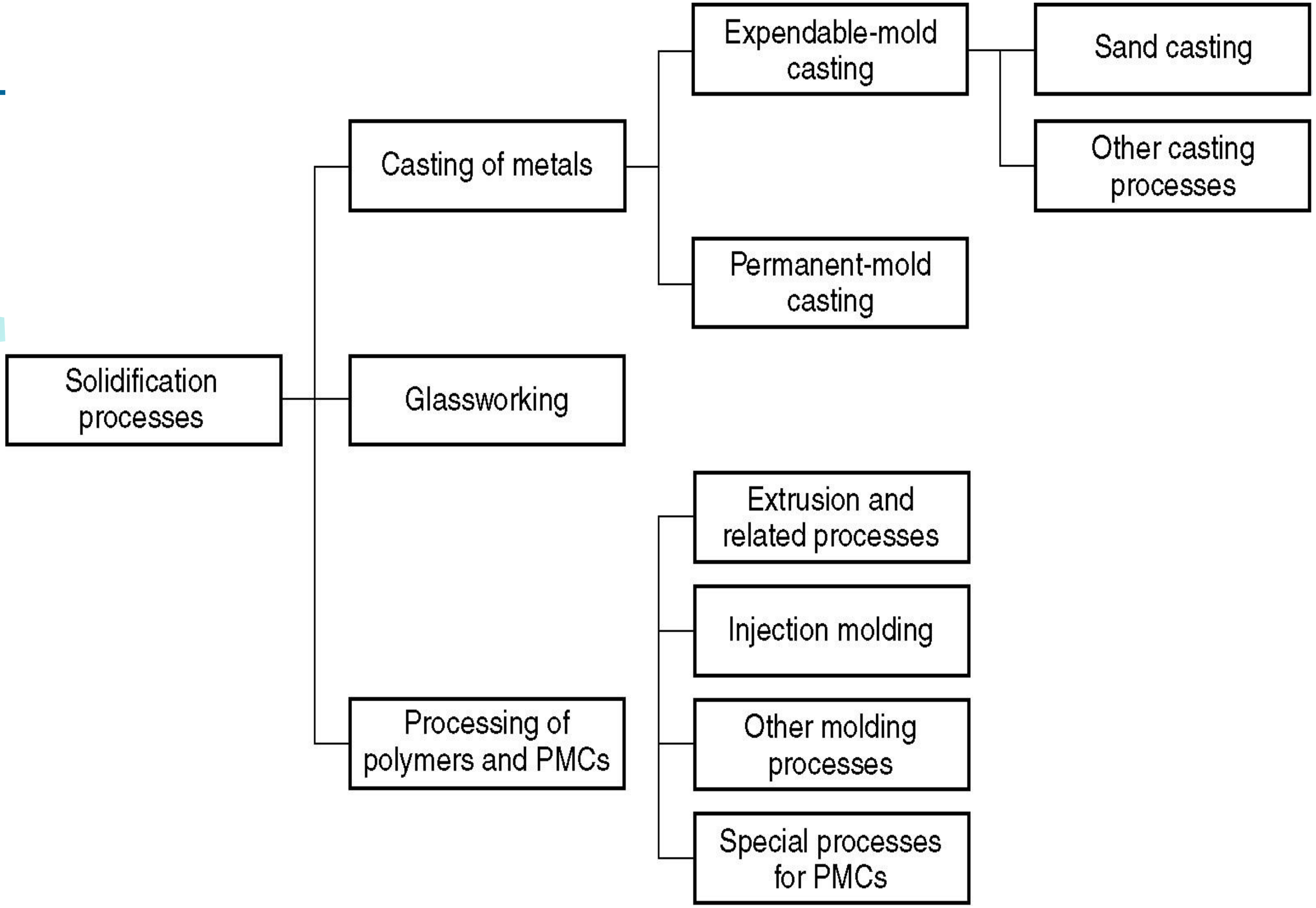
FUNDAMENTALS OF METAL CASTING

1. Overview of Casting Technology
2. Heating and Pouring
3. 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)



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, church bells, big statues, pump housings
- Small parts
  - Dental crowns, jewelry, small statues, frying pans
- All varieties of metals can be cast, ferrous and nonferrous

Overview of Casting Technology

- Casting is usually performed in a foundry

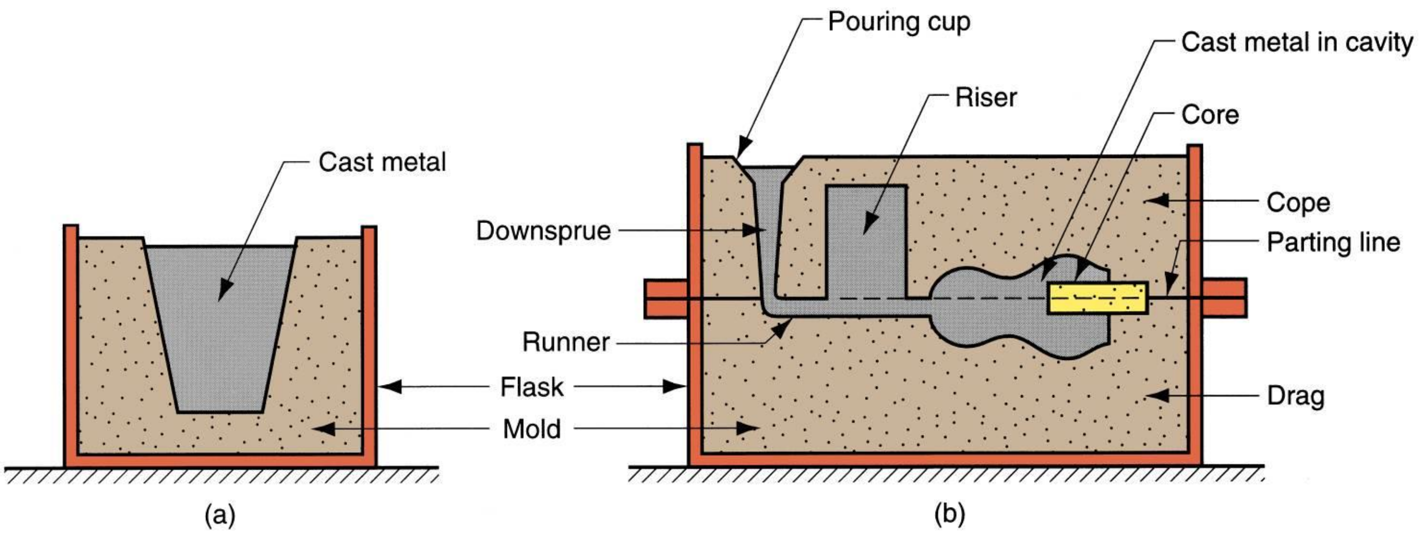
Foundry = factory equipped for making molds, melting and handling molten metal, performing the casting process, and cleaning the finished casting

- Workers who perform casting are called *foundrymen*

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.

