other PM metals include copper, nickel, and refractory metals such as molybdenum and tungsten
- Metallic carbides such as tungsten carbide are often included within the scope of powder metallurgy

PM Parts

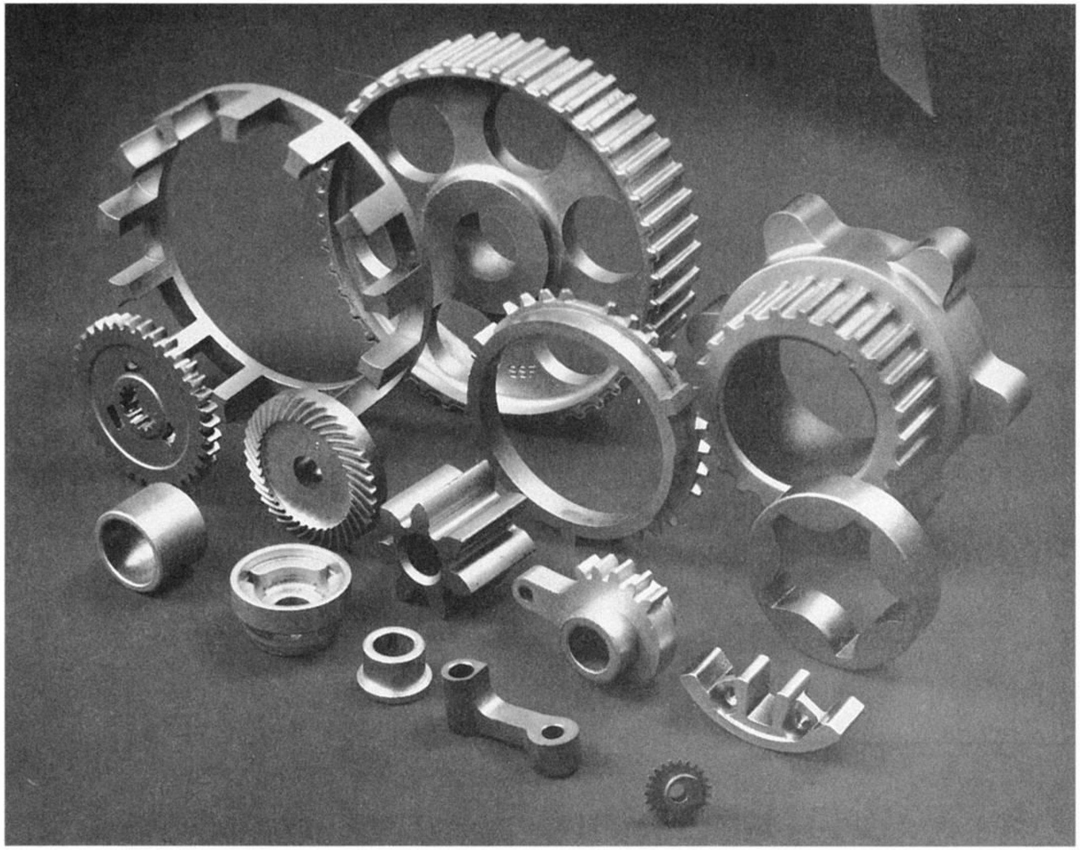


Figure 16.1 A collection of powder metallurgy parts (photo courtesy of Dorst America, Inc.).

Engineering Powders

A *powder* can be defined as a finely divided particulate solid

- Engineering powders include metals and ceramics
- Geometric features of engineering powders:
  - Particle size and distribution
  - Particle shape and internal structure
  - Surface area

Measuring Particle Size

- Most common method uses screens of different mesh sizes
- *Mesh count* – refers to the number of openings per linear inch of screen
  - A mesh count of 200 means there are 200 openings per linear inch
  - Since the mesh is square, the count is equal in both directions, and the total number of openings per square inch is $200^2 = 40{,}000$
  - Higher mesh count = smaller particle size

Screen Mesh

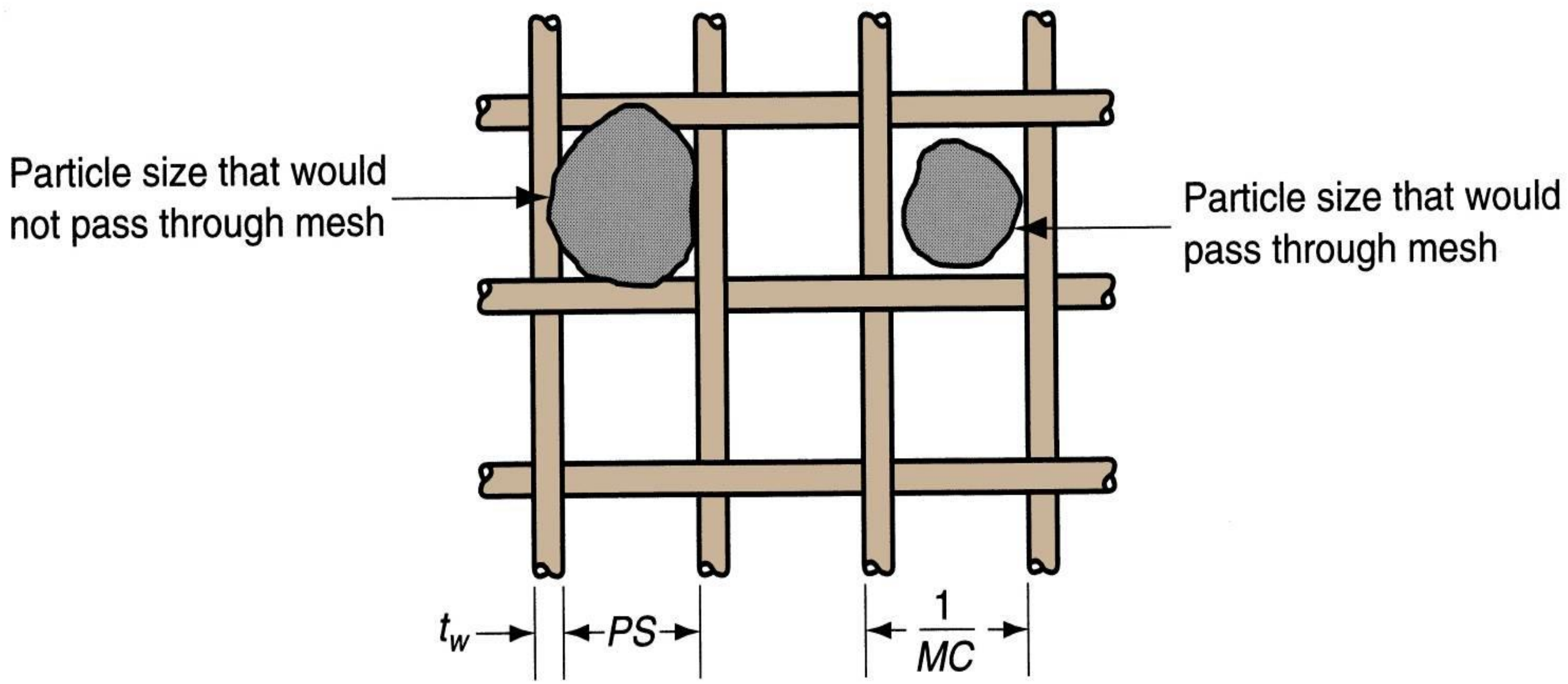


Figure 16.2 Screen mesh for sorting particle sizes.

