Fundamentals of Casting

Chapter 11

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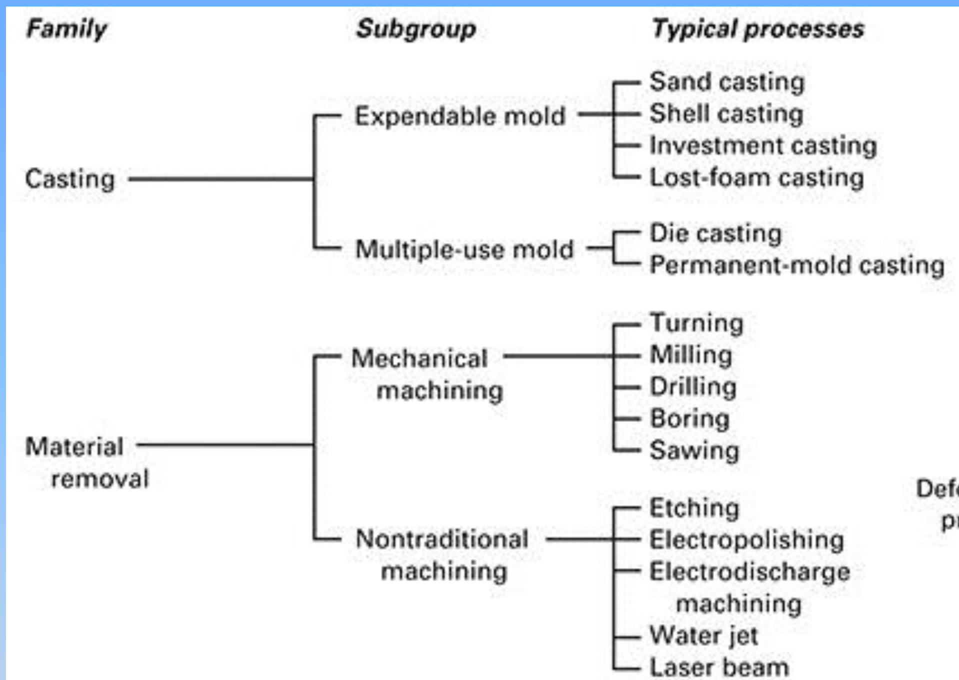
11.1 Introduction

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

Shape-Producing Processes

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

Shape-Producing Processes



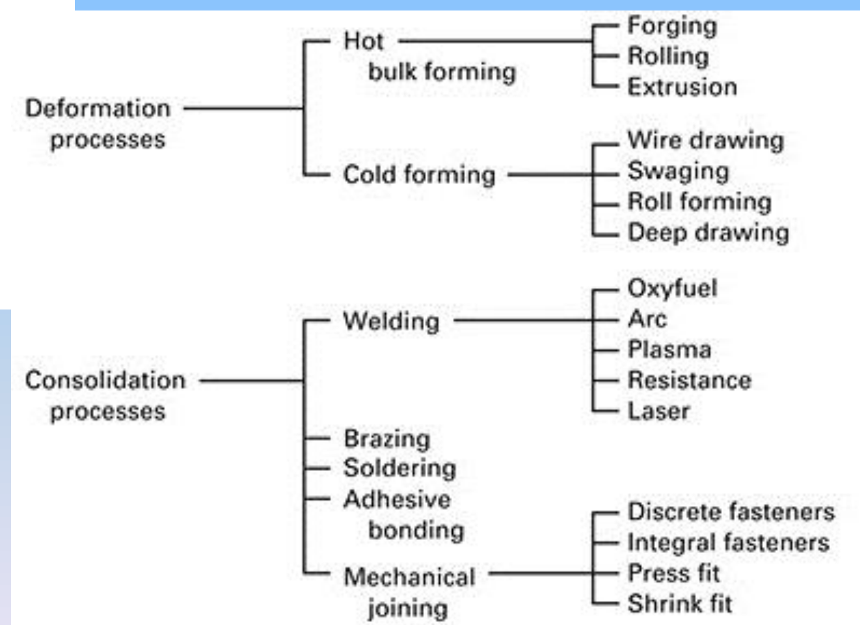


Figure 11-1 The four materials processing families, with subgroups and typical processes.

11.2 Introduction to Casting

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

Advantages of Casting

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

Basic Requirements of Casting Processes

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

Six Basic Steps of Casting

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

11.3 Casting Terminology

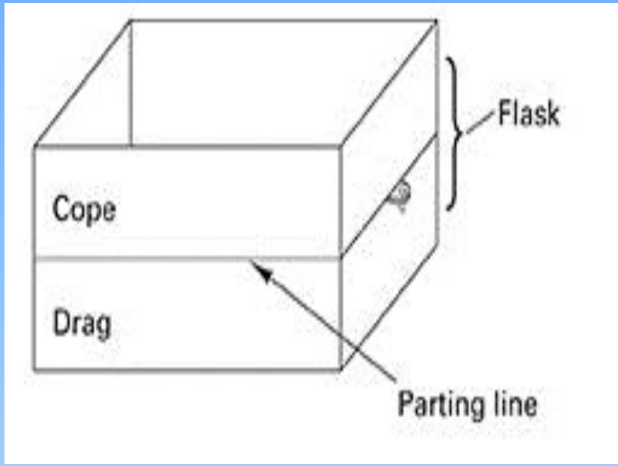
- Pattern- approximate duplicate of the part to be cast
- Molding material- material that is packed around the pattern to provide the mold cavity
- Flask- rigid frame that holds the molding aggregate
- Cope- top half of the pattern
- Drag- bottom half of the pattern
- Core- sand or metal shape that is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

