

CHAPTER 10

Fundamentals of Metal Casting

HoweWork Assignment

Due Monday 3/5/2010

1. A round casting 0.2 m in diameter and 1.0 m in length. Another casting of the same metal is elliptical in cross section, with a major to minor axis ratio of 2, and has the same length and cross sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?
2. The volume flow rate of metal into a mold is $0.02 \text{ m}^3/\text{s}$. The top of the sprue has a diameter of 20 mm, and its length is 200 mm. What diameter should be specified at the bottom of the sprue to prevent aspiration? What is the resultant velocity and Reynolds number at the bottom of the sprue if the metal being cast is aluminum with a viscosity of 0.004 Ns/m^2 ?
3. Pure aluminum is poured into a sand mold. The metal level in the pouring basin is 10-in above the metal level in the mold, and the runner is circular with a 0.4-in diameter. What are the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar?

Case Study 5

Due Monday 3/5/2010

- The fluidity test shown in Figure 10-9 illustrates only the principle of this test. Design a setup for such a test, showing the type of materials and the equipment to be used. Explain the method by which you would determine the length of the solidified metal in the spiral passage.

INTRODUCTION

The casting process (CP) basically involves:

- a) pouring molten metal into a mold patterned after the part to be mfg
- b) allowing it to cool
- c) removing the metal from the mold

Important considerations in casting operations:

1. flow of the molten into the mold cavity
2. solidification and cooling of the metal in the mold
3. the influence of the type of mold material

SOLIDIFICATION OF METALS

Pure Metals

- A pure metal solidifies at a constant temperature.
- After the temp. of the molten metal drops to its freezing point, its temp. remains constant while the latent heat of fusion is given off.
- The solidification front moves through the molten metal, solidifying from the mold walls in toward the center.

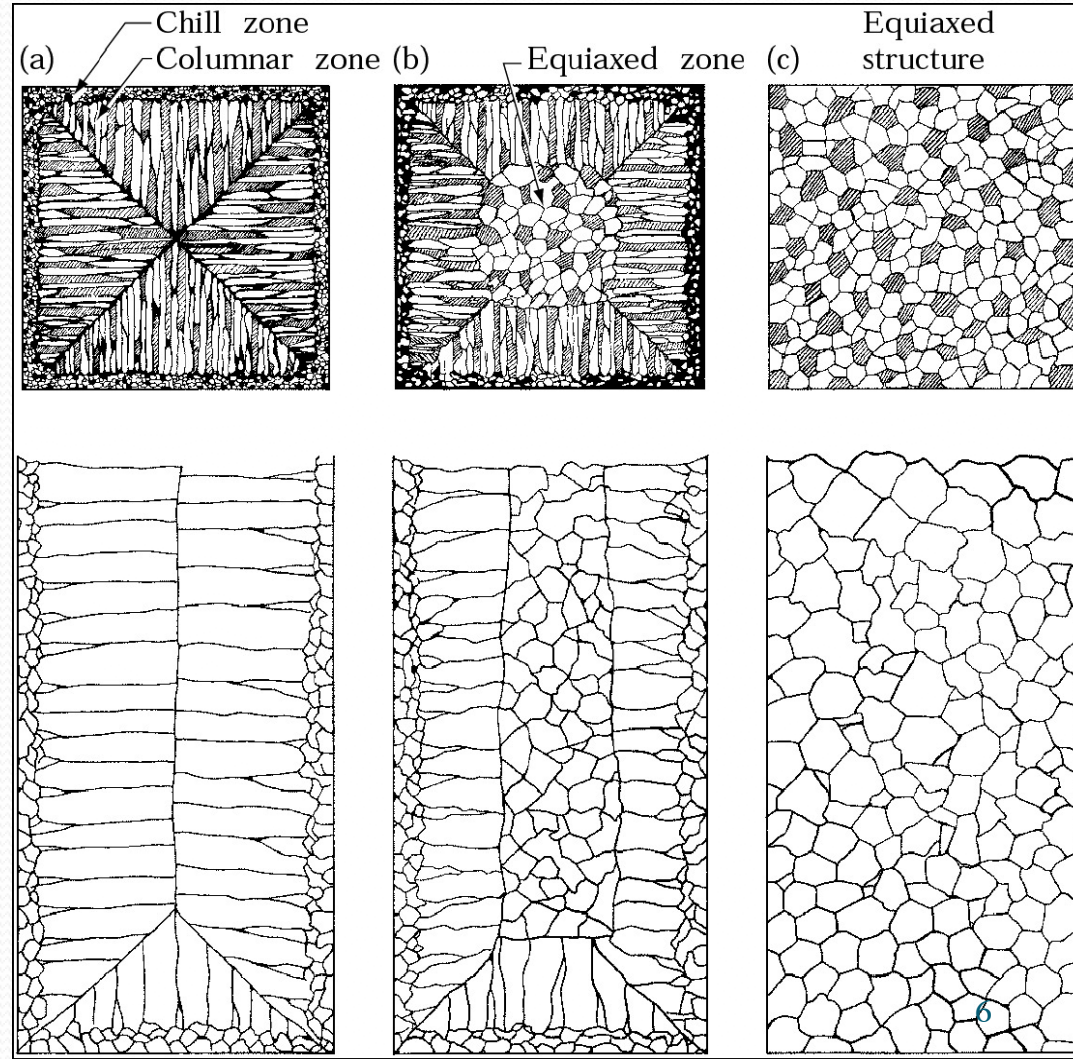
SOLIDIFICATION OF METALS

Pure Metals - Grain Structure

Figure 10.1: Schematic illustration of 3 cast structures of metals solidified in a square mold:

- a) Pure metals
- b) solid-solution alloys
- c) structure obtained by using nucleating agents.

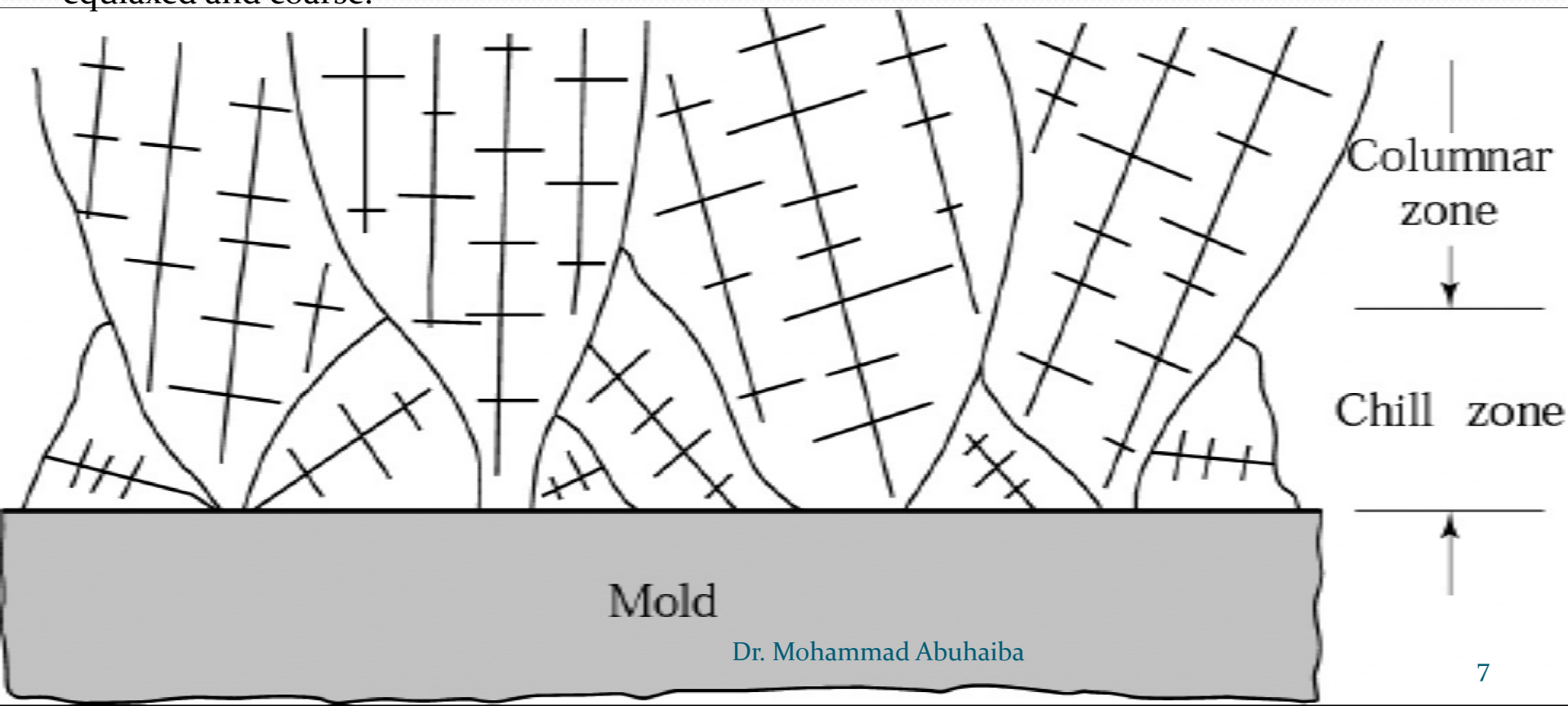
At the mold walls, the metal cools rapidly. Rapid cooling produces a solidified skin, or shell, of fine equiaxed grains.



