

Basics of Mechanical Engineering-2

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Week 03

Lecture 10

Basics of Casting (Part 2 of 3)

Welcome to the second lecture on Castings. So, till now what we went through in Casting is Basics of Casting, Sand Casting. The casting process is understood in four stages: first, heating; then superheating; followed by Solidification; then Cooling; and finally, the finishing process. These are the four process generally which comes in Casting. The finishing process or the machining process is called a post-process for casting.

Then we looked into the need for riser process. What truly happens to the Grain, Grain Structure, Grain Growth in Casting? There is a big shift in understanding is required between Pure Metal Casting and Alloy Casting. Pure metal Casting had a freezing point start and freezing point end only one temperature. But whereas when it is an alloy, it will always be a slope.

So, that means to say there will be a range. So, moment there is a range, then what happens is, we use that range called as Mushy Zone. So, the mushy zone is where there is a possibility of a phase change happening. Above that, it will be liquid; in the mushy zone, it will be liquid plus solid; and in the Cooling zone, it will be exclusively solid. Two terminologies were introduced: local Solidification time and total Solidification time.

Contents



- Cooling and solidification
 - Pure Metals
 - Alloys
- Grain Growth & Distribution:
 - Pure Metal
 - Alloys
- Rate of solidification, etc
- To Recapitulate



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Friends, with that understanding, let us proceed further in understanding solidification. In this lecture, we will try to see pure metal alloy, cooling and solidification, then grain growth and distribution in pure and alloy, then finally we will try to look at the rate of solidification.

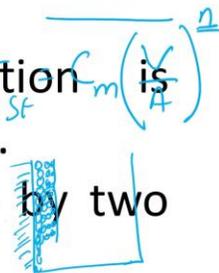
Solidification Mechanism

- There are a few methods by which ~~damages~~ due to shrinkage can be minimized.

Directional solidification

- The desired directional solidification is achieved by observing Chvorinov's rule.
- Directional solidification can be done by two methods

Liquid → Solid.
↑



➤ Providing risers

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Solidification mechanism. This is very important. There are a few methods by which damage due to shrinkage can be minimized.

So, where does this shrinkage come from? Shrinkage occurs when there is a liquid-to-solid transformation; the liquid for a slab may be reduced to a smaller slab. So, there is a shrinkage that comes into existence. So, shrinkage occurs during the liquid-to-solid transformation. If we want to balance this shrinkage, we must first understand directional solidification. The desired directional solidification is achieved by observing Chvorinov's rule.

What is Chvorinov's rule? Solidification time equals a mold constant V divided by A , all to the power of n , and by empirical formulas, n is assumed to be 2. We have seen V divided by A . Now, directional solidification can be done by two methods. There are several methods, but basically two: providing a riser or providing a chiller.

Riser—I am sure, friends, you will be able to connect it back. We saw the importance of V by A , for a riser. Remember, V by A for a riser, if the volume is large, area is small, then the V by A ratio is high, then the solidification time will be longer. The riser's function is to ensure that during solidification, it compensates for shrinkage. So, the moment it has to compensate, it must solidify last.

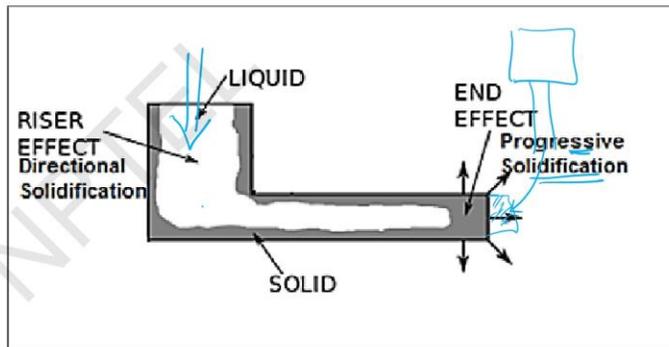
So, now we will try to use this as an advantage for Solidification. So, providing a riser is one way to achieve directional solidification, along with using a chiller. What is a chiller? Sorry, chills. Chills are materials added to the mold to extract heat faster, aiding in controlled solidification. When you extract the heat faster, you know the grains become equiaxial grains.