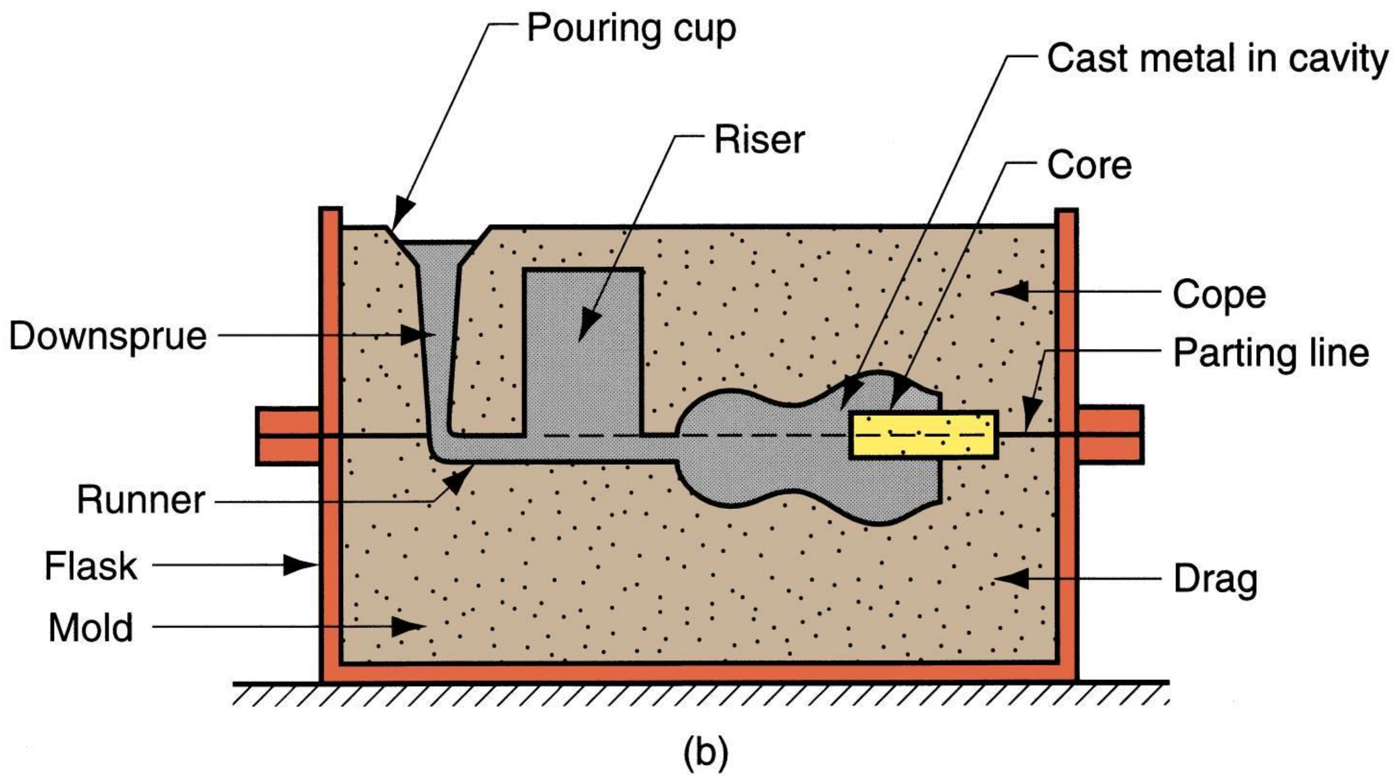
Two Categories of Casting Processes

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 over and over 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 the mold
- Permanent mold processes are more economic in high production operations

Sand Casting Mold



(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 of the packed sand has desired shape of cast part
- The pattern is usually oversized to allow for shrinkage of metal during solidification and cooling
- Sand for the mold is moist and contains a binder to maintain its 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 the top of downsprue, a *pouring cup* is often used to minimize splash and turbulence as the metal flows into downsprue

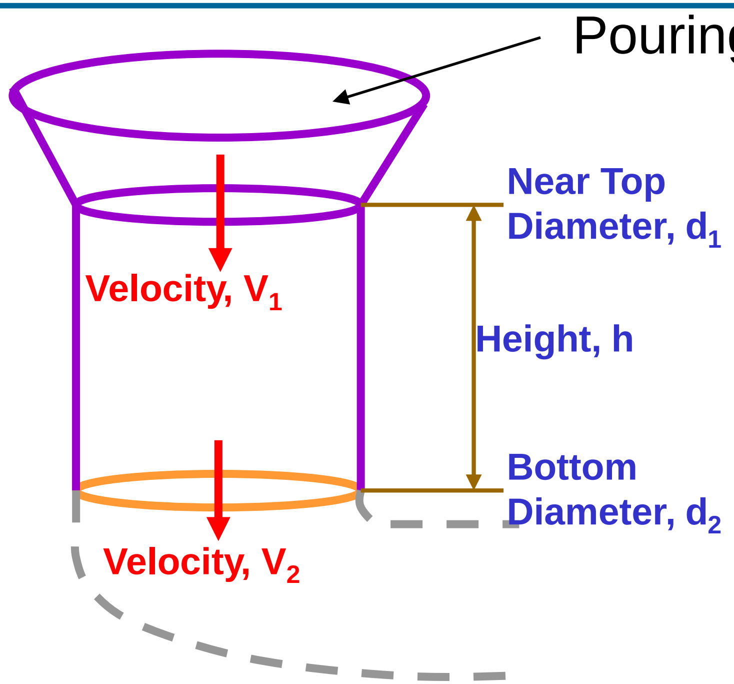
Riser

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

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

Pouring (Sprue Design)

Sprue Diameter



Let Q = Pour Rate (volume/unit time) or (in^3/sec or liter/s)

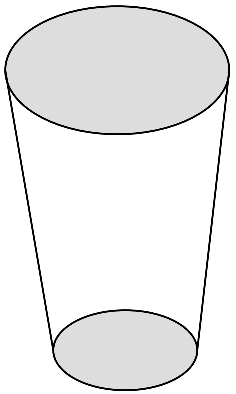
Q = Flow Area * Velocity

$Q = A*V$

Near Top, $Q = A_1V_1$ **Bottom, $Q = A_2V_2$**

Sprue Diameters

Design Concept: To avoid gas entrapment or Aspiration



FLOW Continuity → constant flow rate

$$A_1V_1 = A_2V_2$$

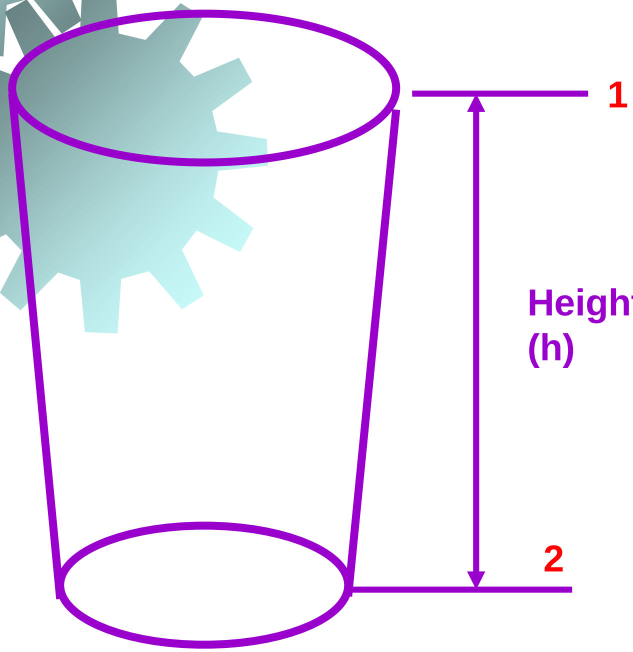
$$\frac{\pi d_1^2}{4}V_1 = \frac{\pi d_2^2}{4}V_2 \quad \rightarrow \quad d_1^2V_1 = d_2^2V_2$$

