



**ME 333**

# Manufacturing Processes II



## Chapter 2 Foundry Processes

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- **Foundry processes (*döküm prosesleri*)** consist of making **molds (*kalıp*)**, preparing and melting metal into the molds, cleaning **castings (*döküm*)**, and reclaiming the sand for reuse.
- **Founding (casting)** is the process of forming objects by putting liquid or viscous material into a prepared mold or form. Solidification generally takes place by cooling (in case of metallic materials) although it may not be necessary in case of some plastics.
- **A casting (*döküm*)** is a part (an object) formed by allowing the material to solidify. In other words, casting is the product of foundry, which may vary from a fraction of a gram to several tons. Almost all metals and alloys can be cast.
- **A foundry (*dökümhane*)** is a collection of all necessary material and equipment to produce a casting.

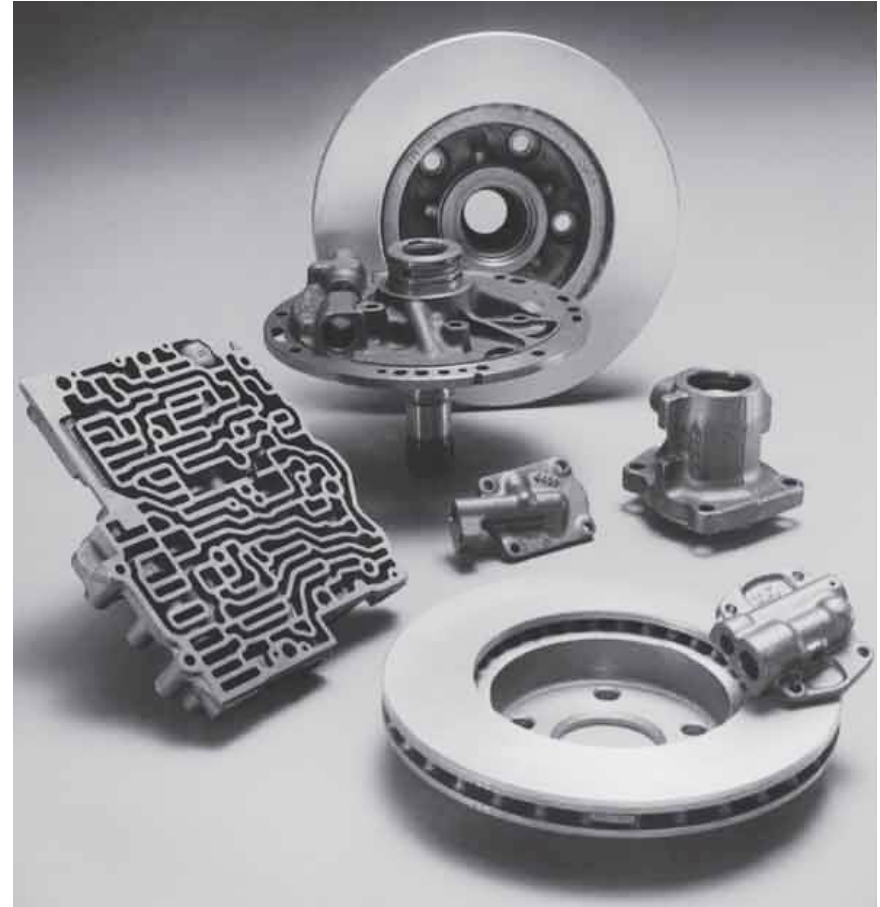


## Advantages

- ☺ Complex shapes
- ☺ Net-shape ability
- ☺ Very large parts
- ☺ Variety of metals
- ☺ Mass production

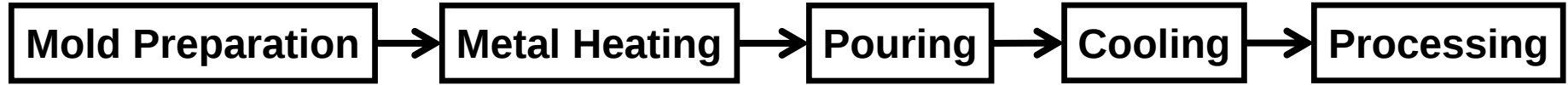
## Disadvantages

- ☹ Poor accuracy
- ☹ Poor surface
- ☹ Internal defects
- ☹ Mechanical properties
- ☹ Environmental impact

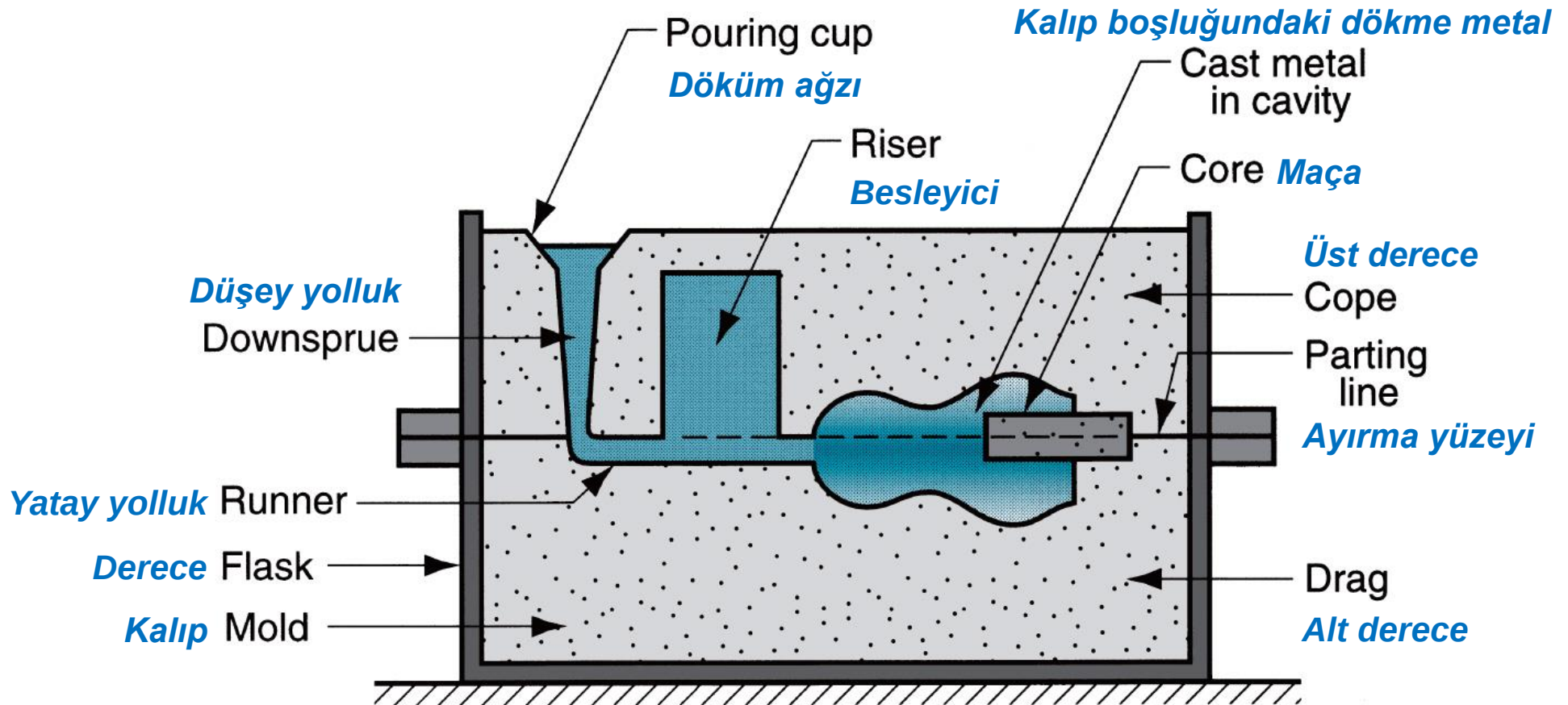




- Casting technology involves the following steps:

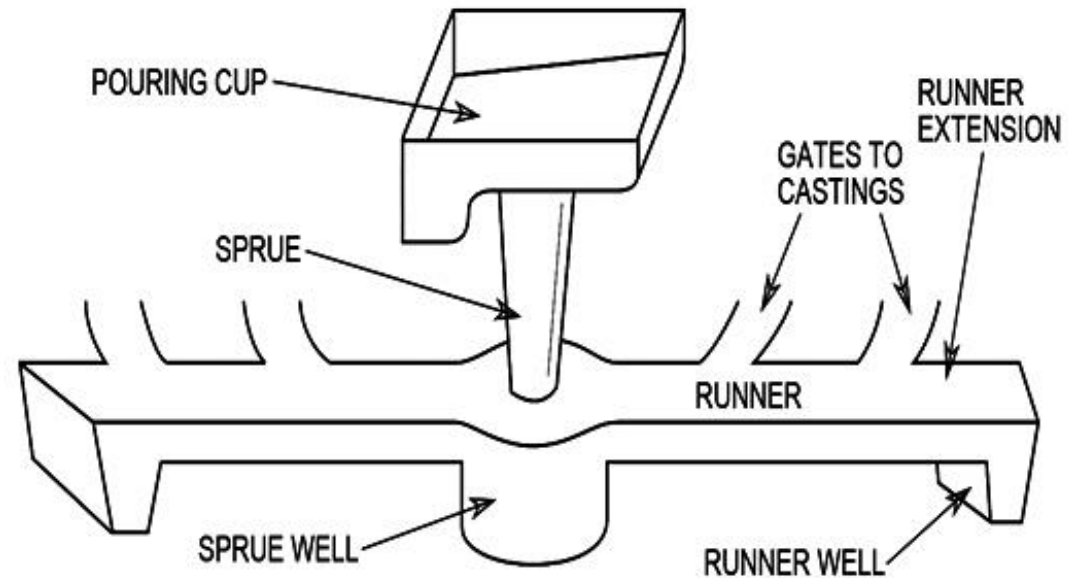


- The figure below shows the nomenclature of mold and castings in sand casting:





- **Pouring cup, downsprue, runners and others** are known as **mold gating system**, which serves to deliver the molten metal to all sections of the mold cavity.





- To understand the foundry process, it is necessary to know how a mold is made and what factors are important to produce a good casting.
- The following elements that are necessary for the production of sand casting will be considered throughout this chapter:

**1. Mold**

**2. Pattern**

**3. Core**

**4. Molding procedure**

**5. Sand**

**6. Properties of cast liquid**

**7. Behavior of cast material**



- **A mold (*kalip*)** is the container that has the cavity of shape to be cast. It is made of metal, plaster, ceramics, or other refractory substances. Good castings can not be produced without good molds.
  