SOLIDIFICATION OF METALS

Pure Metals - Grain Structure

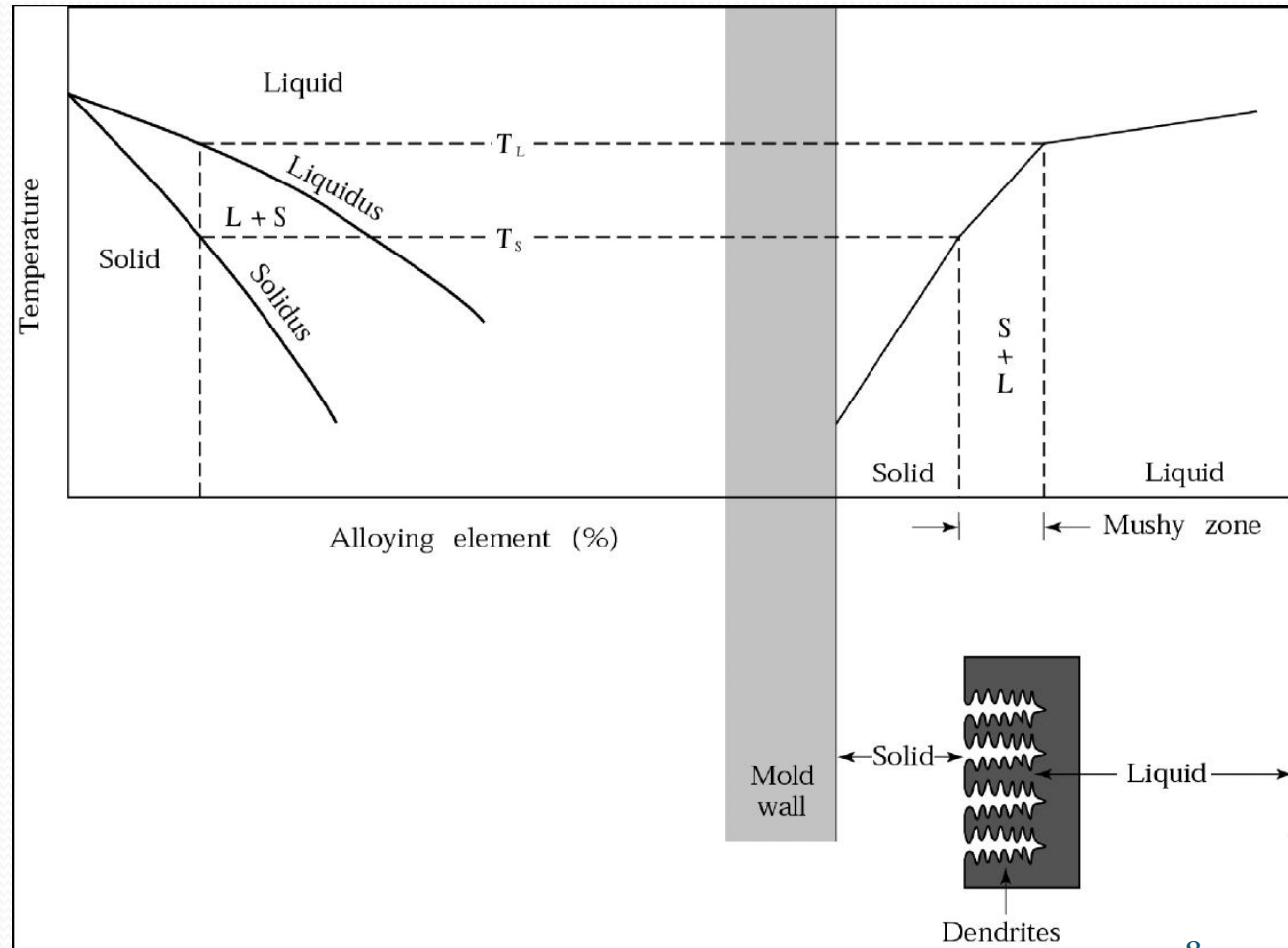
- Grains grow in a direction opposite to that of the heat transfer out through the mold, producing columnar grains (Fig. 10.2).
- As the driving force of the heat transfer is reduced away from the mold walls, the grains become equiaxed and coarse.