And depending on this extraction, you can try to thicken the layer of equiaxed grains. So, this is very, very important, equiaxed grains, right. So, chills are provided. Chills can be an integral part of the mold.

Directional Solidification

Providing risers

- It is desirable for the regions of the casting far away from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the location of riser.
- In this way, molten metal will continually be available from the risers to prevent shrinkage voids during freezing.



Providing riser. It is desirable for regions of the casting that are far away from the liquid metal supply.

Liquid metal supply happens from here, right? And you see, this is the end—where the volume is less and the surface area is more—so solidification occurs there. So, this solidification, which moves forward, is called progressive solidification. It is a desirable riser. Where do you put the riser?

It is desirable for the regions of the casting that are far away from the liquid metal supply to freeze first, allowing solidification to progress from those remote regions toward the location of the riser. So, now, solidification has started here. You may try to place a riser here so that it can supply molten metal into the mold. As this portion solidifies, additional material can flow from the riser to fill up the space. In this way, molten metal will continuously be available from the riser to prevent shrinkage voids during freezing. You also remember from the previous lecture that shrinkage occurs in various stages.

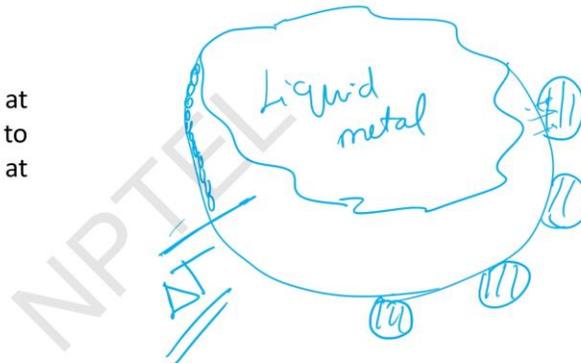
So, it is very simple. You pour the liquid metal, and as it travels through, it begins to freeze and solidify. Now, if it gets solidified, what happens to the furthestmost point in the mold? So, there will not be enough material. So, what we do is place the riser close to that area so that as solidification occurs, the remaining molten metal can flow in, ensuring a continuous solid part. This is, providing riser.

Directional solidification

Method 2:

Providing chills:

- Chills can be provided at appropriate locations to have rapid solidification at those points.
- There are two type
 - Internal chills
 - External chills



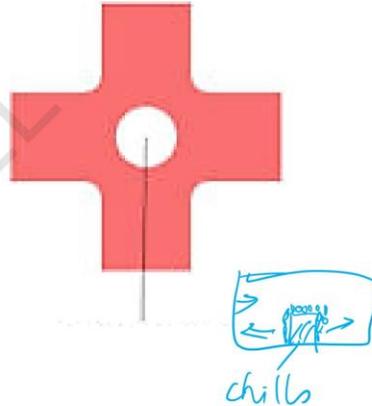
The second method is providing chills. Chills can be provided at appropriate locations to have rapid solidification at the point. For example, if you have a large area in the mold—let us assume something like this. Large area in the mold, where it is filled with liquid metal.

Now, it is going to take a lot of time for this metal to solidify, because the volume is large, surface area is small, So, it is very large, right. So, now, what we do is try to place these chills. These are inserts, something like this. These chills will try to extract heat. The moment they extract heat, solidification will start, and grains will begin to form.

Because the thermal gradient, the ΔT , should be very large for the grains to get formed. Chills can be provided at appropriate locations to have rapid solidification at these points. The chills can be of two types: internal chills or external chills. These are all external chills.

Internal Chills \Rightarrow Solidification $\Rightarrow T_{st} = C_m \left(\frac{V}{A}\right)^2$

- Small metal parts are placed inside the mould cavity before pouring.
- So that the molten metal will solidify first around these parts.
- The internal chill should have a chemical composition similar to the metal being poured.