- There are two types of molds:
  - 1. Permanent Mold:** A mold that is used more than once. They are generally produced from metallic materials such as **heat resisting (Ni-Cr) steels**.
  
  - 2. Expendable Mold:** A mold that is used only once, then destroyed to separate the part. They are generally produced from sand. **For casting of ferrous materials**, we have to use this type of mold since **their melting points are very high**.



➤ There are several types of expendable molds, but **we will deal with sand molds only**:

**a) Green Sand Mold:** The most common type consisting of forming the mold from **damp molding sand (silica, clay and moisture)**.

**b) Skin-dried Mold:** It is **done in two ways**: **(1)** Sand around the pattern to a depth of about 1/2 inches (10 mm) is mixed with a binder so that when it is dried it will leave a hard surface on the mold. **(2)** Entire mold is made from green sand, but a spray or wash, which hardens when heat is applied, is used.

**c) Dry Sand Mold:** It is made entirely from fairly coarse molding sand, mixed with binders such as **linseed oil (*bezir yağı*)** or **gelatinised starch (*nişasta*)**. They are baked before being used. A dry sand mold holds its shape when poured, and it is free from gas problems due to moisture.



➤ A mold should have the following characteristics:

- The mold **must be strong enough** to hold the weight of metal.
- The mold **must resist the erosive action** of rapidly flowing metal during pouring.
- The mold **must generate the minimum amount of gas** when filled with molten metal.
- The mold must be constructed in such a way that any gas formed can pass through body of the mold itself (i.e. **permeability**).
- The mold **must be refractory enough** to withstand high temperature of the metal.
- The mold **must collapse easily** after the casting solidifies.



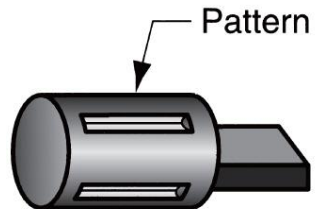
- **A pattern (*model*)** is a form **used to prepare and produce a mold cavity**. It is generally made from **wood** (which has the disadvantage of humidity absorption). Therefore, it can be produced from materials like **aluminum alloys** (which are low in density).
- Designer of a casting must look forward to the pattern to assure economical production. The design **should be as simple as possible** to make the pattern easy to draw from the sand and avoid more cores than necessary.
- The pattern **may be permanent**, so that it may be reused repeatedly. Alternatively, it **may be expendable (disposable)**, made up of a material that is melted out before or burnt up during casting.
- The pattern has some dimensional variations from the real component (i.e. casting). These variations are called **pattern allowances**.



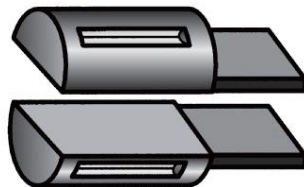
- One major requirement is that patterns (and therefore the mold cavity) **must be oversized**:
  - to account for shrinkage in cooling and solidification
  - to provide sufficient metal for the subsequent machining operation(s)

- **Types of patterns** used in sand casting:

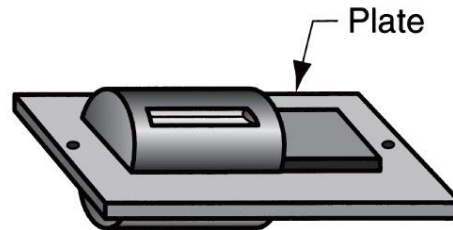
(a) solid pattern



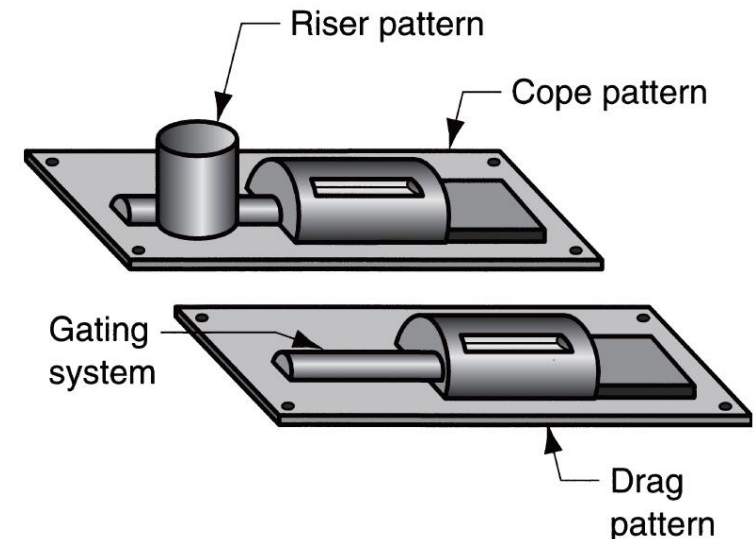
(b) split pattern

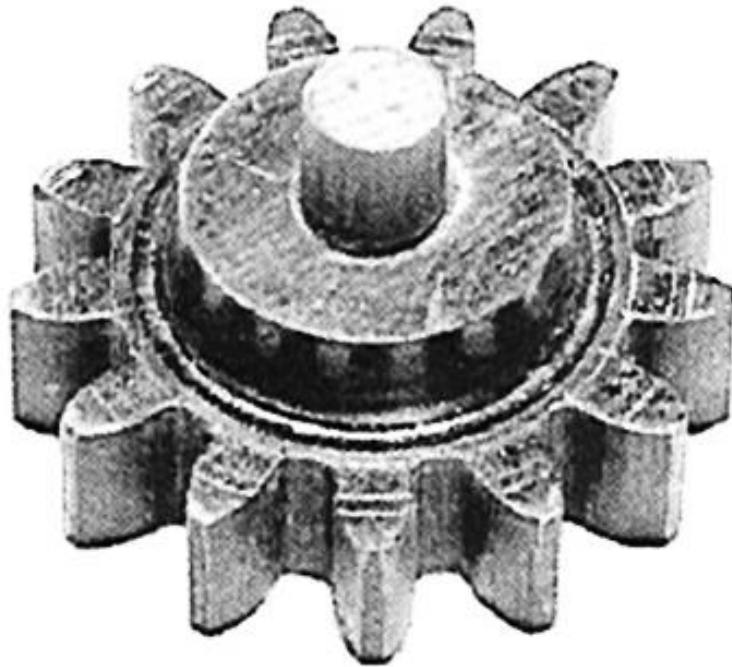


(c) match-plate pattern

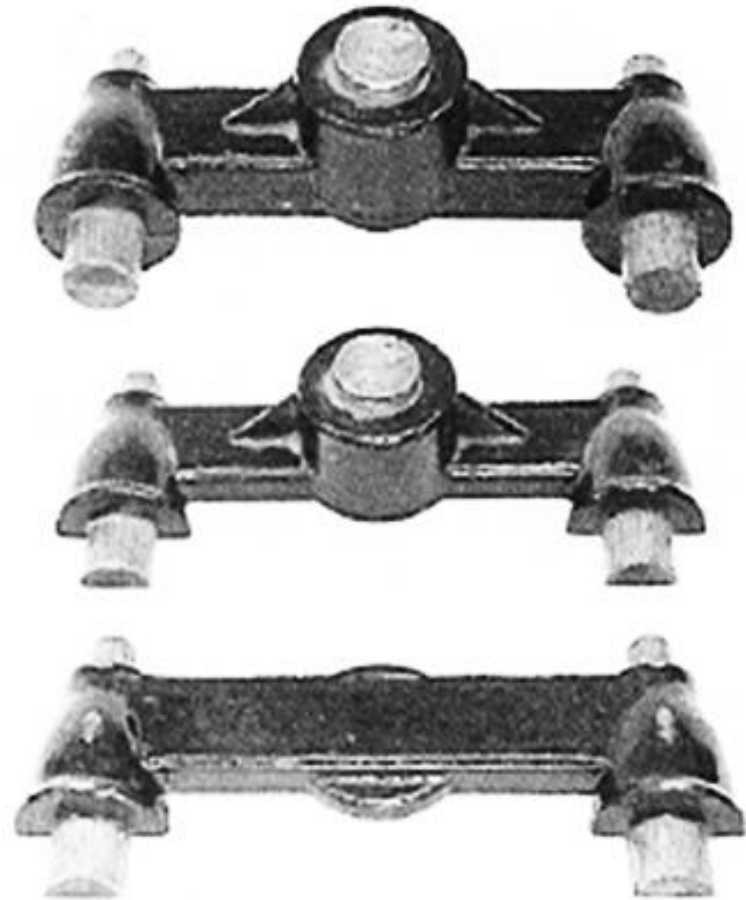


(d) cope-and-drag pattern





**Solid pattern** for a pinion gear



**Split pattern** showing the two sections together and separated. Light-colored portions are core prints.



- Shrinkage Allowance:** Shrinkage takes place in a volumetric way, but **it is given linearly**. Each dimension is measured with a shrinkage rule, which automatically gives shrinkage allowance (expressed as **in/ft**). When metal patterns are to be cast from an original master pattern, double shrinkage must be given.

|              | Cast Iron | Steel | Al   | Brass | Bronze    |
|--------------|-----------|-------|------|-------|-----------|
| <b>in/ft</b> | 1/8       | 1/4   | 5/32 | 3/36  | 1/8-1/4   |
| <b>%</b>     | 1.04      | 2.08  | 1.30 | 2.0   | 1.04-2.08 |

- Draft:** **The taper placed on sides of pattern on parting line**. Allows pattern to be removed from the mold without damaging sand surface. Added to dimensions on the parting line:

**Exterior dimensions:** 1/8 - 1/4 (in/ft), 1.04 - 2.08 (%)

**Interior dimensions:** As large as 3/4 (in/ft), 6.25 (%)

- Machining Allowance:** It is given on the working areas of part where further machining will be performed. In value, **it is equal to the shrinkage allowance**.

- Shake:** **Negative allowance is given** by making pattern slightly smaller to compensate for rapping (*takalama*) of the mold.