SOLIDIFICATION OF METALS

Solidification of Alloys

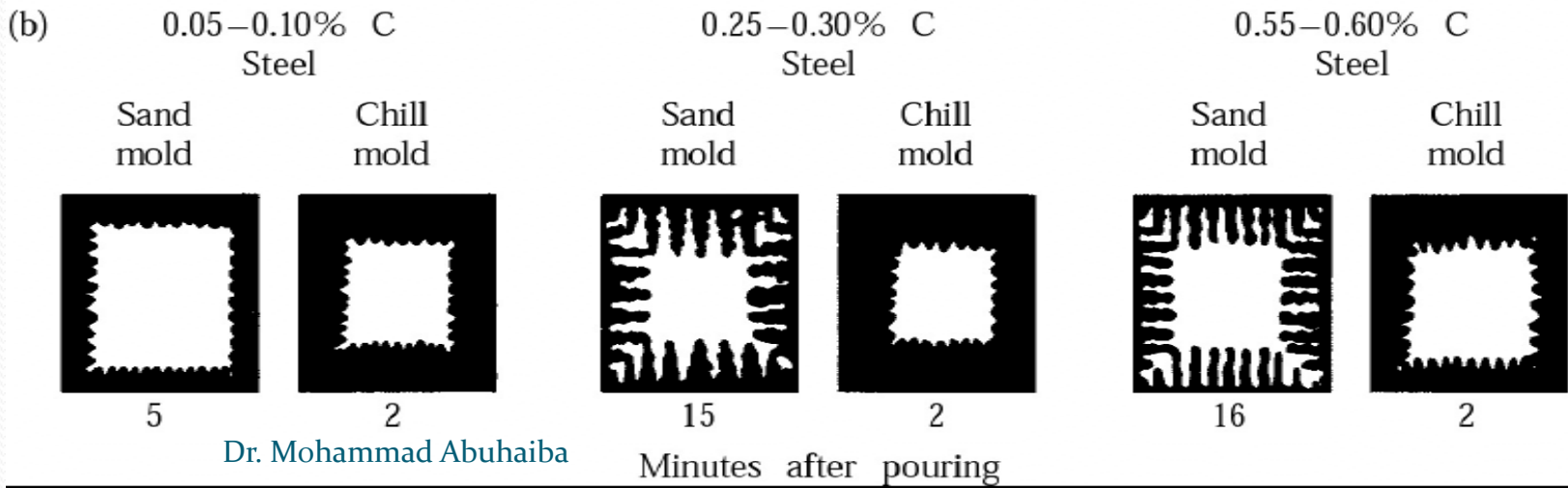
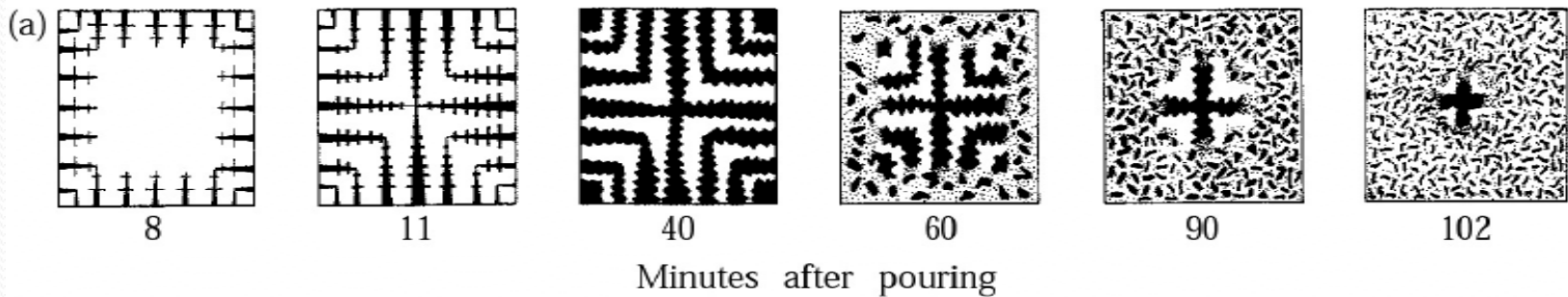
Solidification begins when temperature drops below liquidus, T_L , and is complete when it reaches the solidus, T_S (Fig.10.3)



SOLIDIFICATION OF METALS

Solidification Patterns

- a) Solidification patterns for gray cast iron in a 180-mm square casting.
- b) Solidification of carbon steels in sand and chill (metal) molds. Note the difference in solidification patterns as carbon content increases.



SOLIDIFICATION OF METALS

Solidification Concepts

- Freezing range = $T_L - T_S$
- Pure metals have no freezing range, and that the solidification front moves as a plane front without forming a mushy zone
- The type of solidification structure developed depends on the composition of the eutectic.
- In alloys with a nearly symmetrical phase diagram, the structure is generally lamellar, with two or more solid phases present, depending on the alloy system.
- When the volume fraction of the minor phase of the alloy is less than about 25% , the structure generally becomes fibrous.

SOLIDIFICATION OF METALS

Effects of Cooling Rates

- Slow cooling rates result in coarse dendritic structures with large spacing between the dendrite arms.
- For faster cooling rates, the structure becomes finer with smaller dendrite arm spacing
- For still higher cooling rates the structures developed are amorphous.
- As grain size decreases, strength and ductility of the cast alloy increase, microporosity (interdendritic shrinkage voids) in the casting decreases, and the tendency for the casting to crack during solidification decreases.
- A criterion for describing the kinetics of the liquid-solid interface is the ratio G/R , Where G is the thermal gradient and R is the rate at which the liquid-solid interface moves.
- Dendritic type structures (Figs. 10.5a and b) typically have an R ratio in the range of 10^5 to 10^7 , where-as ratios of 10^{10} to 10^{12} produce a plane-front, nondendritic liquid-solid interface (Fig. 10.6).

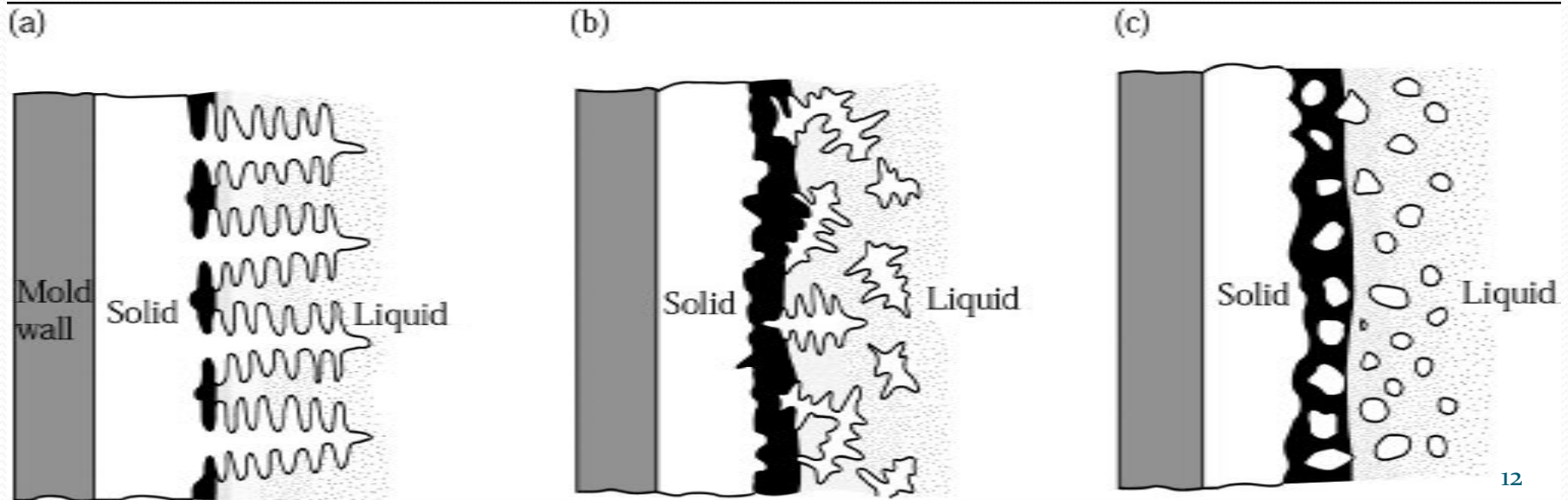
SOLIDIFICATION OF METALS

Effects of Cooling Rates

Figure 10.5: Schematic illustration of three basic types of cast structures:

- a) columnar dendritic
- b) Equiaxed dendritic
- c) Equiaxed nondendritic

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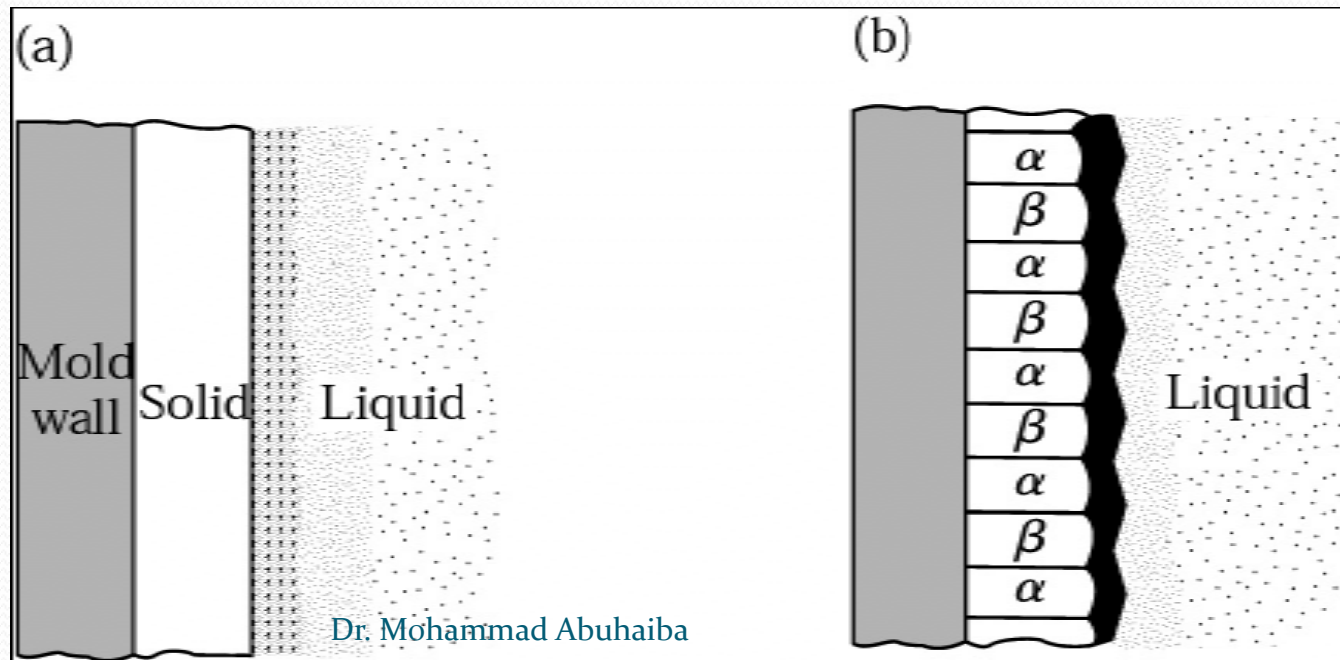


SOLIDIFICATION OF METALS

Effects of Cooling Rates

Figure 10.6: Schematic illustration of cast structures in:

- a) plane front, single phase
- b) plane front, two phase



SOLIDIFICATION OF METALS

Structure-Property Relationships

- The compositions of dendrites and the liquid metal are given by the phase diagram of the particular alloy.
- When the alloy is cooled very slowly, each dendrite develops a uniform composition.
- Under normal (faster) cooling rates, cored dendrites are formed.
- Cored dendrites have a surface composition different from that at their centers
- This difference is referred to as a concentration gradient.

SOLIDIFICATION OF METALS

Structure-Property Relationships

INVERSE MICROSEGREGATION

- The surface has a higher concentration of alloying elements than does the core of the dendrite, owing to solute rejection from the core toward the surface during solidification of the dendrite (microsegregation).
- In dendritic structures: the center of the casting has a lower concentration of alloying elements (inverse segregation).
- The darker shading in the interdendritic liquid near the dendrite roots in Fig. 10.5 indicates that these regions have a higher solute concentration; microsegregation in these regions is much more pronounced than in others.

SOLIDIFICATION OF METALS

Structure-Property Relationships

NORMAL MICROSEGREGATION

- In situations where the solidifying front moves away from the surface of a casting as a plane front (Fig. 10.6), lower-melting point constituents in the solidifying alloy are driven toward the center.
- Consequently, such a casting has a higher concentration of alloying elements at its center than at its surfaces.
- The reason is that liquid metal (having a higher concentration of alloying elements) enters the cavities developed from solidification shrinkage in the dendrite arms, which have solidified sooner.

SOLIDIFICATION OF METALS

Structure-Property Relationships

GRAVITY SEGREGATION

- Describes the process whereby higher-density inclusions or compounds sink, and lighter elements float to the surface.
- Macrosegregation involves differences in composition throughout the casting itself.

SOLIDIFICATION OF METALS

Structure-Property Relationships

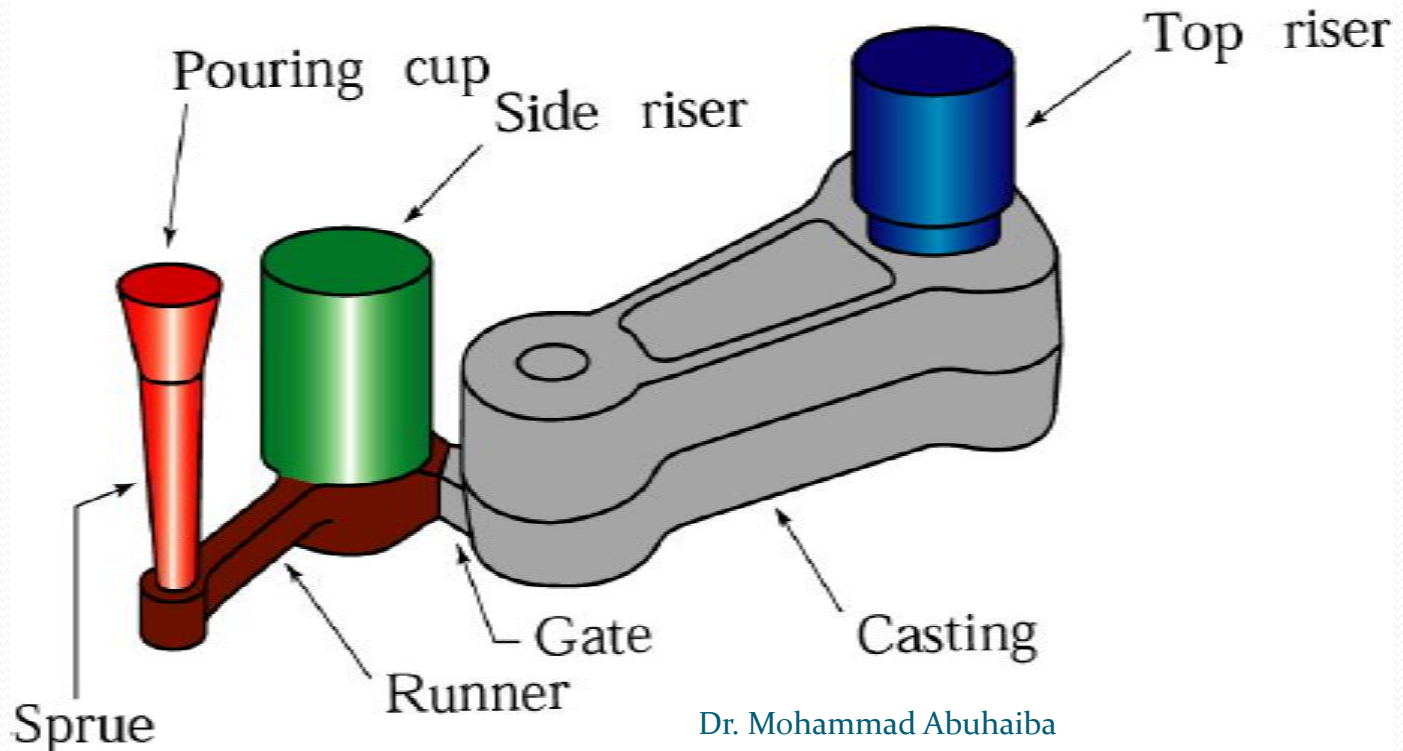
EFFECTS OF CONVECTION

- Convection has a strong influence on the structures developed because of:
 - the presence of thermal gradients in a solidifying mass of liquid metal
 - gravity and the resultant density differences
- Convection promotes the formation of an outer chill zone; refines grain size, and accelerates the transition from columnar to equiaxed grains.
- The structure shown in Fig. 10.5b can also be obtained by increasing convection within the liquid metal, whereby dendrite arms separate (dendrite multiplication).
- Conversely, reducing or elimination convection results in coarser and longer columnar dendritic grains.

FLUID FLOW

Riser-Gated Casting

- Fig. 10.7: Molten metal is poured through a pouring basin or cup. It then flows through the gating system (sprue, runners and gates) into the mold cavity.



