Basics of Mechanical Engineering-2

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Week 03

Lecture 09

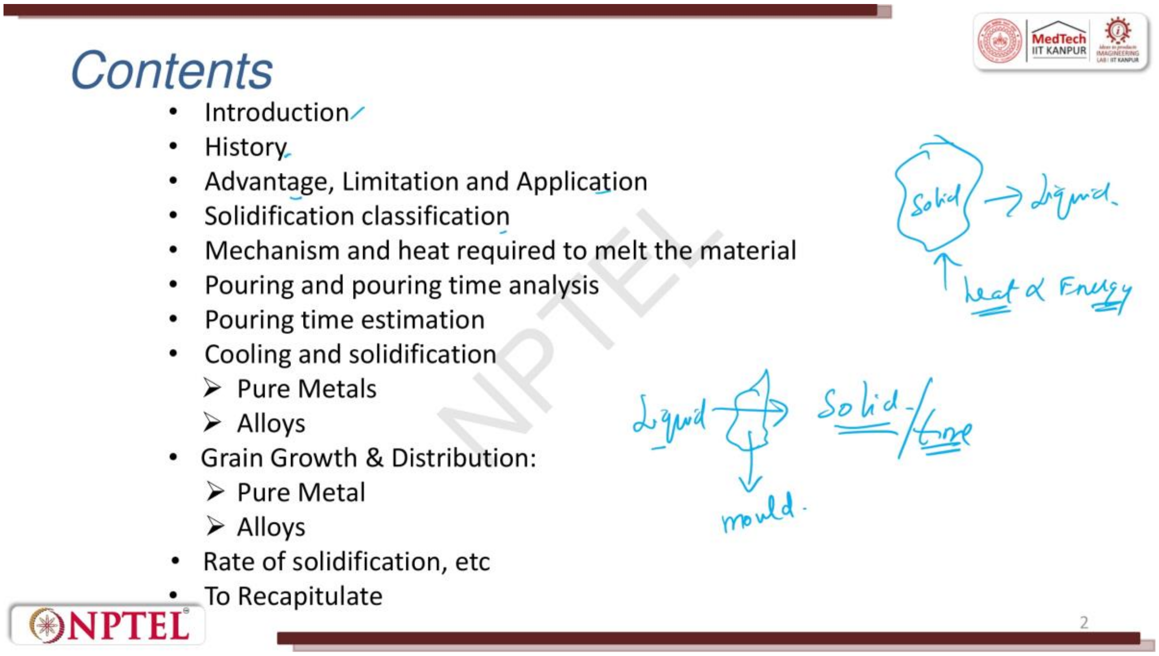
Basics of Casting (Part 1 of 3)

Welcome to the new topic in our course: Casting. We have studied the basics of materials in the last two weeks. Then, we studied crystal structure, phase diagrams, and heat treatment. With this basic understanding, let us get into the first manufacturing process of this course: casting. Casting is a very old process. It has been practiced since BC, back when kings wanted to make their swords or coins; they were all made through casting.

If you look at the Statue of Liberty, it is also made through casting. A big structure. If you go to a church, the bells are made out of casting. If you want to change the frequency, you can change the thickness of the casting and get varying sounds to meet your requirements. So, casting plays a very important role.

For casting, the fundamental understanding you need is to comprehend phase change. What happens when liquid turns to solid? The second thing is, when liquid turns to solid, what is the time duration you allow for this to happen? If you can have these two understandings properly, then this chapter will become very easy for you. So, first, let us look into the introduction, and throughout the basic discussion, we will always focus on one process, which is called the sand-casting process.

There are several processes that have come into existence, but we will understand one thoroughly and then move on to the others.



So, first, we will see the introduction, and then we will look into the history. When was it started? Where is the evidence for casting? How did it start, and where did it go? So, we will see the history. Then, we will try to look at the advantages, limitations, and applications.