Casting Terminology

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

Casting Terminology

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



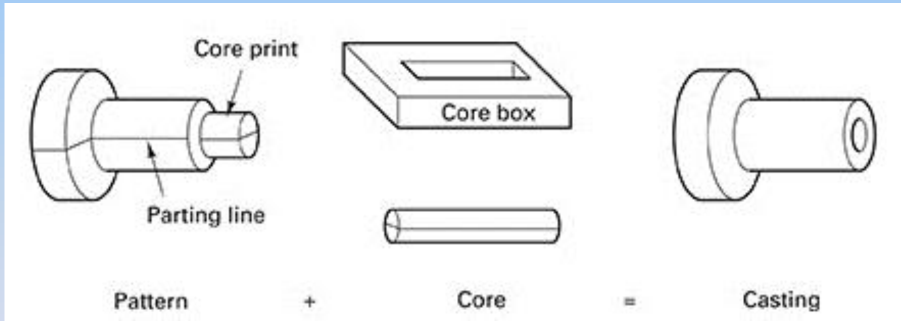


Figure 11-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

Cross Section of a Mold

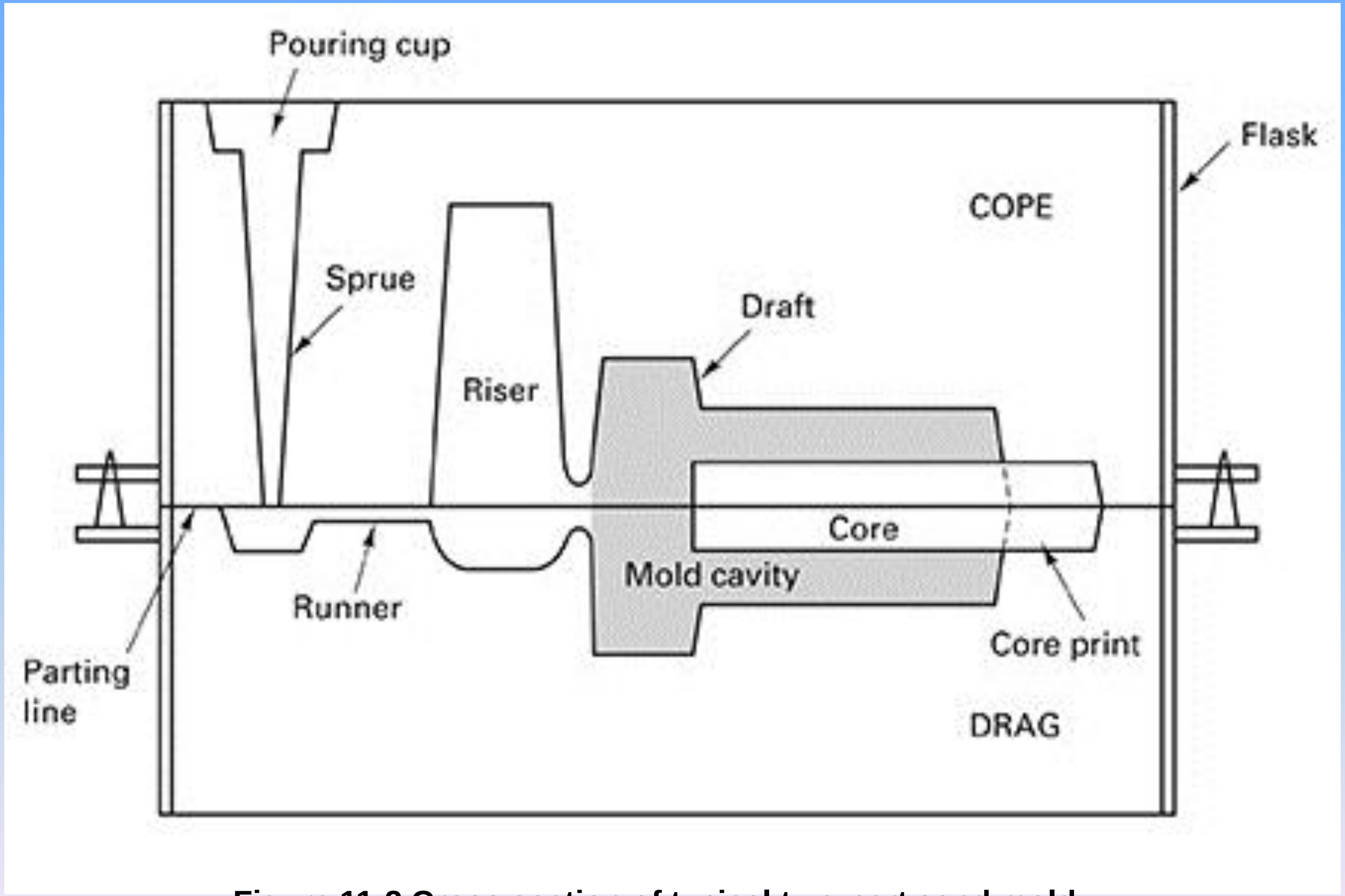


Figure 11-2 Cross section of typical two-part sand mold

11.4 The Solidification Process

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

Nucleation

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

Grain Growth

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

Cooling Curves

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

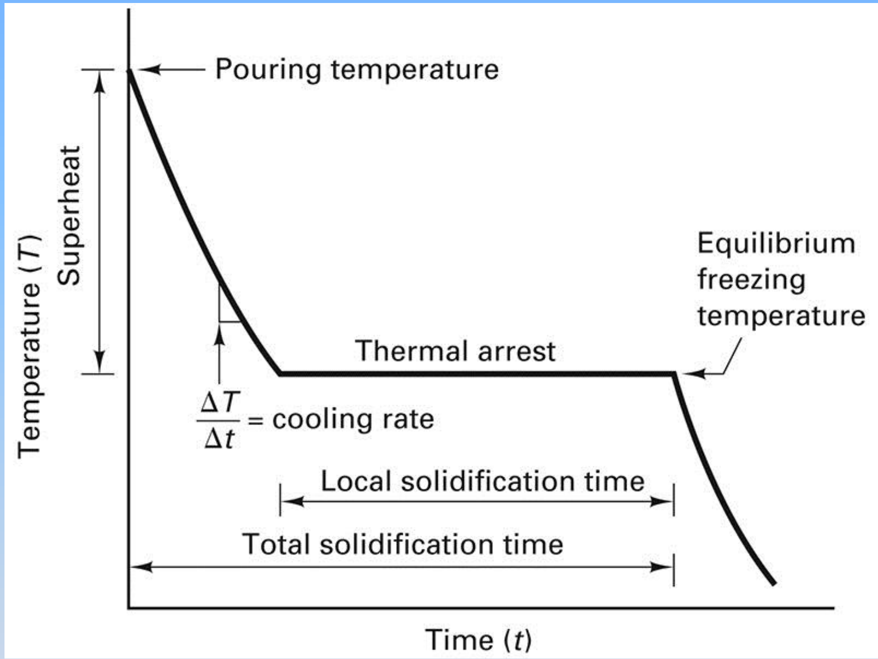


Figure 11-3 Cooling curve for a pure metal or eutectic-composition alloy (metals with a distinct freezing point), indicating major features related to solidification.