$$d_2 = \sqrt{\frac{V_1}{V_2}} \times d_1$$

NOTE: $V_2 > V_1$ so $d_2 < d_1$

Thus diameter decreases from top to bottom

Sprue Height



At 1, Total Energy, E_1

$$E_1 = PE + KE$$

$$E_1 = mgh + \frac{1}{2}mv_1^2$$

$v_1 \approx 0$ **(pouring) – In the basin**

Thus $E_1 = mgh$

At bottom

$$E_2 = mgh + \frac{1}{2}mv_2^2 \qquad h \approx 0$$

$$E_2 = \frac{1}{2}mv_2^2$$

Conservation of Energy

$$E_1 = E_2$$

$$mgh = \frac{1}{2} m v_2^2$$

$$v_2 = \sqrt{2gh}$$

***h* can be calculated if v_2 is known**

Desired Area at Base of Sprue

$$A_b = \frac{Q}{V_2}$$

OR

$$A_b = \frac{Q}{\sqrt{2gh}}$$

Desired Sprue Height for a given Flow Rate

$$h = \frac{1}{2g}\left(\frac{Q}{A_b}\right)^2$$

Mold Fill Time (MFT)

$$MFT = \frac{Volume\ \ Poured}{Q}$$

Example – Flow Analysis

10.3 The downsprue leading into the runner of a certain mold has a length = 175 mm. The cross-sectional area at the base of the sprue is 400 mm^2. The mold cavity has a volume = 0.001 m^3. Determine: (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow, and (c) the time required to fill the mold cavity.

Example – Sprue Design

10.5 The flow rate of liquid metal into the downsprue of a mold = 1 liter/sec. The cross-sectional area at the top of the sprue = 800 mm^2 and its length = 175 mm. What area should be used at the base of the sprue to avoid aspiration of the molten metal?

Example – Riser Design

In the casting of steel under certain mold conditions, the mold constant in Chvorinov's Rule is known to be Cm = 4.0 min/cm2, based on previous experience. The casting is a flat plate whose length = 30 cm, width = 10 cm, and thickness = 20 mm. Determine how long it will take for the casting to solidify.

A steel casting has a cylindrical geometry with 4.0 in diameter and weighs 20 lb. This casting takes 6.0 min to completely solidify. Another cylindrical-shaped casting with the same diameter-to-length ratio weighs 12 lb. This casting is made of the same steel and the same conditions of mold and pouring were used. Determine: (a) the mold constant in Chvorinov's Rule; and (b) the dimensions, and (c) the total solidification time of the lighter casting. Note: The density of steel = 490 lb/ft3.

Riser Design - Try

A riser in the shape of a sphere is to be designed for a sand casting mold. The casting is a rectangular plate, with length = 200 mm, width = 100 mm, and thickness = 18 mm. If the total solidification time of the casting itself is known to be 3.5 min, determine the diameter of the riser so that it will take 25% longer for the riser to solidify.

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

Technical Issues in Casting

A. Heating / Pouring / Solidification

Solid : ↓	Heat / Energy Required
Liquid : ↓	Pouring Temperature (Degree of Superheat)
Molding : ↓	Sprue Design
Pouring : ↓	Pouring Rate, Mold Fill Time
Solidification :	Solidification Time, Riser Design

B. Process Selection

(i) Performance Index / Rating

(ii) Cost per Part Analysis

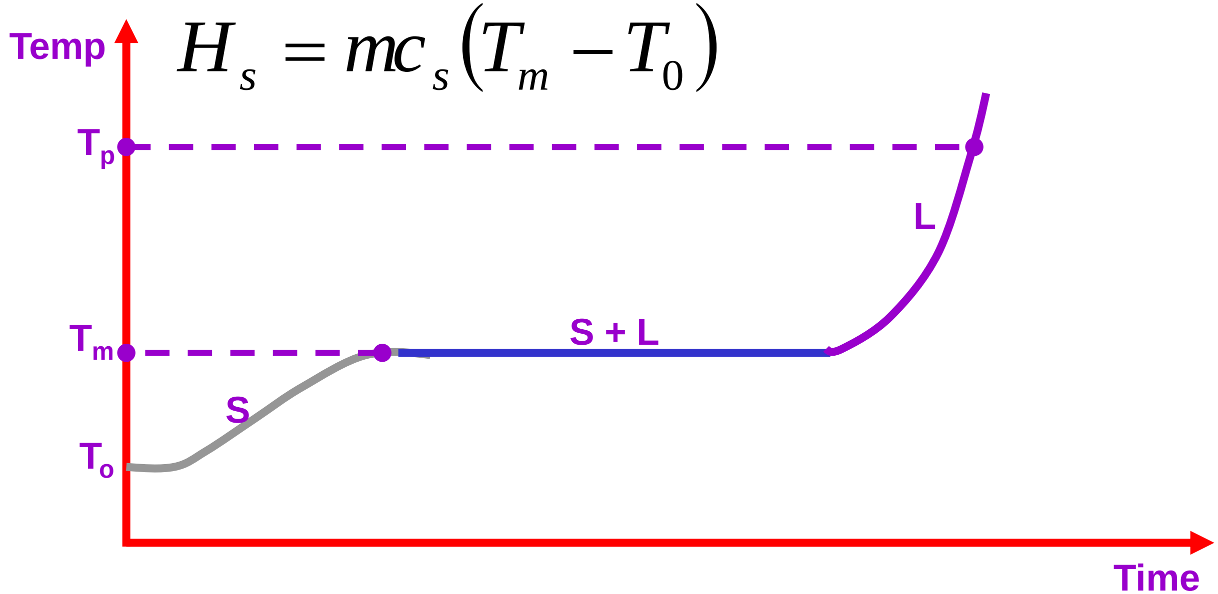
Heat Required

a. **Solid (Room Temperature) ⟶ Solid (Melting Point)**

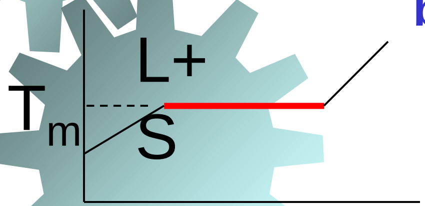
$$Heat,\ H_s = Mass \times Specific\ Heat \times Temperature\ Change$$

$$H_s = mc_s \Delta T$$

$$H_s = mc_s \left(T_m - T_0\right)$$



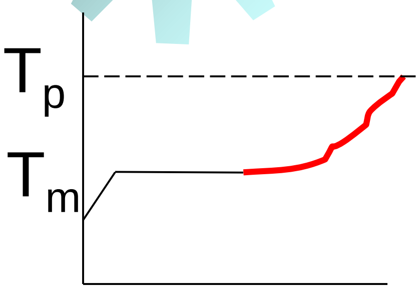
Heat Required Continued



b. Solid (Melting Point) → Liquid (Melting Point)

$$Latent\ Heat, H_f = mh_f$$

h_f → Latent heat of Fusion per unit mass.



c. Liquid (Melting Point) → Liquid (Pouring Temp.)

$$H_l = mc_l \Delta T$$

$$H_l = mc_l \left(T_p - T_m\right)$$

d. Total Heat Required (H)

$$H = H_s + H_f + H_l$$

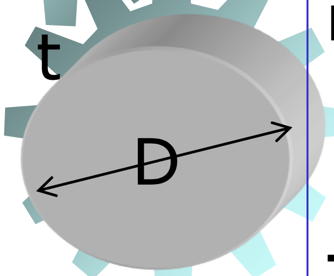
$$note: mass, m = \rho \times V$$

Example 1- Heating

10.1 A disk 40 cm in diameter and 5 cm thick is to be casted of pure aluminum in an open mold operation. The melting temperature of aluminum = 660°C and the pouring temperature will be 800°C. Assume that the amount of aluminum heated will be 5% more than needed to fill the mold cavity. Compute the amount of heat that must be added to the metal to heat it to the pouring temperature, starting from a room temperature of 25°C. The heat of fusion of aluminum = 389.3 J/g. Other properties can be obtained from Tables 4.1 and 4.2 in this text. Assume the specific heat has the same value for solid and molten aluminum.