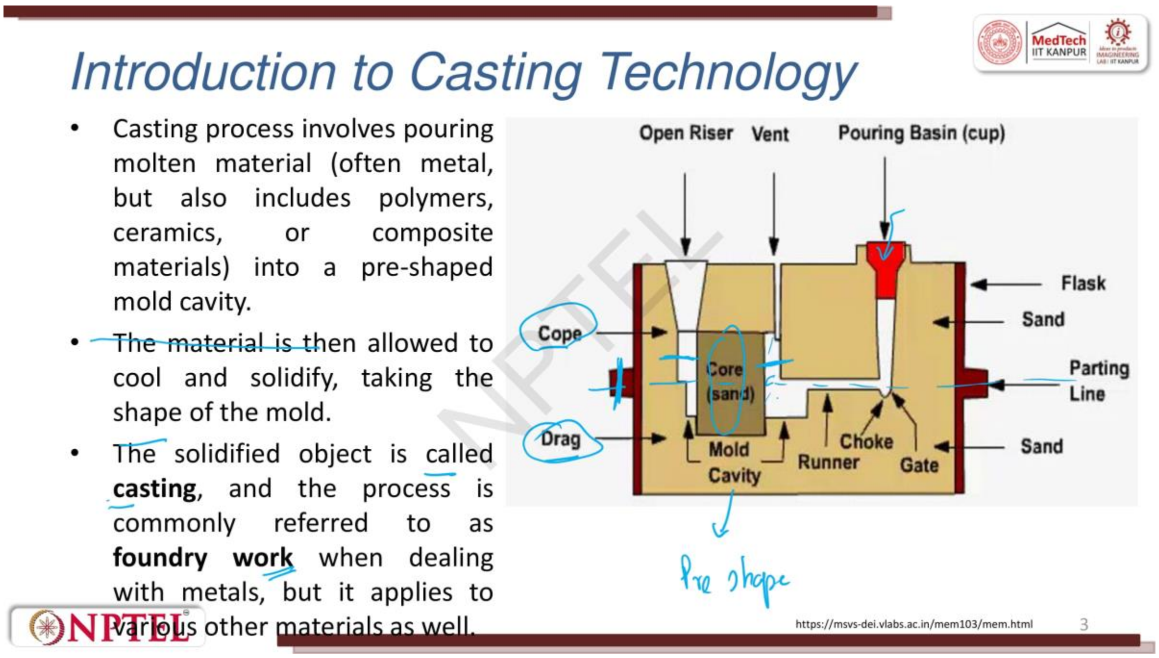
Then, we will see solidification and classification. Then, a little bit of understanding of the mechanism of heat required to melt the material, because here you have a solid. This solid is heated, and then it is converted into a liquid; from solid to liquid. So, now this liquid is used for or during the process. So, now, what should be the heat you apply?

And this heat, in turn, is proportional to energy. So, you can try to calculate the cost. We will try to see pouring and pouring time analysis. So, when you have a liquid that is poured, it has to be converted into a solid, and in between, you try to give it a shape. This is called a mold.

So, now, what you need to determine is the time it takes to pour and fill this mold in such a way that you can later get a solid. So, pouring time analysis will then lead to pouring time estimation. How are cooling and solidification different for a pure metal and for an alloy? Then, grain growth for pure metal and alloy. Then, the rate of solidification because, when it has to convert from liquid to solid, it will always be with respect to time.

So, we now look into the rate of solidification. Then, finally, we try to capture what we went through in this lecture. So, when we look into casting, it is a process in which the liquid metal is poured into a pre-shaped mold. This is the liquid being poured, and this is the pre-shaped mold. The mold cavity is pre-shaped.

So, I make a shape, I keep it in the sand, and that pre-shaped object makes the mold. When a liquid is poured, it tries to fill the mold, and the moment it tries to fill the mold, it begins to convert into a part.



Casting is a process that involves pouring a liquid into a pre-shaped mold cavity. This is a pre-shaped mold cavity. The material that is poured is allowed to solidify.