Particle Shapes in PM

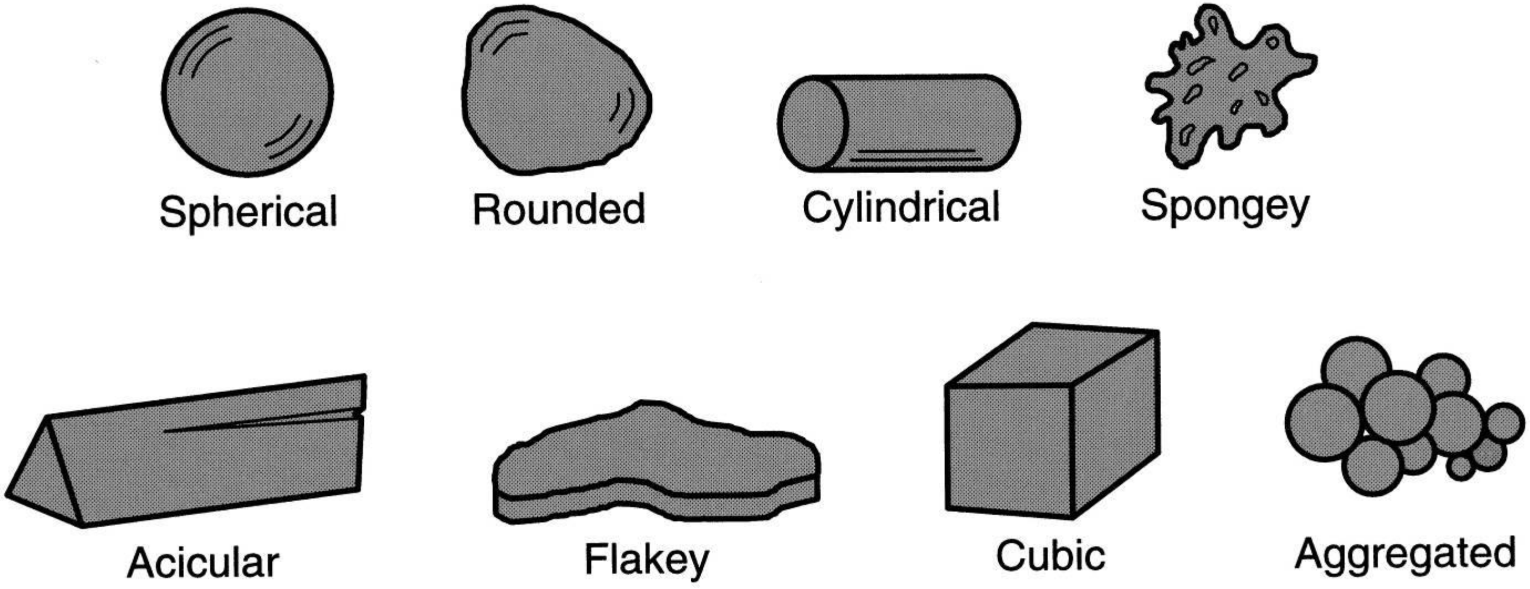


Figure 16.3 Several of the possible (ideal) particle shapes in powder metallurgy.

Interparticle Friction and Powder Flow

- Friction between particles affects ability of a powder to flow readily and pack tightly
- A common test of interparticle friction is the *angle of repose*, which is the angle formed by a pile of powders as they are poured from a narrow funnel

Angle of Repose

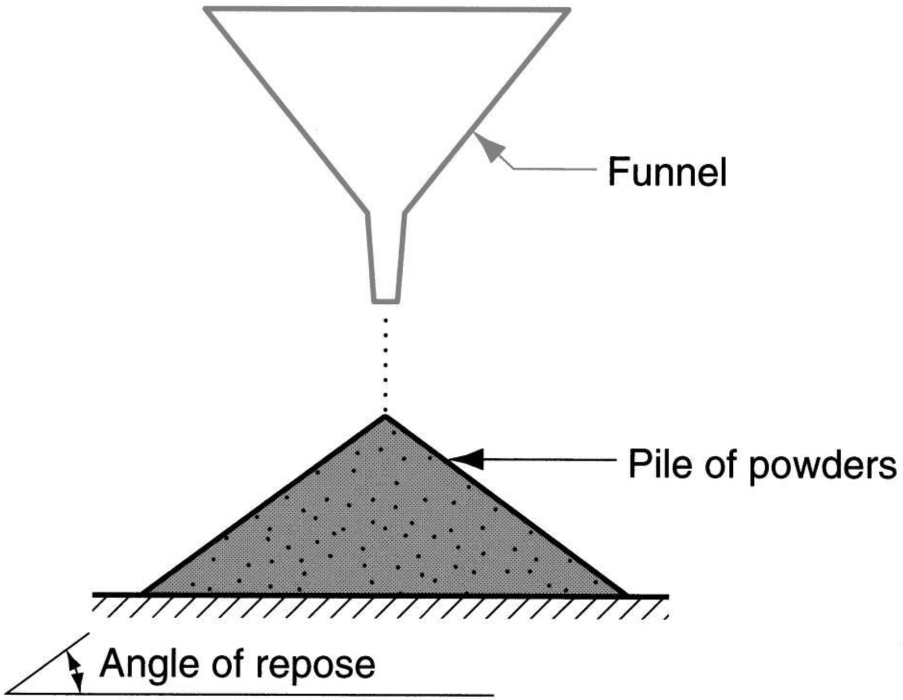


Figure 16.4 Interparticle friction as indicated by the angle of repose of a pile of powders poured from a narrow funnel. Larger angles indicate greater interparticle friction.