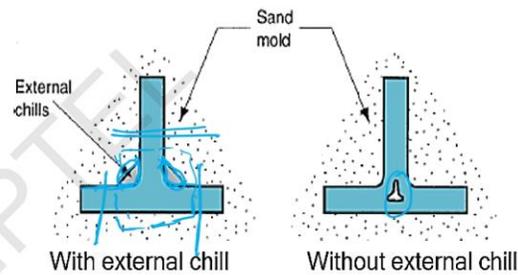


Internal chills, small metal parts are placed inside the mold cavity before pouring. So, you have a mold, and you place the chills here. These small metal parts are the chills. Small metal parts are placed inside the mold cavity before pouring. So, the molten metal will solidify first around this material and then start expanding further. For example, it will try to form equiaxial grains around this chill. From here, it will start expanding, and then, in parallel, it will start doing so.

So, what will happen is that such types of defects, whatever they are, which can occur without chills, can be avoided. The internal shell should have a chemical composition similar to that of the metal being poured, so it becomes an integral part of the part itself. These are very important for the internal shell. Basically, why are we doing it? So, we are trying to dictate the solidification. And, this follows Chernoff's rule. Solidification time is $C_m (V/A)^2$.

External Chills

- Chills are metal inserts placed in mold walls to rapidly extract heat, promoting localized solidification.
- They are primarily used in casting sections that are difficult to supply with molten metal.



External chills. So, as I told you, these are external chills. Because, when we look here, at this point where there is a change in the cross-section, the liquid metal will be larger.

When the liquid metal is large, So, then there will be taking lot of time for this part to solidify. By then, this portion will have solidified. Now, you see, the center portion will not solidify as easily. So, if it does not solidify, it leads to defects. So, now what we have to do is, parallelly, when the solidification happens at the smaller cross-section areas, we place the chill at the larger cross-section area.

This will extract heat. The chills are metal inserts placed in the mold walls to rapidly extract heat, promoting localized solidification. They are primarily used in casting sections that are difficult to supply with molten metals. So, if we do not put a chill, you will see that a void is formed. This void is nothing but a defect.

So, wherever it is possible, we try to place the riser. Wherever possible, we will try to place the riser. If there is a condition where it So, happens that you cannot use a riser, what we do is try to keep this chill.

Effect: Chills

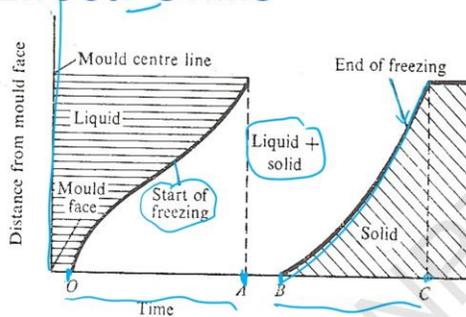


Fig- Solidification diagram for ordinary sand mould

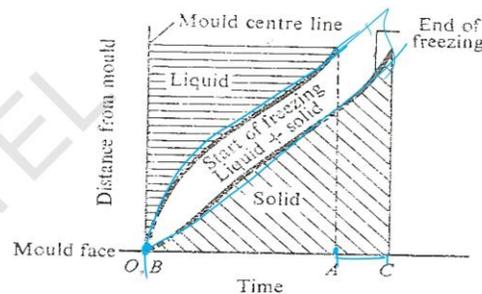


Fig- Solidification diagram for chilled mould

So, effect of chill. If you see here, the y-axis plots the distance from the mold face, and the x-axis plots the time it takes.

So, this is the mold face. The y-axis is the mold face. So, now you can see the liquid is there. The liquid is there, and then this portion is solid. So, in between these two, you have liquid plus solid.

The moment you have liquid that is getting converted, that portion is called the start of freezing, and this becomes the end of freezing. So, if you try to make this O, A, B, and C, this is O, A – the start of the freezing line, and B, C will be the end of the freezing line. Whatever you have seen here, B and C, O and A, I have just changed it here. So, you can see here, this is the distance from the mold face. Again, this is also the distance from the mold face.

Here is the time you have taken, and then you see here. So, this is the solid-liquid transition zone, right? The mushy zone. So, the solidification diagram for an ordinary sand mold shows the distance where it is very far away. This is the time, O, A, B, you see that time. When you see here, when you put the chill, you see it almost starts from the same point as O, the B also gets shifted.

