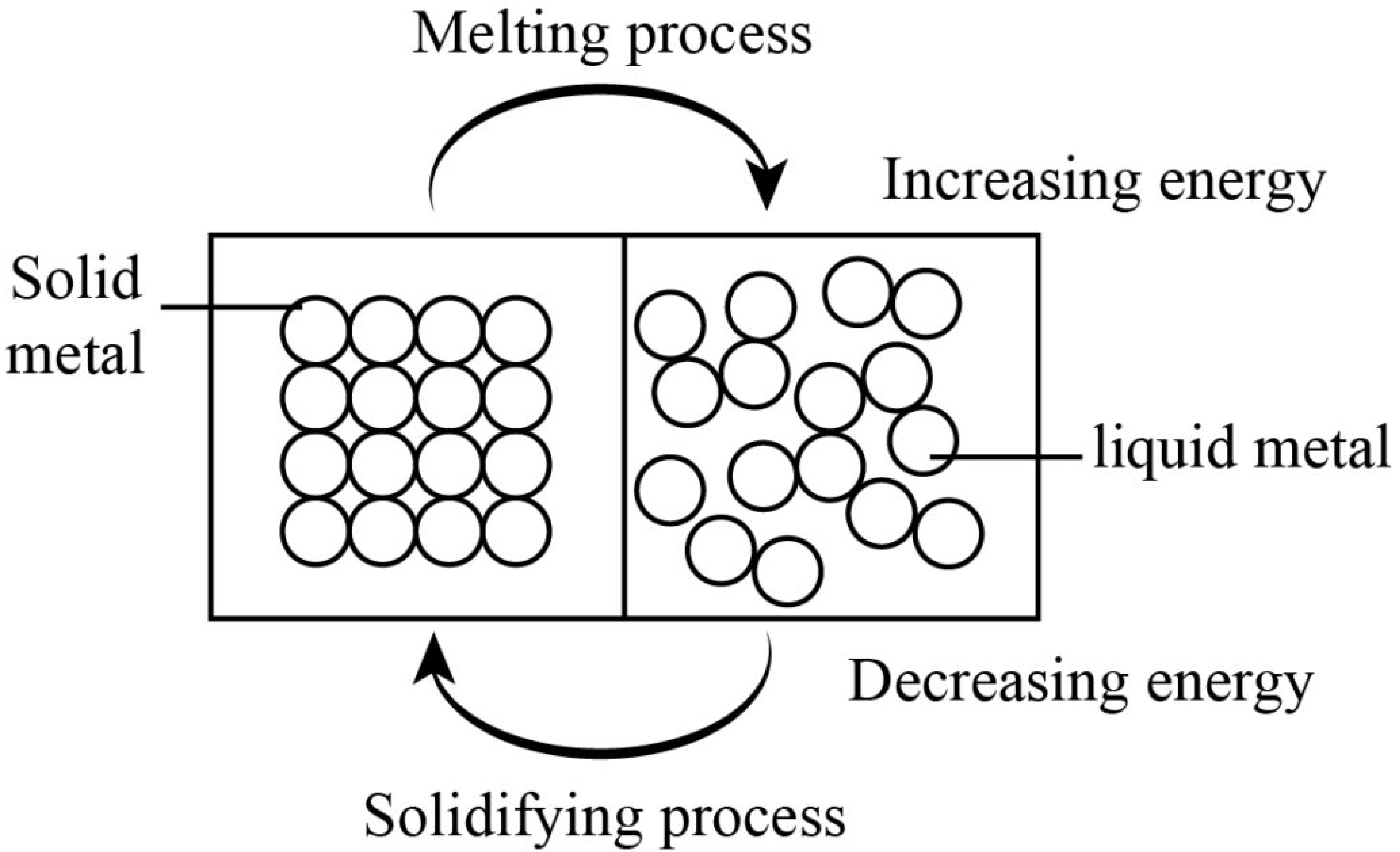
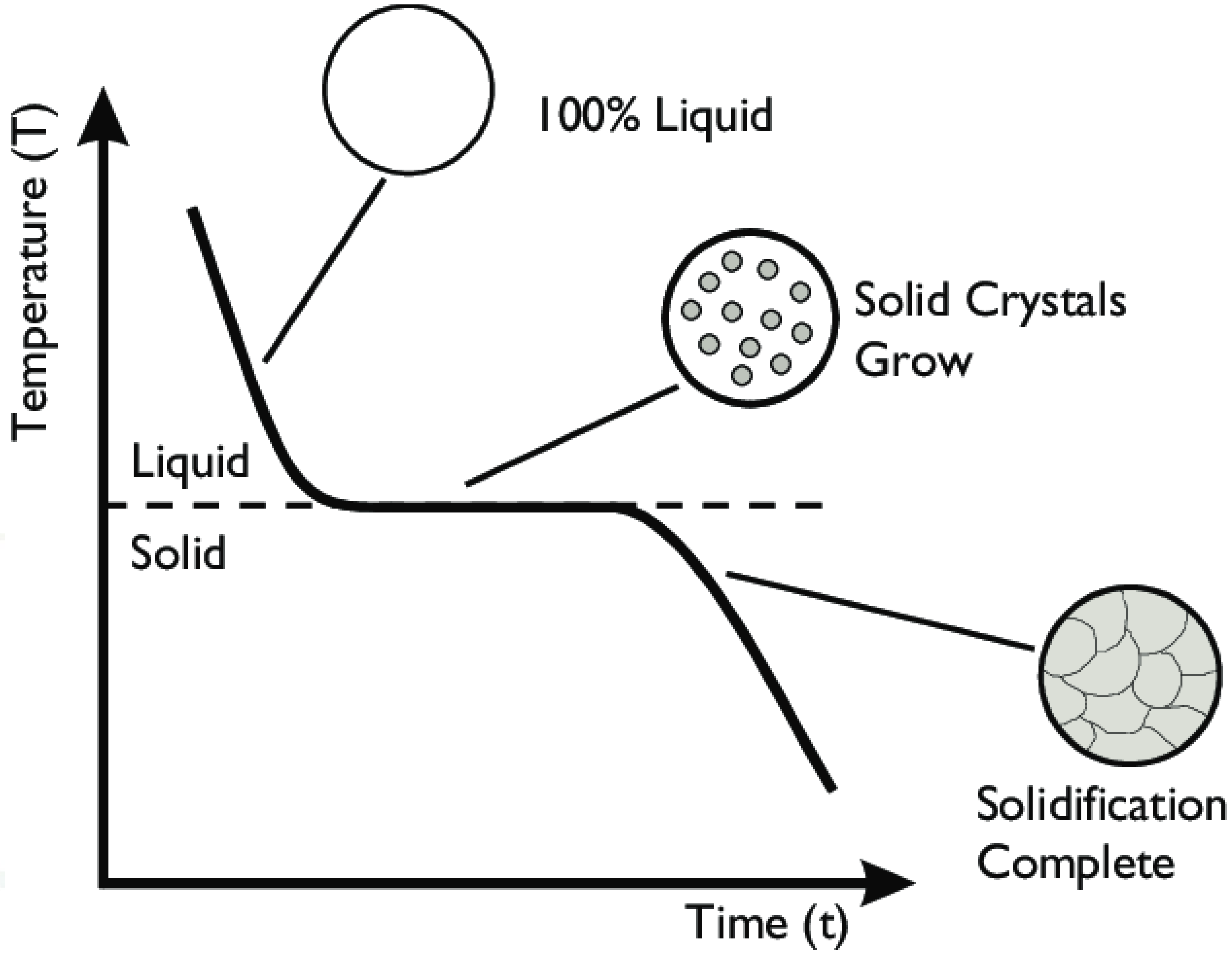
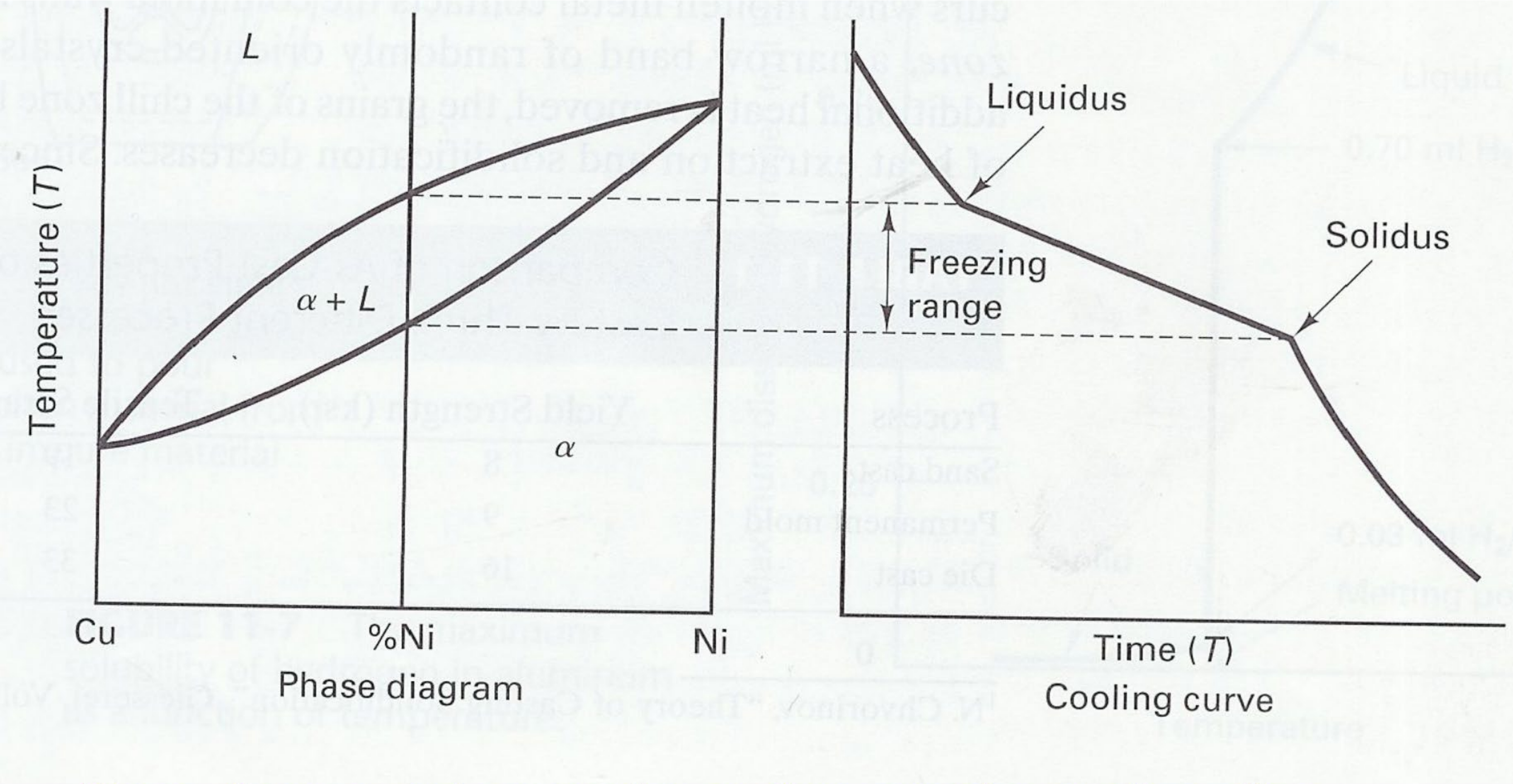
Module 1