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## Volumetric Solidification Contraction or Expansion for Various Cast Metals

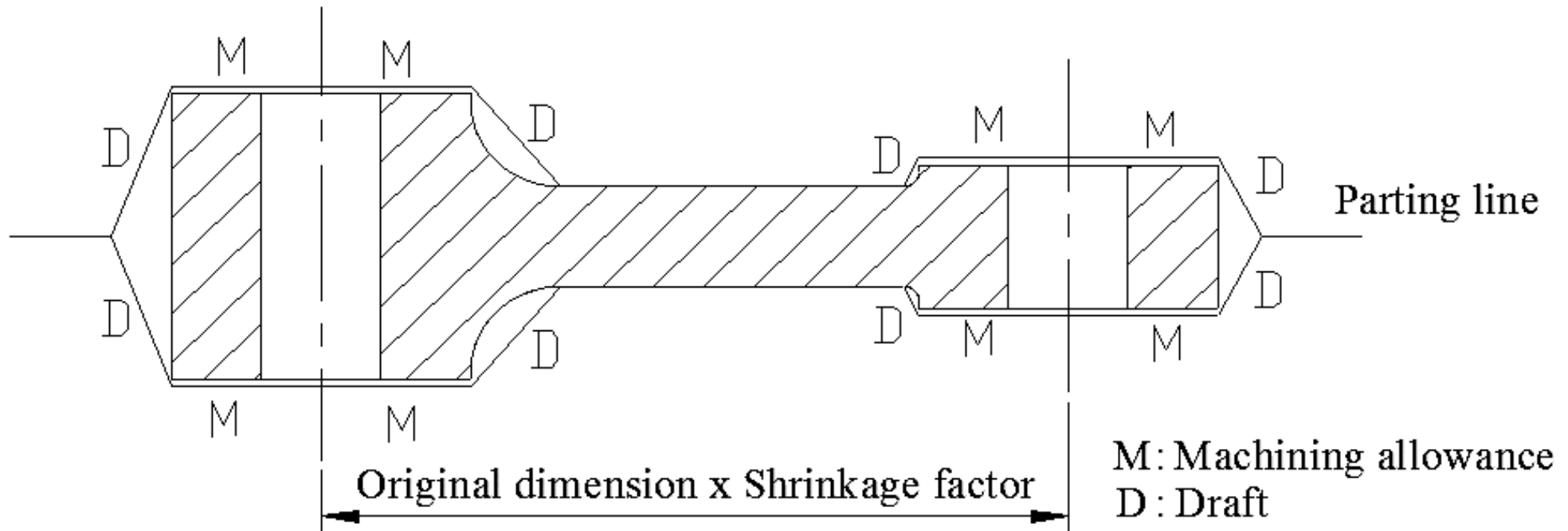
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| Contraction (%)     |       | Expansion (%) |     |
|---------------------|-------|---------------|-----|
| Aluminum            | 7.1   | Bismuth       | 3.3 |
| Zinc                | 6.5   | Silicon       | 2.9 |
| Al - Cu (4.5%)      | 6.3   | Gray Iron     | 2.5 |
| Gold                | 5.5   |               |     |
| White Iron          | 4-5.5 |               |     |
| Copper              | 4.9   |               |     |
| Brass (70-30)       | 4.5   |               |     |
| Magnesium           | 4.2   |               |     |
| Cu (90%) - Al (10%) | 4.0   |               |     |
| Carbon Steels       | 2.5-4 |               |     |
| Al - Si (12%)       | 3.8   |               |     |
| Lead                | 3.2   |               |     |

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- The following figure shows **pattern allowances** for a cast connecting rod:





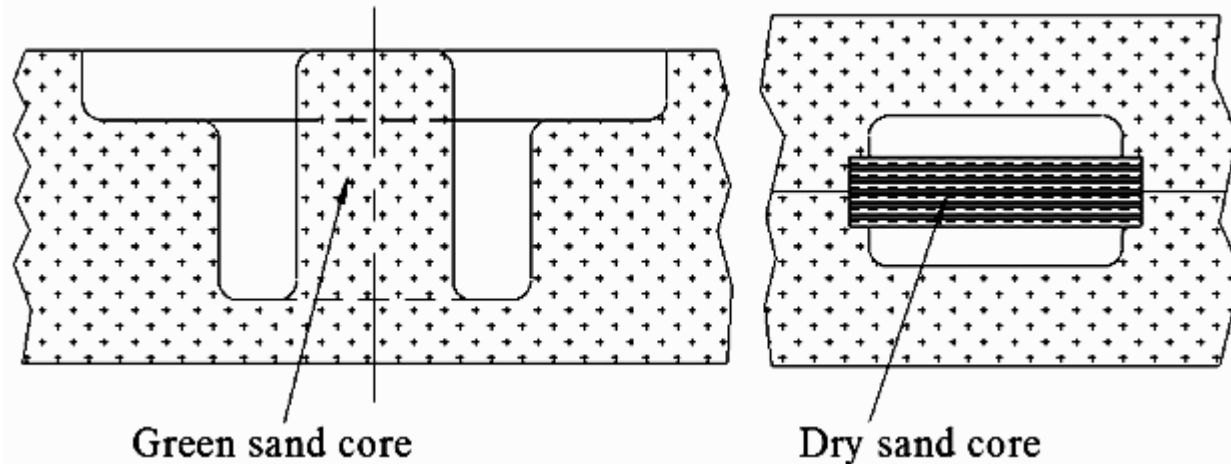
➤ **A core (*maça*)** is a body of material, usually sand, used to produce a cavity in/on a casting. A core must have sufficient strength to support itself and should not fracture when liquid metal is approaching to it.

➤ **Cores are classified as below:**

a) **Green-sand cores:** formed by the pattern and **made from the same sand** as rest of mold.

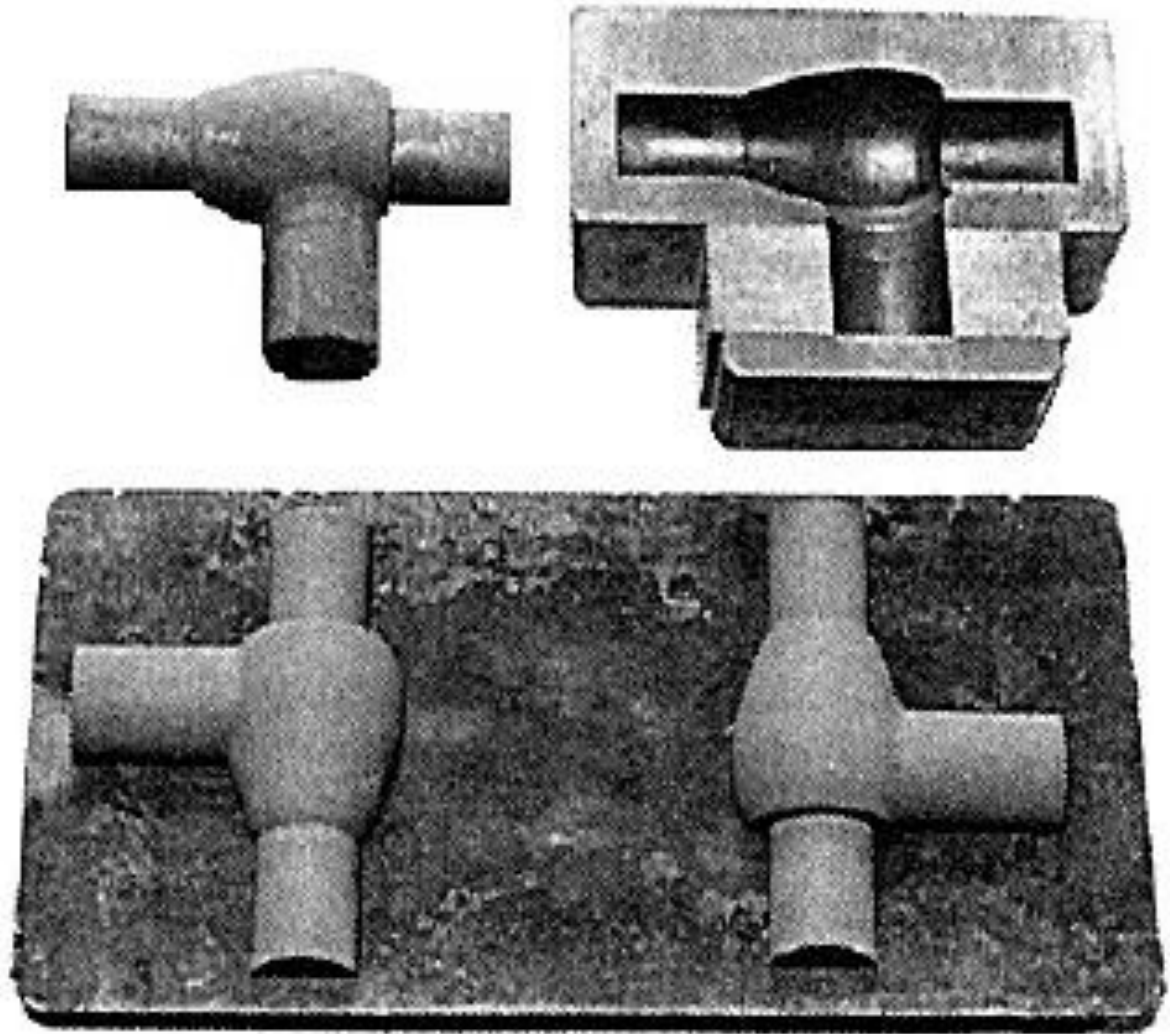
b) **Dry-sand cores:** made separately to be inserted after the pattern is drawn, but before mold is closed. They are **usually made of clean river sand (40 parts) which is mixed with a binder (1 part)** and then baked to give the desired shape.

➤ The most commonly used binder is **linseed oil (*bezir yağı*)**, which forms a film around sand grain and hardens when baked at 180-2200 °C for 2 hours. Others are wheat flour, dextrin, starch and some thermoset plastics.