Note: 1 cal = 4.2 J

Solution



Disc, D = 40 cm   Thickness, t = 5 cm
Pure Aluminum; Latent heat, h_f = 389.3 J/kg
Specific Heat, C_s = 0.21 Cal/g-°C
C_l = 0.21 Cal/g-oC
Density ρ = 2.70 g/cm³
Temperatures: T_o = 25 C T_m = 660 C T_p = 800 C

Volume of Casting, V = $(\pi D^2/4)t = (\pi * 40^2/2)*5 = 6283\ cm^3$

Heated Volume, $V_H = 1.05V = 6597\ cm^3$

Heated Mass, $m = \rho V = 2.70 \times 6597 = 17{,}812\ g$

Heat Required = $Ht(T_o \text{ to } T_m) + Ht(\text{Fusion}) + Ht(T_m \text{ to } T_p)$

$$= mC_s(T_m - T_0) + mh_f + mC_l(T_p - T_m)$$

$$= 9.95\ MJ + 6.93\ MJ + 2.19\ MJ$$

$$= 19.07\ MJ$$

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

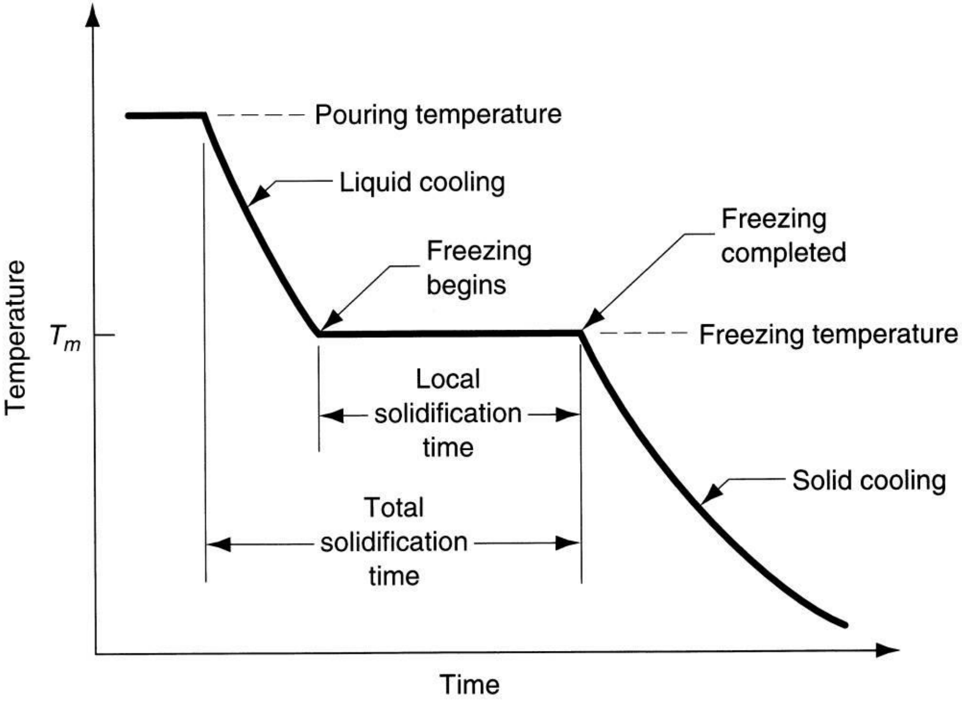
Solidification of Metals

Transformation of molten metal back into solid state

- Solidification differs depending on whether the metal is
  - A pure element or
  - An alloy

Cooling Curve for a Pure Metal

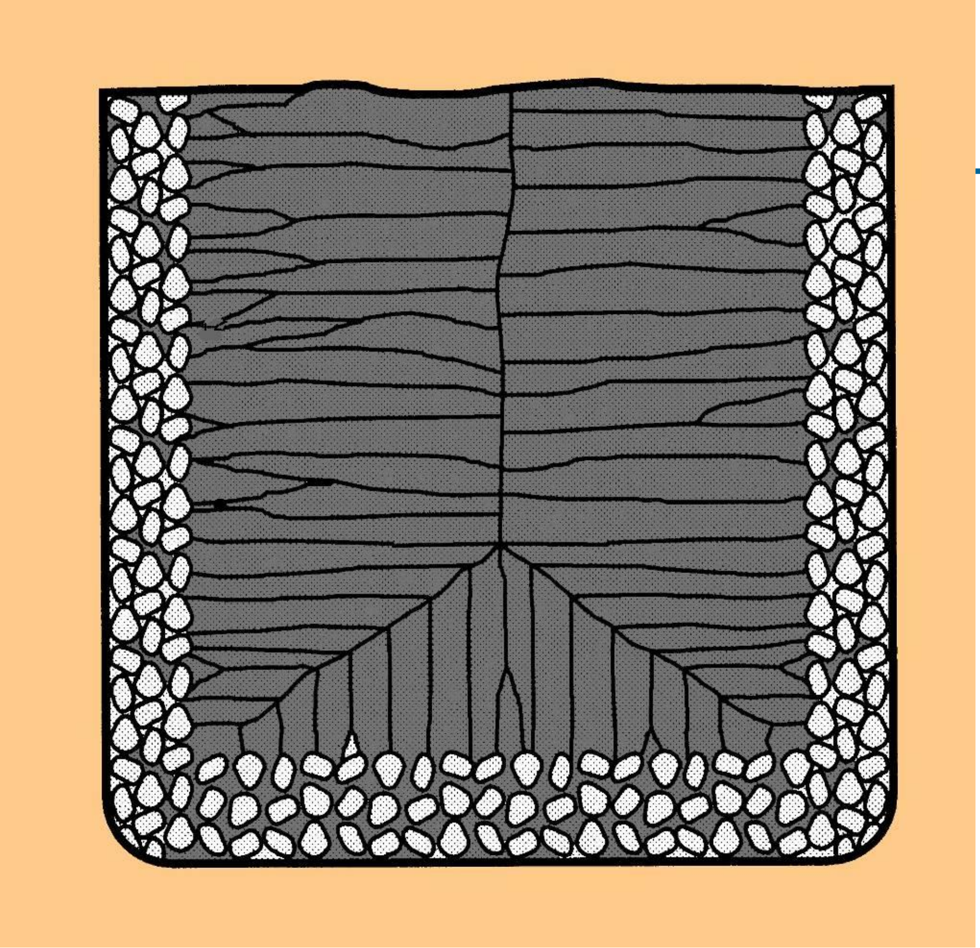
- A pure metal solidifies at a constant temperature equal to its freezing point (same as melting point)



Cooling curve for a pure metal during casting.