Cooling Curves

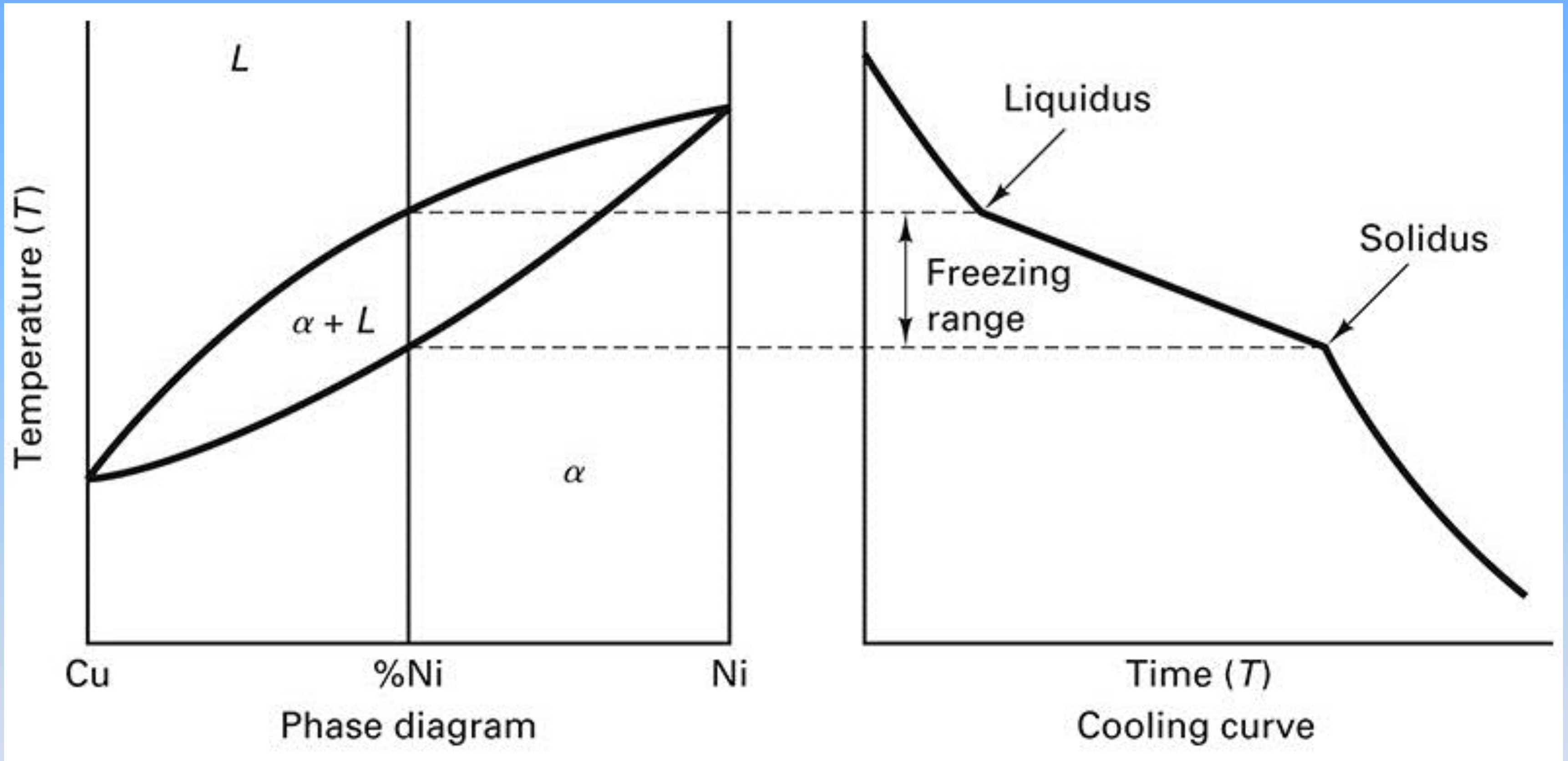


Figure 11-4 Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes indicate the onset and termination of solidification.

Prediction of Solidification Time: Chvorinov's Rule

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

Cast Structure

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

Cast Structure

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

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

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

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

Molten Metal Problems

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

Molten Metal Problems

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

Molten Metal Problems

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

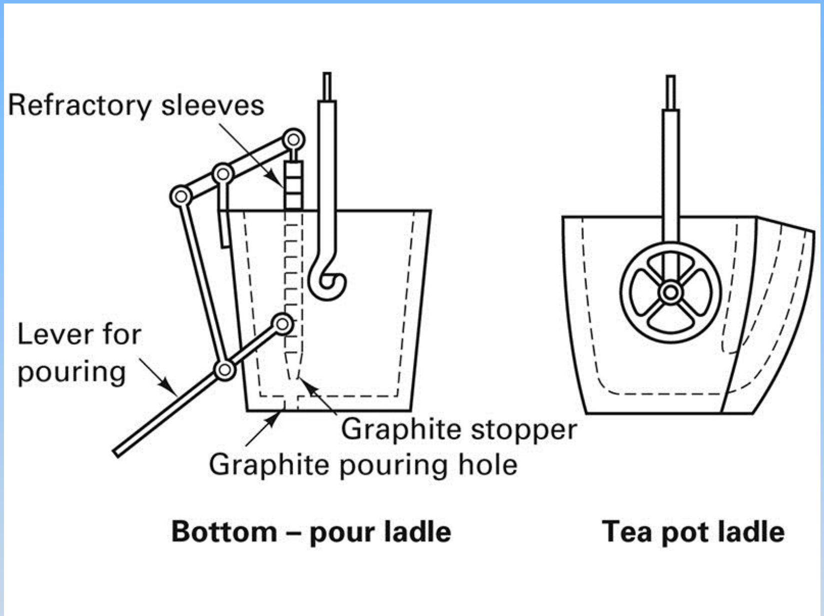
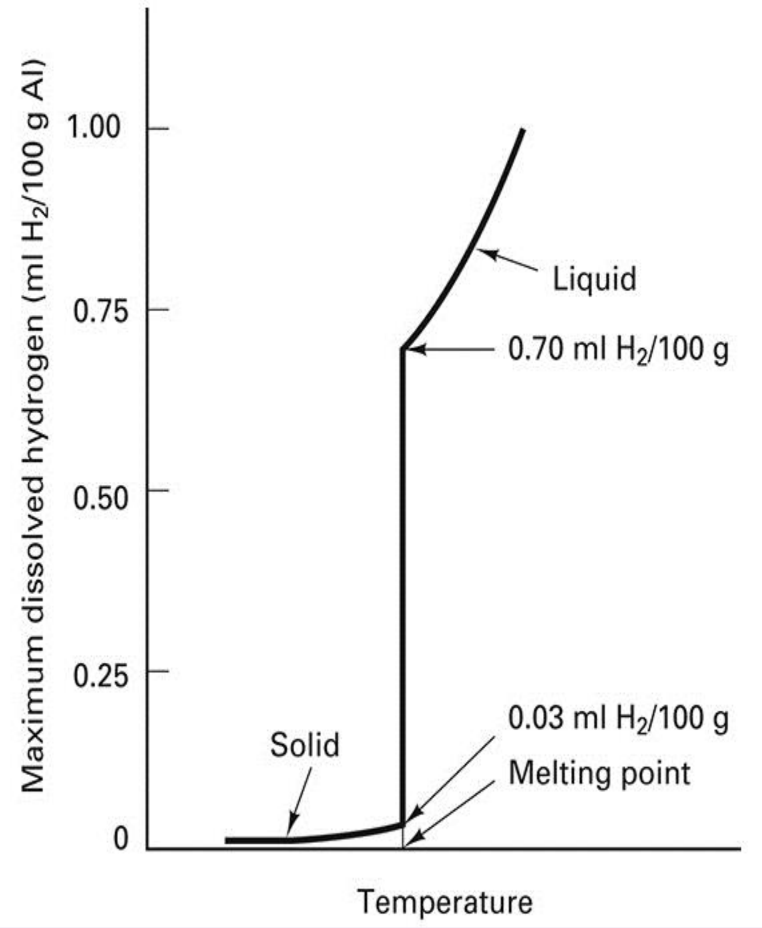