So, what does this specify? The time given for solidification can be shortened drastically to achieve the required output. Friends, it is very clear from this diagram, you can dictate

the process. You can dictate the process by putting chill or putting risers to get the best out of the mold.



Solidification Shrinkage

Centre-line feeding resistance (CFR)

$$\text{CFR} = \frac{\text{time interval between start and end of freezing at centre line (AC)}}{\text{total solidification time of casting (OC)}}$$

CFR > 70% : FEEDING IS CONSIDERED TO BE DIFFICULT



So, now the other important discussion is going to be Solidification Shrinkage. The Centerline Feeding Resistance (CFR). What is a CFR? CFR is nothing but time interval between start and end of the freezing at center line divided by total Solidification time of casting (AC / OC). CFR should always be greater than 70%. Feeding is considered to be very difficult.

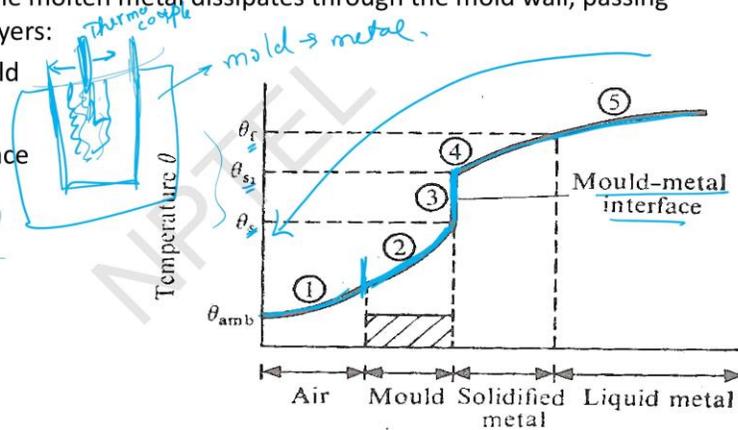
Rate of Solidification

Solidification with respect to time



The heat rejected by the molten metal dissipates through the mold wall, passing through five distinct layers:

- Air Around the Mold
- Mold Material
- Mold-Metal Interface
- Solidified Metal
- Liquid Metal



This is another very important factor while designing a mold: the rate of solidification. This is also very important because, as you know, we have been talking about solidification with respect to time. Solidification with respect to time. So, now, the rate comes into existence — the rate of solidification and the heat rejected.

By the molten metal dissipating through the mold wall, it passes through five distinct layers. You have a container, right? The heat is getting rejected by the mold from the molten metal. So, here is the liquid metal, and here is the mold. mold is made out of a mold. So, this mold is made out of metal, right?

So, the heat rejected by the molten metal dissipates through the mold wall. This is the mold wall, right? When passing through, there are five stages that come into existence. The first one is the air around the mold, right? The air, whatever is there. The next one is the mold material.

The third one is the mold-metal interface—this is an interface. Then comes the solidified metal, and the last one is the liquid metal. So, there are five distinct layers you should understand. Now, once you understand this, now you know how to play with these things. So, now whatever we have these five distinct layers, let us plot it with respect to temperature and mold line or mold area.

So, first is ambient. Look at the temperature from here to here. This is ambient heat rejection. Next is the heat which is getting rejected in Mold 2. So, it takes a temperature called theta S.

Then, the mold-metal interface portion is theta 3 or theta S2. At the interface, the temperature increases constantly. If you look at 1 and 2, they increase over area or over time, right? So, this is air, which is almost close to exponential. Or, if you generalize it, 1 and 2 can be thought of as linear, right?

So, then it is 3, which is a straight increase in temperature. Then, you try to reach a point of solidified metal. So, this is the solidified metal. The center portion is liquid. So, there the temperature will be high.

In region 5, it will be very high, nearing freezing. Start theta S, theta S2, and then theta F. Now, this portion 3 is called the Mold Metal Interface. So, if you look at it, the first portion is air. Then, it is going to be the mold, then it is going to be solidified metal, and the last one is going to be liquid metal. If I place a thermometer or a thermocouple here, I can observe how the temperature decreases from top to bottom as I measure along this line. So, this is a temperature-measuring device, a thermocouple.