The material is allowed to cool and solidify to take the shape of whatever it is. The solidified object is called a cast, and the process is commonly referred to as foundry technology or foundry work. This is commonly applied to metals, but it is also used with various other materials. When we pour, you should understand that the liquid passes through a pouring basin. This is a basin that is slightly larger in shape, and then the liquid passes through a straight channel.

The straight channel is tapered. So, that is called the sprue basin. From the sprue, it gets connected to the gate, and the gate leads to the runner. The runner then fills up the mold. Once it is done, we have two things. When there is air here, this air has to be pushed out.

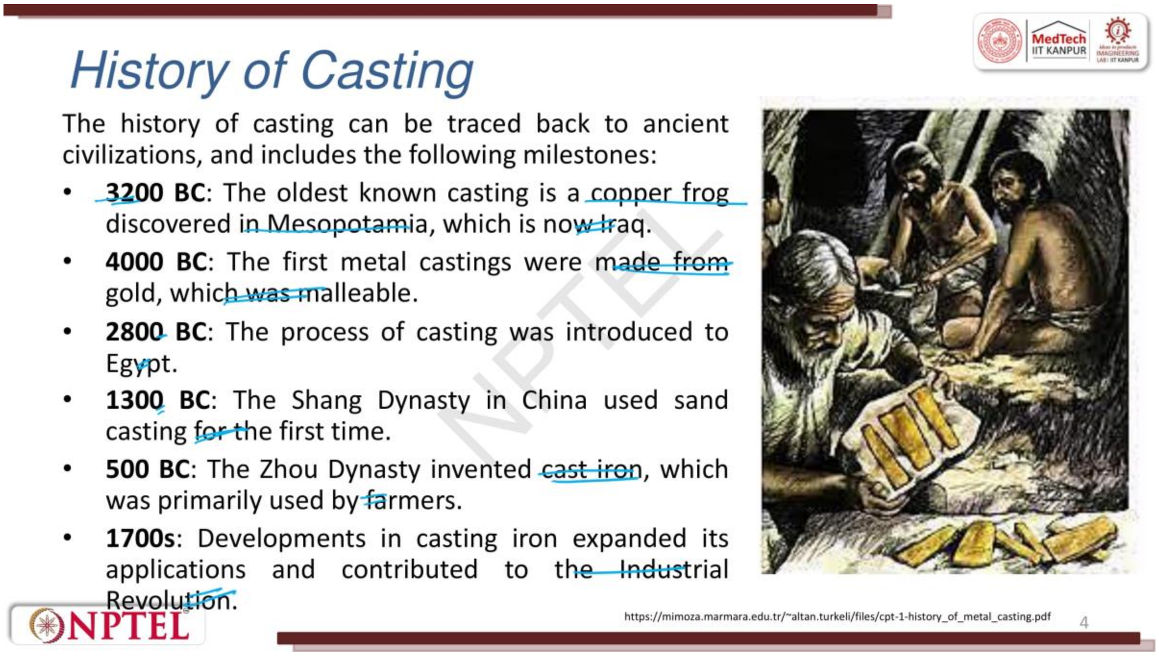
So, that is a vent there. During solidification, you will see that when the liquid converts to solid, there is a contraction phenomenon. So, the excess liquid in the riser will pour into the mold, ensuring that you get a solid part. We will see this in detail, but these are certain things you should know. It is not directly poured into the mold.

Why is it not directly poured into the mold? If it is directly poured into the mold, there can be a possibility of improper filling. So, what do we do? We allow it to pass through a sprue, then from the sprue to a gate, the gate to a runner, and from the bottom, we try to fill. Of course, you can also try to fill from the top, but if you do so, there can be irregularities.

So, we will see it in more detail, but certain names for your knowledge or for your registration: cope and drag. The casting process, whatever is done, is done on a mold cavity which is divided into two parts. The top part is called the cope, and the bottom part is called the drag. The cope and drag are fixed through a pin. So, there are two halves.