FLUID FLOW

Riser-Gated Casting

- Runners are the channels that carry the molten metal from the sprue to the mold cavity, or connect the sprue to the gate.
- The gate is that portion of the runner through which the molten metal enters the mold cavity.
- Risers serve as reservoirs to supply the molten metal necessary to prevent shrinkage during solidification.
- One of the most important function of the gating system in sand casting is to trap contaminants in the molten metal by having the contaminants adhere to the walls of the gating system.
- a properly designed gating system avoids or minimizes problems such as premature cooling, turbulence, and gas entrapment.

FLUID FLOW

Bernoulli's Theorem and Mass Continuity

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f \quad (10.3)$$

$$Q = A_1 v_1 = A_2 v_2 \quad (10.4)$$

- The permeability of the walls of the system is important because otherwise some liquid will permeate through the walls and the flow rate will decrease as the liquid moves through the system.

FLUID FLOW

Sprue Design

- We can determine the shape of the sprue by using Eqs. (10.3) & (10.4). Assuming that the pressure at the top of the sprue is equal to the pressure at the bottom and that there are no frictional losses.

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}} \quad (10.5)$$

- If we design a sprue with a constant x-sectional area and pour the molten metal into it, regions may develop where the liquid loses contact with the sprue walls.
- As a result aspiration, a process whereby air is sucked in or entrapped in the liquid, may take place.
- On the other hand, tapered sprues are now replaced in many systems by straight-sided sprues with a choke to allow the metal to flow smoothly.

FLUID FLOW

Flow Characteristics

$$\text{Re} = \frac{vD\rho}{\eta} \quad (10.6)$$

- laminar flow: $0 \leq \text{Re} \leq 2000$
- Transition flow: $2000 \leq \text{Re} \leq 20000$
- Turbulent flow: $20000 \leq \text{Re}$, resulting in air entrainment and the formation of dross (the scum that forms on the surface of molten metal) from the reaction of the liquid metal with air and other gases.
- Dross or slag can be almost completely eliminated only by vacuum casting.

FLUIDITY OF MOLTEN METAL

- Fluidity: The capability of the molten metal to fill mold cavities.
- It consists of two basic factor:
 - characteristics of the molten metal
 - casting parameters

FLUIDITY OF MOLTEN METAL

Characteristics of Molten Metal

- a) Viscosity: As viscosity and its sensitivity to temperature (viscosity index) increase, fluidity decreases.
- b) Surface tension. A high surface tension of the liquid metal reduces fluidity.
- c) Inclusions.
- d) Solidification pattern of the alloy: The manner in which solidification takes place.
 - Fluidity is inversely proportional to the freezing range. The shorter the range, the higher the fluidity. Conversely, alloys with long freezing ranges have lower fluidity.

FLUIDITY OF MOLTEN METAL

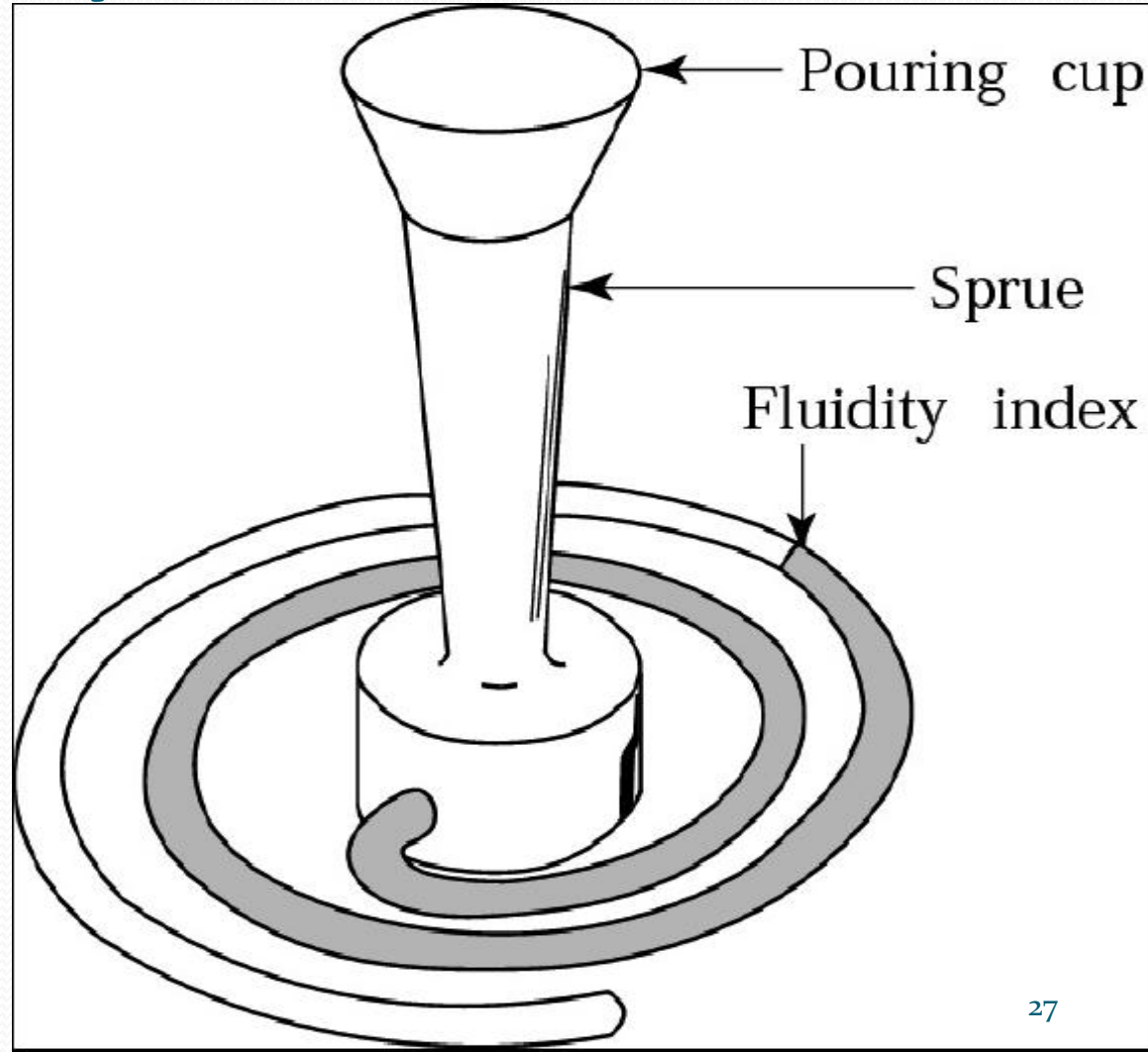
Casting Parameters

- a) Mold design.
- b) Mold material and its surface characteristics. The higher the thermal conductivity of the mold and the rougher the surfaces, the lower the fluidity of the molten metal.
- c) Degree of superheat: Defined as the increment of temperature above the melting point of an alloy, superheat improves fluidity by delaying solidification.
- d) Rate of pouring. The slower the rate of pouring molten metal into the mold, the lower the fluidity because of the higher rate of cooling.
- e) Heat transfer.