Casting Fundamentals


Melting process
Increasing energy
Solid metal
liquid metal
Decreasing energy
Solidifying process



Cooling curve for a pure metal or eutectic alloy indicating major features related to solidification



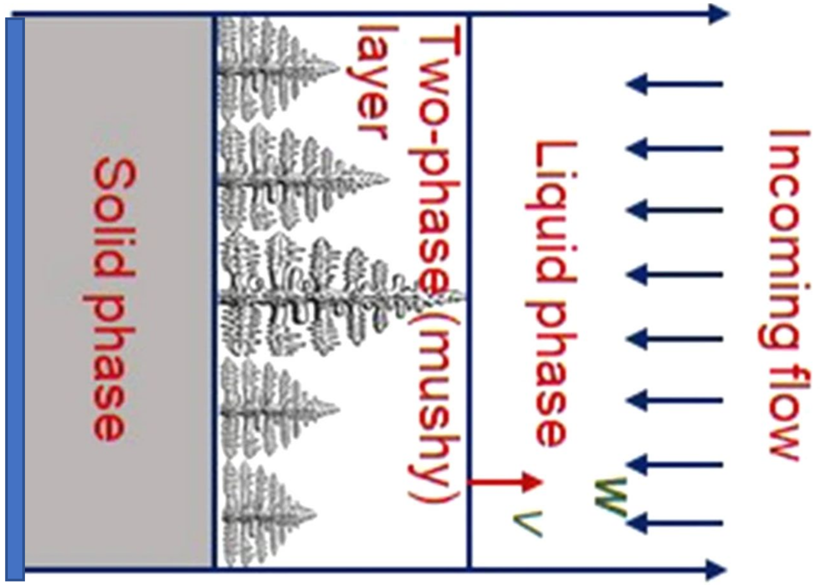
Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes of the cooling curve indicates the onset and termination of solidification.

Concept of Solidification on Casting

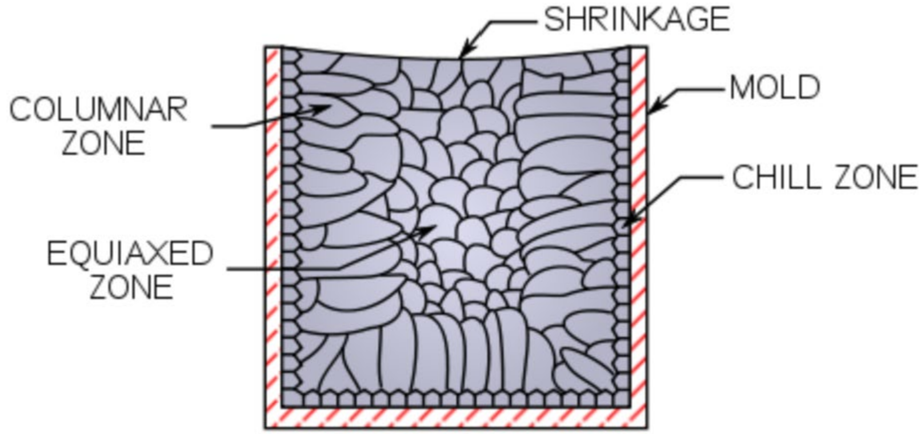
- A metal in molten condition possesses high energy
- As the molten metal cools, it loses energy to form crystals
- Since heat loss is more rapid near the mold walls than any other place, the first metal crystallites called ‘nuclei’ form here.
- Nuclei formed as above tend to grow at the second stage of solidification.
- The crystal growth occurs in a dendrite manner.
- Dendrite growth takes place by the evolution of small arms on the original branches of individual dendrites:

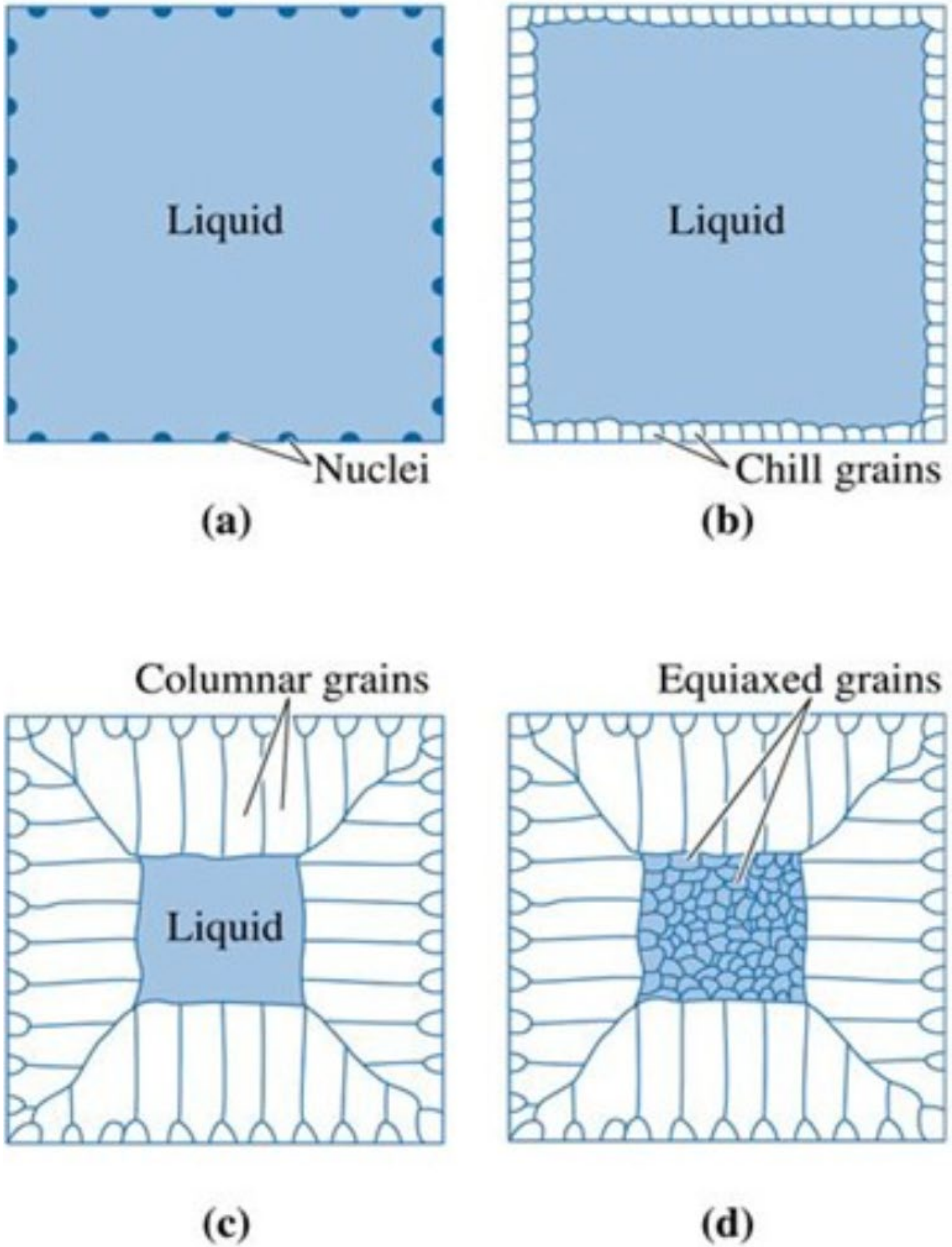
✓ Slow cooling makes the dendrites to grow long whereas fast cooling causes short dendrite growth.

✓ Since eventually dendrites become grains, slow cooling results in large grain structure and fast cooling in small grain structure in the solidified metal.