So, these two halves, there is a mold which is to be made. What is a mold? You scoop out the material to make the mold. So, when you try to scoop out, you will not get the exact shape. So, what we do is make a negative of whatever is to be there in the mold, and then we place it in the sand and later remove it, so you get the mold cavity.

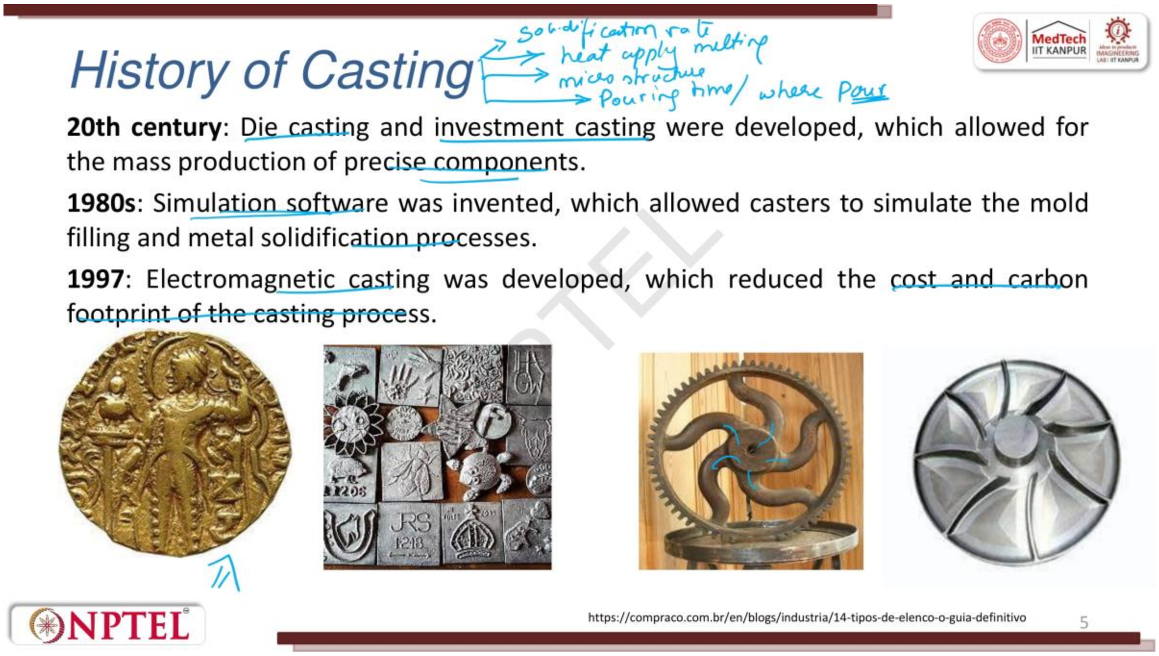
If you want to have internal hole features, then we use a core. Interestingly, the core is held between the top and bottom. If the top and bottom are not there properly, and you want to hold them, you can also hold them through some pins. With this understanding, let us move forward.



Now, the history of casting. The history of casting can be traced back to ancient civilizations and includes the following milestones: 3200 B.C., the oldest known casting is a copper frog discovered in Mesopotamia, which is now Iraq. In 4000 B.C., the first metal castings were made from gold. When they could make it from copper, they extrapolated and did it with gold, which was malleable. So the kings of those days made ornaments, sword handles, and their thrones. All these things were made out of gold, so it was cast.

Then, in 2800 B.C., the process of casting was introduced to Egypt. In 1300 B.C., the Shang dynasty in China used sand casting for the first time. In 500 B.C., Zeodinocity invented cast iron. You remember? Cast iron, we saw in the phase diagram, where we studied the iron-iron carbide diagram.