Solidification of Pure Metals

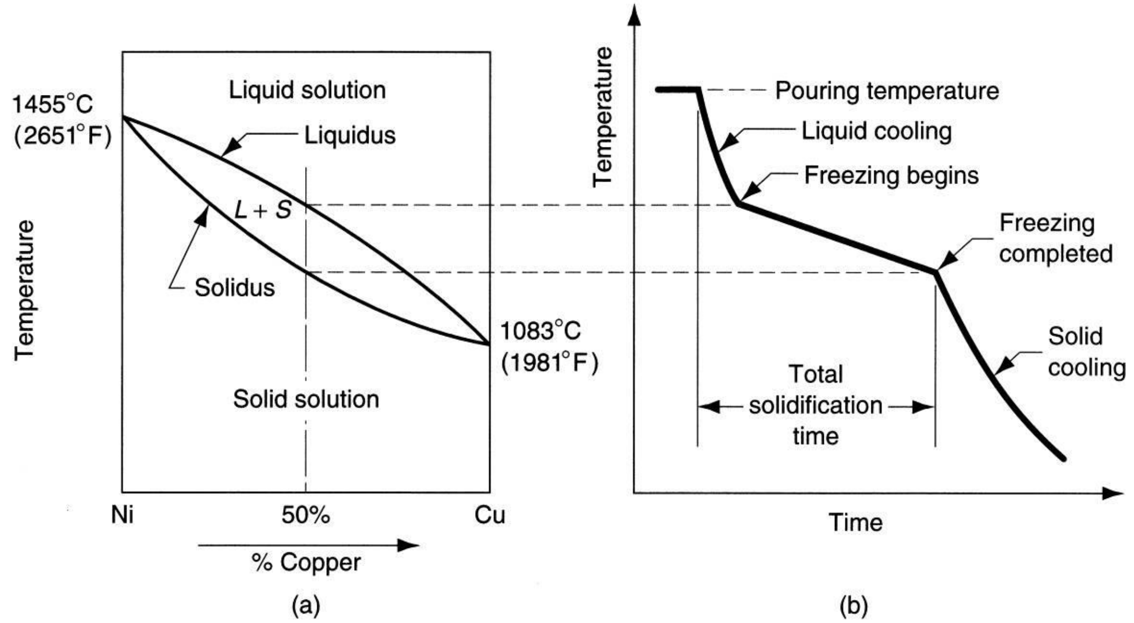
- Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring
- Skin thickness increases to form a shell around the molten metal as solidification progresses
- Rate of freezing depends on heat transfer into mold, as well as thermal properties of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



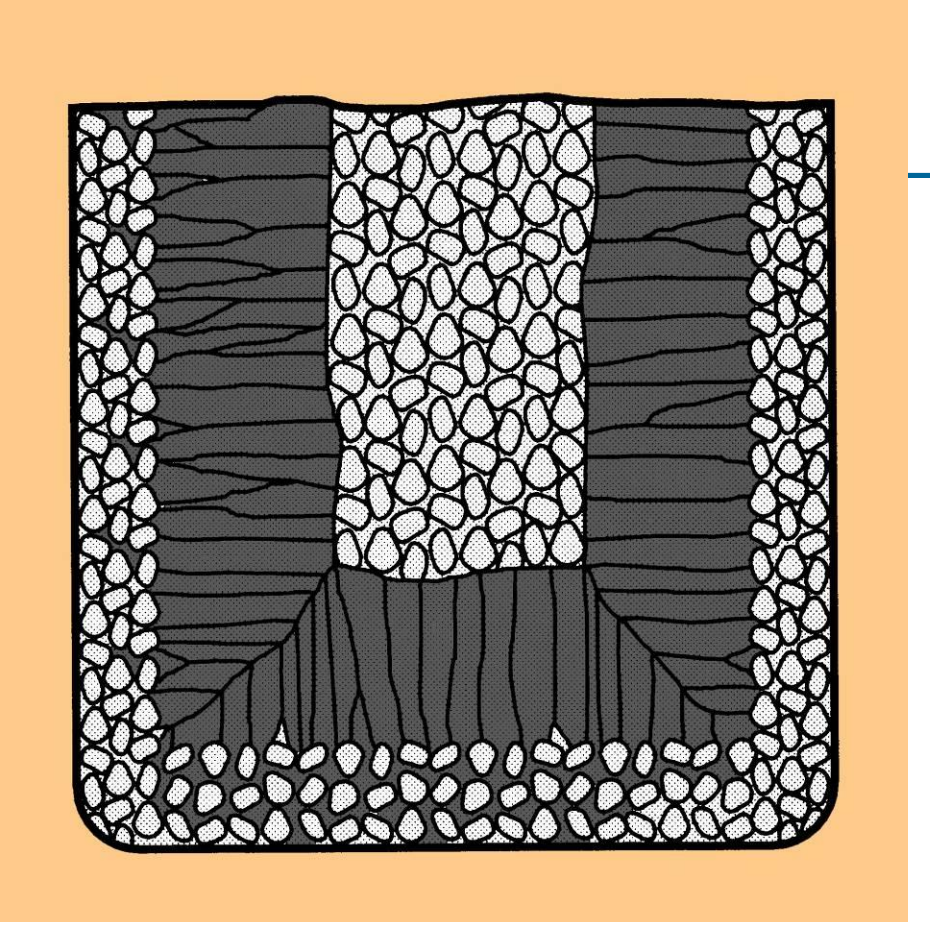
Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting.

Solidification of Alloys

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



(a) 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

- Mold constant C_m depends on:
  - Mold material
  - Thermal properties of casting metal
  - 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 greater than *TST* for main casting
- Since mold constants of riser and casting 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

Total Solidification Time (TST) - Examples

Chvorinov's Rule

Total Solidification Time, *TST*,

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

Where

V = Volume of Casting

A = Surface Area of Casting exposed to Mold and Cores

n = exponent (n =2 for expendable mold castings)

n = 1 for permanent mold castings

V/A = Casting Modulus

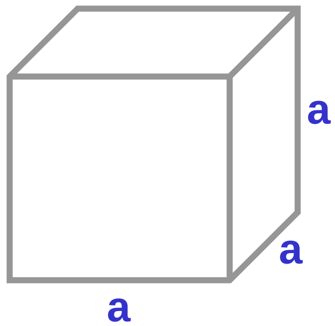
C_m = Mold Constant. This is a function of Mold Material and Cast Material

Mold Material: Specific Heat, Thermal Conductivity, Density

Cast Material: Heat of Fusion, Density, Melting Temperature, Thermal Conductivity

Examples of Casting Modulus (V/A)