Rate of Solidification

Air Around the Mold

- The outermost layer where heat is transferred to the environment.
- The heat is primarily dissipated through convection to the surrounding air and radiation.
- This layer is crucial for cooling the casting as the process progresses.

Mold Material

- The mold material conducts heat from the molten metal to its outer surface.
- Its thermal conductivity plays a key role in how quickly heat is transferred.
- High thermal conductivity speeds up cooling, while lower conductivity prolongs solidification.



So, air around the mold outside, the outermost layer where heat is transferred to the environment. Maybe you can always see that. When you heat a vessel containing a liquid like water, the heat transfers from the bottom to the liquid. As it gets transferred, you can feel the temperature when you touch the vessel. This portion is called the outermost layer.

Where heat is transferred to the environment. So, this gets dissipated into the environment. The heat is primarily dissipated through convection to the surrounding air and radiation. Two phenomena occur: convection and radiation. Radiation transfers heat to the atmosphere, while convection happens if there is forced air or movement around the liquid.

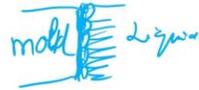
This layer is crucial for cooling the casting as the process progresses. If you can put a fan and then cool, forced convection can occur. If you can have a liquid jacket, you can achieve forced convection there. Now, mold material. The mold material conducts heat from the molten metal to the outer surface.

So, this heat, assuming that you first boil it and then cut off the heat. Then, what happens? The heat, whatever is there, gets dissipated through the vessel. So, this is it. The mold material conducts heat from the molten metal to its outer side.

That is mold material. Its thermal conductivity plays an important role in how quickly heat is transferred. So, with metal dies, you can always get good quality output because you can control the thermal conductivity. So, this thermal conductivity will try to dictate what grains you want. High thermal conductivity speeds up cooling.

If you want to have equiaxial grains, go ahead and use a copper die. If you want slower solidification, try using a steel die. The lower conductivity of the steel die will prolong the solidification. Why? If you control the grains, you control the properties of the metal, and ultimately, the properties of the product.

Rate of Solidification



Mold-Metal Interface

- This interface directly affects the heat transfer rate.
- Any imperfections, roughness, or variations at this boundary can create
 - Thermal resistance
 - Slowing heat dissipation
 - Affecting the solidification of the casting.

Solidified Metal

- As molten metal cools, it solidifies along the mold walls, forming a solid shell.
 - This layer conducts heat inward from the mold to the remaining liquid metal, influencing the overall cooling rate and shape of the casting.
-



The mold-metal interface is the exact boundary between the mold and the liquid. This is the liquid interface. This interface directly affects the heat transfer rate because, at this mold-metal interface, the grains will slowly start forming. Now, these grains will become a bottleneck for further heat to be transferred out. So, this interface directly affects the heat transfer rate because it is almost like a thin skin forming there. Any imperfection, roughness, or variation at this boundary can create thermal resistance, slowing heat dissipation and affecting the solidification of the casting. So, the mold-metal interface is very important.

Then, the solidified metal, the center portion. As molten metal cools, it solidifies along the mold wall, forming a solid shell. So, now I said the mold interface is here. Next, after this, is the solidified metal. Now, the equiaxial grains we are talking about.

Before the equiaxial grains, you have the mold interface: air, metal, and metal-mold interface. Then, you have the solidified metal, followed by the liquid. So, this layer conducts heat inward from the mold to the remaining liquid metal, influencing the overall cooling rate and shaping of the casting.