Figure 11-6 Two types of ladles used to pour castings. Note how each extracts molten material from the bottom, avoiding transfer of the impure material from the top of the molten pool.



Fluidity and Pouring Temperature

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

The Role of the Gating System

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

Gating Systems

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

Gating System

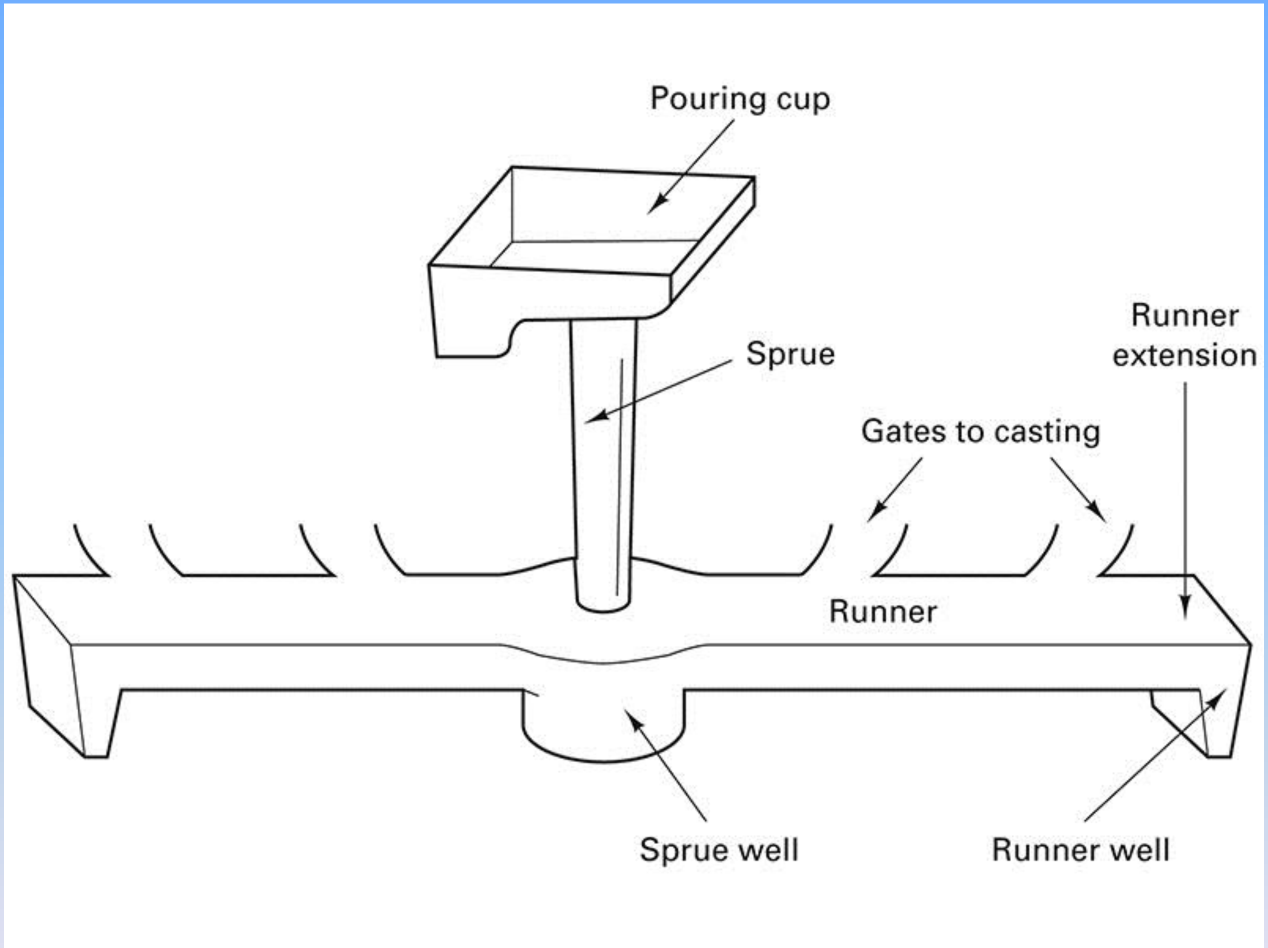


Figure 11-9 Typical gating system for a horizontal parting plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