FLUIDITY OF MOLTEN METAL

Castability - Fluidity Test

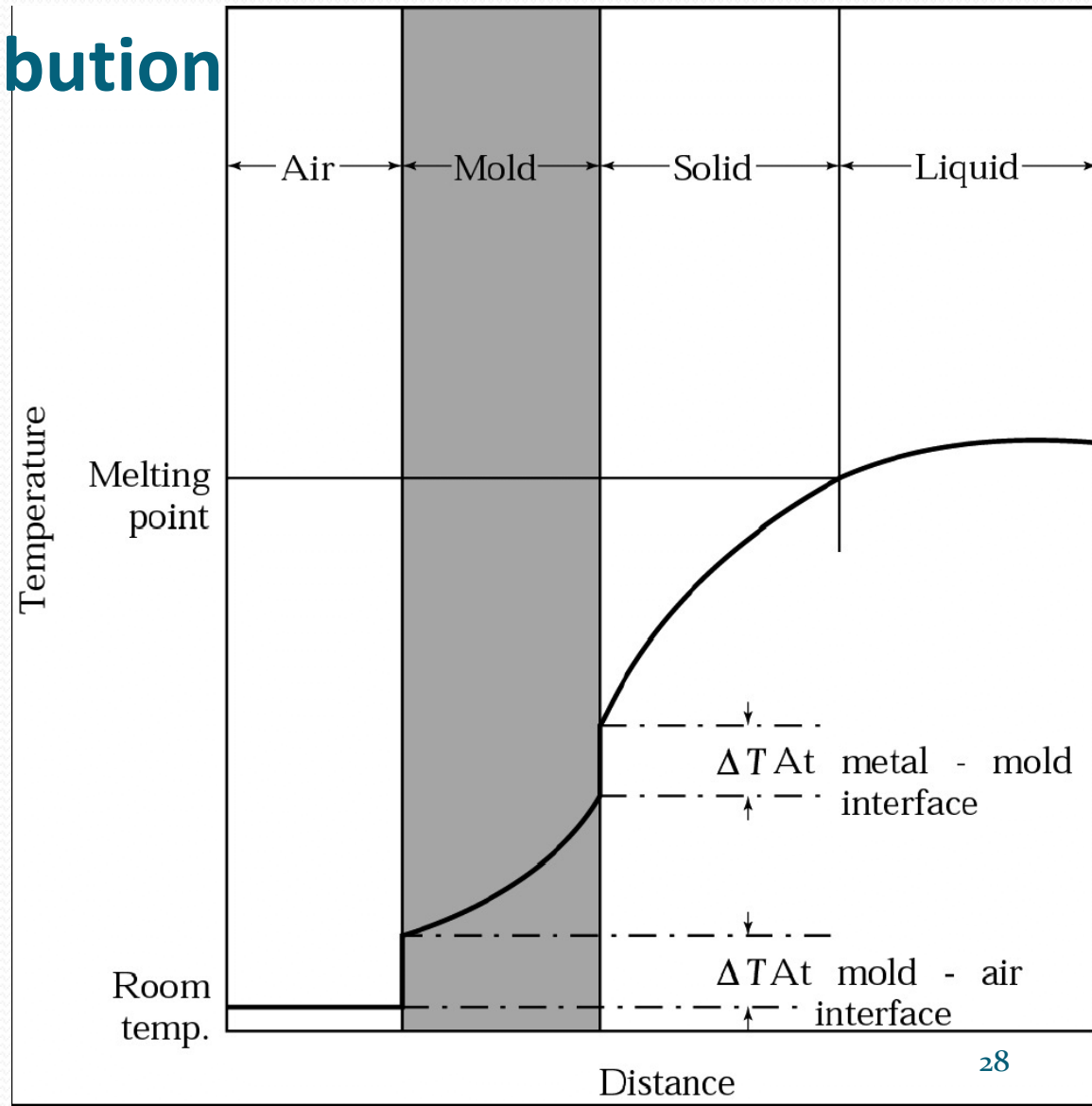
Castability is the ease with which a metal can be cast to obtain a part with good quality. This term includes not only fluidity but casting practices as well.



HEAT TRANSFER

Temperature Distribution

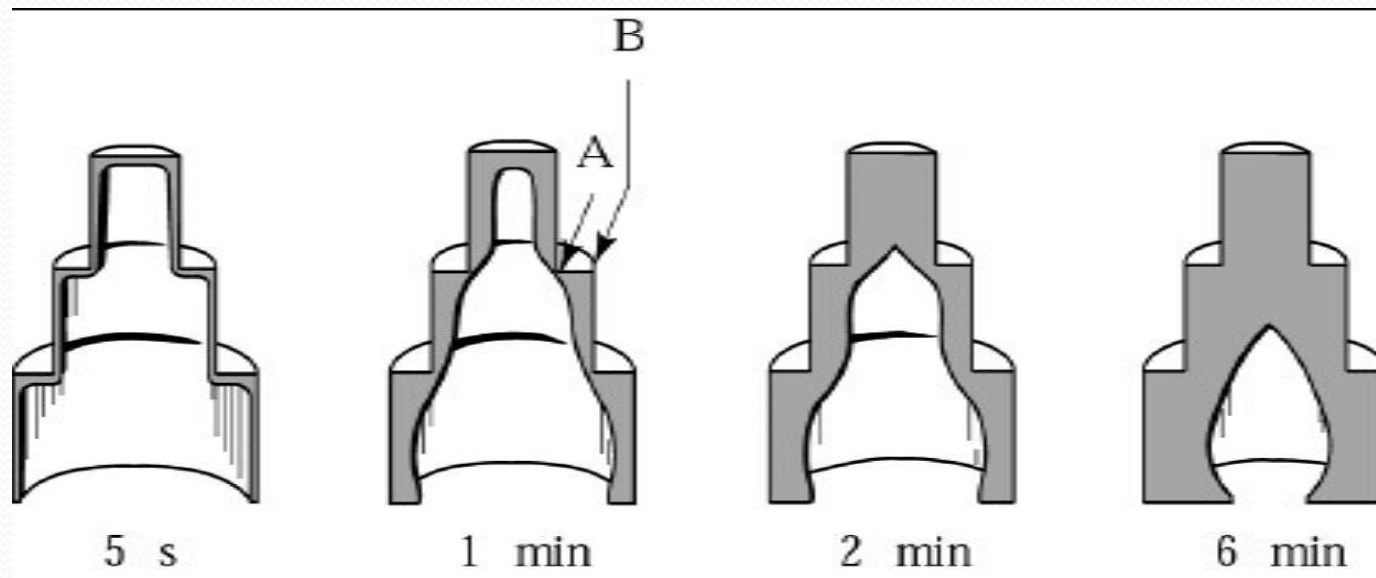
Figure 10.9:
Temperature distribution at the interface of the mold wall and the liquid metal during solidification of metals in casting.



HEAT TRANSFER

Solidification Time

- During the early stages of solidification, a thin, solidified skin begins to form at the cool mold walls and, as time passes, the skin thickens (Fig. 10.10). With flat mold walls, this thickness is proportional to the square root of time.



HEAT TRANSFER

Solidification Time (ST)

- ST is a function of the volume of a casting and its surface area (Chvorinov's rule):

$$ST = C \left(\frac{\text{volume}}{\text{surface area}} \right)^2 \quad (10.7)$$

- C is a constant that reflects mold material, metal properties (including latent heat), and temperature.
- The effects of mold geometry and elapsed time on skin thickness and shape are shown in Fig. 10.10.
- Skin thickness increases with elapsed time, but that the skin is thinner at internal angles (location A) than at external angles (location B).
- This condition is caused by slower cooling at internal angles than at external angles.