Observations

- Smaller particle sizes generally show greater friction and steeper angles
- Spherical shapes have the lowest interpartical friction
- As shape deviates from spherical, friction between particles tends to increase
- Easier flow of particles correlates with lower interparticle friction
- Lubricants are often added to powders to reduce interparticle friction and facilitate flow during pressing

Particle Density Measures

- True density – density of the true volume of the material
  - The density of the material if the powders were melted into a solid mass
- Bulk density – density of the powders in the loose state after pouring
  - Because of pores between particles, bulk density is less than true density

Packing Factor

Bulk density divided by true density

- Typical values for loose powders range between 0.5 and 0.7
- If powders of various sizes are present, smaller powders will fit into spaces between larger ones, thus higher packing factor
- Packing can be increased by vibrating the powders, causing them to settle more tightly
- Pressure applied during compaction greatly increases packing of powders through rearrangement and deformation of particles

Porosity

Ratio of volume of the pores (empty spaces) in the powder to the bulk volume

- In principle

  Porosity + Packing factor = 1.0

- The issue is complicated by possible existence of closed pores in some of the particles
- If internal pore volumes are included in above porosity, then equation is exact

Chemistry and Surface Films

- Metallic powders are classified as either
  - Elemental – consisting of a pure metal
  - Pre-alloyed – each particle is an alloy
- Possible surface films include oxides, silica, adsorbed organic materials, and moisture
  - As a general rule, these films must be removed prior to shape processing

Production of Metallic Powders

- In general, producers of metallic powders are not the same companies as those that make PM parts
- Any metal can be made into powder form
- Three principal methods by which metallic powders are commercially produced
  1. Atomization
  2. Chemical
  3. Electrolytic
- In addition, mechanical methods are occasionally used to reduce powder sizes

Gas Atomization Method

High velocity gas stream flows through expansion nozzle, siphoning molten metal from below and spraying it into container