Filters

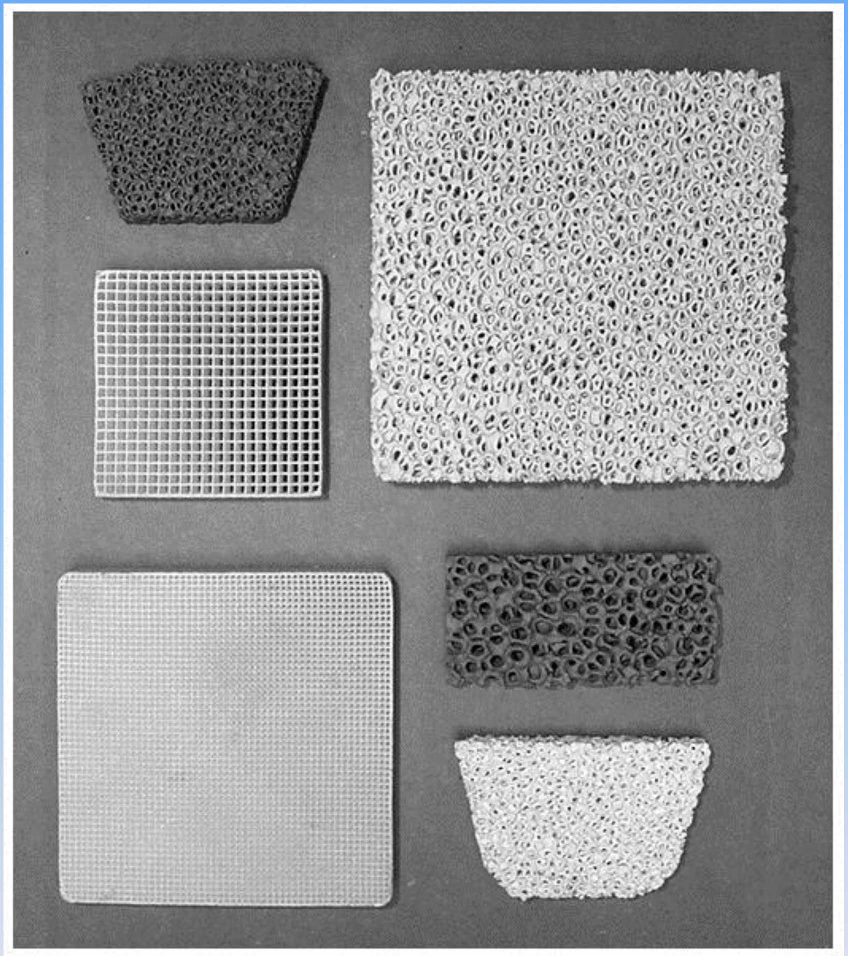


Figure 11-10 Various types of ceramic filters that may be inserted into the gating systems of metal castings.

Solidification Shrinkage

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

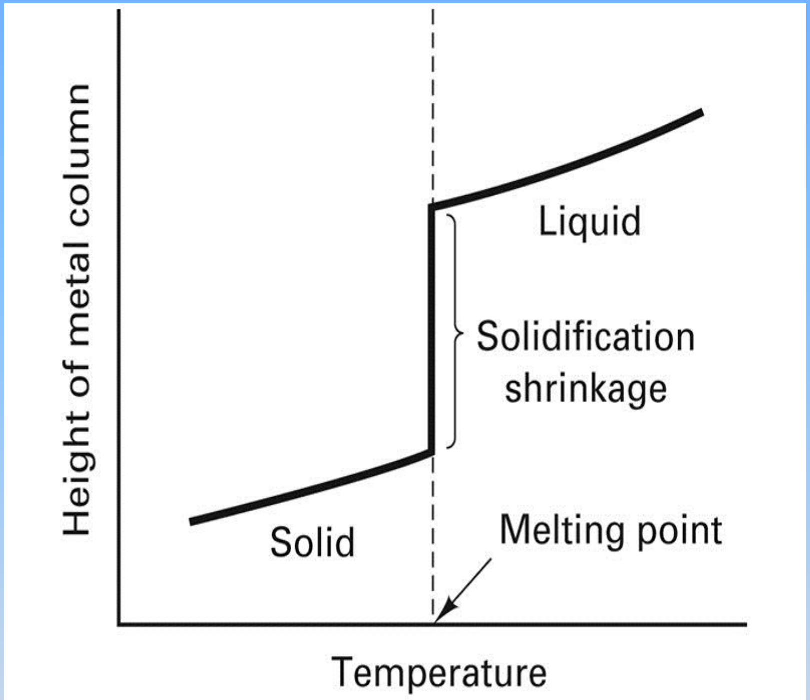


Figure 11-11 Dimensional changes experienced by a metal column as the material cools from a superheated liquid to a room-temperature solid. Note the significant shrinkage that occurs upon solidification.

Solidification Shrinkage

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

Risers and Riser Design

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

Risers and Riser Design

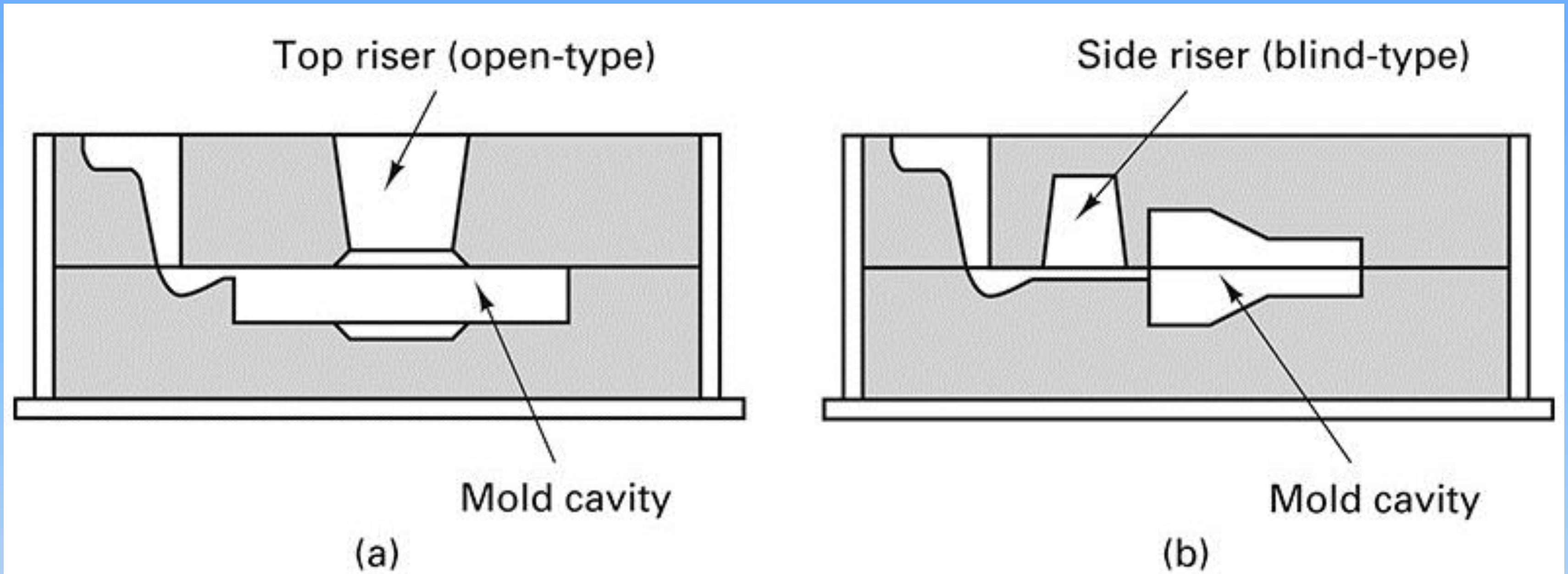


Figure 11-13 Schematic of a sand casting mold, showing a) an open-type top riser and b) a blind-type side riser. The side riser is a live riser, receiving the last hot metal to enter the mold. The top riser is a dead riser, receiving metal that has flowed through the mold cavity.