Cast ingot structure

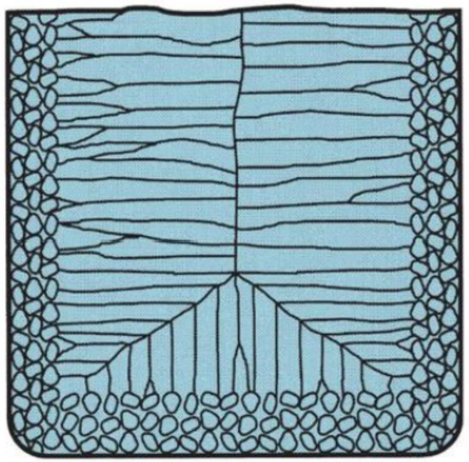




(a) Nucleation, (b) Chill grains, (c) Columnar grains, (d) Equiaxed grains

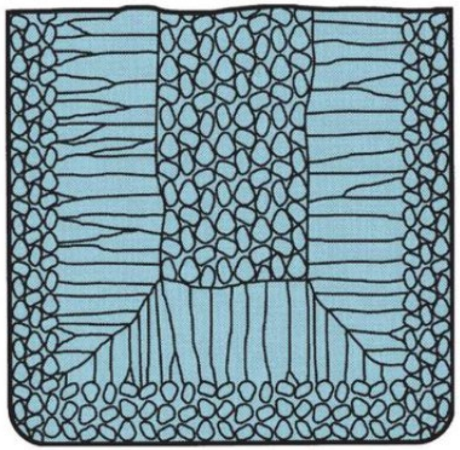
Solidification

- 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

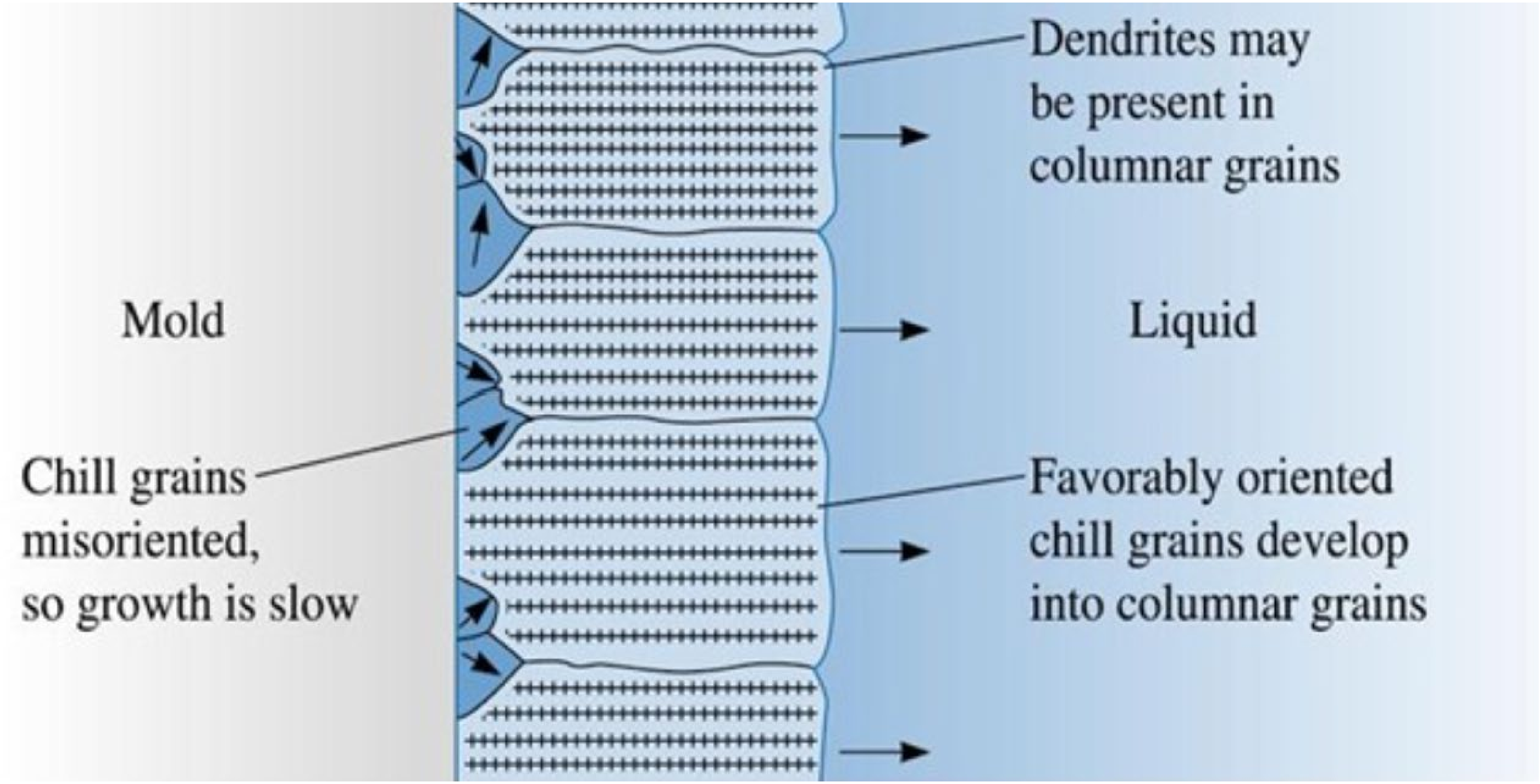


Pure Metals

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

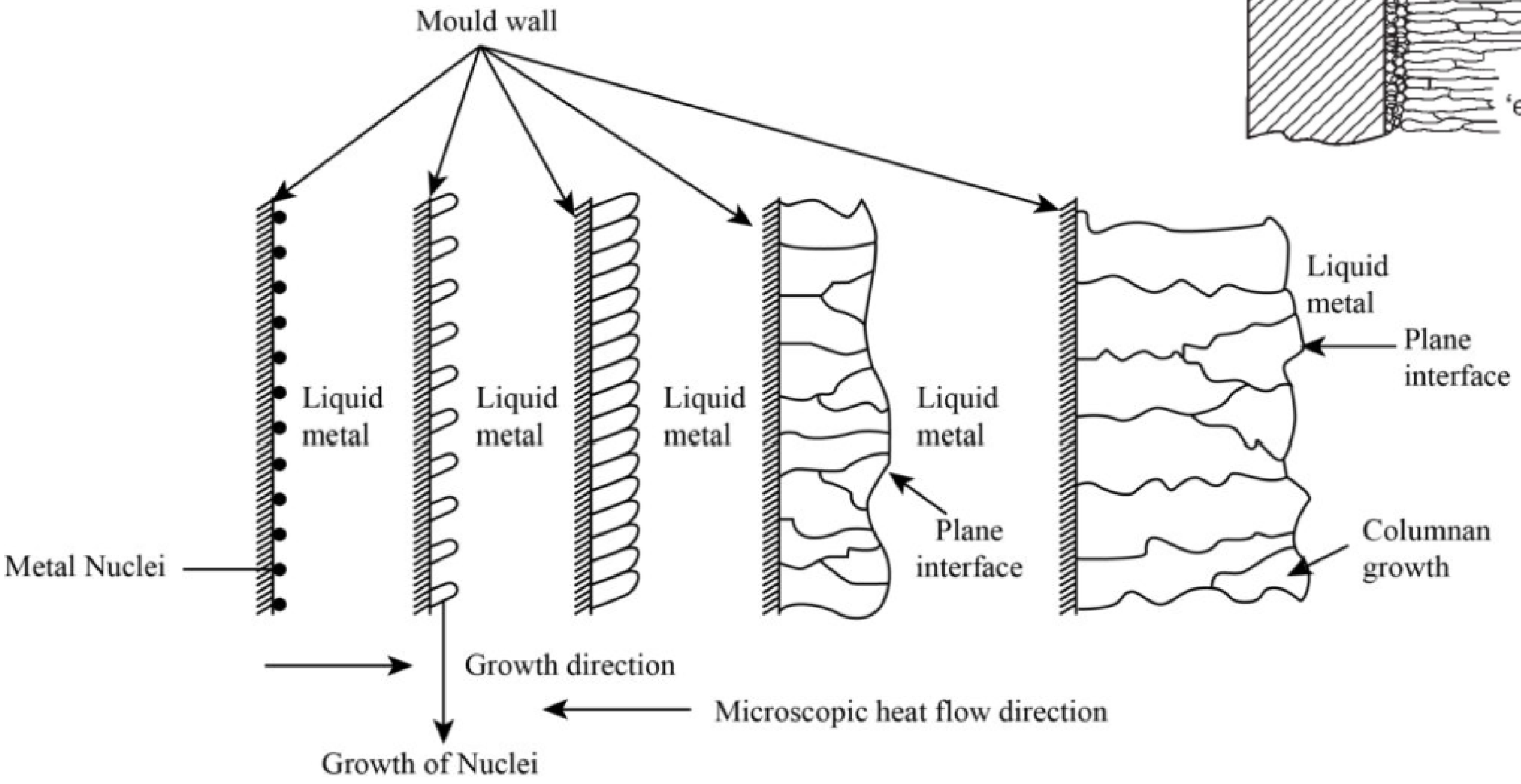


Alloys

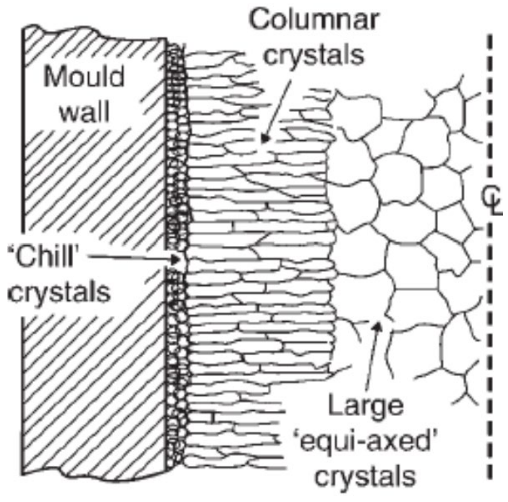


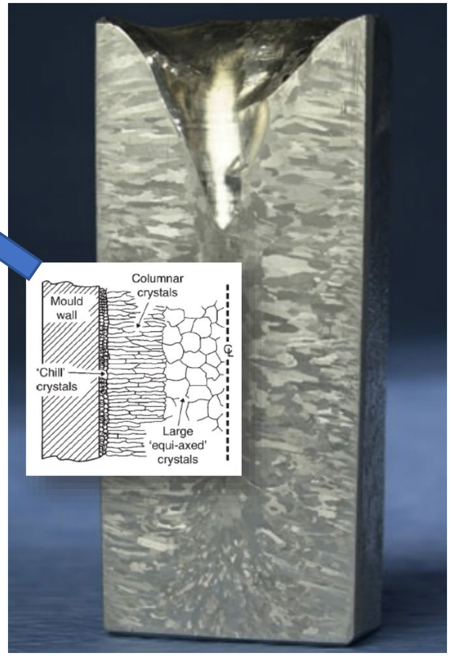
Competitive growth of grains in chill zone results in the orientation developing columnar grains