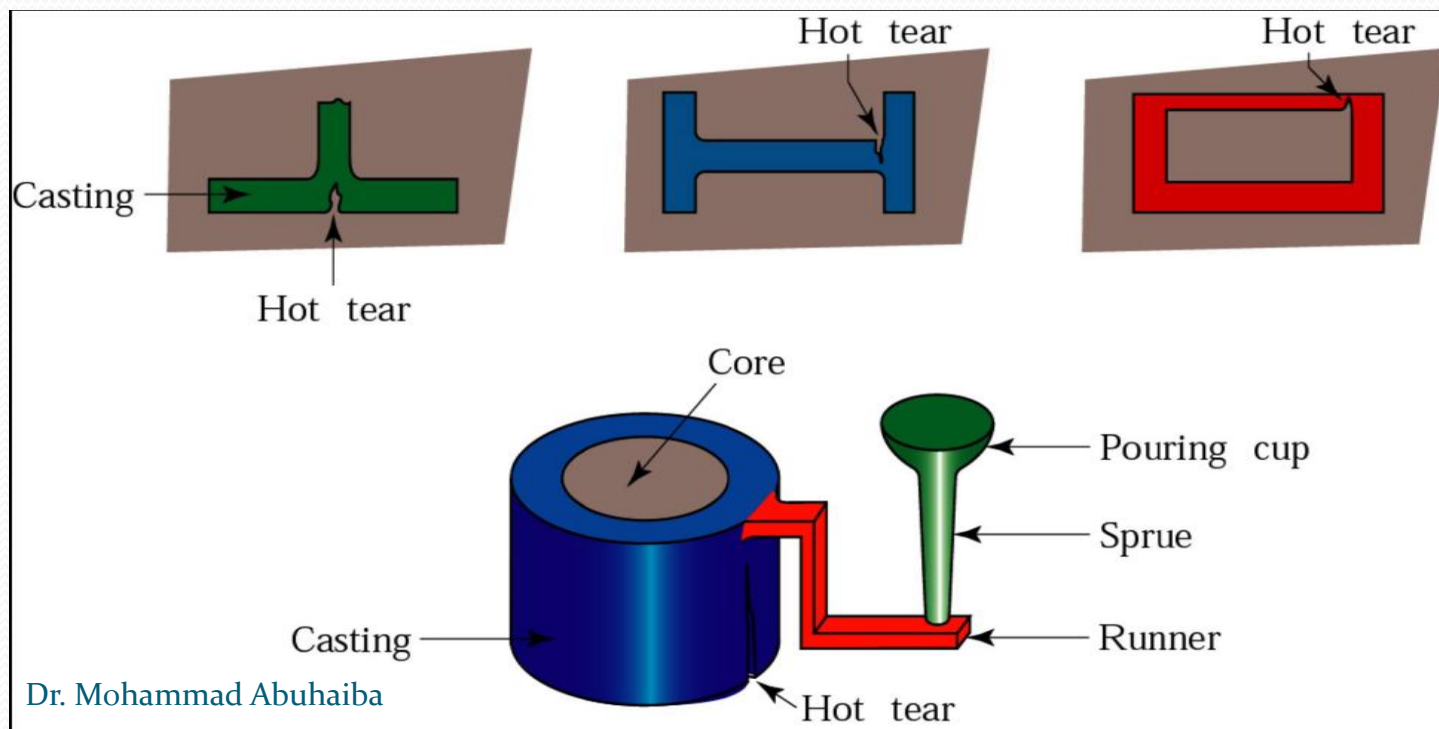
HEAT TRANSFER

Shrinkage

- Shrinkage is the result of the following three events:
 1. Contraction of molten metal as it cools to its solidification.
 2. Contraction of metal during phase change from liquid to solid (latent heat of fusion).
 3. Contraction of solidified metal as its temperature drops to ambient temperature.
- Gray cast iron expands, because graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification, it causes a net expansion of the metal.
- TABLE 10.1: Solidification contraction for various cast metals

DEFECTS

- Metallic projections: fins, flash, or massive projections such as swells and rough surfaces.
- Cavities: rounded or rough internal or exposed cavities, including blow-holes, pinholes, and shrinkage cavities.



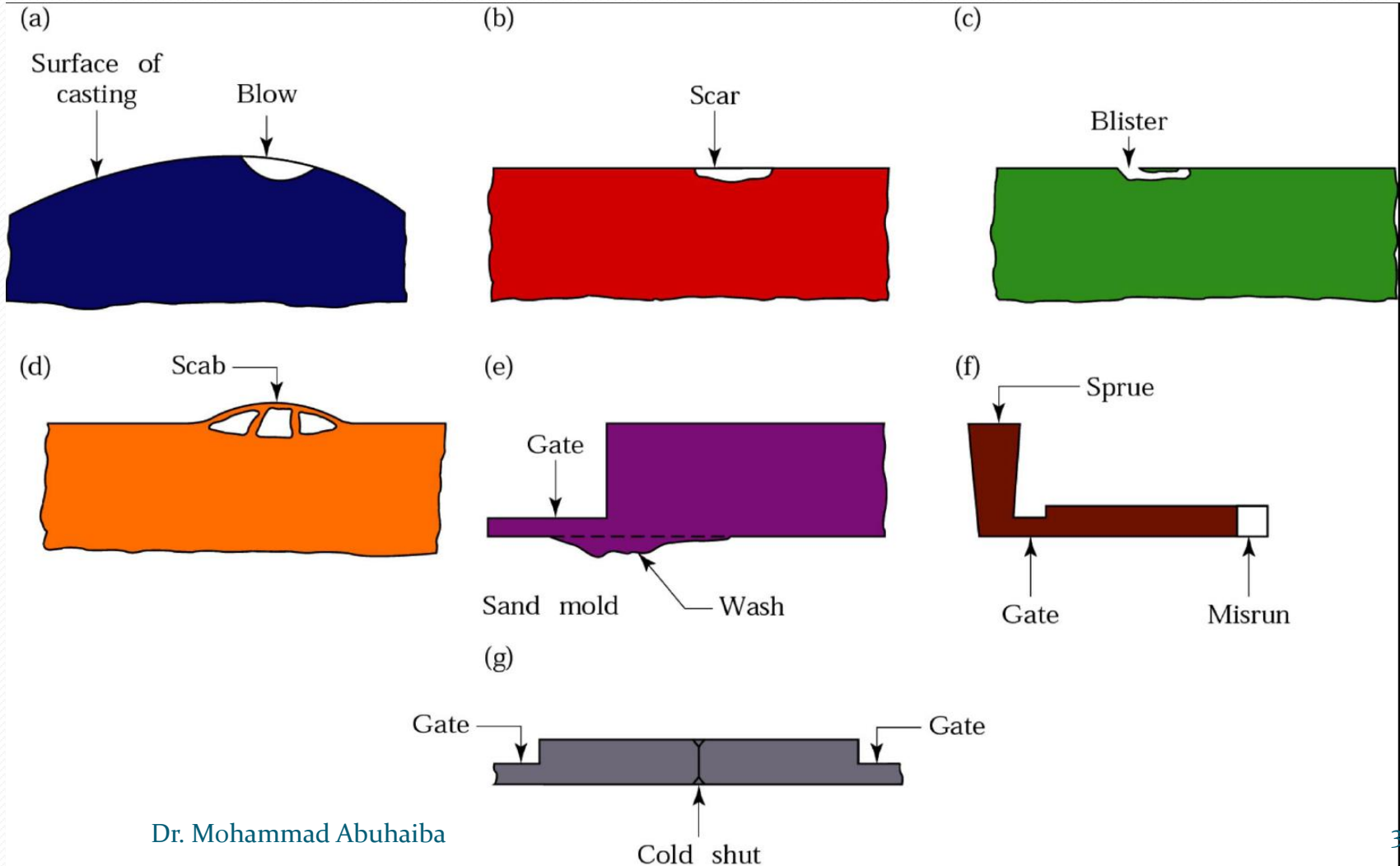
DEFECTS

- Discontinuities:
 1. Cracks
 2. cold or hot tearing
 3. cold shuts
- If the solidifying metal is constrained from shrinking freely, cracking and tearing can occur.
- Coarse grain size and the presence of low melting point segregates along the grain boundaries (intergranular) increase the tendency for hot tearing.
- Cold shut is an interface in a casting that lacks complete fusion because of the meeting of two streams of liquid metal from different gates.