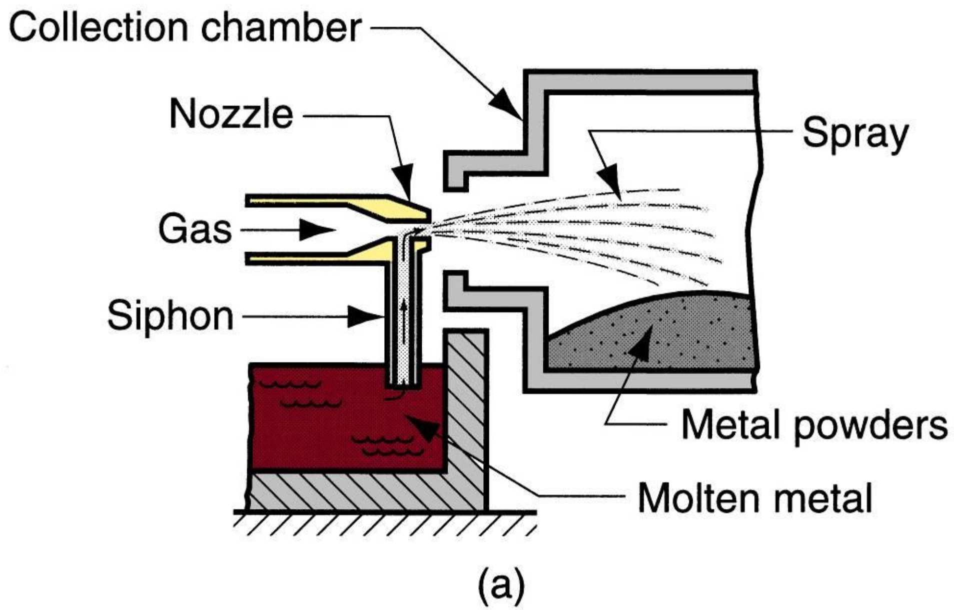


Figure 16.5 (a) gas atomization method

Iron Powders for PM

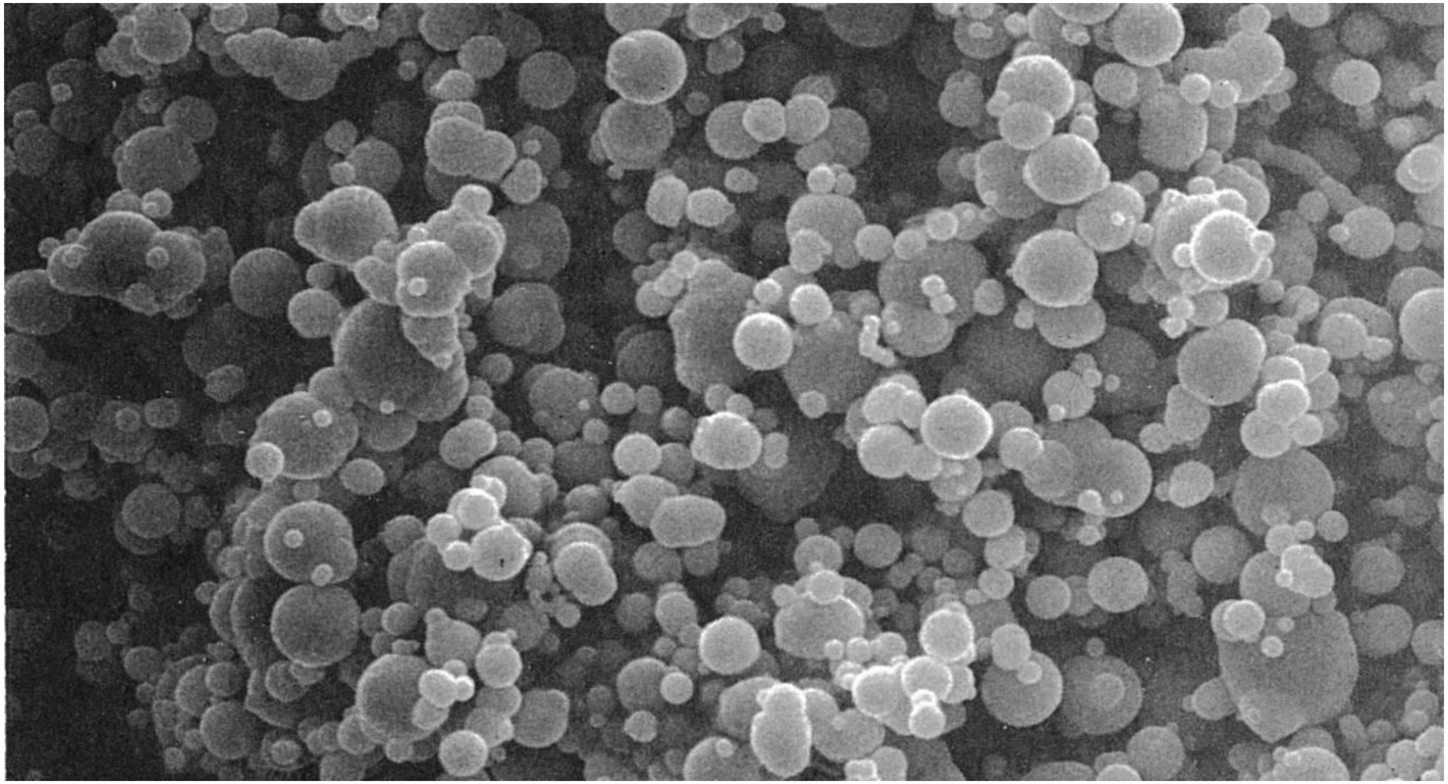


Figure 16.6 Iron powders produced by decomposition of iron pentacarbonyl (photo courtesy of GAF Chemical Corp); particle sizes range from about 0.25 – 3.0 microns (10 to 125 μ-in).

Conventional Press and Sinter

After metallic powders have been produced, the conventional PM sequence consists of:

1. Blending and mixing of powders
2. Compaction – pressing into desired shape
3. Sintering – heating to temperature below melting point to cause solid-state bonding of particles and strengthening of part

- In addition, secondary operations are sometimes performed to improve dimensional accuracy, increase density, and for other reasons

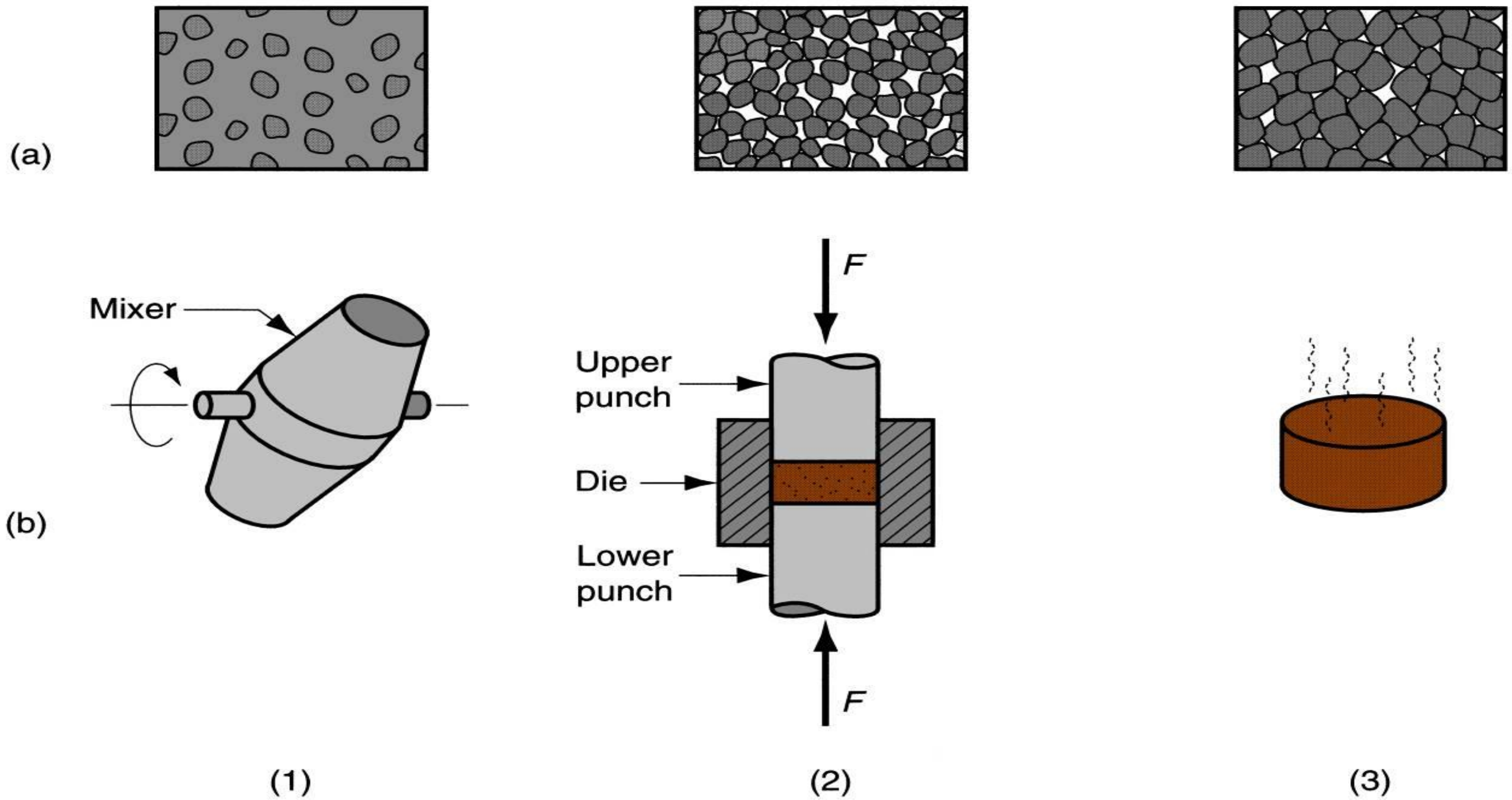


Figure 16.7 Conventional powder metallurgy production sequence: (1) blending, (2) compacting, and (3) sintering; (a) shows the condition of the particles while (b) shows the operation and/or workpart during the sequence.

Blending and Mixing of Powders

For successful results in compaction and sintering, the starting powders must be homogenized

- *Blending* – powders of same chemistry but possibly different particle sizes are intermingled
  - Different particle sizes are often blended to reduce porosity
- *Mixing* – powders of different chemistries are combined