Cast Aluminium alloy structure

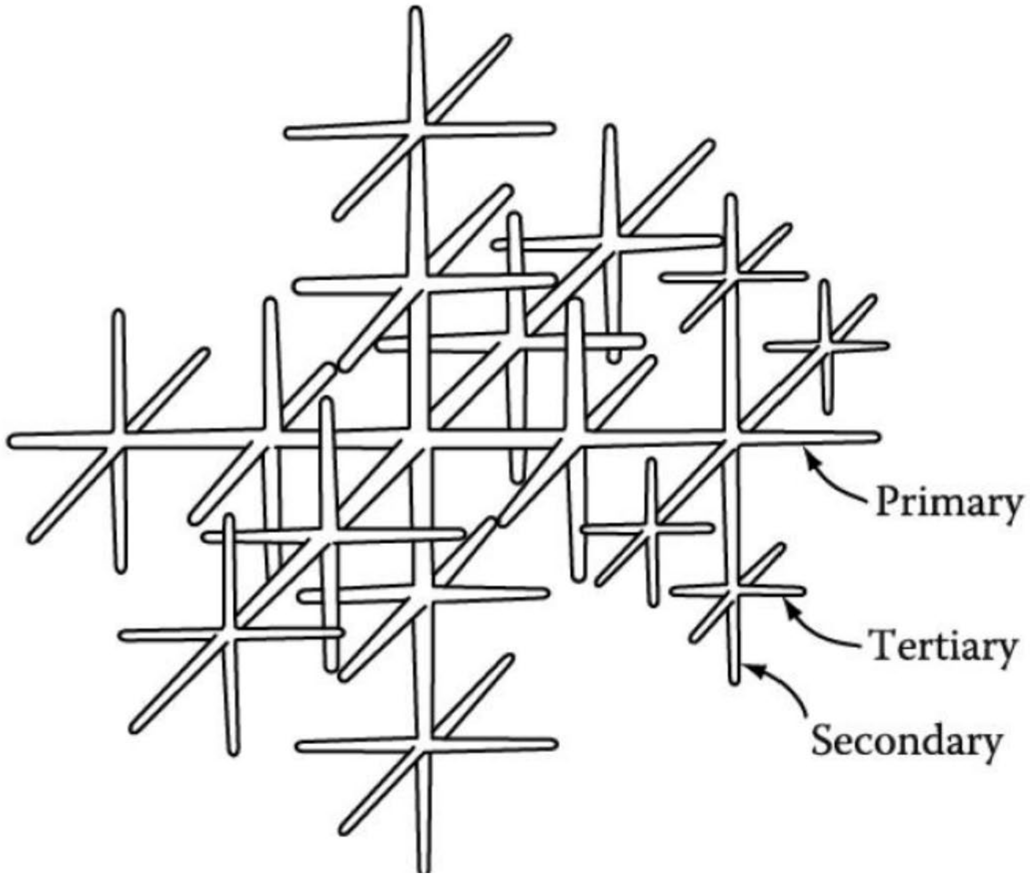


Representation of planar growth giving rise to columnar dendrite

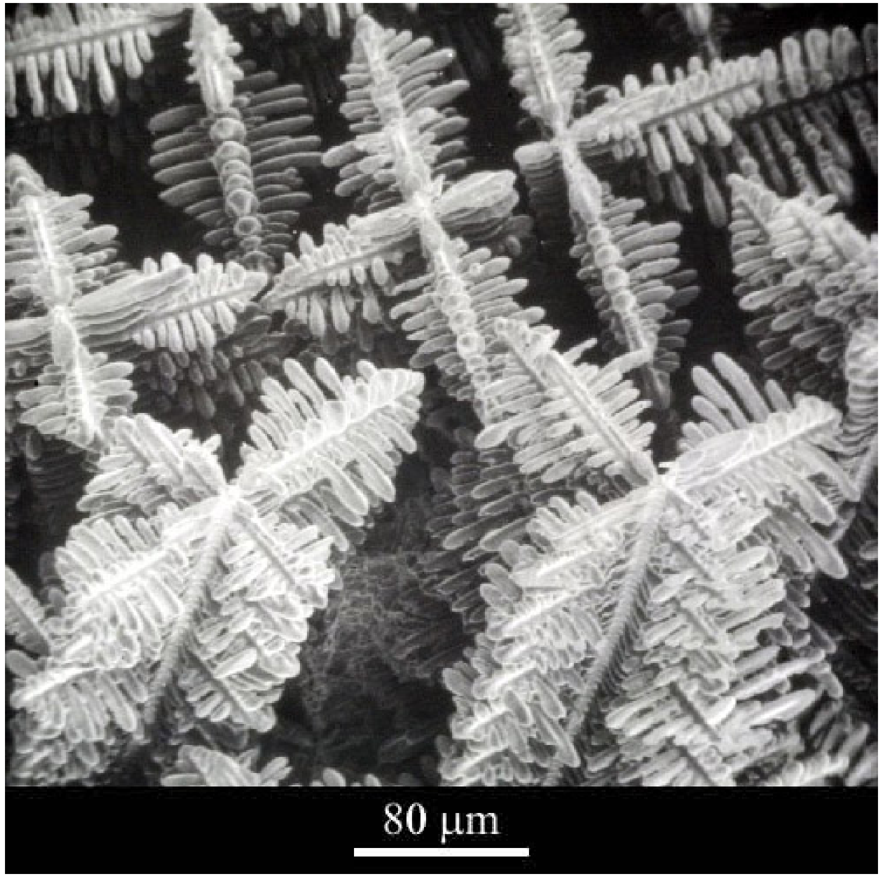




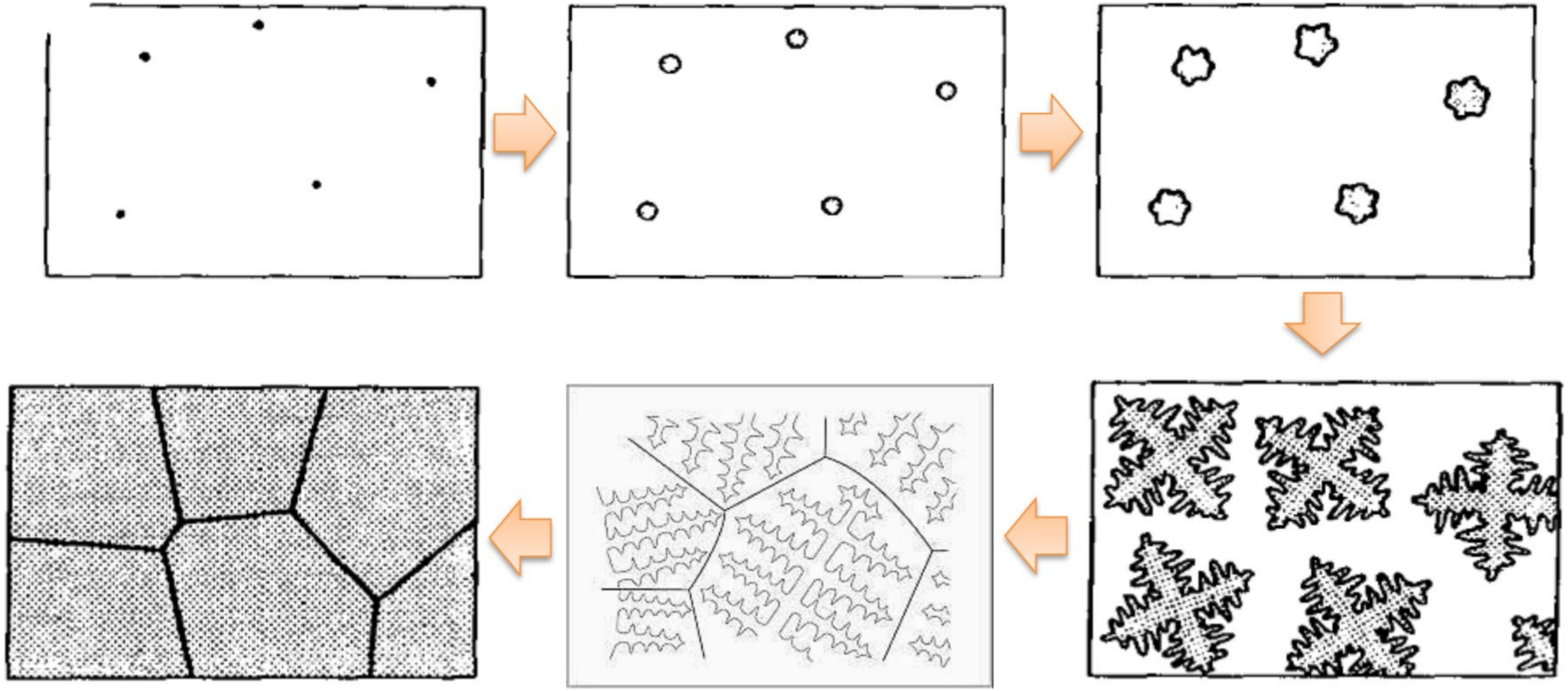
Dendritic structure



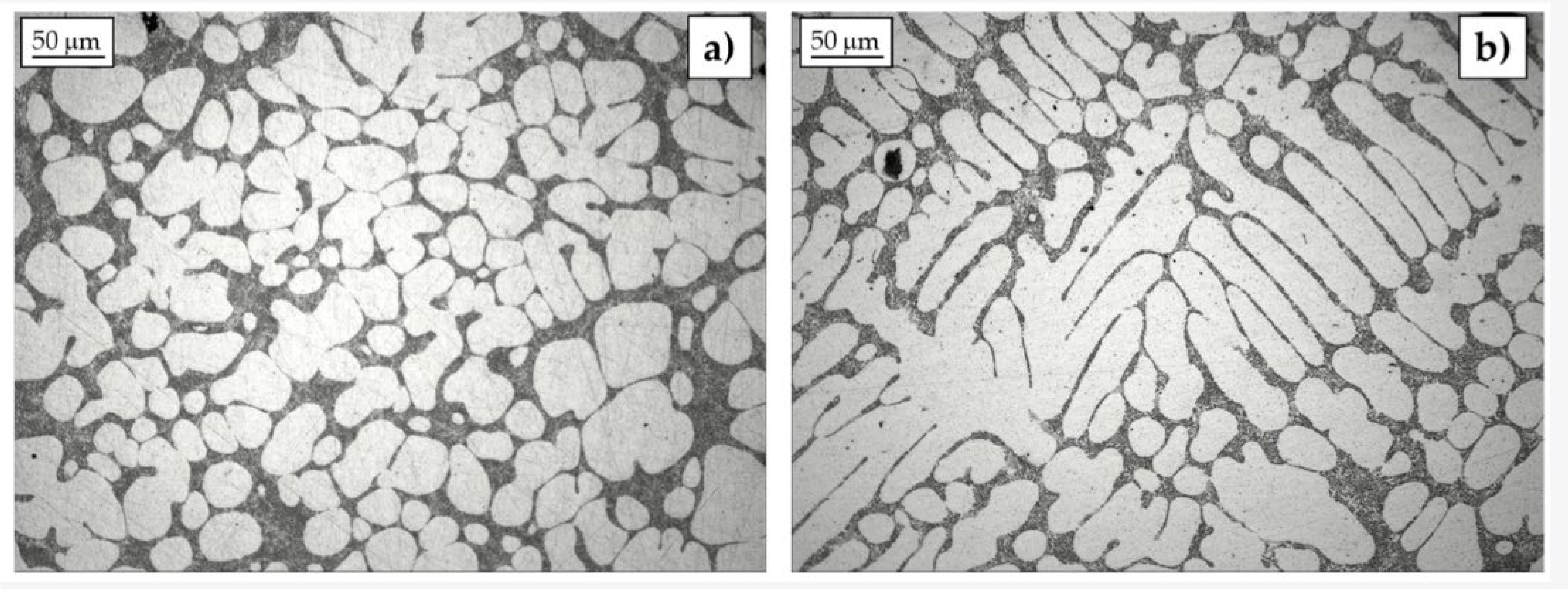
A dendritic crystal formed by three-dimensional dendritic growth