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

Riser Aids

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

11.5 Patterns

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

Dimensional Allowances

- Typical allowances
  - Cast iron 0.8-1.0%
  - Steel 1.5-2.0%
  - Aluminum 1.0-1.3%
  - Magnesium 1.0-1.3%
  - Brass 1.5%
- Shrinkage allowances are incorporated into the pattern using shrink rules
- Thermal contraction might not be the only factor for determining pattern size
- Surface finishing operations (machining, etc.) should be taken into consideration

Pattern Removal

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

Design Considerations

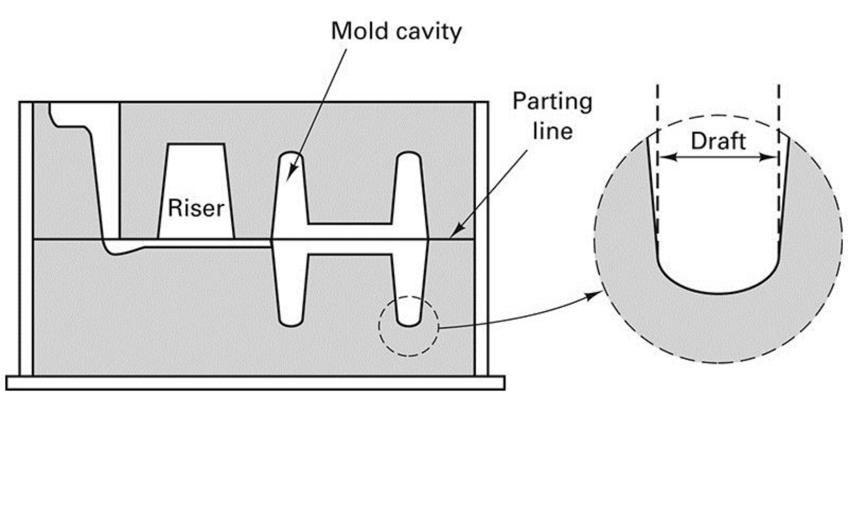


Figure 11-14 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

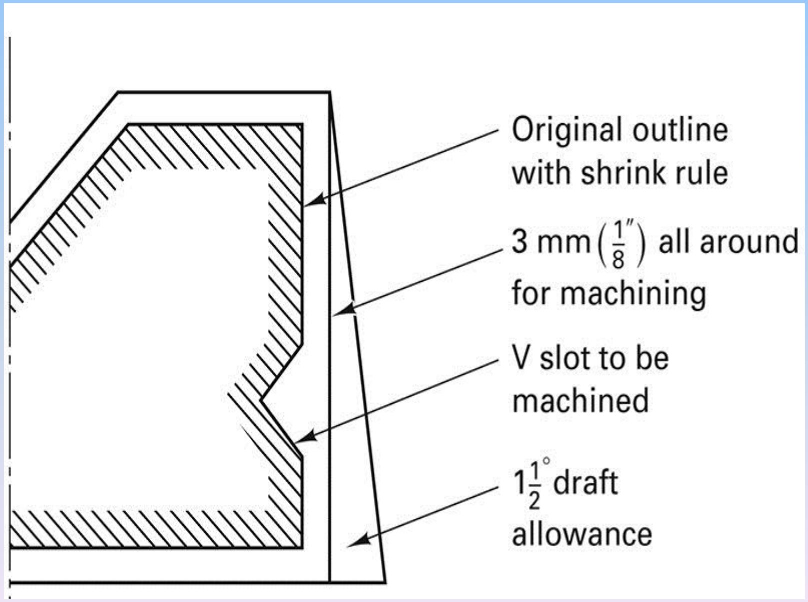


Figure 11-15 Various allowances incorporated into a casting pattern.

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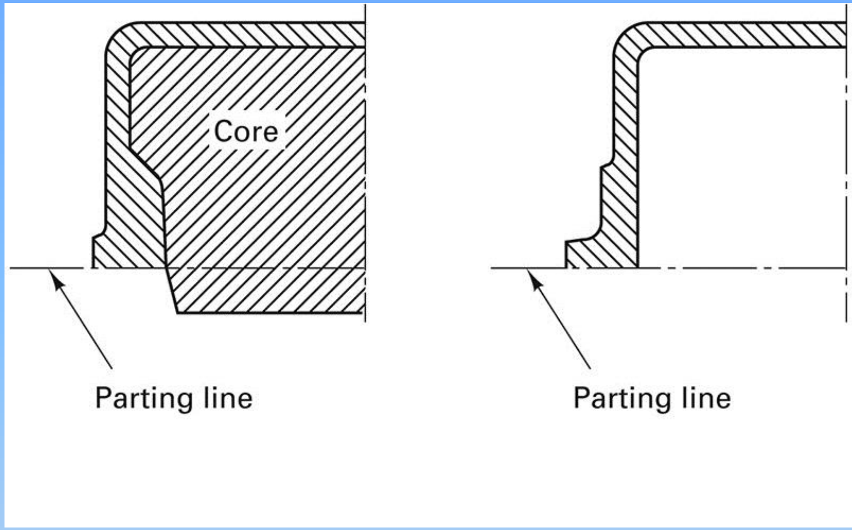
11.6 Design Considerations in Castings

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

Design Considerations

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



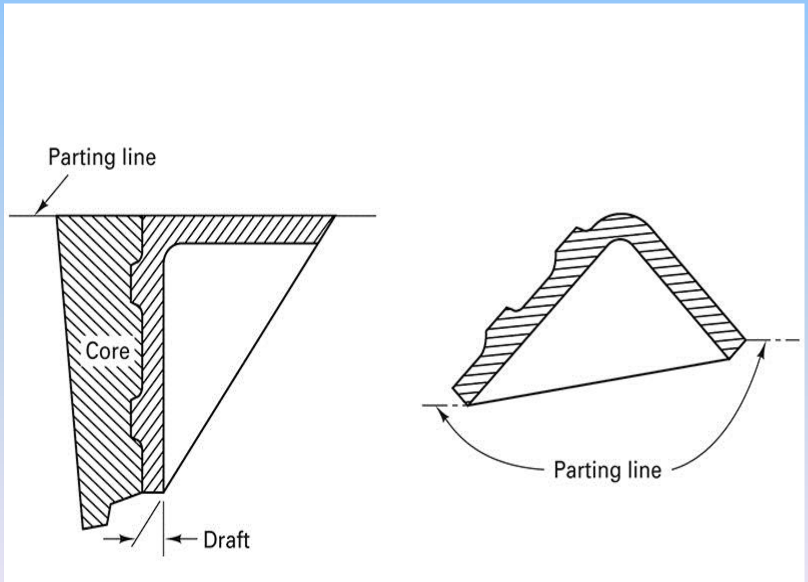


Figure 11-16 (Left) Elimination of a core by changing the location or orientation of the parting plane.