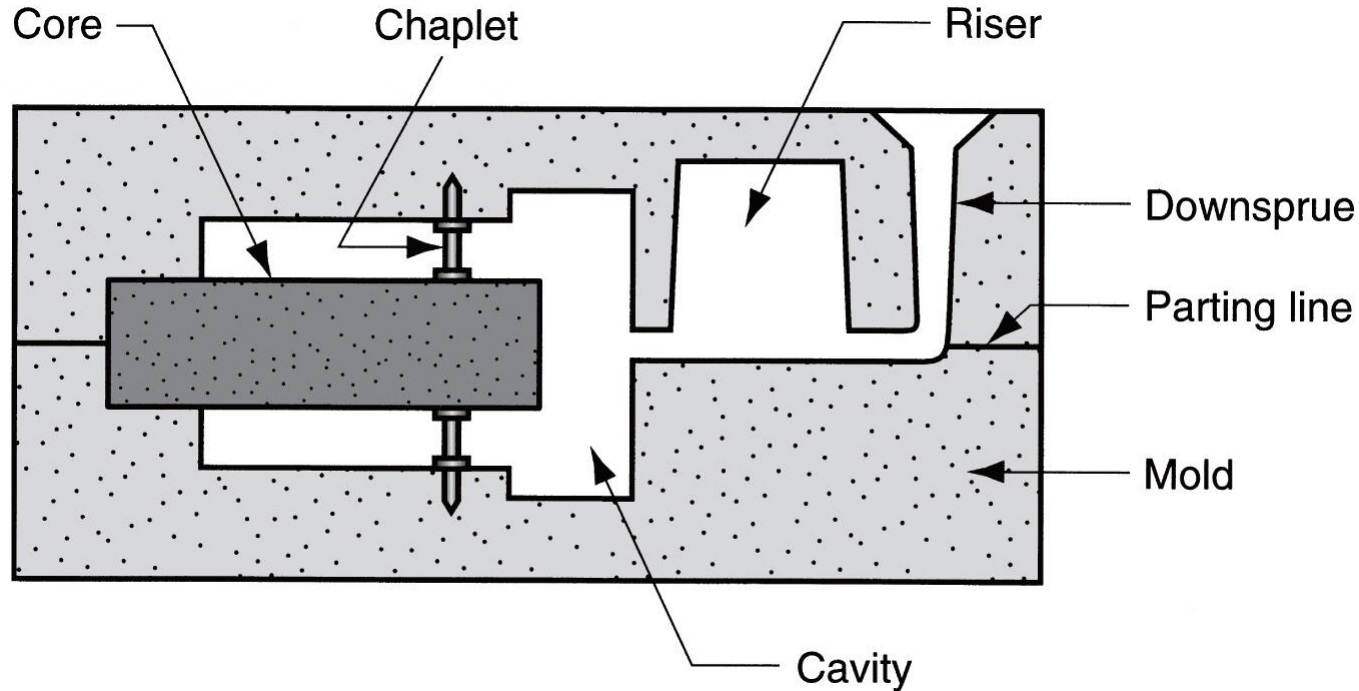


- **A core box (*maça kutusu*)** is the box in which the cores are formed to proper shape. They are **made of foundry sand with addition of some resin** for strength by means of core boxes.
- The figure shows a core box (two core halves ready for baking, and the complete core made by gluing the two halves together).

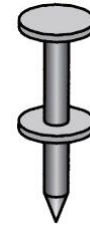




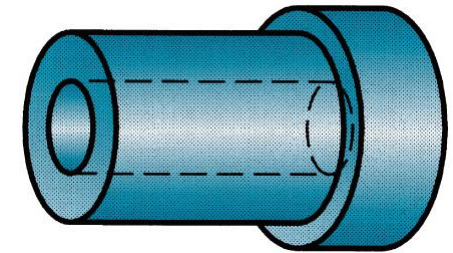
- In some cases, cores are supported by **chaplets** (*maça desteği*) for stable positioning.



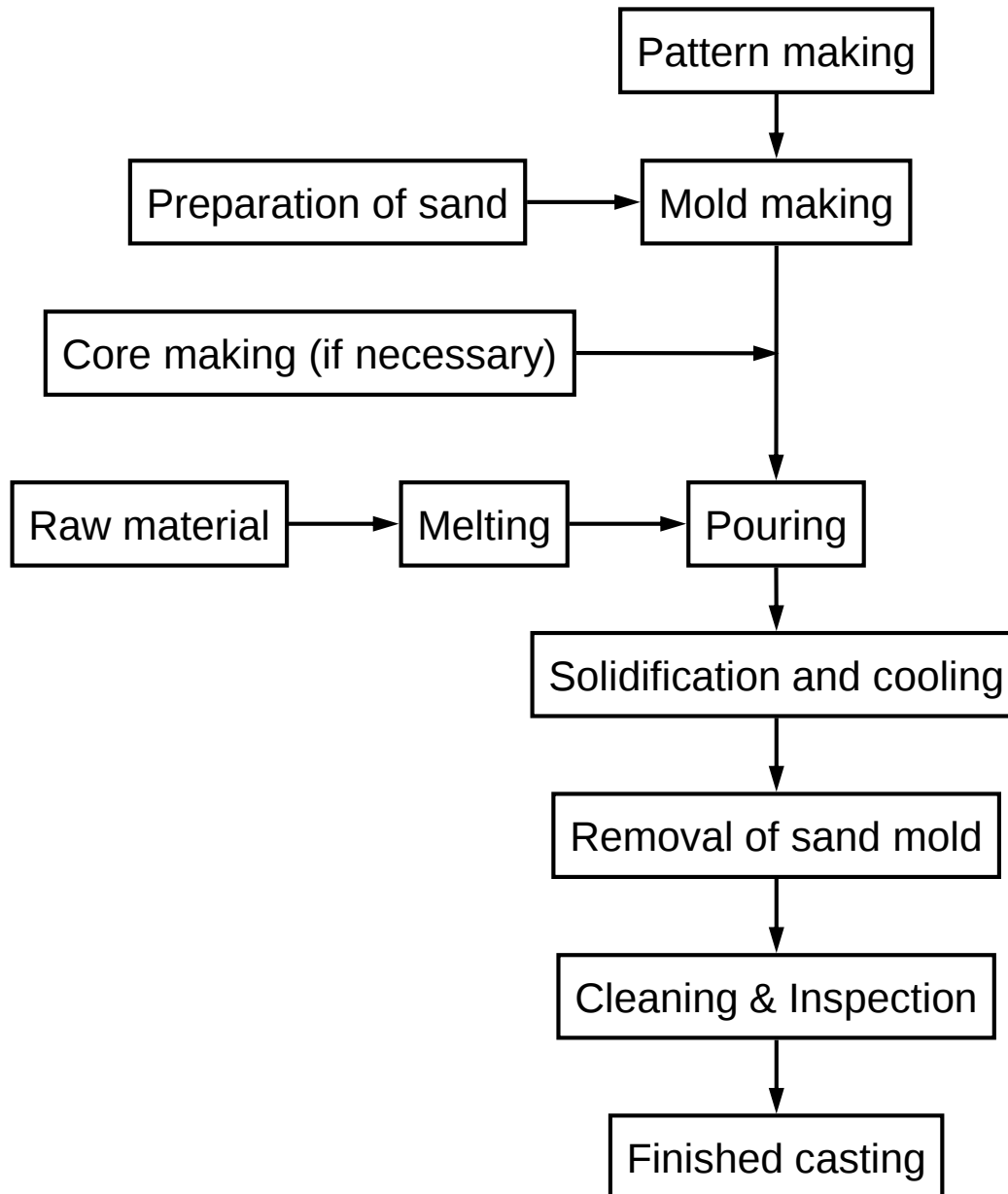
(a) Core held in place in the mold cavity by chaplets



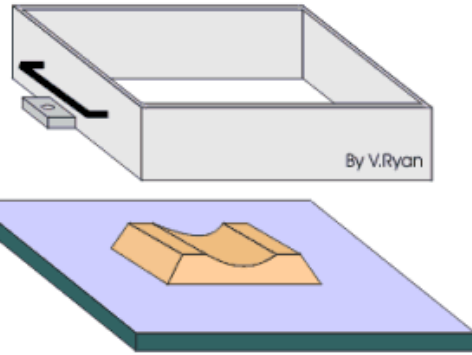
(b) chaplet design



(c) casting with internal cavity

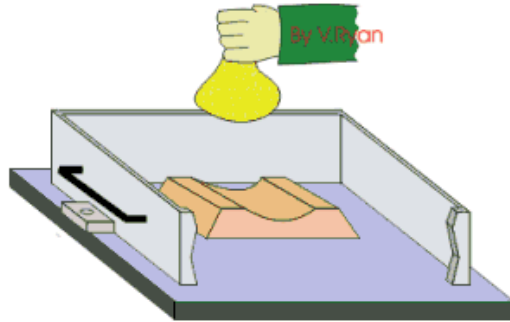


# Sand Casting Procedure



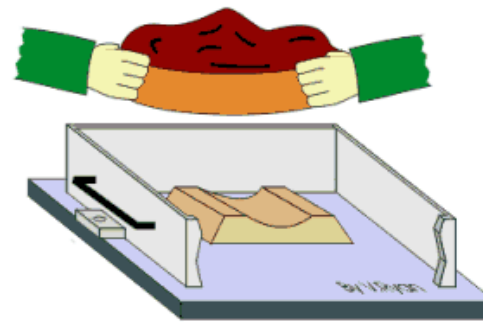
Place model on a base plate, and locate the drag

1



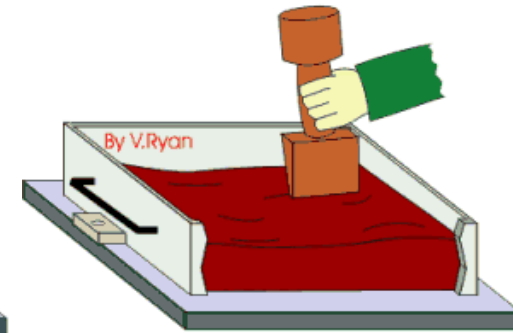
Sprinkle parting powder on the model

2



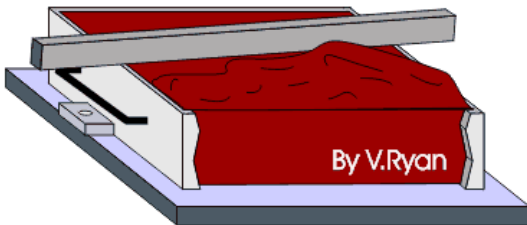
Shake the sand through a sieve

3



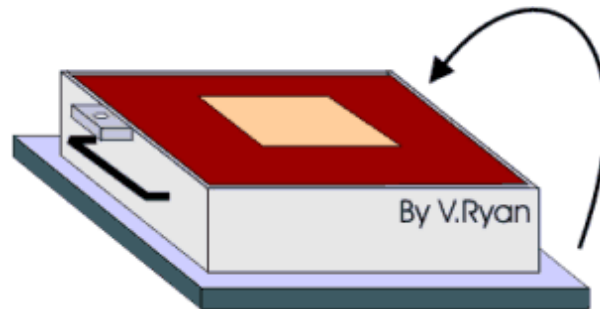
Pack the sand using a ram

4



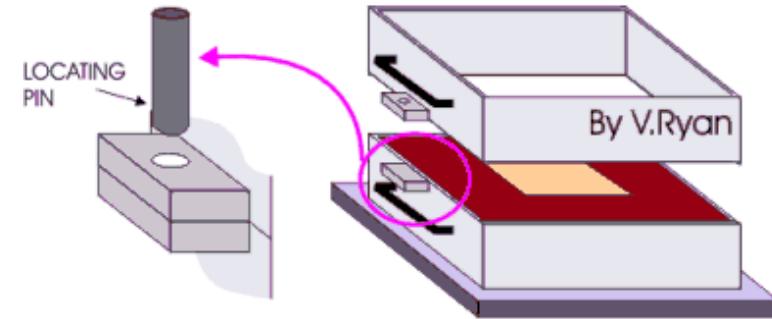
Level off the sand using a straight steel bar