Growth of equiaxed dendrites



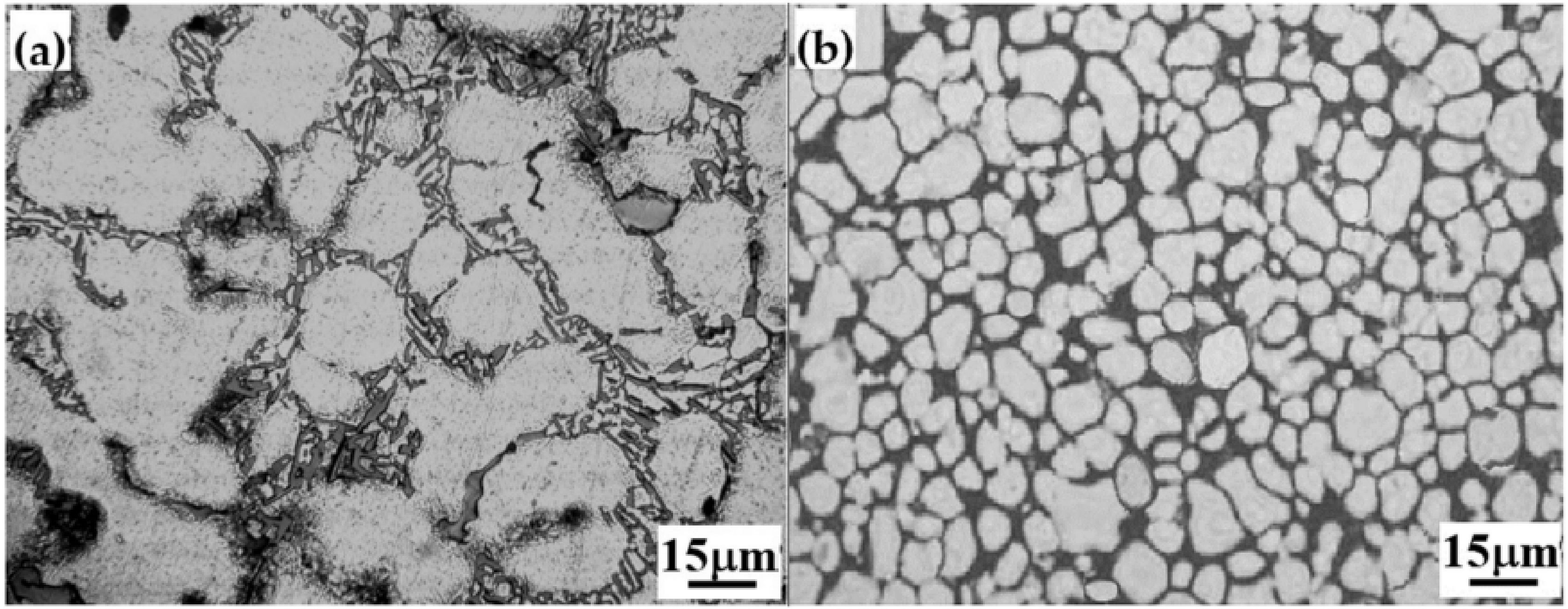
Typical microstructures of AlSi7 component



(a) semi-solid cast

(b) conventionally cast.

Microstructure of cast Al-9Si-4Cu-0.4Mg-0.3Sc alloy



(a) Microstructure of a metal-mold cast alloy (b) Microstructure of a die-cast alloy

Progressive solidification

Solidification begins at the walls of the casting and works its way inward.

Directional solidification

Solidification begins at the bottom of the casting and works its way to the top.

Single crystal

- Single crystal is formed by controlling the cooling rate in such a way as to force the growth of a single crystal with no grain boundaries instead of multiple crystals

- Forming single-crystal metal objects requires both special alloys and special casting techniques.

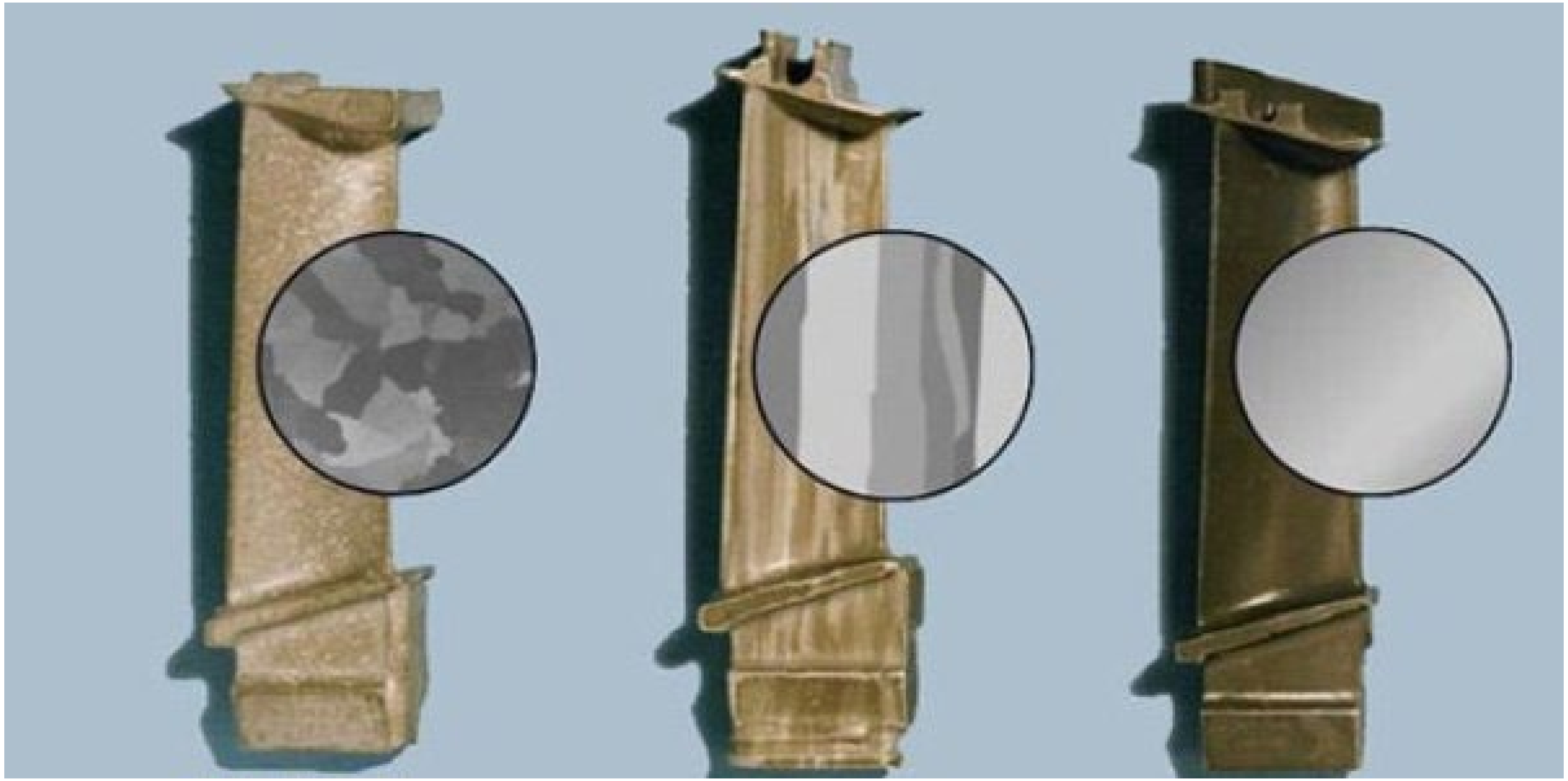
- Alloys are almost always nickel-based, with as many as nine minor metal components including five or more percent chromium, cobalt, tungsten, tantalum, aluminum, and/or rhenium.

- The casting method is known as "directional solidification," and involves carefully cooling a cast metal part starting at one end to guarantee a particular orientation of its crystal structure.

- The primary application for single crystal superalloys is the manufacture of jet engine turbine blades, which must endure tremendous forces at extremely high temperatures for prolonged periods of time.

- Under such conditions, metals with a grain structure tend to "creep," or slowly deform, along grain boundaries. Because single-crystal alloy parts have no grain boundaries, however, they are highly resistant to this kind of wear.

Single Crystal cast



Equiaxed crystal structure | Columnar crystal structure | Single crystal structure

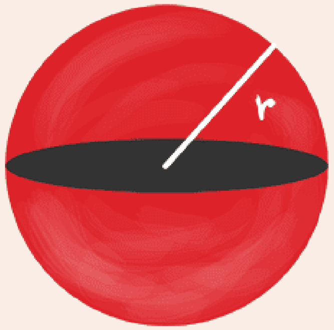
Prediction of Solidification Time

- *Chvorinov's* rule:
  V = volume
  A = surface area
  n = 1.5 to 2
  B = constant for metal cast, mold material and casting conditions

$$t_s = B\left(\frac{V}{A}\right)^n$$

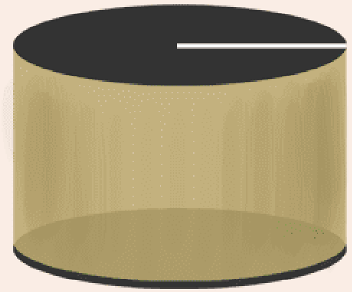
Volume (V) and Surface area (SA) of different shapes

Sphere



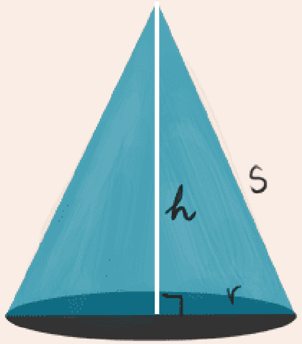
$SA = 4\pi r^2$ | $v = 4/3\ \pi r^3$

Cylinder



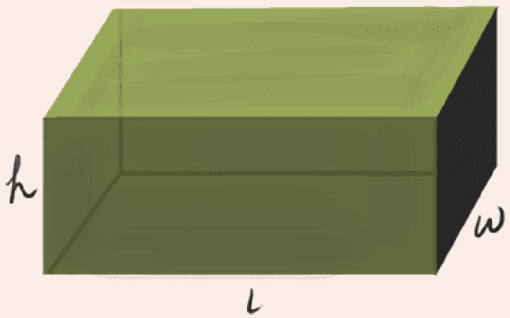
$SA = 2\pi r^2 + 2\pi rh$ | $v = \pi r^2 h$

Cone



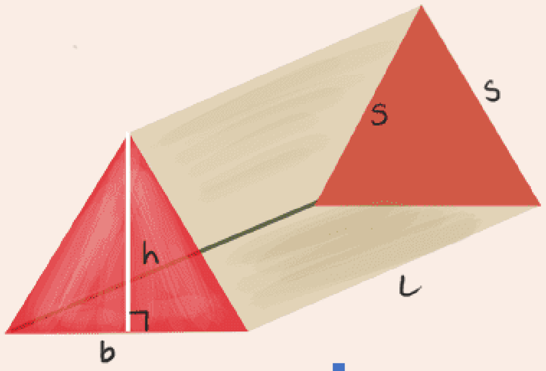
$SA = \pi rs + \pi r^2$ | $v = 1/3\ \pi r^2 h$

Rectangular Prism



$SA = 2(lw + lh + wh)$ | $v = lwh$

Triangular Prism



$SA = bh + 2ls + lb$ | $v = 1/2(bl)h$

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

Solution:

l = 30 cm
w = 10 cm
h = 20 mm

Area $A = 2(30 \times 10) + 2(30 \times 2) + 2(10 \times 2) = 760\ \text{cm}^2$

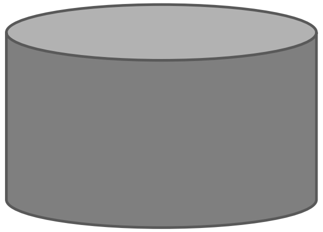
Volume $V = 30 \times 10 \times 2 = 600\ \text{cm}^3$

Apply Chvnorinov's rule,

$$t_s = B(V/A)^n$$
$$= 4(600/760)^2$$
$$= 2.5\ \text{min}$$

A cylindrical-shaped part is to be cast out of aluminum. The radius of the cylinder r**= 250 mm** and its thickness h**= 20 mm**. If the mold constant is **2 s/mm²** in Chvorinov's Rule, how long will it take the casting to solidify?