Design Considerations

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

Parting Line and Drafts

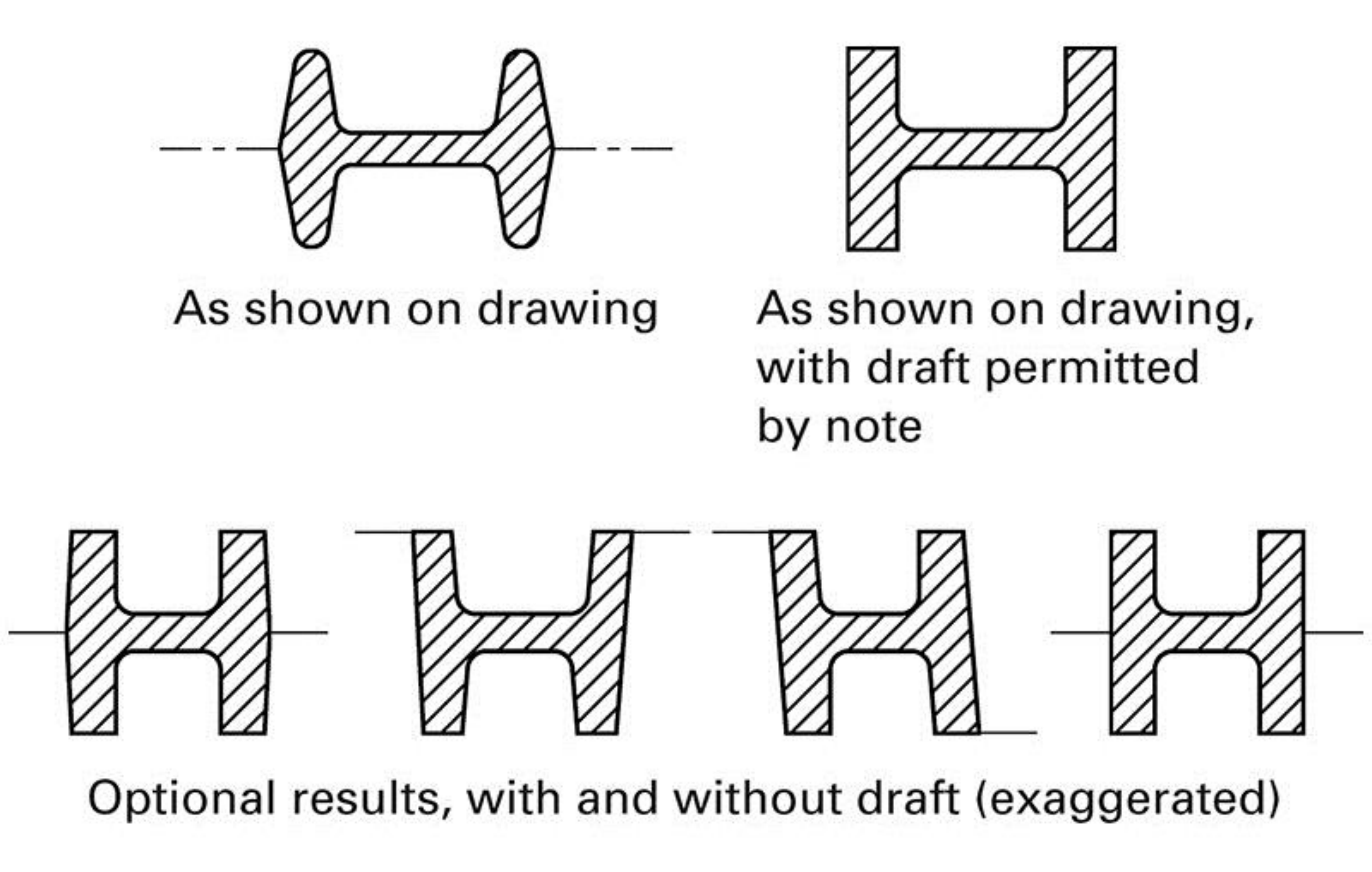


Figure 11-18 (Top left) Design where the location of the parting plane is specified by the draft. (Top right) Part with draft unspecified. (Bottom) Various options to produce the top-right part, including a no-draft design.

Section Thicknesses

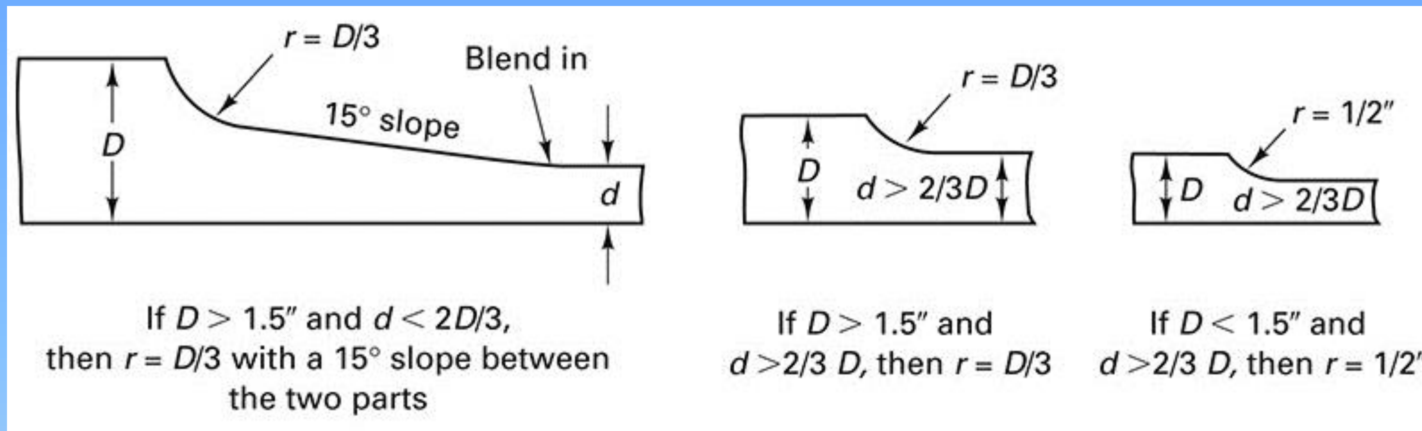


Figure 11-19 (Above) Typical guidelines for section change transitions in castings.