5



Turn over the drag

6

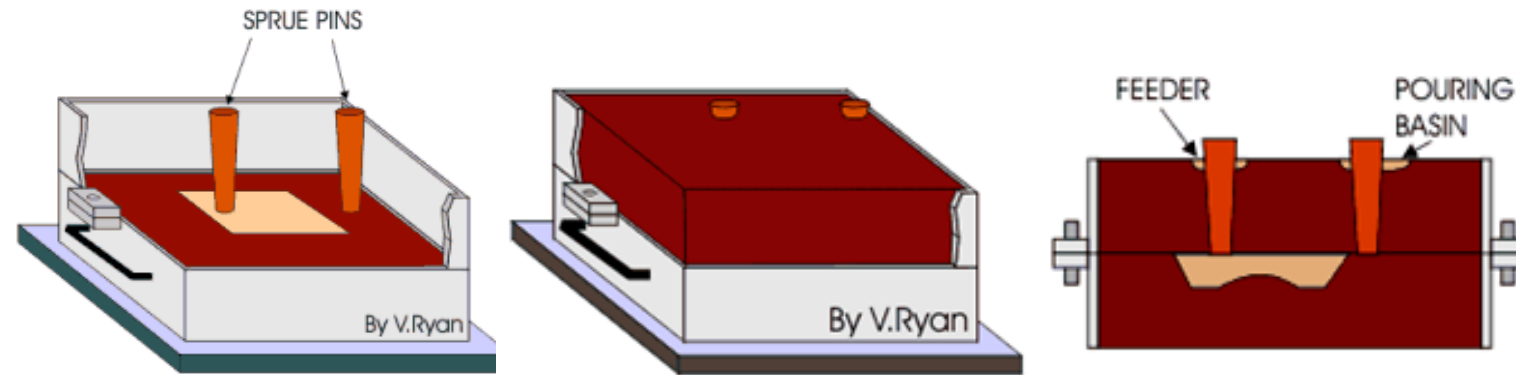


Locate the cope on the drag using locating pins

7

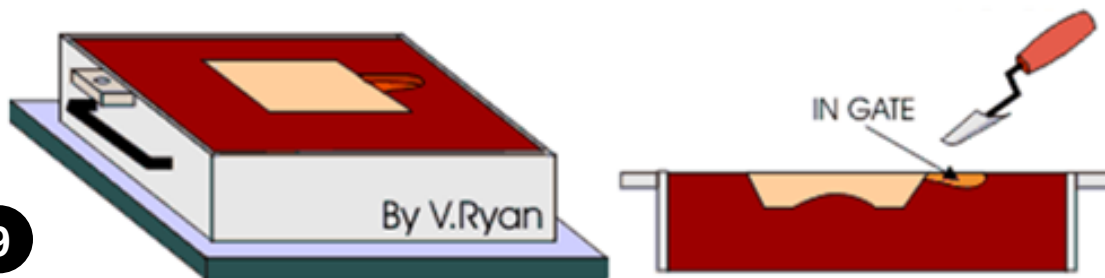
8

Position the sprue pins in the cope, add the sand, pack and level off (notice small depressions at the top of pins)



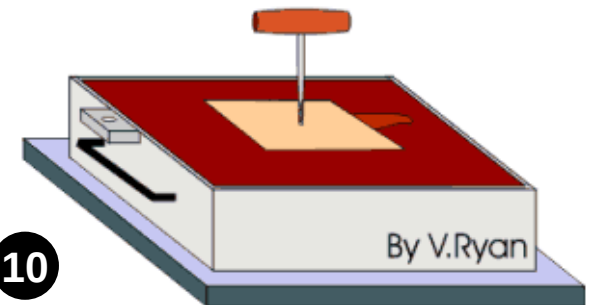
9

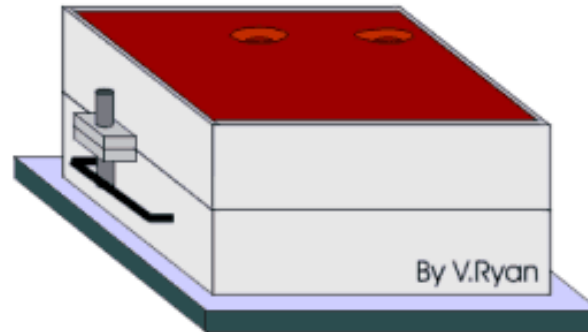
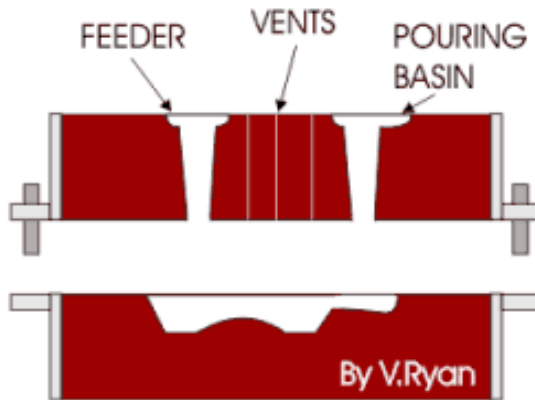
Remove the cope and cut a small gate on the drag surface (this will help the molten metal flow into the cavity)



10

Remove the pattern using a spike (end of spike can be threaded for easier removal of pattern)

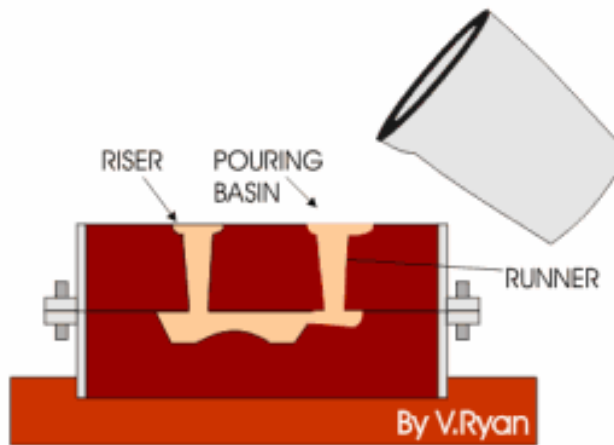




11

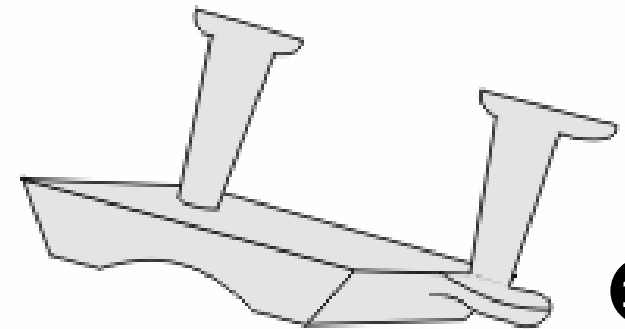
Make some vents in the cope (for allowing gases to escape during pouring of metal).

Then, place the cope on top of the drag using locating pins.



12

Pour the molten metal carefully through pouring basin (the excess metal will rise through riser)

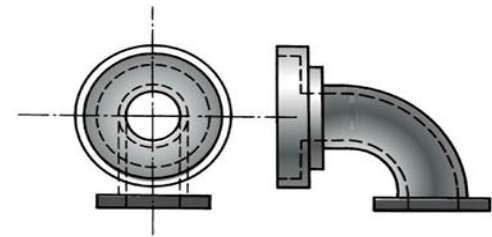


13

Once removed out of sand, cut away riser and runner; and then the casting will be ready for machining

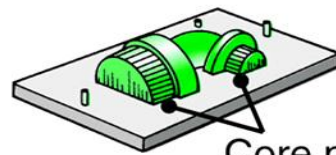
# Sand Casting - An Example with Core

Manufacturing Engineering and Technology (S. Kalpakjian, S.R. Schmid)



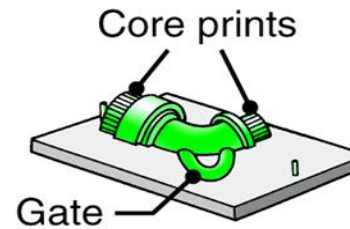
Mechanical drawing of part

(a)



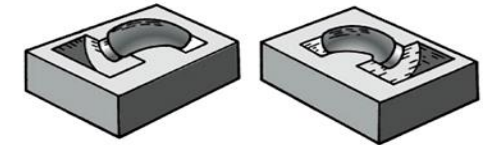
Core prints  
Cope pattern plate

(b)



Core prints  
Gate  
Drag pattern plate

(c)



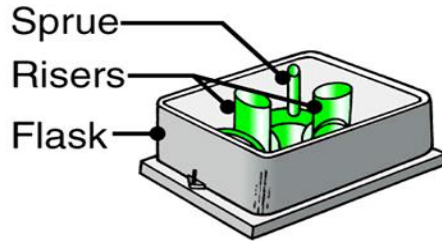
Core boxes

(d)



Core halves  
pasted together

(e)



Sprue  
Risers  
Flask

Cope ready for sand

(f)



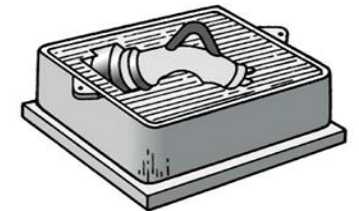
Cope after ramming  
with sand and  
removing pattern,  
sprue, and risers

(g)



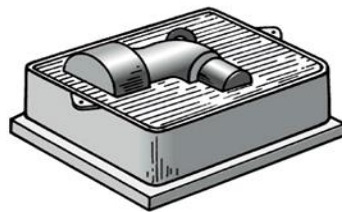
Drag ready  
for sand

(h)



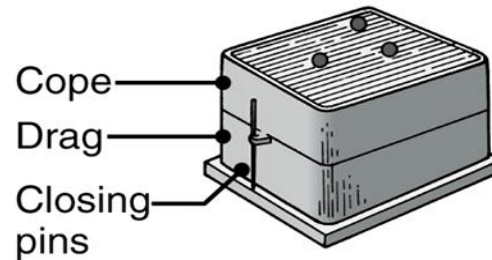
Drag after  
removing pattern

(i)



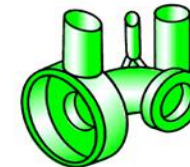
Drag with core  
set in place

(j)



Cope  
Drag  
Closing  
pins  
Cope and drag assembled  
and ready for pouring

(k)



Casting as removed  
from mold; heat treated

(l)



Casting ready  
for shipment

(m)