So, anything more than 2.1 percent of carbon falls into the cast iron zone. So, they invented cast iron, which was primarily used for farming equipment, basically tools for plowing and sickle cutting. They were all made out of cast iron, primarily for farmers. In 1700, the development in cast iron expanded its application and contributed to the Industrial Revolution. So, the wheels started rolling. The wheels were initially made out of casting.



In the 20th century, several advancements happened. So, die casting and investment casting were developed. Die casting means where in sand casting you saw in the sand to make a mold, but now you replace the sand with a solid material, and then it becomes a die. So, die casting, investment casting here, we will see investment casting, in which you can try to generate precision parts. In fact, today gold ornaments are made out of investment casting because the pattern is made so precisely and nicely.

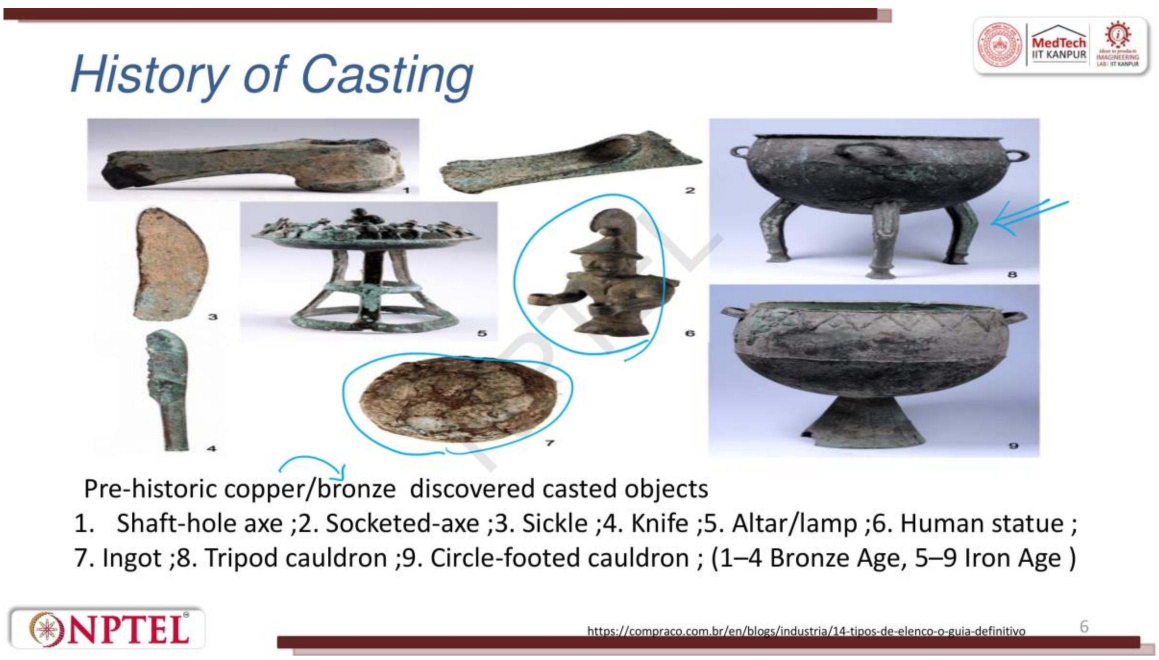
So, investment casting was developed, which allowed the mass production of precision components. In the 1980s, simulation software. If you look at casting, what is so complex there? Why do you need simulation? One, the solidification rate is very important. Then the next one is, what should be the heat that I apply for melting?

What will be the microstructure formed during cooling in solidification? What is the pouring time? And the next one is, where should I pour to get a solid part mainly? So, all these things are very complex. First-order differential equation, second-order differential equation, conductivity loss. Everything we apply, and we still try to get the approximation by using simulation. In 1980, simulation software came into existence, which allowed the caster to simulate the mold filling and the metal solidification process.