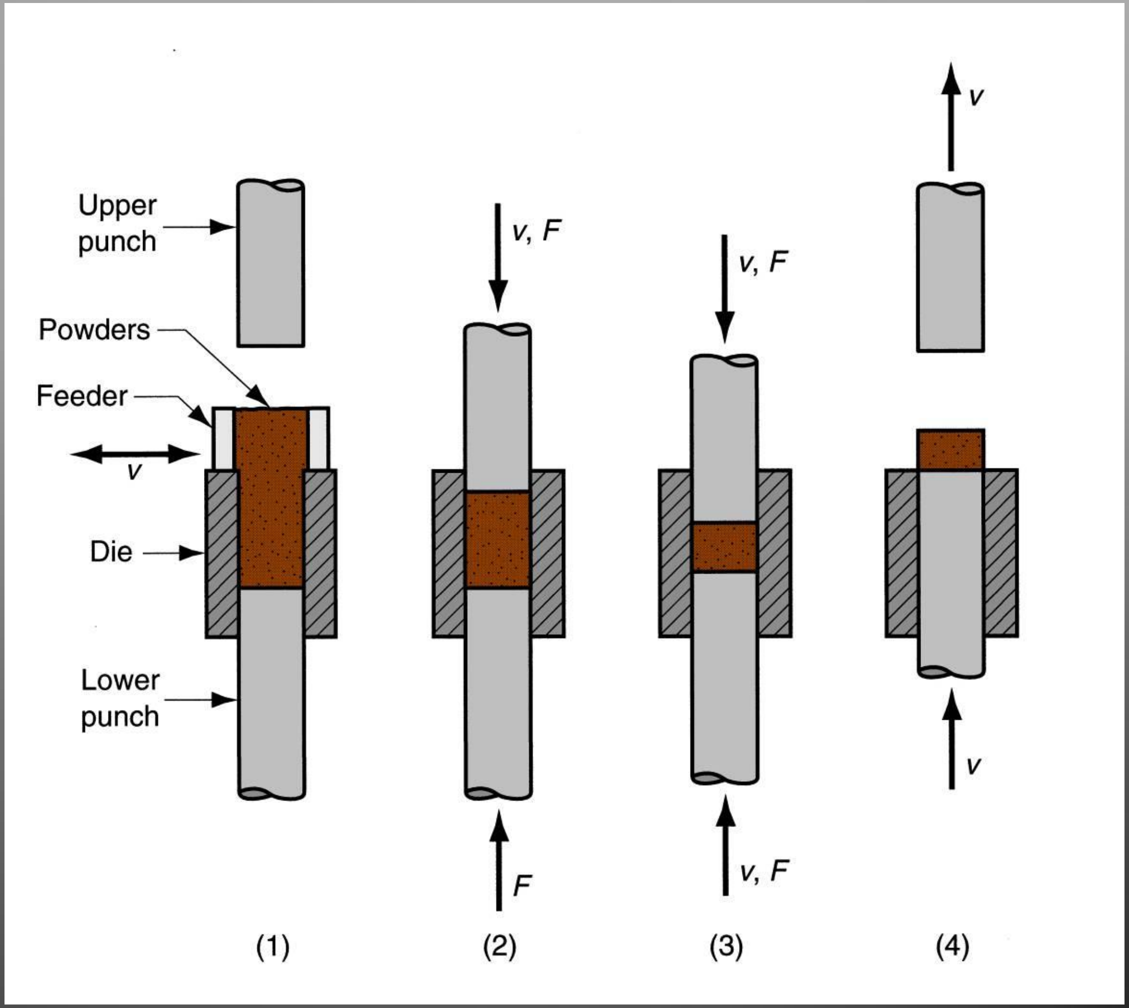
Compaction

Application of high pressure to the powders to form them into the required shape

- Conventional compaction method is *pressing*, in which opposing punches squeeze the powders contained in a die
- The workpart after pressing is called a *green compact*, the word green meaning not yet fully processed
- The *green strength* of the part when pressed is adequate for handling but far less than after sintering

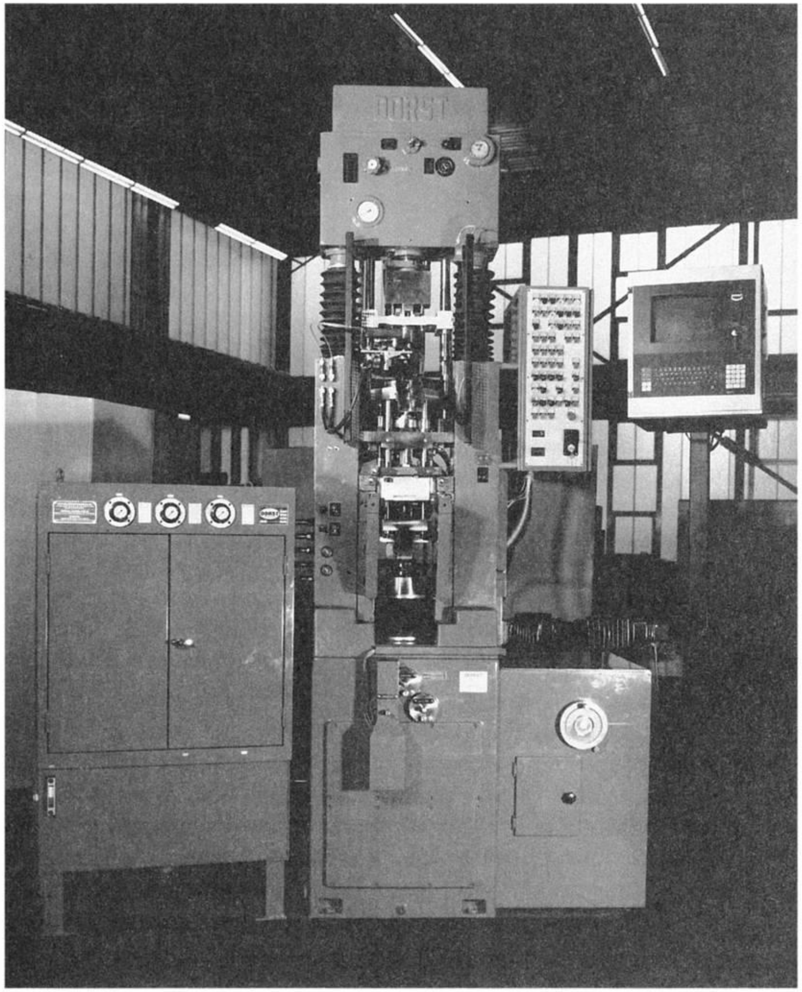
Conventional Pressing in PM

Figure 16.9 Pressing in PM: (1) filling die cavity with powder by automatic feeder; (2) initial and (3) final positions of upper and lower punches during pressing, (4) part ejection.



Press for Conventional Pressing in PM

Figure 16.11 A 450 kN (50-ton) hydraulic press for compaction of PM parts (photo courtesy of Dorst America, Inc.).