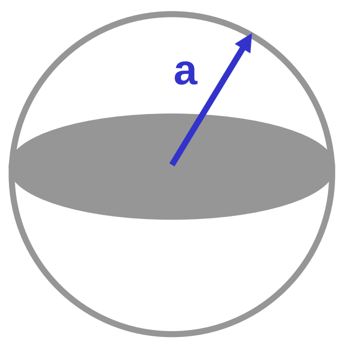
1. Cube



$$V = a^3 \qquad A = 6a^2$$

$$Modulus, \ \frac{V}{A} = \frac{a}{6}$$

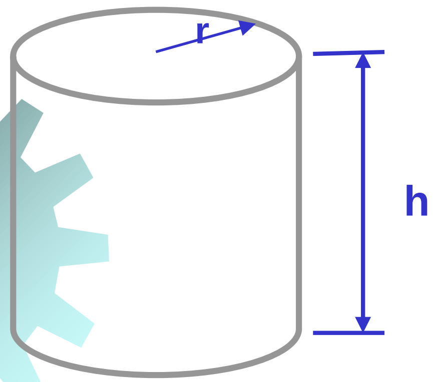
2. Sphere



$$V = \frac{4}{3}\pi a^3 \qquad A = 4\pi a^2$$

$$Modulus, \ \frac{V}{A} = \frac{a}{3}$$

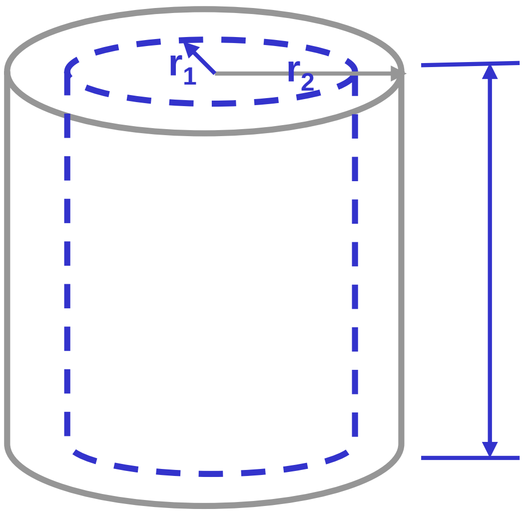
3. Solid Cylinder / Disk



$$V = \pi r^2 h$$

$$A = 2\pi r h + 2\left(\pi r^2\right)$$

4. Hollow Cylinder / Disk



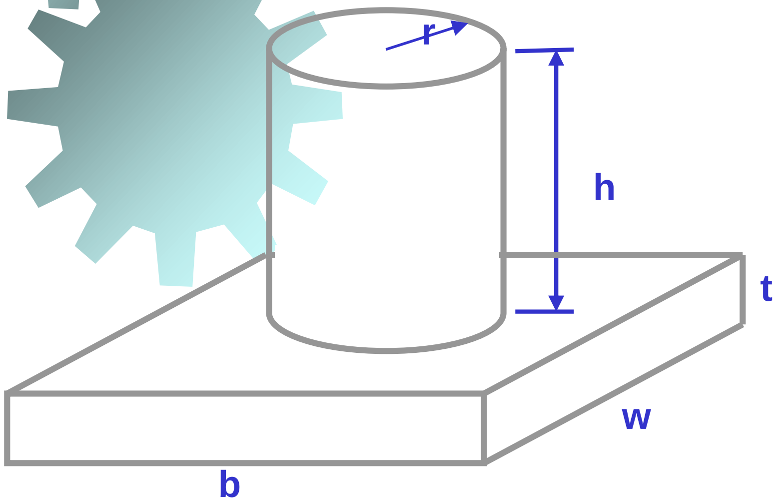
$$V = \left(\pi r_2^2 - \pi r_1^2\right) h$$

A = Exposed Area

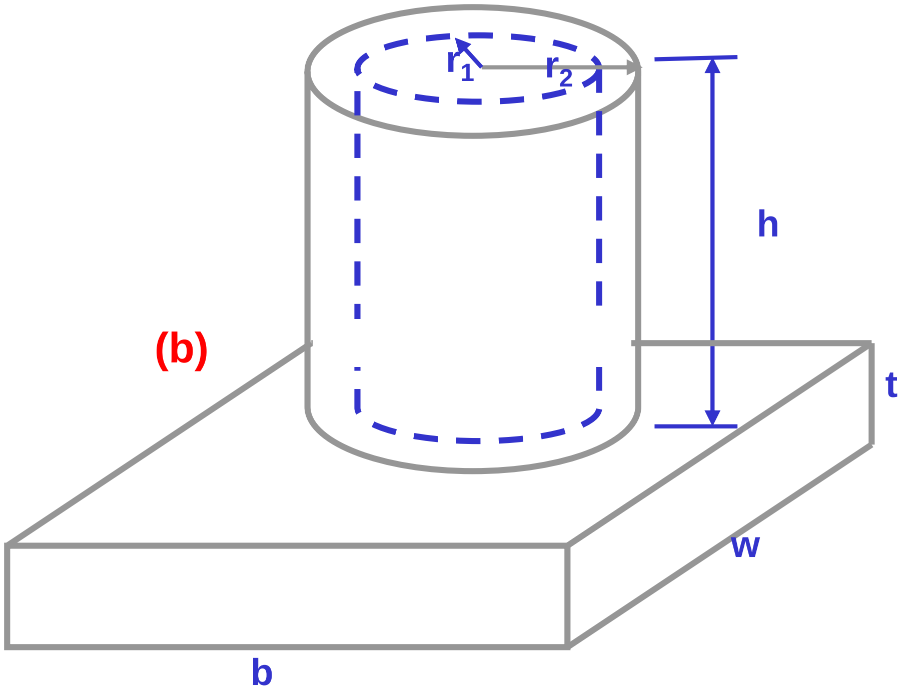
$$A = 2\pi r_2 h + 2\pi r_1 h + 2\pi\left(r_2^2 - r_1^2\right)$$

5. Modulus of Composite Shapes

(a)



(b)



Riser Design

Concept: Riser should be last section to solidify

Steps

1. Calculate TST for the Casting
2. Decide on TST for Riser such that $(TST)_{riser} > (TST)_{casting}$
3. Determine Riser Modulus

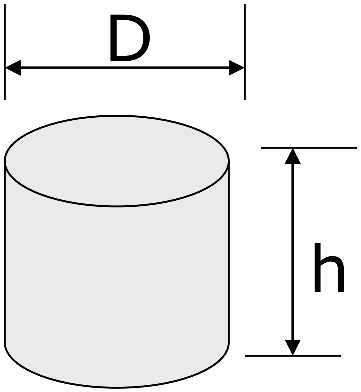
$$(TST)_{riser} = C_m \left(\frac{V}{A}\right)^2_{riser}$$

Solve $$\left(\frac{V}{A}\right)_{riser} = \left(\frac{TST}{C_m}\right)^{\frac{1}{2}}$$

Cylindrical Riser

Modulus of Solid Cylinder:

$$\left(\frac{\left[\pi D^2/4\right]h}{\pi D h + \pi D^2/4}\right)_{riser} = \left(\frac{TST}{C_m}\right)^{\frac{1}{2}}$$



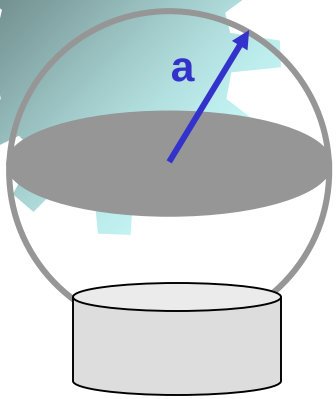
Determine D/h ratio.