- **Silica sand ( $\text{SiO}_2$ )** is well suited for molding since it can withstand high temperatures without decomposition. It is cheap, has longer life, and available in wide range of grain sizes and shapes.
- Pure silica sand is not suitable in itself for molding as it lacks binding qualities. The binding qualities can be obtained by adding 8-15 % clay (*kil*).

|                                                     |                                                        |
|-----------------------------------------------------|--------------------------------------------------------|
| <b>Silica (<math>\text{SiO}_2</math>) + Binders</b> | ⇒ <b>Green Sand Mold</b>                               |
| Moisture 5-10%                                      | (used in castings of cast iron and non-ferrous alloys) |
| Clay 8-15%                                          |                                                        |

|                                                    |                              |
|----------------------------------------------------|------------------------------|
| <b>Silica (<math>\text{SiO}_2</math>) + Binder</b> | ⇒ <b>Dry Sand Mold</b>       |
| (40 part) Linseed Oil (1 part)                     | (used in castings of steels) |

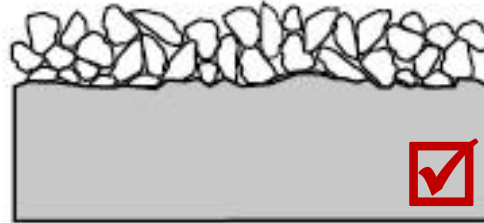
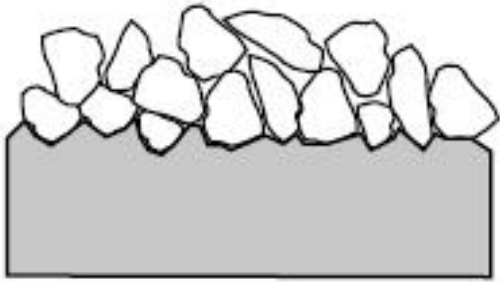
*Dry it first and then bake at 180-2200 °C for 2 hours.*



- **Synthetic molding sands** are composed of washed, sharp grained silica to which 3-5 % clay is added. Less gas is generated with synthetic sands since less than 5 % moisture is necessary to develop adequate strength.
- The size of sand grains will depend on the type of work to be molded. For small and intricate castings, fine sand is desirable so that all details of the mold are brought out sharply. Sharp, irregular-shaped grains are usually preferred as they interlock and add strength to the mold.



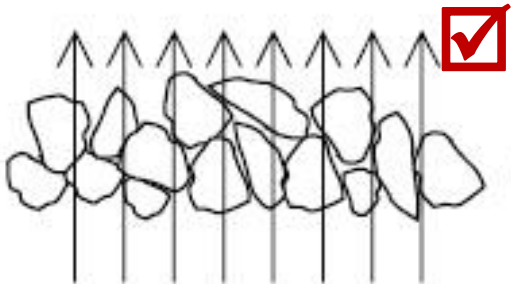
- **Foundry sands:** Typical foundry sand is a mixture of fresh and recycled sand, which contains **90% silica ( $\text{SiO}_2$ )**, **3% water**, and **7% clay**.
- Size and shape of grains are very important since they define the surface quality of casting and the major mold parameters such as strength and permeability:



**Smaller grain size** results in better surface finish



**Irregular-shaped grains** produce stronger mold



**Larger grain size** ensures better permeability

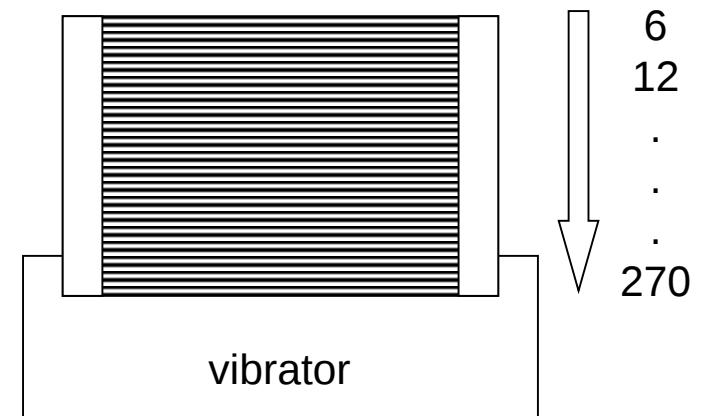


➤ Periodic tests are necessary to determine the essential qualities of foundry sand. Various tests are designed to determine the following properties of molding sand:

**a) Hardness Test (Mold Hardness):** A spring-loaded (2.3 N) steel ball (5.08 mm in diameter) is pressed onto surface of the mold, and **the depth of penetration is recorded as hardness**. Medium hardness is about 75.

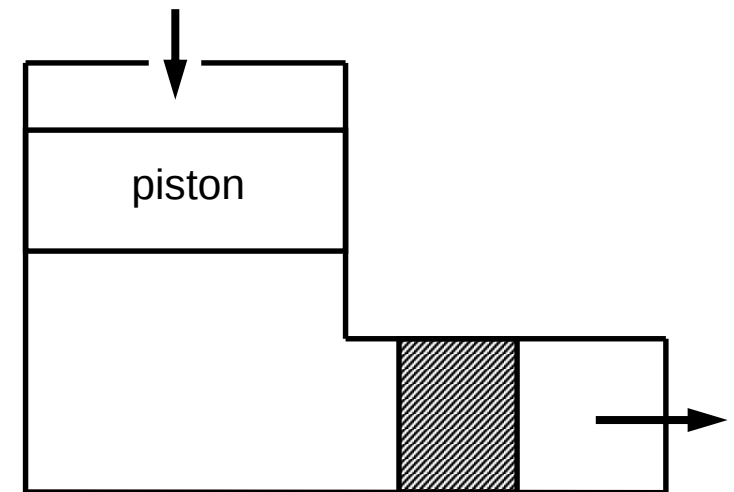
**b) Fineness Test:** It is used to obtain **the percentage distribution of grain sizes in the sand**. Sand is cleaned and dried to remove clay. Then, it is placed on graded sieves, which are located on a shaker. Standard sieve sizes (mesh) are: 6,12,20,30,40,50,70,100,200,270. Shaking time is 15 minutes.

**c) Moisture Content:** Measure weight of the given sand sample. Dry it around 1000 °C, and then weigh it again. **Calculate the percentage.**





- d) Clay Content:** A sample of sand is dried and weighed. Then, clay is removed by washing the sand with caustic soda ( $\text{NaHO}$ ) that will absorb the clay. Sand is dried and weighed again. **The percentage gives the clay content.**
- e) Strength Test:** **The most commonly used compression test.** A universal strength tester loads a specimen (50 mm long & 50 mm in diameter) by means of dead weight pendulum with a uniform loading rate.
- f) Permeability:** It is measured by **the amount of air that passes through a given sample of sand** in a prescribed time under standard pressures.
- g) Refractoriness Test:** **High-temperature withstanding ability** of sand is measured.

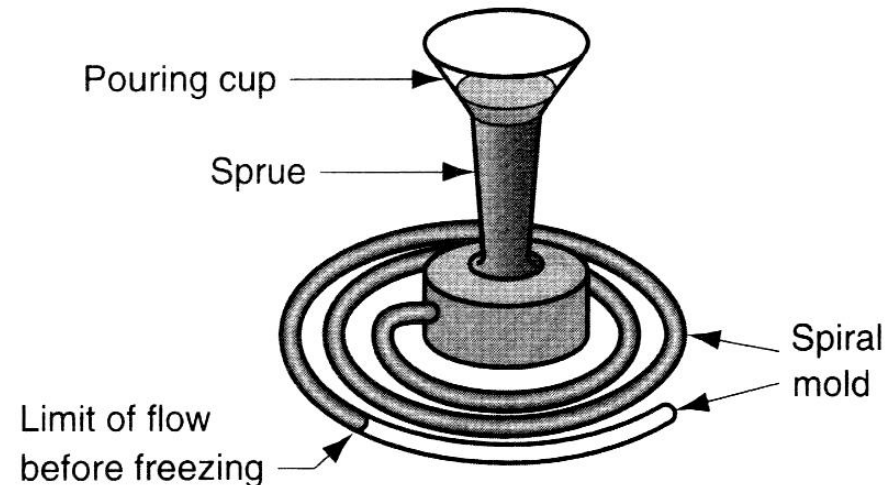




➤ Properties of castings depend on foundry skin as well as other material properties. Under similar foundry conditions, the properties will be affected by:

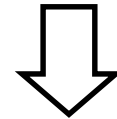
- a) **Viscosity of liquid metal:** It is a function of superheat that is **the degree of overheating above the melting temperature**. Lower viscosity is beneficial.
- b) **Surface Tension:** It **affects the wetting of inclusions** and also limits the minimum radius that can be filled without pressure (typically to 0.1 mm in cavity casting).
- c) **Oxide Films:** **Surface of liquid metal quickly oxidizes**, and metal act as if it is flowing in an envelope. Aluminum produces many problems due to quick formation of strong oxides.
- d) **Fluidity:** Both material and mold property. It is **a measure of the capability of a metal to flow into and fill the mold before freezing**. It defines, to the great extend, the quality of casting.

- **Fluidity is affected by:** pouring temperature, composition of metal, heat transfer to the surroundings, and viscosity of liquid metal.
- In the foundry practice, **fluidity test** is carried out for each ladle just before pouring the molten metal into the mold.





$$\begin{array}{ccccccc} \text{Heat energy required} & & \text{Heat for raising temp.} & & \text{Heat for fusion from} & & \text{Heat for raising temp.} \\ \text{for heating the metal} & = & \text{to melting point} & + & \text{solid to liquid} & + & \text{for pouring} \\ (H_{\text{total}}) & & (H_{\text{melting}}) & & (H_{\text{fusion}}) & & (H_{\text{pouring}}) \end{array}$$



$$H = \rho V \left\{ C_s (T_m - T_o) + H_f + C_l (T_p - T_m) \right\}$$

$H$  : Total heat required (J)

$\rho$  : Density (g/cm<sup>3</sup>)

$V$  : Volume of metal being heated (cm<sup>3</sup>)

$C_s$  : Weight specific heat for solid metal (J/g-°C)

$T_m$  : Melting temperature of metal (°C)

$T_o$  : Ambient (room) temperature (°C)

$H_f$  : Heat of fusion (J/g)

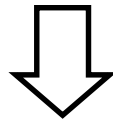
$C_l$  : Weight specific heat of liquid metal (J/g-°C)

$T_p$  : Pouring temperature (°C)



- **Bernoulli's theorem:** the sum of the energies (**head + pressure + kinetic + friction**) at any two points in a flowing liquid **are equal**:

$$h_1 + \frac{P_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{P_2}{\rho} + \frac{v_2^2}{2g} + F_2$$