Sintering

Heat treatment to bond the metallic particles, thereby increasing strength and hardness

- Usually carried out at between 70% and 90% of the metal's melting point (absolute scale)
- Generally agreed among researchers that the primary driving force for sintering is reduction of surface energy
- Part shrinkage occurs during sintering due to pore size reduction

Sintering Sequence

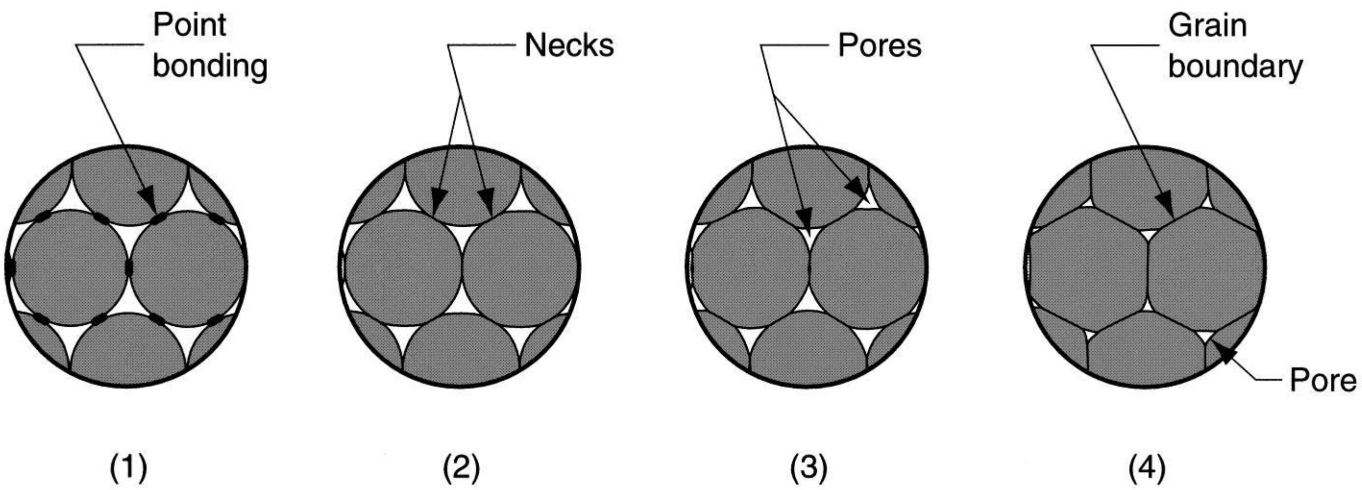


Figure 16.12 Sintering on a microscopic scale: (1) particle bonding is initiated at contact points; (2) contact points grow into "necks"; (3) the pores between particles are reduced in size; and (4) grain boundaries develop between particles in place of the necked regions.

Sintering Cycle and Furnace

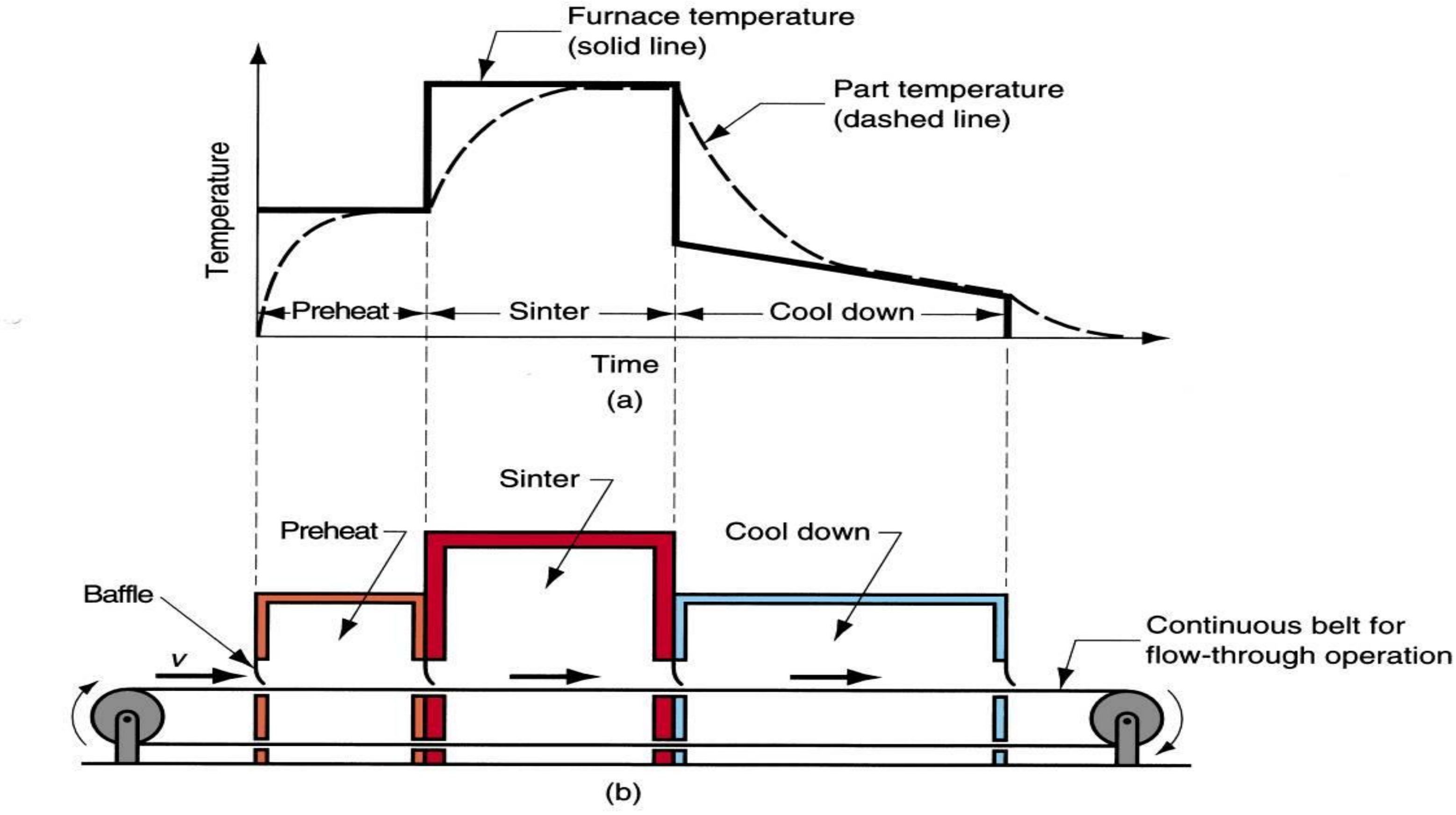


Figure 16.13 (a) Typical heat treatment cycle in sintering; and (b) schematic cross section of a continuous sintering furnace.