- **Put D in terms of h, solve for h**

  OR

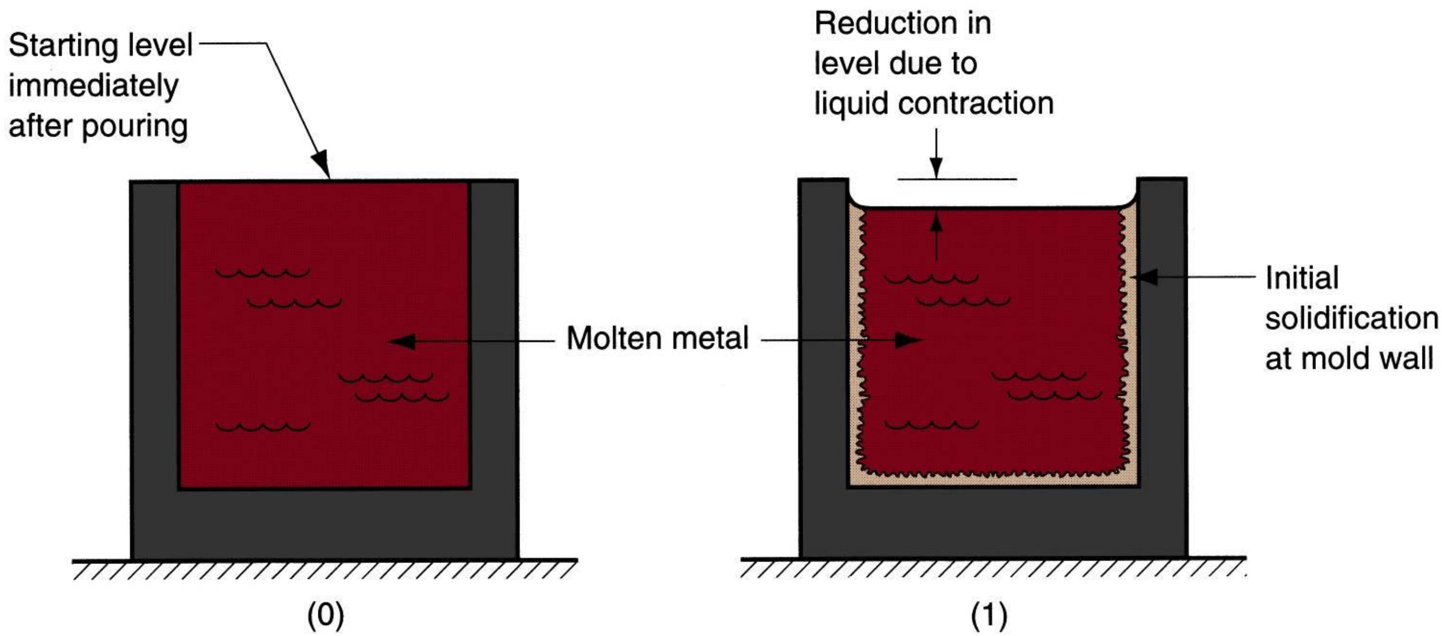
- **Using D/h ratio and knowing h, solve for D**

Spherical Riser



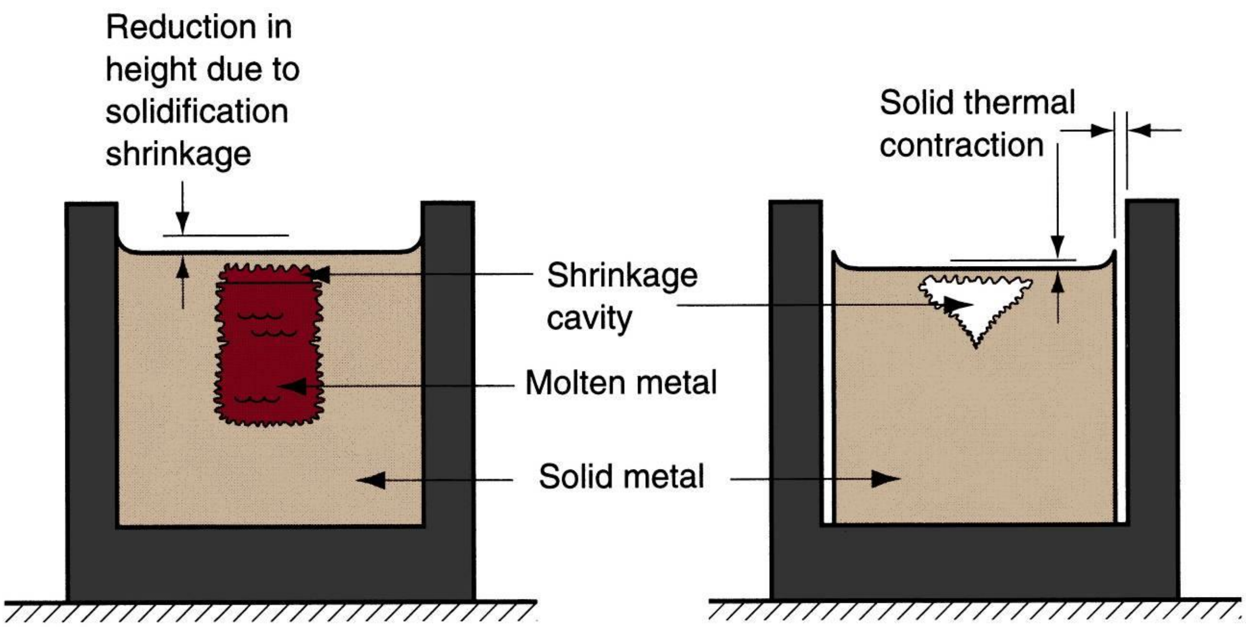
$$\frac{a}{3} = \left(\frac{TST}{C_m} \right)^{\frac{1}{2}}$$

Shrinkage in Solidification and Cooling



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).

Shrinkage in Solidification and Cooling



(2) (3)

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 solid metal (dimensional reductions are exaggerated for clarity).

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

Pattern Allowances

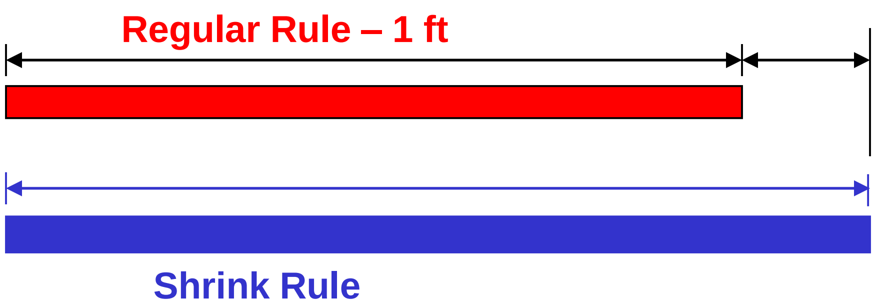
Pattern: A replica of the part to be cast and is used to prepare the mold.

It is made either of wood or metal. Metals: Al, Mg, commonly used.

It is made somewhat larger than the final part for various reasons.