DEFECTS

- Defective surface: surface folds, laps, scars, adhering sand layers, and oxide scale.
- Incomplete casting: misruns, insufficient volume of the metal poured, and runout (due to loss of metal from mold after pouring). Incomplete castings can result from the molten metal being at too low a temperature or from pouring the metal too slowly.
- Incorrect dimensions or shape.
- Inclusions: act as stress raisers and reduce the strength of the casting.

DEFECTS- Surface

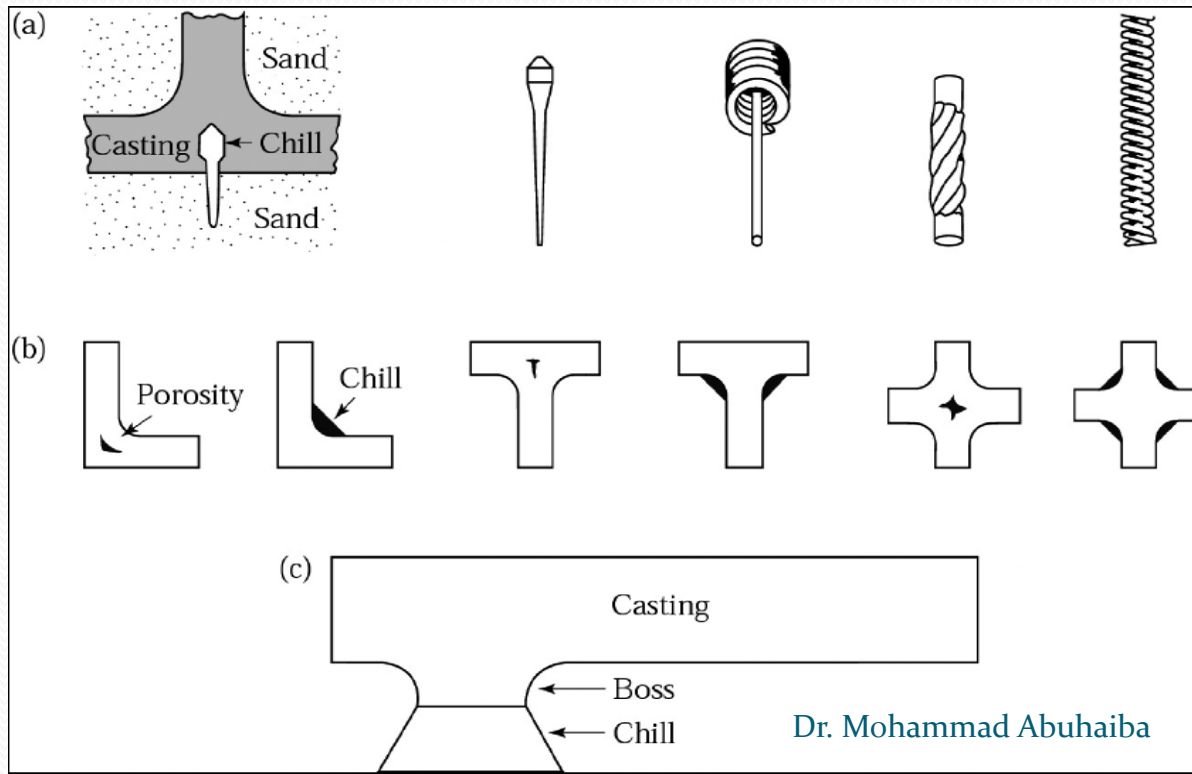


POROSITY

- Porosity may be caused by shrinkage or gases or both.
- Microporosity can also develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches.
- Adequate liquid metal should be provided to avoid cavities caused by shrinkage.

POROSITY

- Internal or external chills, used in sand casting (Fig. 10.13), also are an effective means of reducing shrinkage porosity.



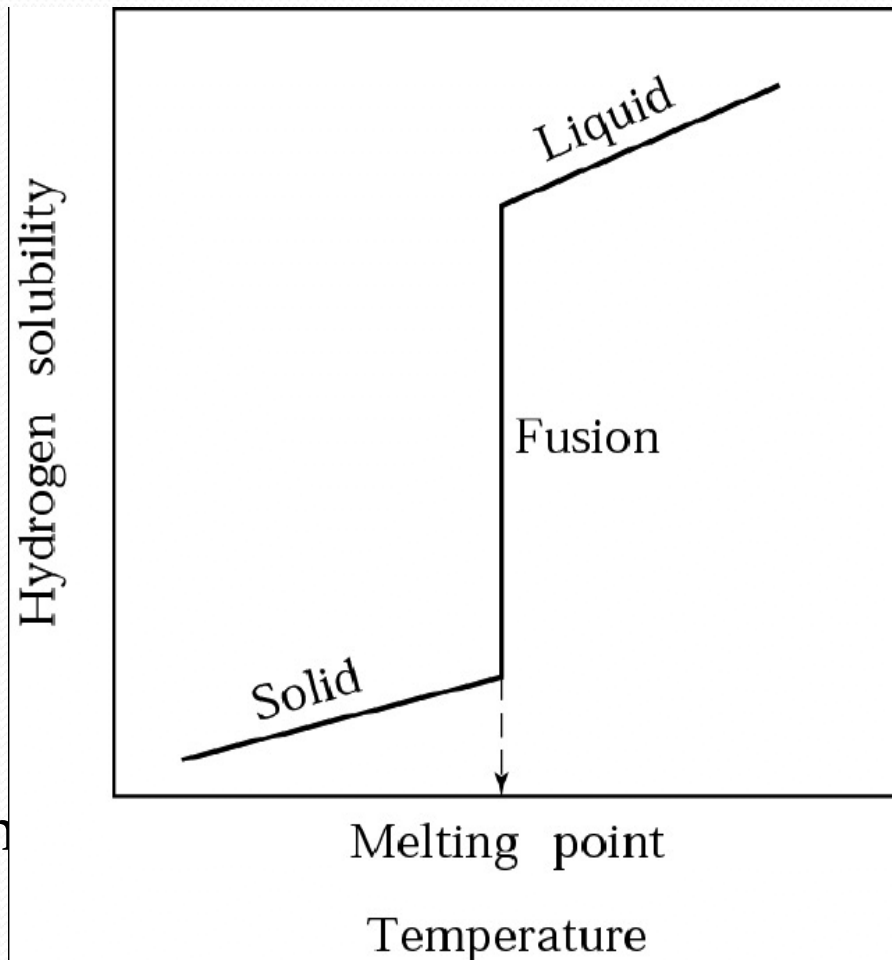
POROSITY

- The function of chills is to increase the rate of solidification in critical regions. Internal chills are usually made of the same material as the casting and are left in the casting.
- External chills may be made of the same material or may be iron, copper, or graphite.

POROSITY

Ways to Reduce Porosity

- With alloys, porosity can be reduced or eliminated by making the temperature gradient steep.
- For example, mold materials that have higher thermal conductivity may be used.
- Subjecting the casting to hot iso-static pressing is another method of reducing porosity.
- Liquid metals have much greater solubility for gases than do solid metals (Fig. 10.14).



POROSITY

Ways to Reduce Porosity

- When a metal begins to solidify, the dissolved gases are expelled from the solution.
- Gases either accumulate in regions of existing porosity (such as in interdendritic regions) or they cause microporosity in the casting, particularly in cast iron, aluminum, and copper.
- Dissolved gases may be removed from the molten metal by flushing or purging with an inert gas, or by melting and pouring the metal in a vacuum.

POROSITY

Ways to Reduce Porosity

- If the dissolved gas is oxygen, the molten metal can be deoxidized. Steel is usually deoxidized with aluminum, silicon, copper-based alloys with phosphorus copper, titanium, and zirconium-bearing materials.
- If the porosity is spherical and has smooth walls, it is generally from gases.
- If the walls are rough and angular, porosity is likely from shrinkage between dendrites.
- Gross porosity is from shrinkage and is usually called a shrinkage cavity.