Densification and Sizing

Secondary operations are performed to increase density, improve accuracy, or accomplish additional shaping of the sintered part

- Repressing – pressing sintered part in a closed die to increase density and improve properties
- Sizing – pressing a sintered part to improve dimensional accuracy
- Coining – pressworking operation on a sintered part to press details into its surface
- Machining – creates geometric features that cannot be achieved by pressing, such as threads, side holes, and other details

Impregnation and Infiltration

- Porosity is a unique and inherent characteristic of PM technology
- It can be exploited to create special products by filling the available pore space with oils, polymers, or metals
- Two categories:
  1. Impregnation
  2. Infiltration

Impregnation

The term used when oil or other fluid is permeated into the pores of a sintered PM part

- Common products are oil-impregnated bearings, gears, and similar components
- Alternative application is when parts are impregnated with polymer resins that seep into the pore spaces in liquid form and then solidify to create a pressure tight part

Infiltration

Operation in which the pores of the PM part are filled with a molten metal

- The melting point of the filler metal must be below that of the PM part
- Involves heating the filler metal in contact with the sintered component so capillary action draws the filler into the pores
  - Resulting structure is relatively nonporous, and the infiltrated part has a more uniform density, as well as improved toughness and strength

Alternatives to Pressing and Sintering

- Conventional press and sinter sequence is the most widely used shaping technology in powder metallurgy
- Additional methods for processing PM parts include:
  - Isostatic pressing
  - Hot pressing – combined pressing and sintering

Materials and Products for PM

- Raw materials for PM are more expensive than for other metalworking because of the additional energy required to reduce the metal to powder form
- Accordingly, PM is competitive only in a certain range of applications
- What are the materials and products that seem most suited to powder metallurgy?

PM Materials – Elemental Powders

A pure metal in particulate form

- Applications where high purity is important
- Common elemental powders:
  - Iron
  - Aluminum
  - Copper
- Elemental powders can be mixed with other metal powders to produce alloys that are difficult to formulate by conventional methods
  - Example: tool steels

PM Materials – Pre-Alloyed Powders

Each particle is an alloy comprised of the desired chemical composition

- Common pre-alloyed powders:
  - Stainless steels
  - Certain copper alloys
  - High speed steel

PM Products

- Gears, bearings, sprockets, fasteners, electrical contacts, cutting tools, and various machinery parts
- Advantage of PM: parts can be made to near net shape or net shape
- When produced in large quantities, gears and bearings are ideal for PM because:
  - The geometry is defined in two dimensions
  - There is a need for porosity in the part to serve as a reservoir for lubricant

PM Parts Classification System

- The Metal Powder Industries Federation (MPIF) defines four classes of powder metallurgy part designs, by level of difficulty in conventional pressing
  - Useful because it indicates some of the limitations on shape that can be achieved with conventional PM processing

Four Classes of PM Parts

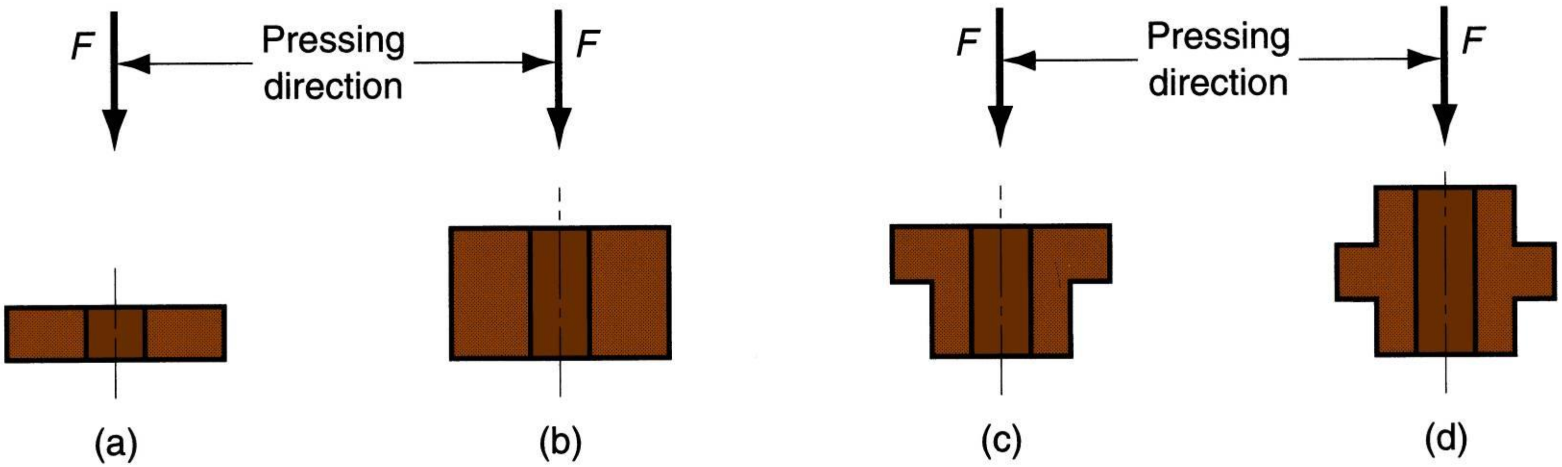


Figure 16.16 (a) Class I Simple thin shapes, pressed from one direction; (b) Class II Simple but thicker shape requires pressing from two directions; (c) Class III Two levels of thickness, pressed from two directions; and (d) Class IV Multiple levels of thickness, pressed from two directions, with separate controls for each level.

Design Guidelines for PM Parts – I

- Economics usually require large quantities to justify cost of equipment and special tooling
  - Minimum quantities of 10,000 units are suggested
- PM is unique in its capability to fabricate parts with a controlled level of porosity
  - Porosities up to 50% are possible
- PM can be used to make parts out of unusual metals and alloys – materials that are difficult if not impossible to produce by other means

Design Guidelines for PM Parts – II

- Part geometry must permit ejection from die
  - Part must have vertical or near-vertical sides, although steps are allowed
  - Design features like holes and undercuts on part sides must be avoided
  - Vertical undercuts and holes are permissible because they do not interfere with ejection
  - Vertical holes can have cross-sectional shapes other than round without significant difficulty