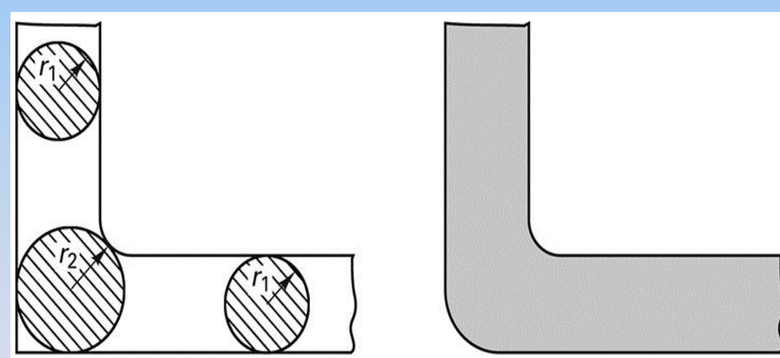


Figure 11-20 a) The “hot spot” at section r_2 is cause by intersecting sections. B) An interior fillet and exterior radius lead to more uniform thickness and more uniform cooling.

Design Modifications

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

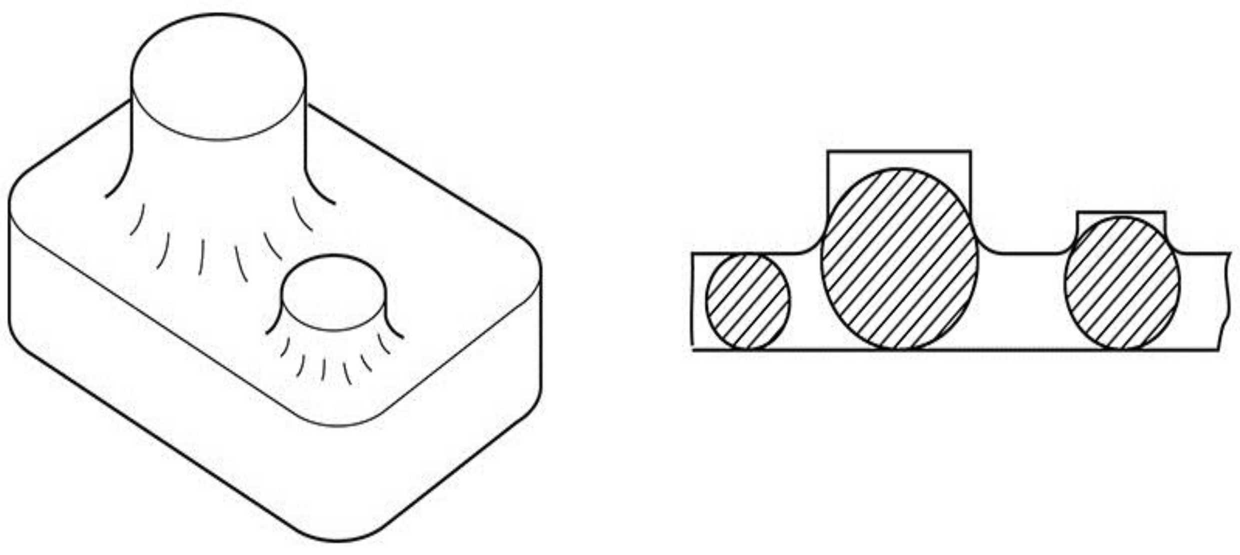


Figure 11-21 Hot spots often result from intersecting sections of various thickness.

Design Modifications

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

Design Modifications

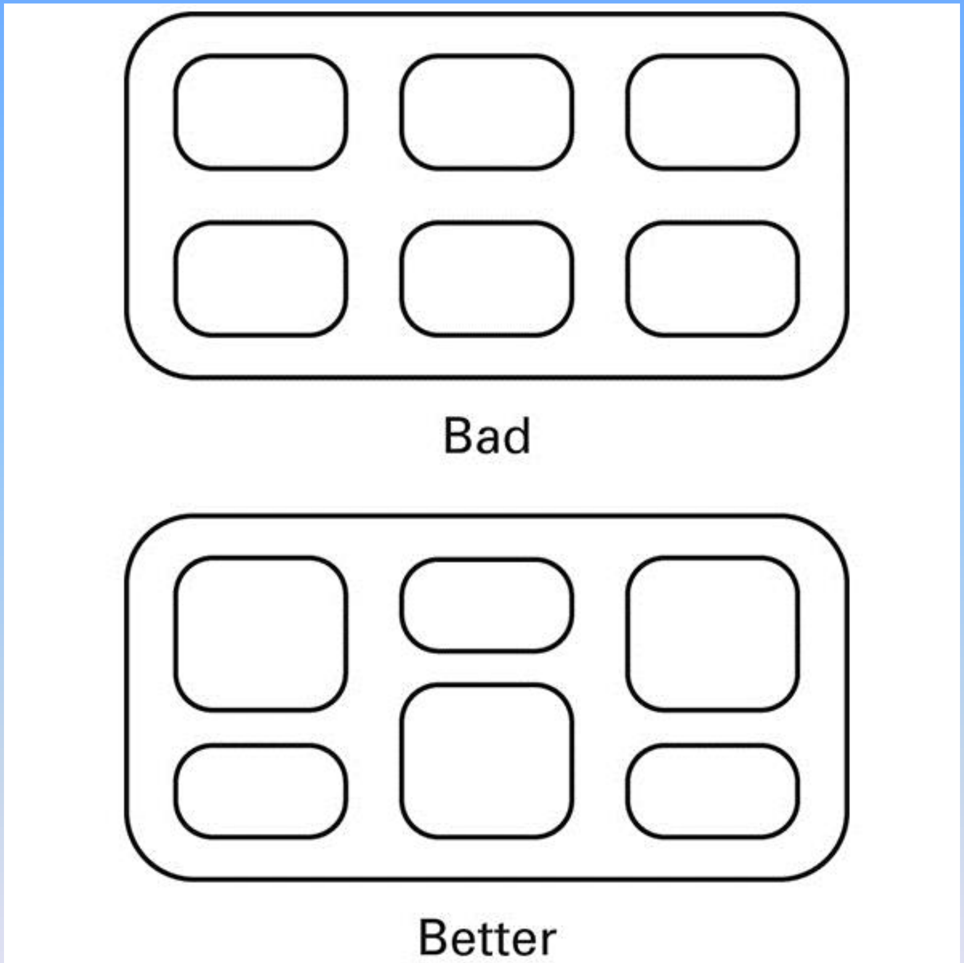


Figure 11-23 Using staggered ribs to prevent cracking during cooling.

Casting Designs

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

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

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

11.7 The Casting Industry

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

Summary

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