This excess in dimensions is referred to as **"pattern allowance".**

Shrink Rule: A special ruler with the expansion added to the dimensions



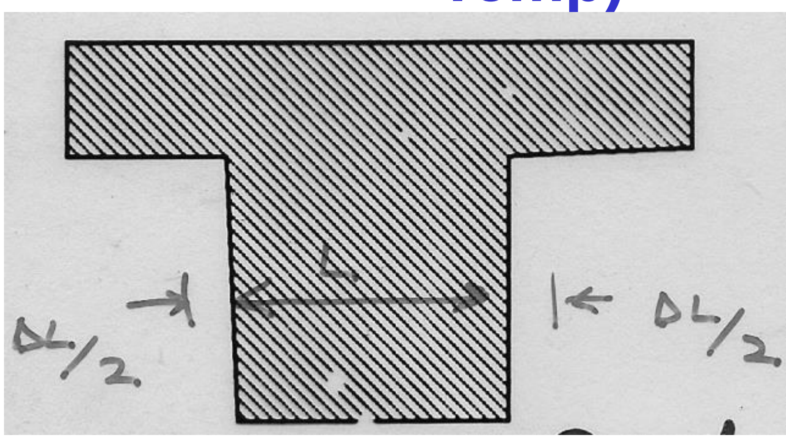
$$\Delta L = \alpha L \Delta T$$

Major Pattern Allowances

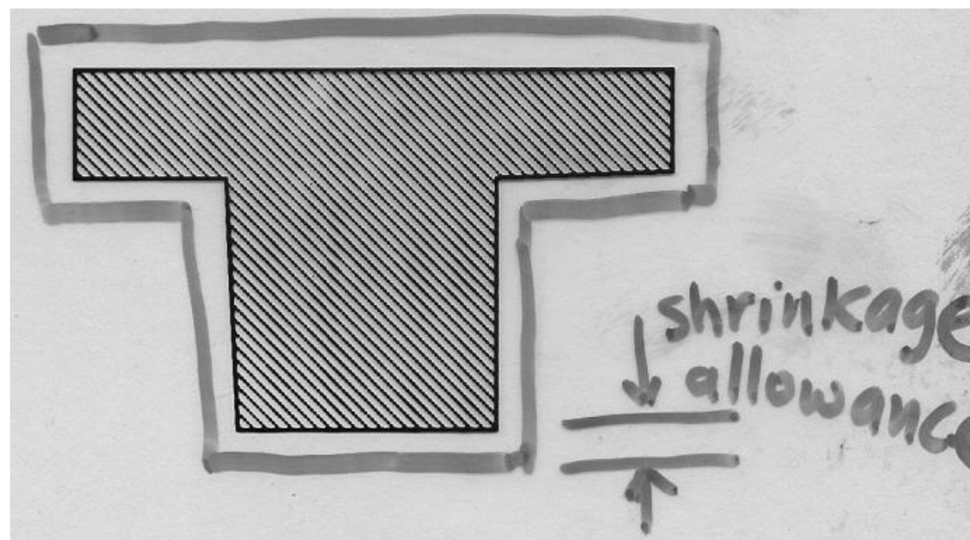
1. Shrinkage Allowance:

A linear allowance added to the dimensions to compensate for contractions of the casting.

Liquid → Solid (Freezing Temp) → Solid (Room Temp)



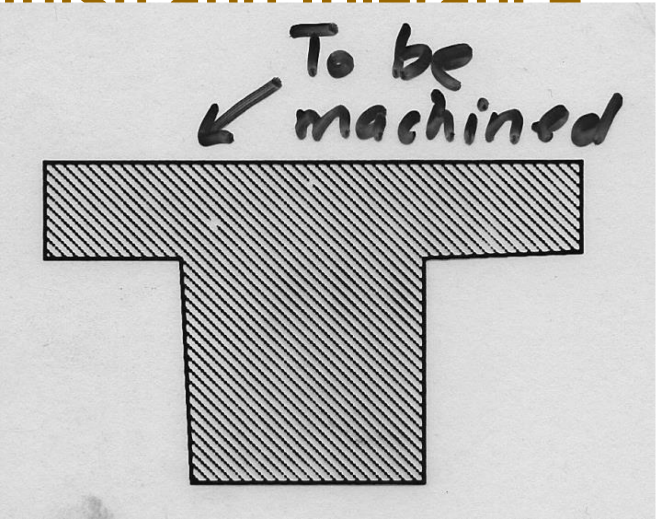
Desired Part

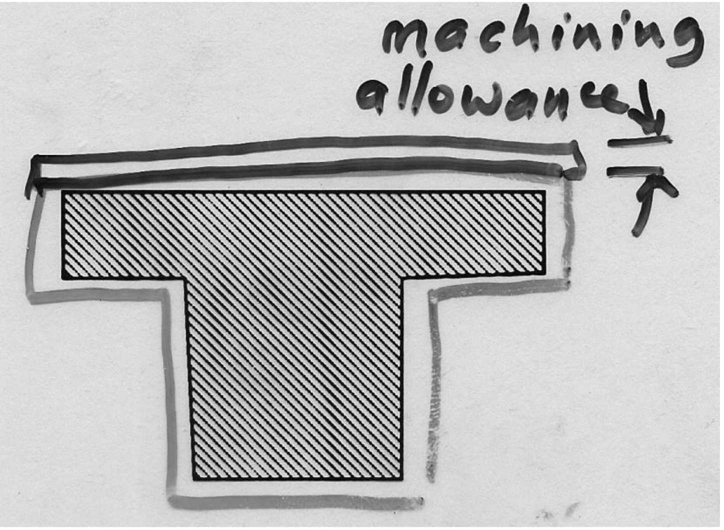


Major Pattern Allowances

2. Machining Allowance:

An allowance added to the dimensions so that we may later machine it off to produce better surface finish and tolerance.





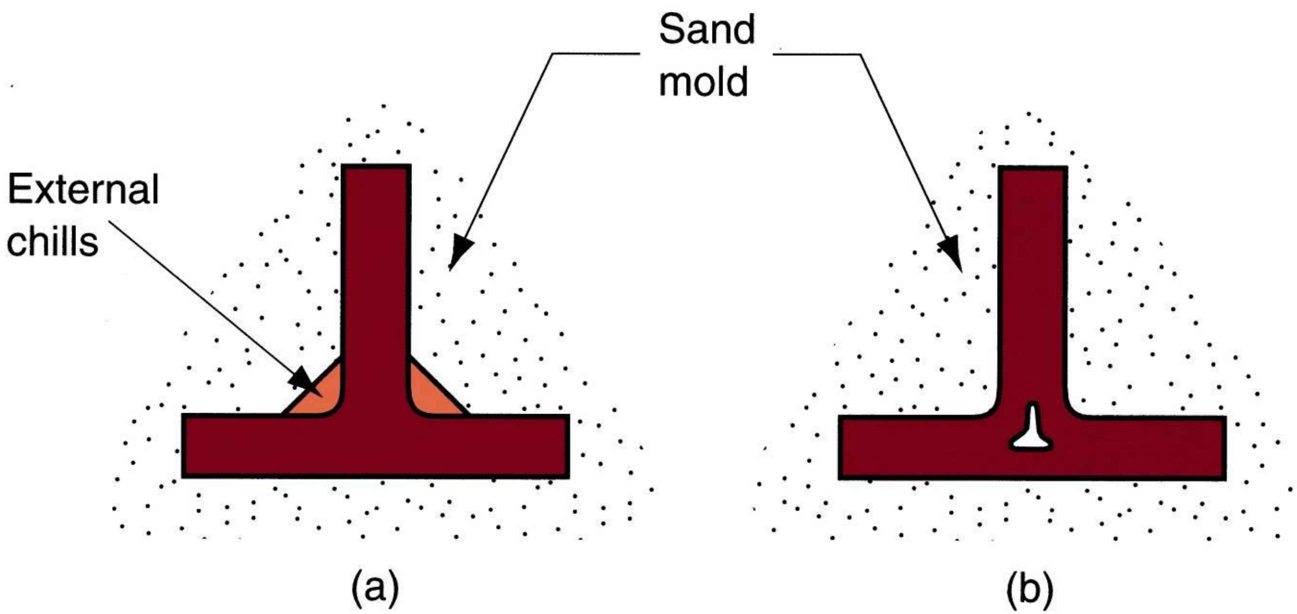
Directional Solidification

- 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

External Chills



(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 riser volume to be reduced to the minimum possible value