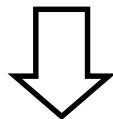


$P_1 = P_2 = 0 \rightarrow$  Atmospheric pressure

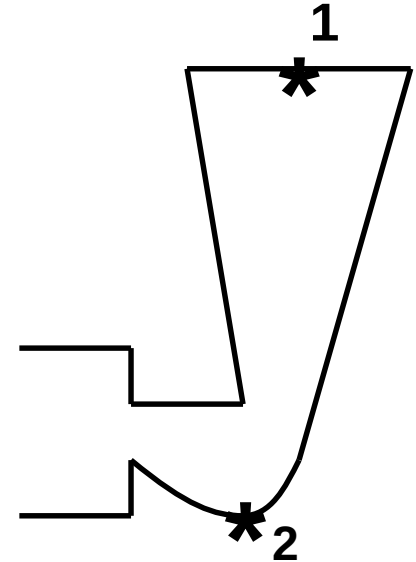
$F_1 = F_2 = 0 \rightarrow$  Neglected

$h_2 = 0 \rightarrow$  Base (Datum) point

$v_1 = 0 \rightarrow$  Speed at the beginning of pouring



$$h_1 = \frac{v_2^2}{2g} \Rightarrow v_2 = \sqrt{2gh_1}$$



$h$  : Head (cm)

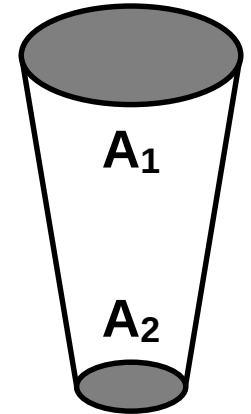
$\rho$  : Density (g/cm<sup>3</sup>)

$P$  : Pressure on the liquid (N/cm<sup>2</sup>)

$v$  : Flow velocity (cm/s)

$g$  : Gravitational acceleration (981 cm/s<sup>2</sup>)

$F$  : Head loss due to friction (cm)



➤ **Continuity Law:** the volume rate of flow remains constant

(The sprue is tapered, and thus the flow rate at top and bottom of the sprue are the same)

$$Q = v_1 A_1 = v_2 A_2$$

$Q$  : Volumetric flow rate (cm<sup>3</sup>/s)

$v$  : Flow velocity (cm/s)

$A$  : Cross-sectional area of liquid (cm<sup>2</sup>)

➤ We also assume that **the runner** from the base of sprue to the mold cavity is **horizontal** (i.e. the head is the same as at the sprue base). Thus, **the flow rate** through the gate and into the mold cavity **remains constant**.

➤ Therefore, **the time required to fill a mold cavity of volume** is estimated:

$$T_{MF} = \frac{V}{Q}$$

$T_{MF}$  : Mold filling time (s)

$V$  : Volume of mold cavity (cm<sup>3</sup>)

$Q$  : Volumetric flow rate (cm<sup>3</sup>/s)

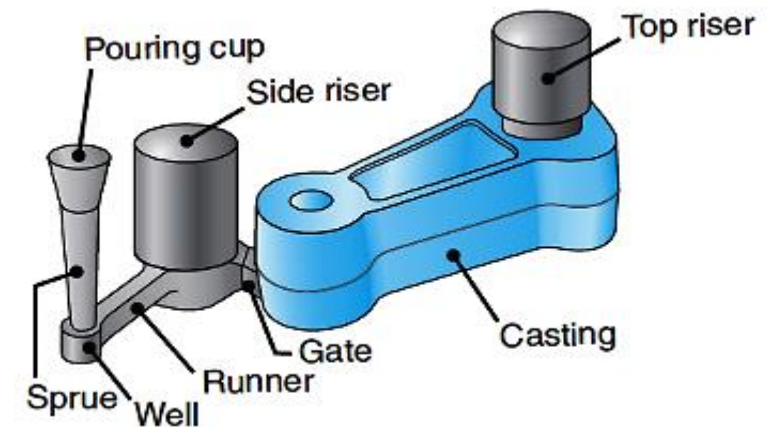
# Riser Design (Solidification and Cooling)



- Successful casting requires **proper riser design** to ensure adequate fluid flow in the system.
- **Risers serve as reservoirs**, supplying molten metal to casting as it shrinks during solidification.
- As mentioned before, **the riser must remain molten until the casting solidifies**.

| Riser design | Open | Blind |
|--------------|------|-------|
| Top          |      |       |
| Side         |      |       |

Possible types and positions for risers



Typical riser-gated casting



- **Chvorinov's Rule** gives time required for casting to solidify after pouring:

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

$T_{TS}$  : Total solidification time (min)  
 $C_m$  : Mold constant (min/cm<sup>2</sup>)  
(based on experimental data)  
 $V$  : Volume of the casting (cm<sup>3</sup>)  
 $A$  : Surface area of the casting (cm<sup>2</sup>)  
 $n$  : An exponent (usually equals to 2)

- Chvorinov's rule is used to obtain **the riser dimensions**. The following figure shows typical cooling curve for a pure metal during casting:

increase in  $V/A \rightarrow$  increase in  $T_{TS}$

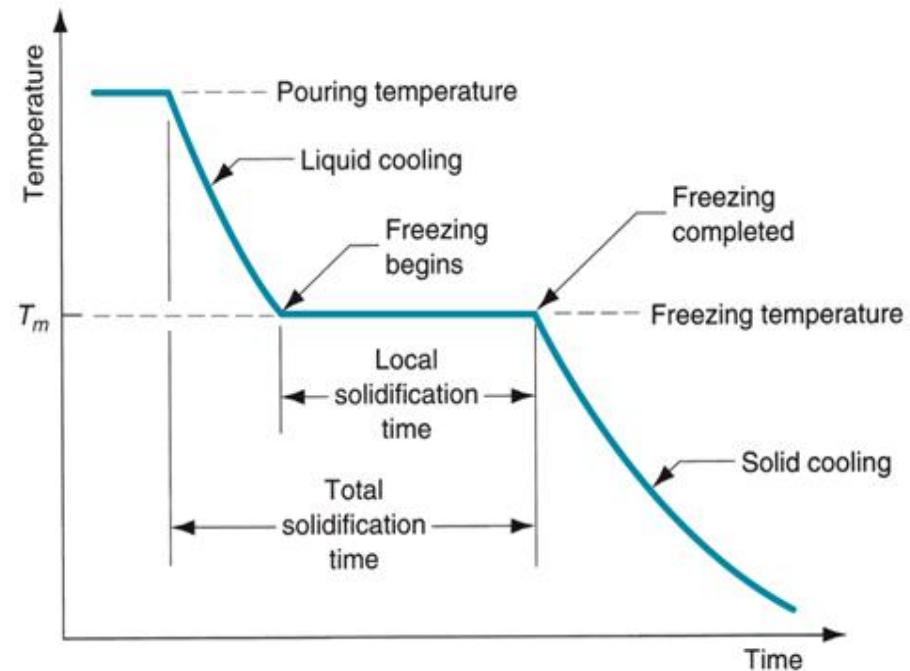


$$T_{TS} (\text{casting}) < T_{TS} (\text{riser})$$



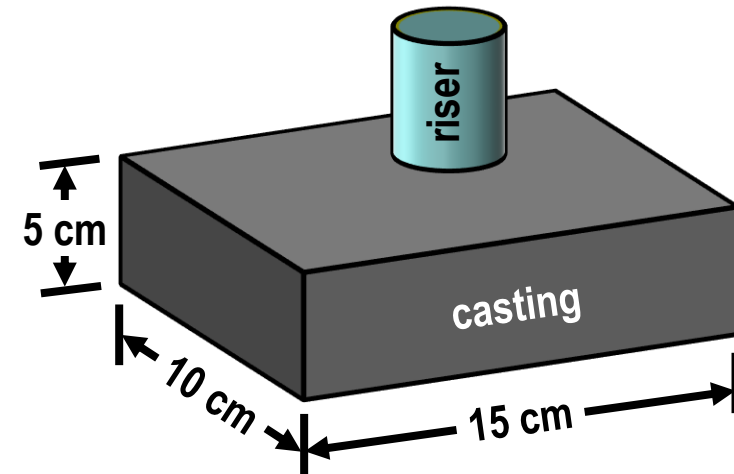
**Lower  $V/A$  is located away from risers**

(so that riser remains liquid until the casting solidifies)





A cylindrical riser (having equal diameter and length) will be designed for the casting, as shown in the figure. Previous observations showed that the total solidification time for this casting is 1.6 min. Determine the dimensions of riser so that its solidification time will be 2 min.



**Solution:** First, determine mold constant ( $C_m$ ) based on the casting data:

$$\left. \begin{aligned} V_c &= 15 * 10 * 5 = 750 \text{ cm}^3 \\ A_c &= 2(15 * 10 + 15 * 5 + 10 * 5) = 550 \text{ cm}^2 \\ (T_{TS})_c &= 1.6 \text{ min} \quad \& \quad n = 2 \end{aligned} \right\} T_{TS} = C_m \left( \frac{V}{A} \right)^n \Rightarrow C_m \cong 0.86 \text{ min/cm}^2$$