Side Holes and Undercuts

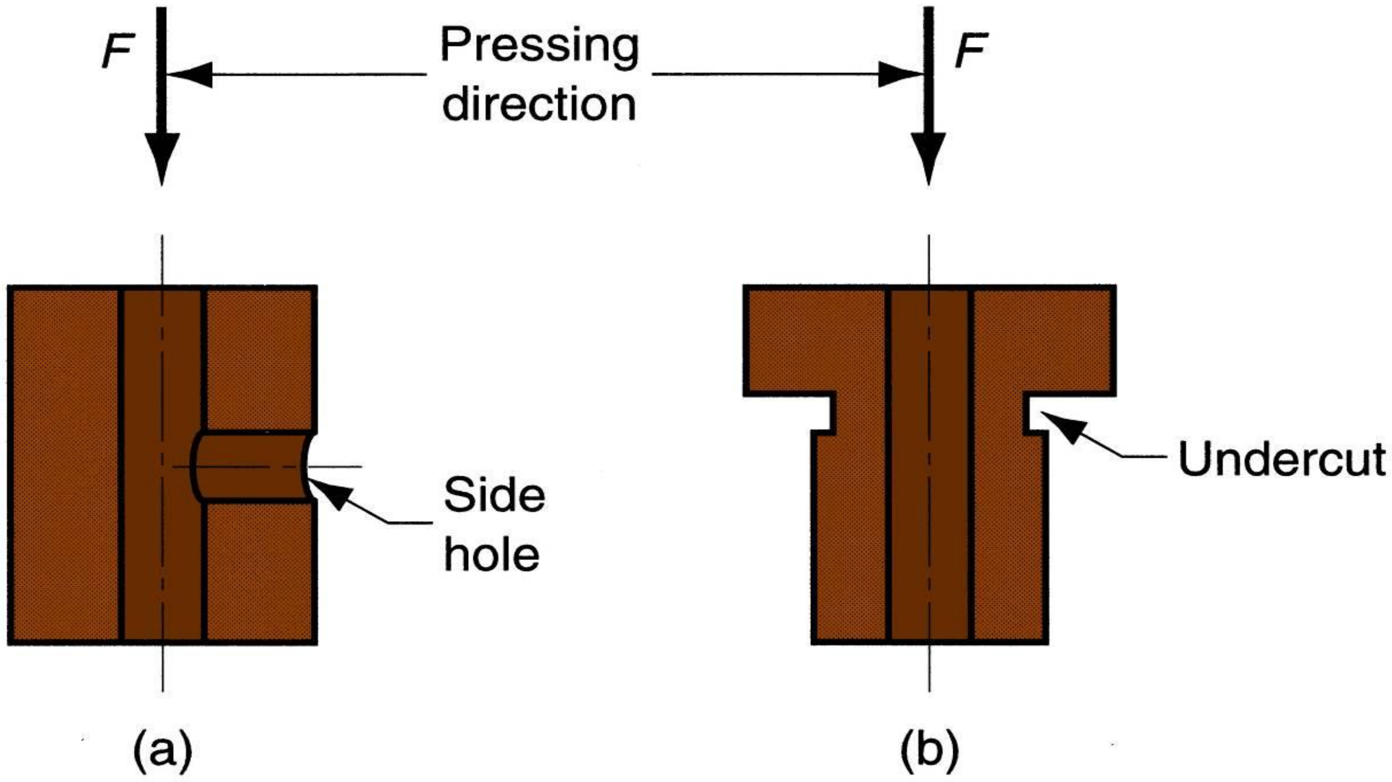


Figure 16.17 Part features to be avoided in PM: side holes and (b) side undercuts since part ejection is impossible.

Design Guidelines for PM Parts – III

- Screw threads cannot be fabricated by PM
  - They must be machined into the part
- Chamfers and corner radii are possible in PM
  - But problems occur in punch rigidity when angles are too acute
- Wall thickness should be a minimum of 1.5 mm (0.060 in) between holes or a hole and outside wall
- Minimum recommended hole diameter is 1.5 mm (0.060 in)

Chamfers and Corner Radii

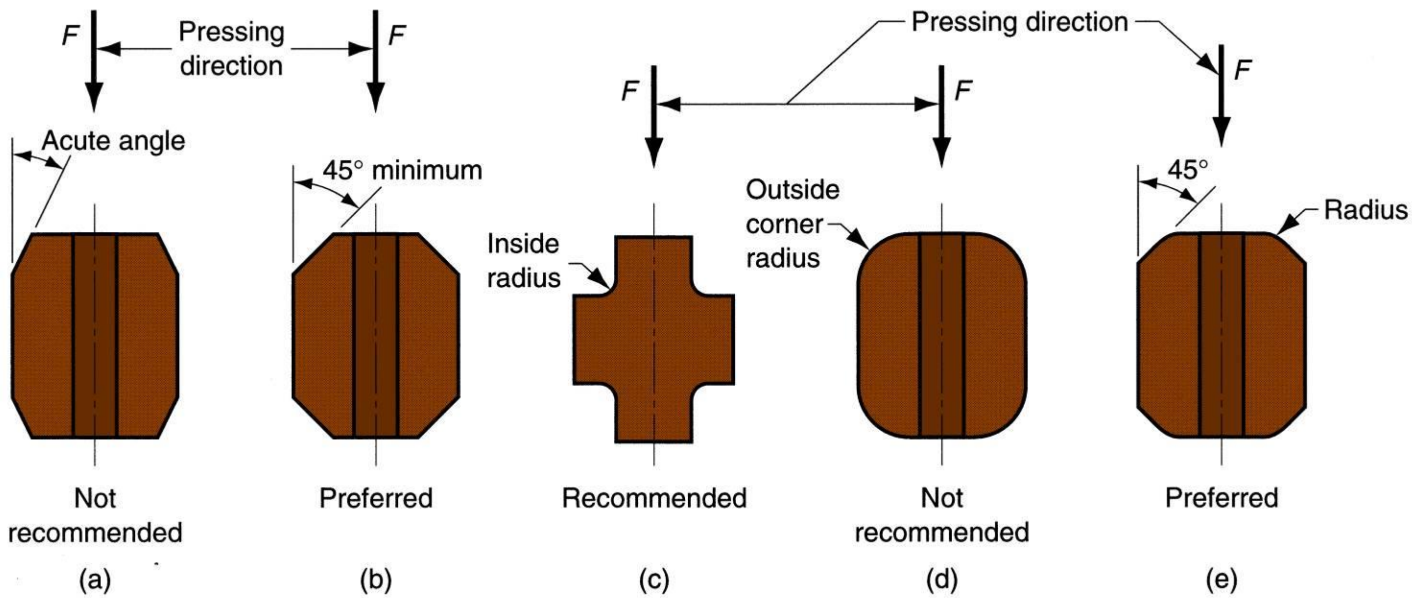


Figure 16.19 Chamfers and corner radii are accomplished but certain rules should be observed: (a) avoid acute angles; (b) larger angles preferred for punch rigidity; (c) inside radius is desirable; (d) avoid full outside corner radius because punch is fragile at edge; (e) problem solved by combining radius and chamfer.