Rate of Solidification

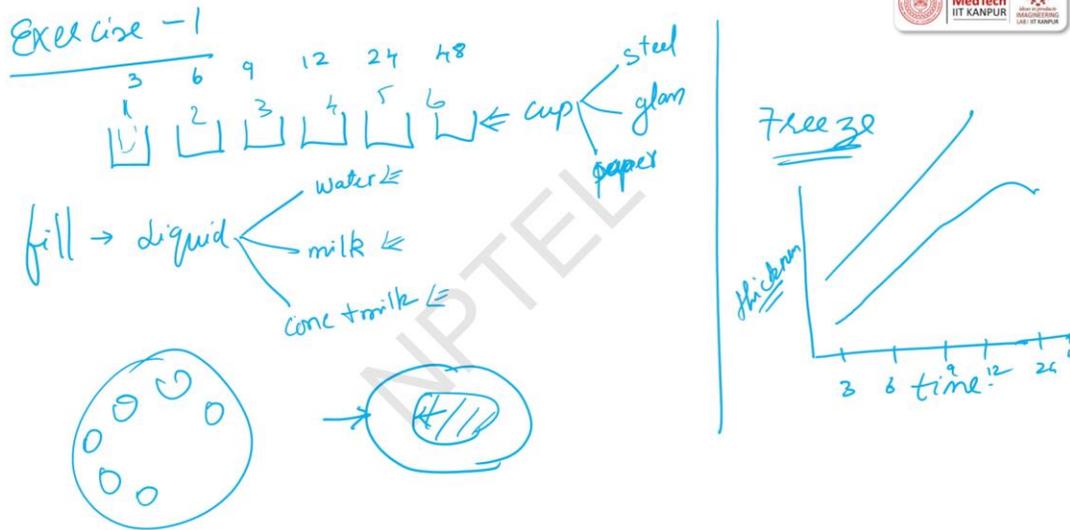
Liquid Metal

- The molten core, which has the highest temperature, transfers heat to the surrounding layers as it cools.
- The solidification process starts at the mold walls and progresses inward.
- The rate of cooling here impacts the casting's final structure and quality.



Finally, the liquid metal—the molten core with the highest temperature—transfers heat to the surrounding layers as it cools. The molten core, which has the highest temperature, transfers heat to the surrounding layers as it cools.

The solidification process starts at the mold wall and progresses inward. What we are trying to say is that after the grains are formed, the solidification will move toward the center. The heat dissipation will happen here. This is the solidification front. The solidification process starts at the mold wall and progresses inward. The rate of cooling here impacts the final structure of the casting and its quality.



Now, I would like to give you two exercises so that you understand what we have studied till now. First, for the exercise, you will try to take maybe a small stainless-steel cup—around six of them. These are stainless cups. Now, take these cups in three varieties. One, try to take a steel cup. Then, try to take a glass cup, and finally, take a ceramic cup or a paper cup. Try to take a paper cup, right? So, you will have three cups. Now, in each of these cups, try to fill the same amount of liquid.

Again, you will have three types of liquid: one is water, the other is milk, and the third one can be a mixture of some concentration added to the milk. So, concentration plus milk. Let me take it like, this is ordinary milk and this is bull's milk. So, you have water there. Now, you put all these items in the freezer. So, here you have 1, 2, 3, 4, 5, and 6—6 cups. Place everything inside your home freezer.

Now, you try to plot time versus thickness plot. So, what you are supposed to do is, put it inside a freezer and try to run it for 3 hours, 6 hours, 9 hours, 12 hours, 24 hours and 48 hours. So, keep it inside of it. So, that means to say you will take a plate and then you will keep all these cups in the freezer. Do not keep it on the other zone of the refrigerator.

So, you will keep this. So, every 3 hours, 6 hours, 9 hours, 12 hours, 24 and 48 hours, you will try to take each one of these cups. And then what do you do is, the cup liquid

whatever is there, would have got already solidified. There can be Partial Solidification. For example, when you look from the top in the cup, you will see something like this.

This portion will be liquid, this portion would be solid. So, you poke it and throw out the liquid out. So, now you measure the thickness of this skin which is getting formed during freezing. Now you plot, measure the thickness with a scale or whatever it is, you have it at home. And now you plot and see how the graph grows.

So, 3 hours of milk may be going like this, something like this it will go. So, the milk will solidify in a different way, and the water will follow a more linear pattern. I I'm not sure how it will behave exactly, but you need to plot it. By doing this exercise, what you will understand is the influence of the mold material with respect to the solidification process. Now, you are using three different mold materials, and you are varying the time for each, along with the different liquid metals. You are plotting the results for each scenario. This will try to teach you how is the, mold interface getting formed, how is the Solidification going?