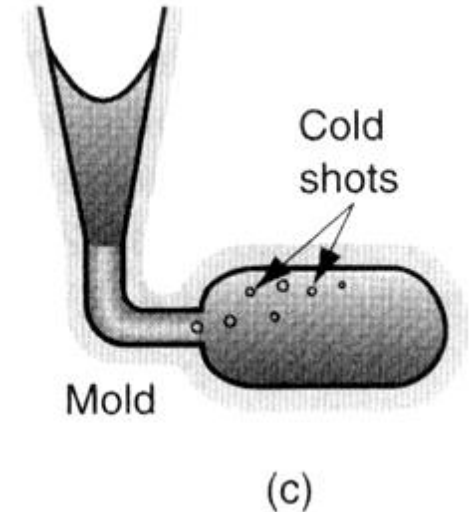
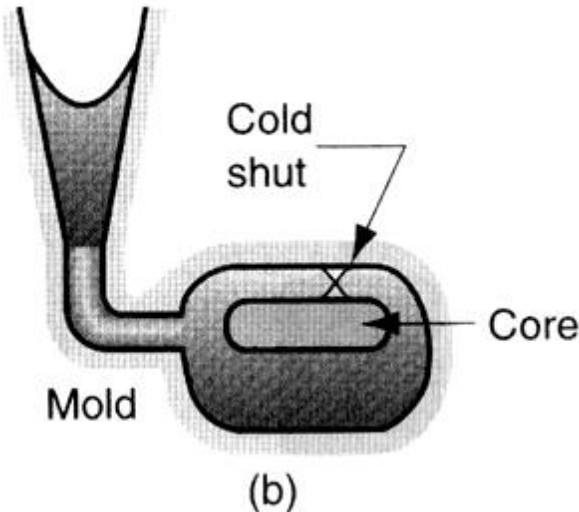
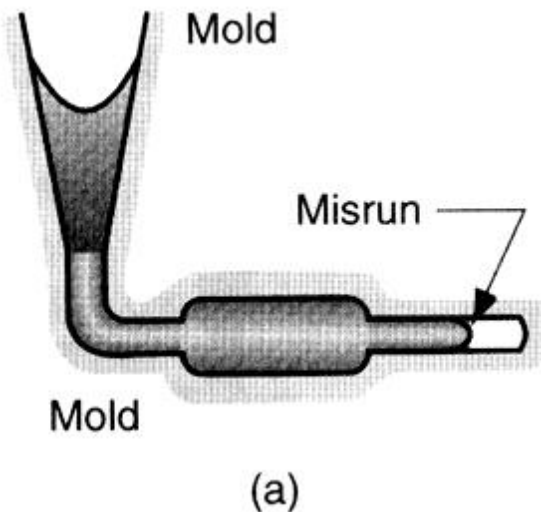
Next, determine the riser dimensions (note that  $D = h$ ):

$$\left. \begin{aligned} V_r &= \pi (D/2)^2 * h = \pi D^3 / 4 \\ A_r &= 2 \left[ \pi (D/2)^2 \right] + \pi D * h = 3\pi D^2 / 2 \\ (T_{TS})_r &= 2 \text{ min} \quad \& \quad n = 2 \quad \& \quad C_m = 0.86 \text{ min/cm}^2 \end{aligned} \right\} \frac{V_r}{A_r} = \frac{D}{6} \Rightarrow \boxed{D = h \cong 9.15 \text{ cm}}$$



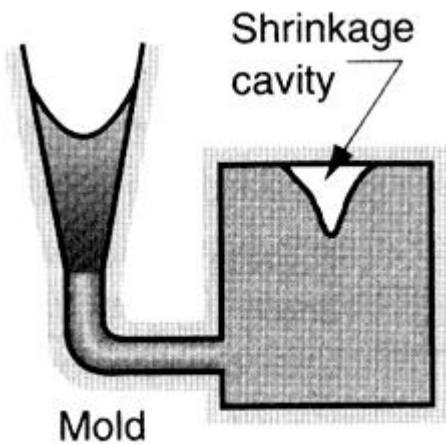
► Casting defects are developed depending on material, part design, processing technique. Some of them are **common to all casting processes**:

- a) **Misruns**: Casting solidifies before filling the mold completely. Causes are insufficient fluidity of molten metal, low pouring temp, slow pouring, and thin cross section of casting.
- b) **Cold shuts**: Two portions of metal flow together without fusion due to premature freezing. Causes are similar to those of a misrun.
- c) **Cold shots**: When splattering occurs during pouring, solid globules of metal are entrapped in the casting. Proper gating system designs could avoid this defect.

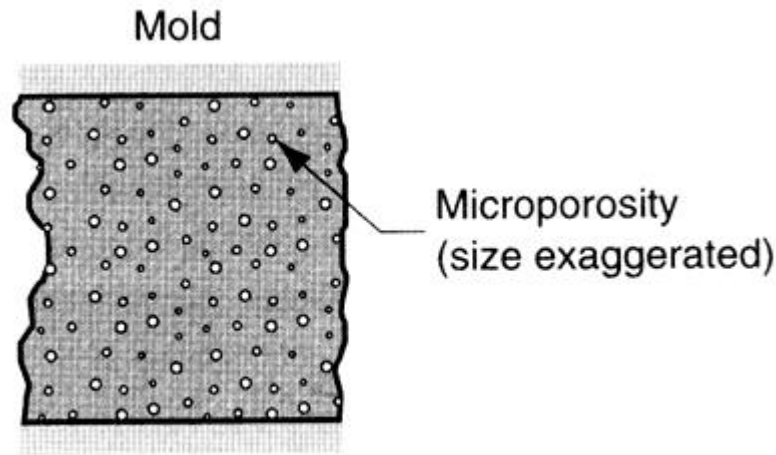




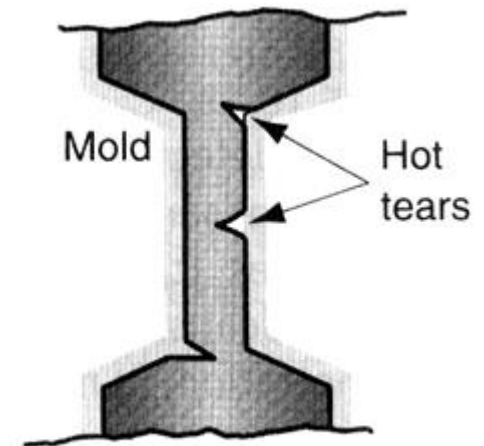
- d) **Shrinkage cavity:** Voids resulting from shrinkage. The problem can often be solved by proper riser design, but some changes may also be required in the part design.
- e) **Microporosity:** Network of small voids distributed throughout the casting. This occurs more often in alloys due to the manner that they solidify.
- f) **Hot tearing:** Cracks caused by low mold collapsibility. They occur when the material is restrained from contraction during solidification. Proper mold design can solve the problem.



(d)



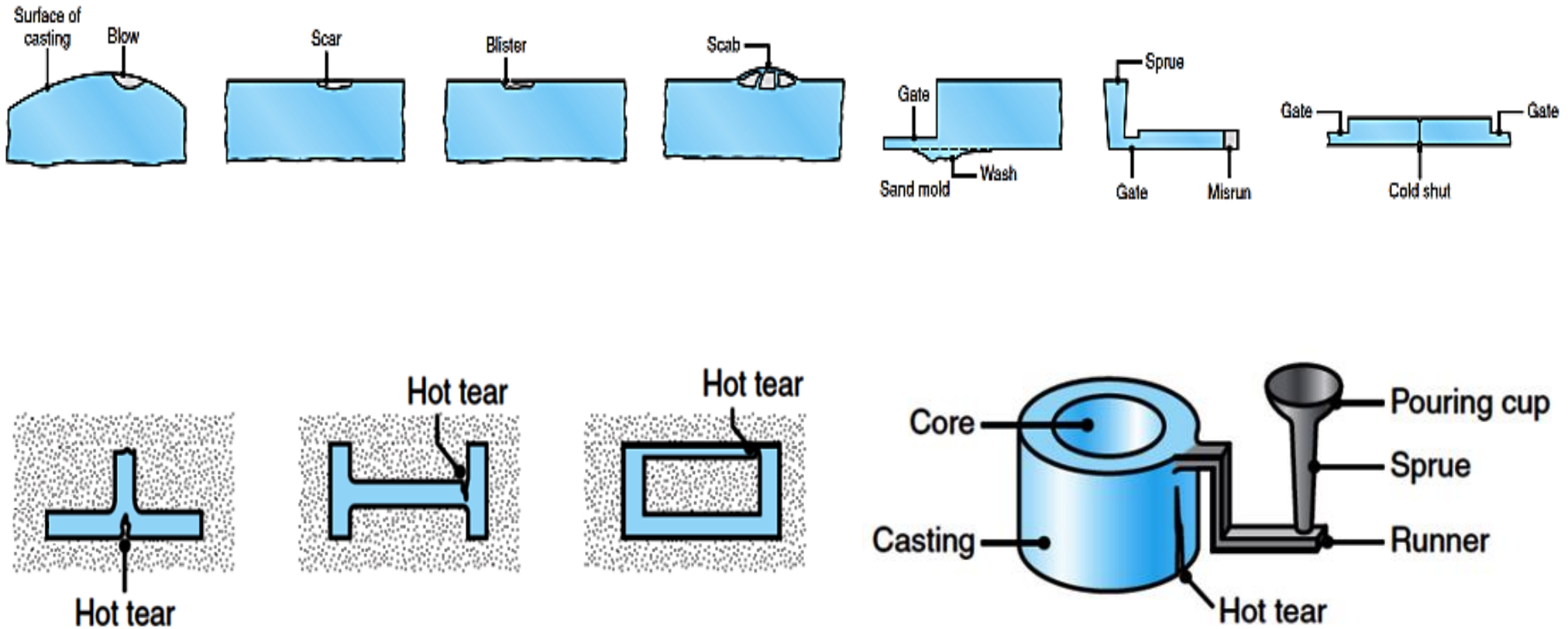
(e)



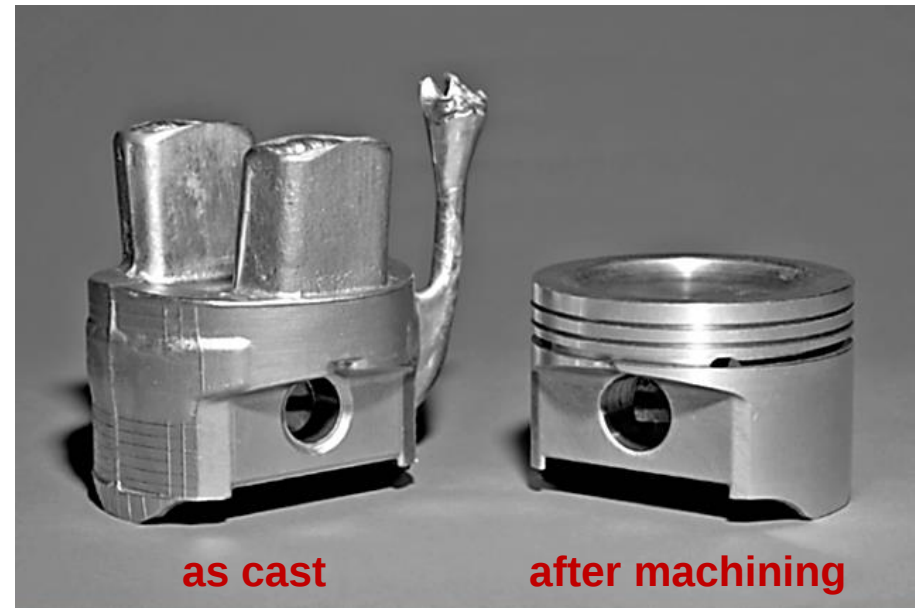
(f)

- Some defects occur only for **particular casting processes** (e.g. many defects occur in sand casting as a result of interaction between the sand mold and the molten metal). Defects found primarily in sand castings are: **gas cavities, rough surface areas, shift of two halves of the mold, shift of the core, etc.**

# Typical Casting Defects



# Casting of Aluminum Piston for Internal Combustion Engine



as cast

after machining