Solution:



Area $A = 2\pi r^2 + 2\pi r h = 2\pi (250)^2 + 2\pi (250)(20) = 424{,}115 \text{ mm}^2$

Volume $V = \pi r^2 h = \pi (250)^2 (20) = 3{,}926{,}991 \text{ mm}^3$

r = 250 mm
h = 20 mm

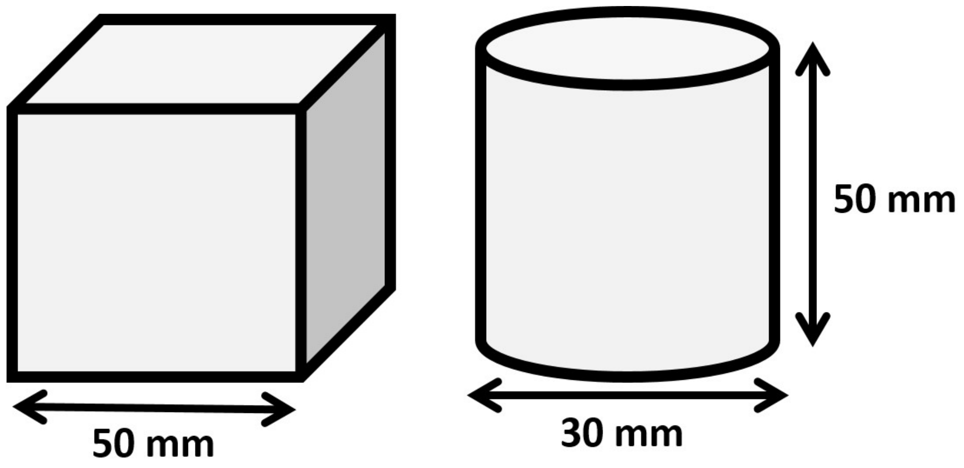
Apply Chvnorinov's rule,

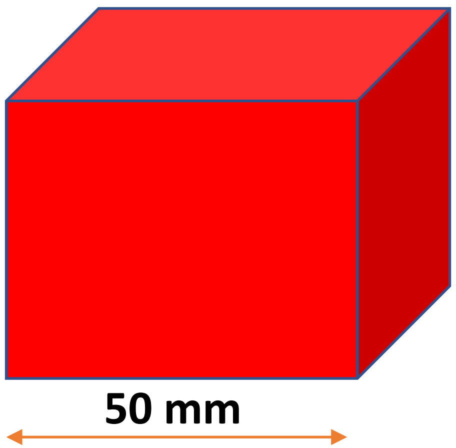
$t_s = B(V/A)^n$
$= 2(3{,}926{,}991/424{,}115)^2$
$= 171.46$ s

In casting experiments performed using a certain alloy and type of sand mold, it took **155 sec for a cube-shaped casting to solidify**. The cube was **50 mm** on a side.

(a) Determine the value **mold constant** in Chvorinov's Rule.

(b) If the same alloy and mold type were used, find the **total solidification time** for a cylindrical casting in which the diameter **r = 15 mm** and length **h = 50 mm**.





Solution:

(a) Area $A = 6 \times (50)^2 = 15{,}000\ \text{mm}^2$

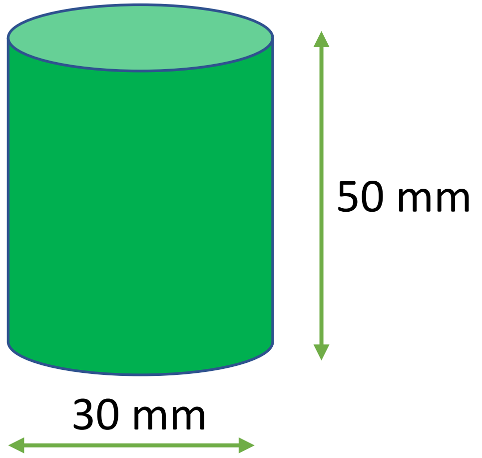
Volume $V = (50)^3 = 125{,}000\ \text{mm}^3$

$(V/A) = 125{,}000 / 15{,}000 = 8.333\ \text{mm}$

$C_m = T_{TS} / (V/A)^2 = 155 / (8.333)^2 =$ **$2.232\ \text{s/mm}^2$**

To find Mold constant B,

$$t_s = B(V/A)^2$$
$$155 = B(8.33)^2$$
$$B = 2.232\ \text{s/mm}^2$$



(b) Cylindrical casting with r = 15 mm and h = 50 mm.

Area $A = 2\pi r^2 + 2\pi rh = 2\pi\,(15)^2 + 2\pi(15)(50) = 6126\ \text{mm}^2$

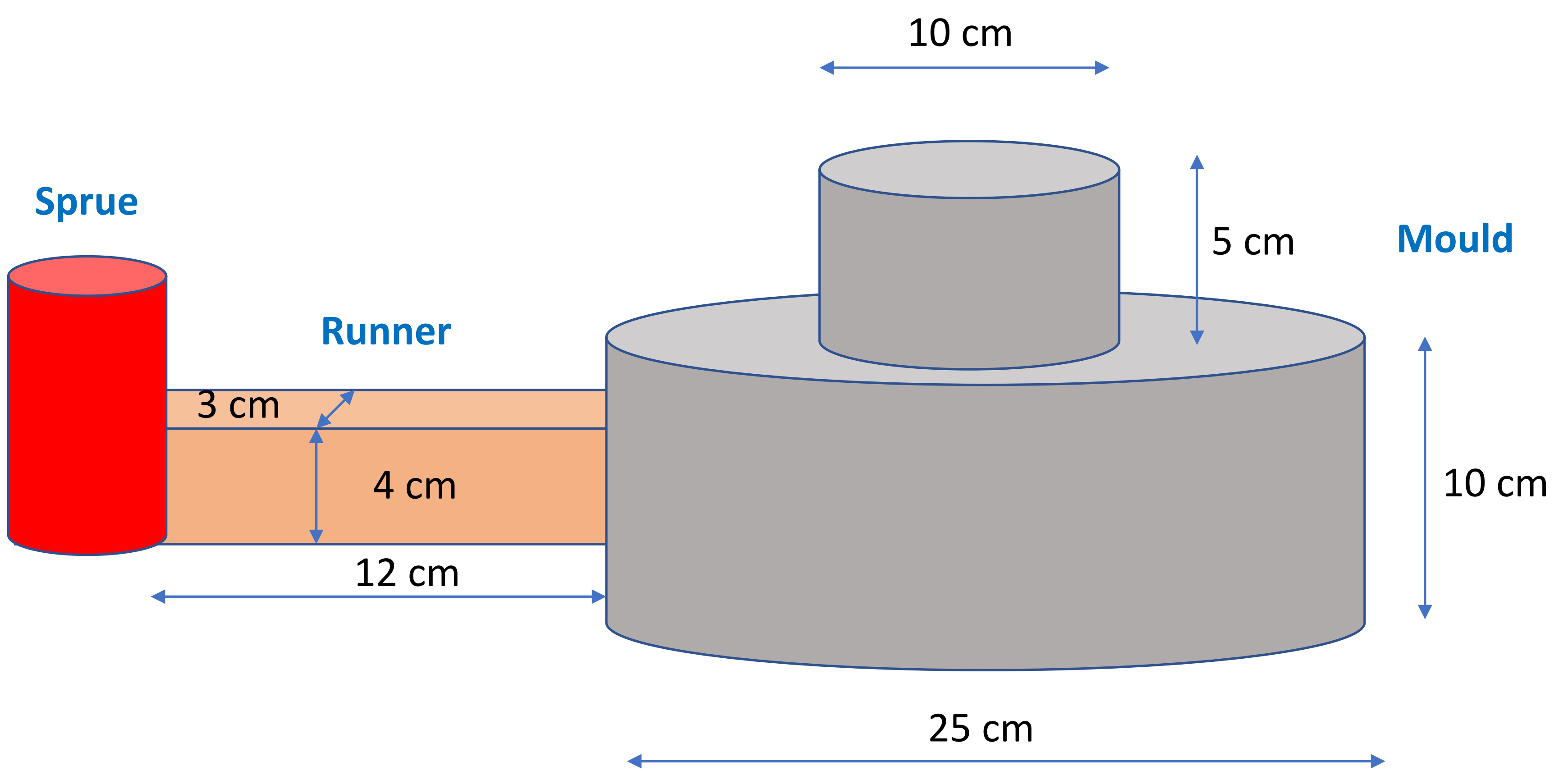
Volume $V = \pi r^2\, h = \pi(15)^2\,(50) = 35{,}343\ \text{mm}^3$