And while doing So, you can also take photos through your smartphone and you can see how beautifully the crystal structures get formed while it is getting frozen. So, this is one exercise you will do.

Exercise 2

Exercise - 3

Aspect ratio = $\frac{d}{L} = 0.5$

taper tube $\frac{d}{L} = 1$

$\frac{d}{L} = 2$

$\frac{d}{L} = 5$

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The other exercise I will try to give you, Exercise 2. Exercise 2: You will take a small vessel, maybe 10 ml, 15 ml, or 20 ml. These are very small sizes. Then, you will try to pour liquid into the vessel.

You will try to pour liquid, and again, there are three liquids you can choose from: water, oil, and something like ketchup, which has a slightly different viscosity. So, you'll have water, oil, and a high-viscosity liquid like ketchup. Maybe paint or something with high viscosity, and then what you do is try to pour each of these liquids into the vessel at varying heights. Maybe this is the vessel. So, you will first try to fill it from 5 centimeters away, then 10 centimeters away, and then 15 centimeters away.

Each time you fill it with one of these liquids, you will observe how the liquid pours out. Sometimes, the liquid will not pour out; it will start filling up instead. So, if you do this exercise, it will try to show you the influence of a pouring basin in a casting process. So, this will try to demonstrate the influence of a pouring basin. So, this will be one exercise with respect to varying heights.

So, from what height I pour, if I pour it from a certain height, the splashing should not happen. That's the idea. So, this will be the second exercise, which you will do to understand and appreciate this. The third exercise is going to be this: you will use a funnel and then try to vary its length. You have a funnel, and the length of the funnel that you use should be varied.

Now, take only oil as the filling agent (a viscous material) and try to pour it into the funnel. In this case, you will change the diameter of the funnel tube. Additionally, you will vary the length of the funnel along with the diameter. So, what we are trying to do is we are trying to establish. You can try to convert it in aspect ratio. Aspect ratio is what you do is you try to take diameter to length.

The diameter to length ratio can be varied as follows: 0.5, 1, 2, and 5. This means, for example, if the diameter is 1 millimeter, the length will be 2 millimeters. If the diameter is 1 millimeter, the length will be 1 millimeter. If the diameter is 2 millimeters, the length will be half. So, that is why you get this. So, you try to do this varying ratio. You will try to understand what is the influence of the sprue, pouring basin sprue.

When we do this, you also try to do one more exercise with respect to the taper what is given to the taper to the tube, funnel taper to the tube. So, here you can have only two tapers. For example, the funnel can be straight or slightly tapered. This will help

demonstrate the influence of why we need a tapered tube. Additionally, you should try to close it with a container to observe the effect.

Then only you can start doing this exercise, and there will be meaning. So, the air that gets trapped will resist the flow of the liquid. You can see that. When you do all three exercises, trust me, friends, you will have understood casting in a very big way. There will be varying casting processes.

That is a different story. But these three exercises, which you do at your home, will give you a thorough understanding of what is what. Without any mathematical equations, you are trying to understand the concept.

To Recapitulate



- Introduction, History, advantages, and limitations.
- Solidification classification
- What is the mechanism and heat required to melt the material?
- What are pouring, pouring time analysis, and pouring time estimation?
- How do cooling and solidification happen in
 - Pure Metals & Alloys
- Grain Growth & Distribution happens
 - Pure Metal & Alloys
- Mathematical relation of solidification time
- Rate of solidification, etc
- To Recapitulate



So, friends, till now in the entire casting, what we have gone through is: history, advantages, disadvantages, with some introduction. Solidification of casting we went through.

We understood the mechanism of heating, wherein we talked about melting point, pouring point, and specific heat. Then we went into pouring, pouring time, and pouring time estimate. Then cooling and solidification, grain growth and distribution. Then, solidification time, then rate of solidification, directional solidification, and finally, we had some three or four exercises which we are supposed to do while studying this chapter.

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The content of this lecture was taken from this reference book. You can go through it and read it in full. Thank you very much.