$V/A = 35{,}343 / 6126 = 5.77$

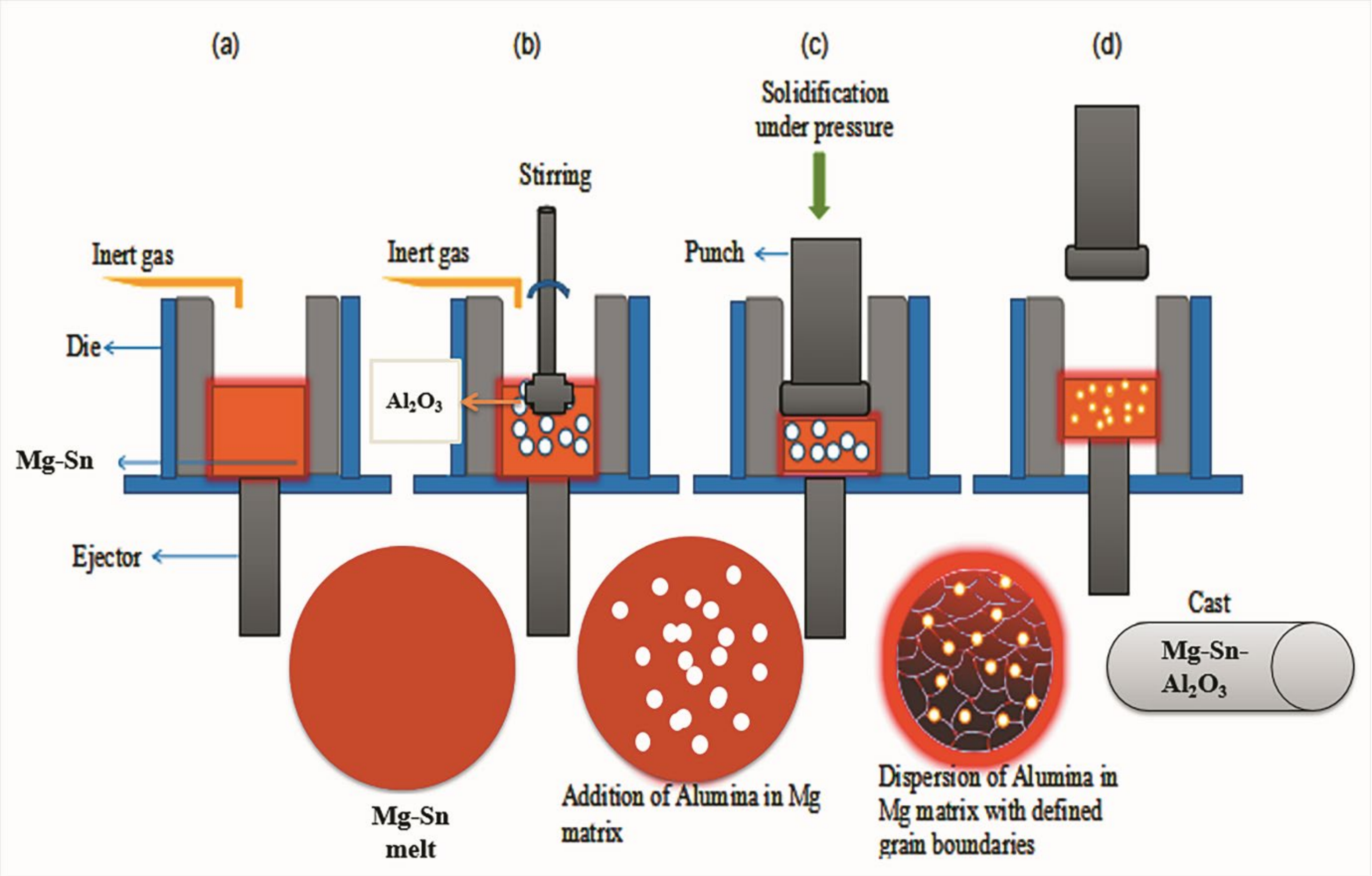
To find solidification time

$$t_s = B(V/A)^2$$
$$= 2.232(5.77)^2$$
$$= 74.3\ \text{s}$$

Find the solidification time for casting the component as shown in figure made of Aluminium by considering the runner between sprue and casting. Take mold constant as 2 s/mm^2



Fabrication of composites by casting

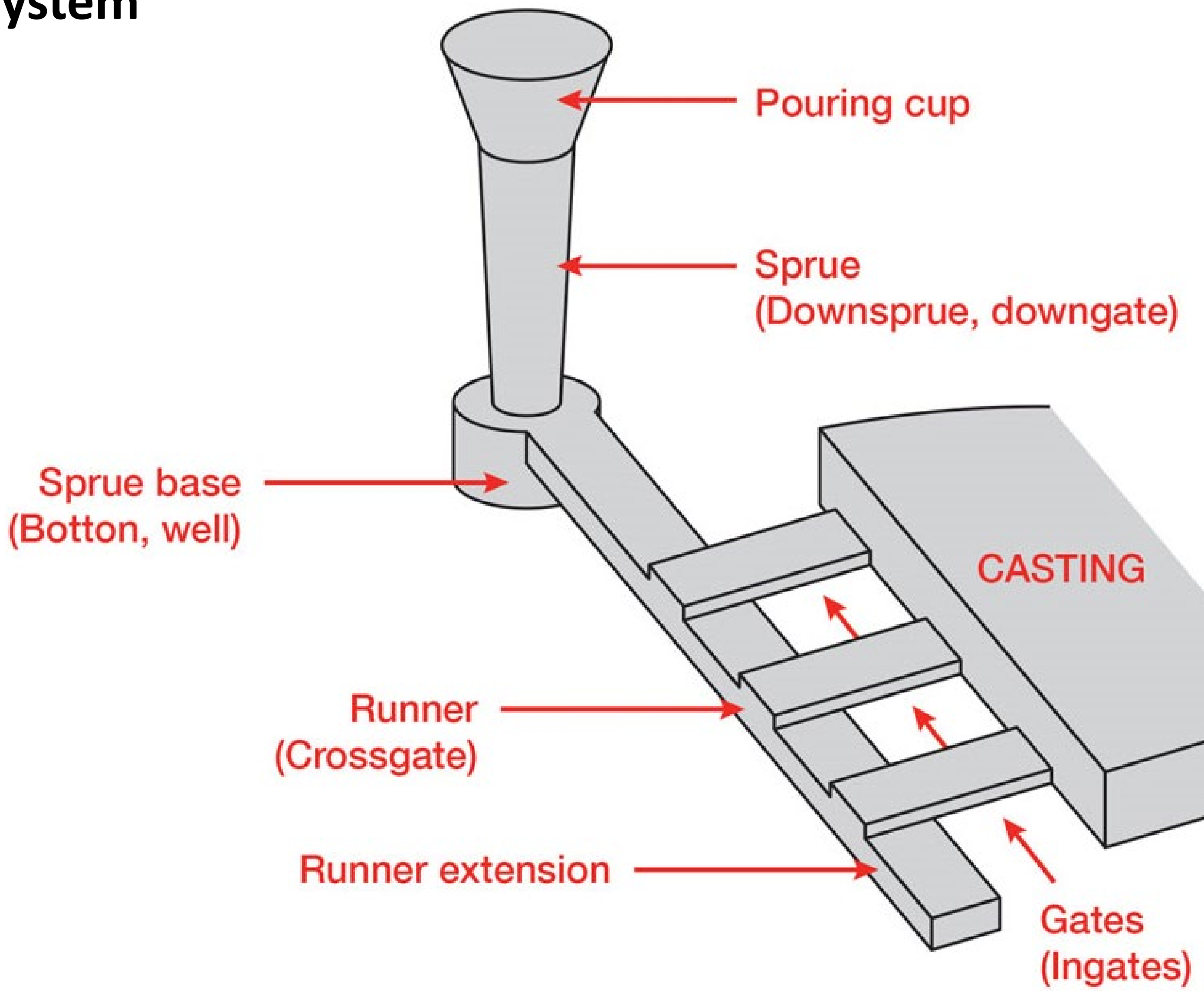


Schematic representation of squeeze casting process of Mg-1Sn/5Al_2O_3 composite

Reference:

Radha, R., Sreekanth, D., Bharti, N. and Rana, A., 2019. Mg-1Sn/Al2O3 biodegradable composites: effect of Al2O3 addition on mechanical, in-vitro corrosion and bioactivity response. *Materials Research Express*, *6*(10), p.105411.

Gating system



Elements of Gating system

Pouring Cup

It is the funnel-shaped opening, made at the top of the mold. The main purpose of the pouring basin is to direct the flow of molten metal from ladle to the sprue.

Sprue

It is a vertical passage connects the pouring basin to the runner or ingate. It is generally made tapered downward to avoid aspiration of air. The cross section of the sprue may be square, rectangular, or circular.

Sprue well

It is located at the base of the sprue. It arrests the free fall of molten metal through the sprue and turns it by a right angle towards the runner.

Runner

It is a long horizontal channel which carries molten metal and distribute it to the ingates .It will ensure proper supply of molten metal to the cavity so that proper filling of the cavity takes place.

Gates

These are small channels connecting the mould cavity and the runner.The gates used may vary in number depends on size of the casting.

Functions of Gating system

- Easy and complete filling of mould cavity
- Less turbulence
- Prevent mold erosion
- Establish proper temperature gradient
- Promote directional solidification
- Regulate the flow of molten metal

Gating ratio

A gating ratio is a term used to describe the relative cross-sectional areas of components of a gating system.

$GR = 1 : A_r/A_s : A_g/A_s$

Pressurized Gating system : Reactive metals (Mg and its alloys) and steel

1:0.75:0.5

1:2:1

Less metal and High yield

Turbulence effect

Non Pressurized Gating system : Mostly for all other metals/alloys

1:2:2

1:1:3

More metal and less yield

POURING THE MOLTEN METAL

- ***Pouring temperature*** is the temperature of the molten metal as it is introduced into the mold

- ***Pouring rate*** refers to the volumetric rate at which the molten metal is poured into the mold.

- ***Fluid flow*** refers to the velocity of flow of the molten metal – **Laminar/Turbulent**

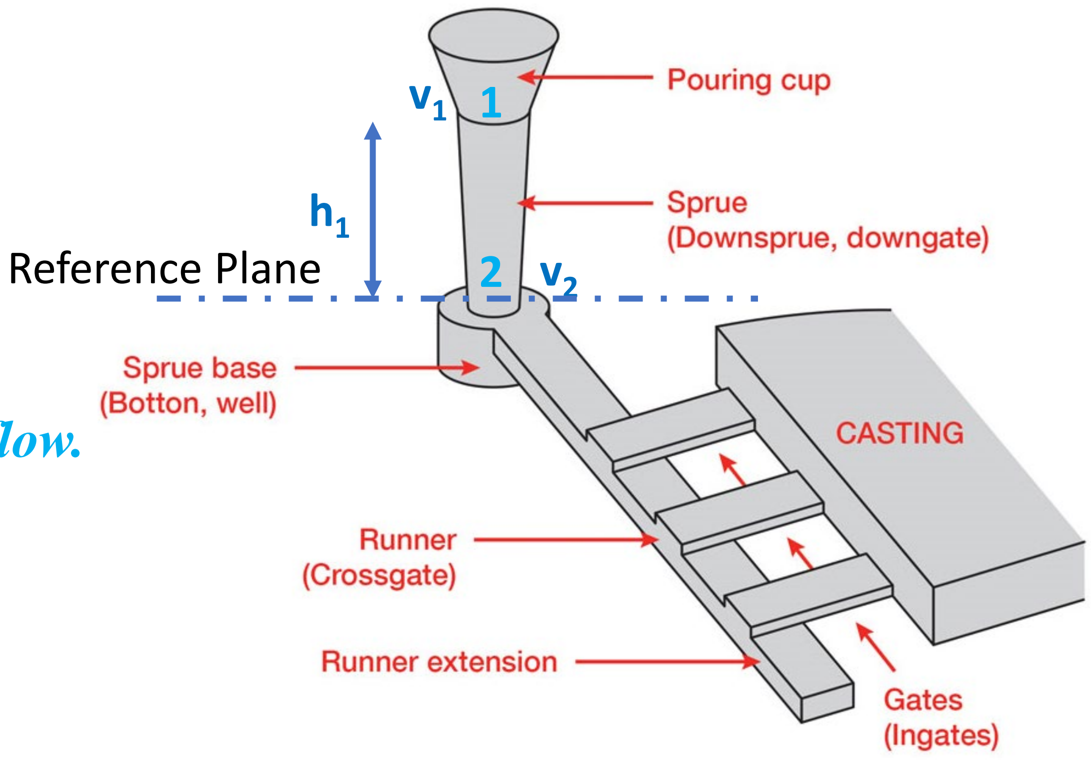
Principles of Fluid flow

Bernoulli's theorem, which states that the sum of the energies (head, pressure, kinetic, and friction) at any two points in a flowing liquid are equal.

$$h_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{p^2}{\rho} + \frac{v_2^2}{2g} + F_2$$

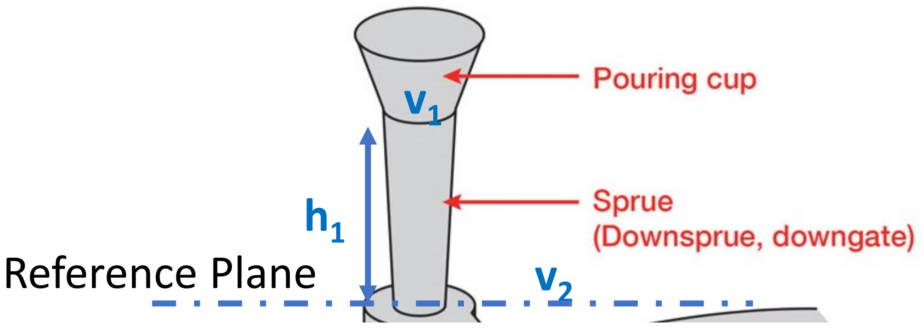
where h head, cm
p pressure on the liquid, N/cm^2
ρ density, g/cm^3
v flow velocity, cm/s
g gravitational acceleration constant, 981 cm/s^2
F head losses due to friction, cm

Subscripts 1 and 2 indicate any two locations in the liquid flow.



If friction losses are ignored and the system is assumed to remain at atmospheric pressure throughout, then the Bernoulli's equation can be reduced to:

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g}$$



- This can be used to determine the velocity of the molten metal at the base of the sprue.
- Let point 1 be defined at the top of the sprue and point 2 at its base.
- If point 2 is used as the reference plane, then the head at that point is zero ($h2 = 0$) and $h1$ is the height (length) of the sprue

When the metal is poured into the pouring cup and overflows down the sprue, its initial velocity at the top is zero ($v1 = 0$). Hence, Equation simplifies to:

$$h_1 = \frac{v_2^2}{2g} \quad \Rightarrow \quad v_2 = \sqrt{2gh}$$

Velocity of fluid(molten metal) at the base of the sprue

Continuity law, which states that the volume rate of flow remains constant throughout the liquid.

$$Q = v_1 A_1 = v_2 A_2$$

where Q volumetric flow rate, cm^3/s

v velocity

A cross sectional area of the liquid, cm^2

subscripts refer to any two points in the flow system.

A mold sprue is 20 cm long, and the cross-sectional area at its base is 2.5 cm^2. The sprue feeds a horizontal runner leading into a mold cavity whose volume is 1560 cm^3. Determine: (a) velocity of the molten metal at the base of the sprue, (b) volume rate of flow, and (c) time to fill the mold.

Solution

The velocity of the flowing metal at the base of the sprue

$$v = \sqrt{2(981)(20)} = 198.1 \text{ cm/s}$$

volumetric flow rate is

$$Q = (2.5 \text{ cm}^2)\,(198.1 \text{ cm/s}) = 495 \text{ cm}^3/\text{s}$$

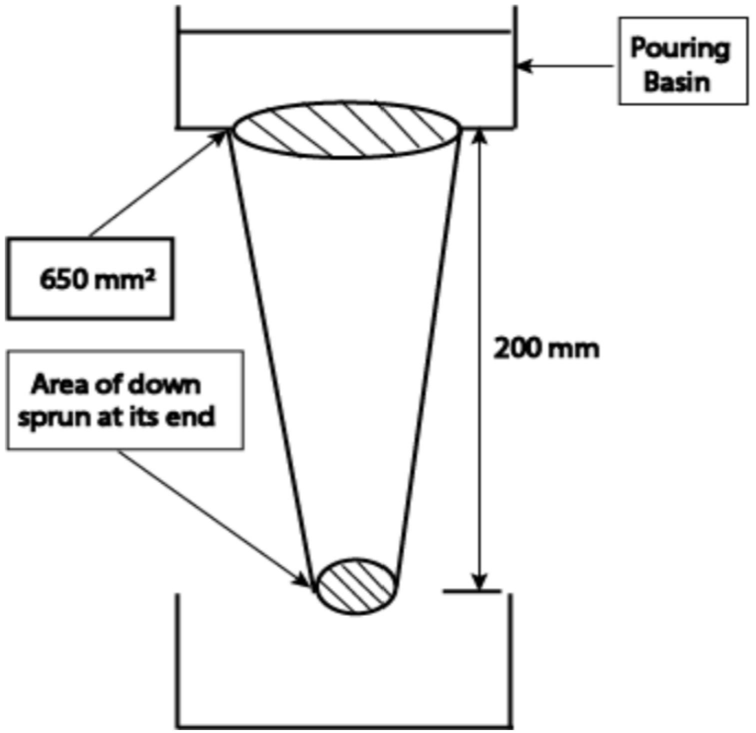
Time required to fi ll a mold cavity

$$T_{MF} = 1560/495 = 3.2 \text{ s}$$

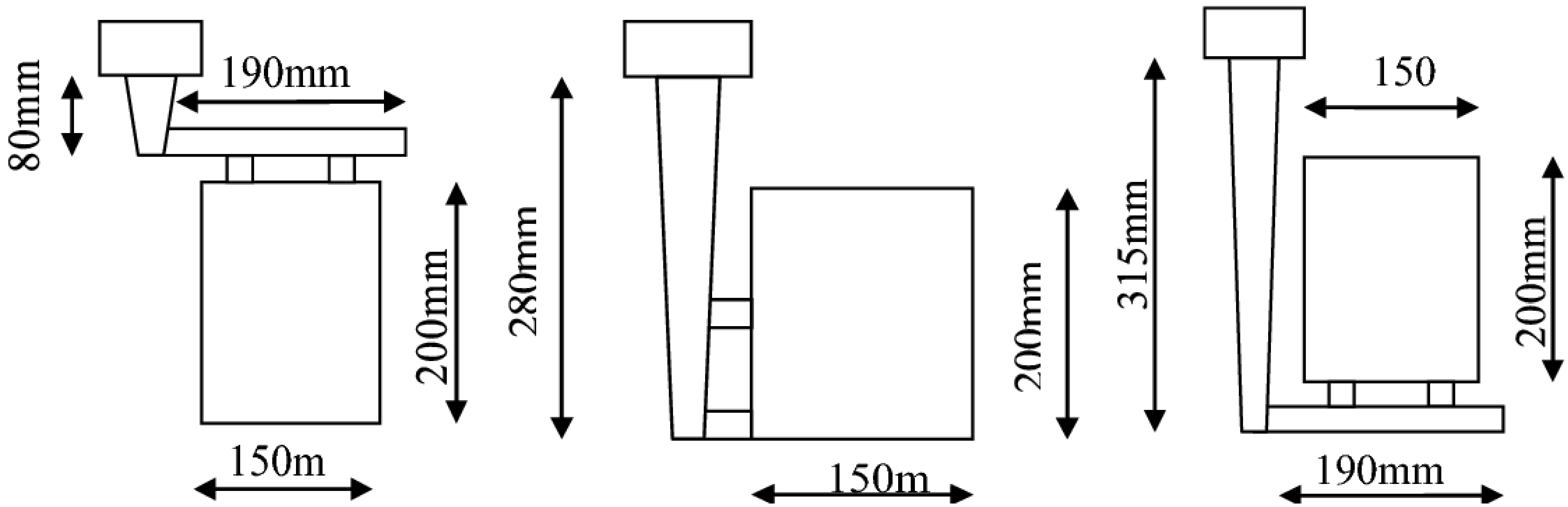
1. The downsprue leading into the runner of a certain mold has a length = 175 mm. The cross-sectional area at the base of the sprue is 400 mm^2. The mold cavity has a volume = 0.001 m^3. Determine (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow,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

v= 1853 mm/s V= **741,200 mm^3/s** T=**1.35 s**

A 200 mm long down sprue has an area of cross-section of 650 mm^2 where the pouring basin meets the down sprue (i.e. at the beginning of the down sprue). A constant head of molten metal is maintained by the pouring basin. The molten metal flow rate is $6.5 \times 10^5 mm^3/s$. Considering the end of down sprue to be open to atmosphere and acceleration due to gravity of $10^4 mm/s^2$, Determine the area of the down sprue in mm^2 at its end to avoid aspiration effect.



Types of Gating system



(a) Top Gating

(b) Side Gating

(c) Bottom Gating

Riser

- The risers in the top mold (the cope) serve as reservoirs to feed molten metal into the casting during solidification and to control and trap solidification shrinkage voids.
- Proper design (location, number, and size) of the risers is critical to prevent shrinkage voids in the casting.
- risers must provide metal feed into all the sections of the casting.
- The risers will be the last to solidify.

Design criteria for riser

- Total solidification of riser (TST_R) > Total solidification of casting (TST_C) ---> To avoid shrinkage voids
- Volume of riser (V_R< Volume of casting (V_C) ---> To improve casting yield

Chvornivo's rule can be used to determine the dimensions of riser

$$TST_R = B(V_R/A_R)^n$$

Where,
TST_R – total solidification time for riser
B – Mold constant
V_R – Volume of riser
A_R – surface area of riser
n = 2

A cylindrical riser must be designed for a sand-casting mold. The casting itself is a steel rectangular plate with dimensions 7.5 cm x 12.5 cm x 2.0 cm. Previous observation have indicated that the total solidification time (*TTS*) for this casting = 1.6 min. The cylindrical riser will have a diameter-to-height ratio = 1. Determine the dimensions of the riser so that its [*TTS* = 2 min].

Casting

1) casting (rectangular plate).

$$V_{casting} = 7.5 * 12.5 * 2 = 187.5\ cm^3$$

$$A_{casting} = 2\ [7.5 * 12.5 + 12.5 * 2 + 7.5 * 2] = 267.5\ cm^2$$

2) Use the *Chvorinov's Rule* to find the mold constant (C_m), by using the time of solidification ($T_{TS} = 1.6$ min).

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

$$1.6 = C_m \left(\frac{187.5}{267.5}\right)^2 \quad \Longrightarrow \quad C_m = 3.26\ \frac{min}{cm^2}$$

Riser

(Cylindrical shape)

$$V_{riser} = \frac{\pi \,.\, d^2 \,.\, h}{4} = \frac{\pi \,.\, d^3}{4}$$

$$A_{riser} = \pi \,.\, d \,.\, h + 2 \,.\, \frac{\pi \,.\, d^2}{4} = \frac{3\,\pi \,.\, d^2}{2}$$

$$\frac{V}{A} = \frac{\frac{\pi \,.\, d^3}{4}}{\frac{3\,\pi \,.\, d^2}{2}} = \frac{d}{6}$$

$$T_{TS} = C_m \left(\frac{V}{A}\right)^n \quad \Longrightarrow \quad 2 = 3.26 * \left(\frac{d}{6}\right)^2 \quad \Longrightarrow \quad d = 4.7 \ cm$$

$$V_{riser} = \frac{\pi \,.\, d^3}{4} = \frac{\pi}{4} \,.\, (4.7)^3 = 81.6 \ cm^3$$

It appears from the above calculation that the volume of the riser is approximately equal to [43.5 %] of the casting volume. This riser volume can be considered as a waste material which can be melting and used again for another casting.