They were able to now dictate the product they wanted by doing simulations and optimizing many parameters. In 1997, electromagnetic casting was developed. Initially, the heat was always applied through flame. Then electromagnetic heating, induction heating, all these things are there. Today, microwave heating is also coming into existence.

Electromagnetic casting was developed, which reduced the cost and the carbon footprint, making casting a sustainable process. The moment you look into casting, it is always called the dirty man's process. Foundry means when people work in a foundry, they get themselves so dirty. So, from there, they tried to change the concept and bring in sustainable, clean solidification processes. So, these are some of the examples you can see made out of casting in ancient times.

You can see here they have made a coin out of gold. Then, this is an artifact, and you can see multiple things have been made, like a gear, which is made through a sprocket. A gear, which is made with spokes in it. And then you can see a turbine blade, made out of a single material, and it is a monoblock. So, it is made. So, all these things are possible by casting. Intricate to complex features can be made through casting.

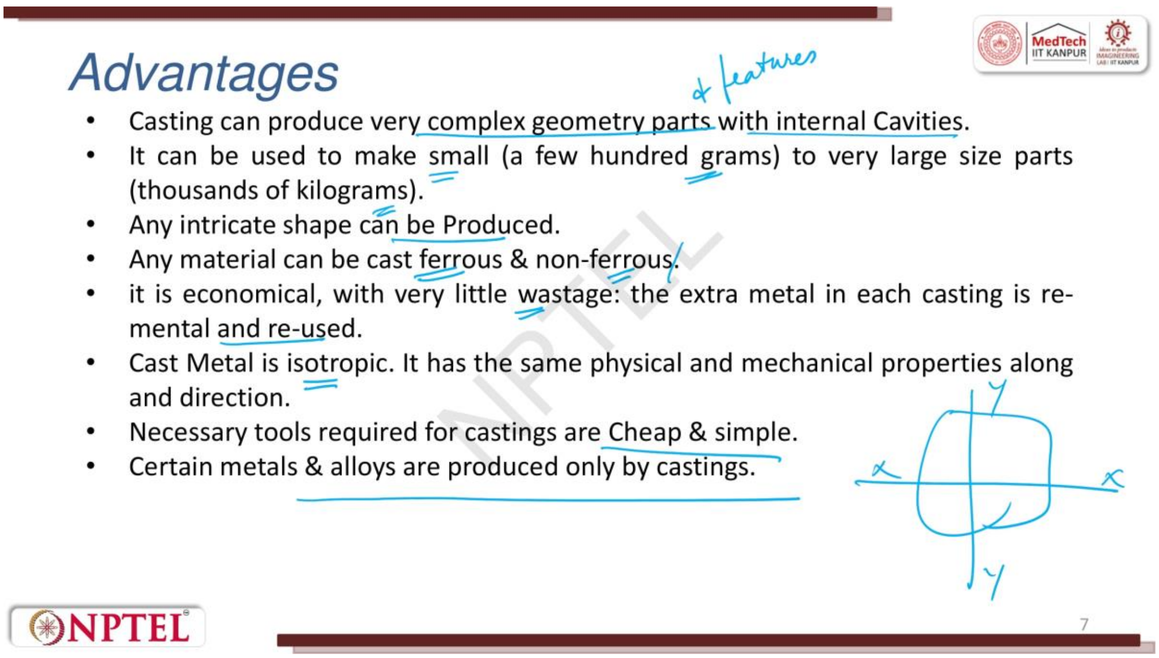


These are some of the prehistory or history of casting, where prehistoric copper-bronze. Copper and bronze are a combination. Bronze is an alloy of copper, right?

So, copper-bronze discovered cast objects. So, first is a shaft hole. An axle is used, for example, as a wheel axle. It is like a rod, a wheel axle. Then is a socketed axle. Then, you can have sickles. Number 3 is a sickle. These are all used for farming. 4 is a knife for killing and cutting.

5 is a lamp; this is like an Aladdin lamp. So, 6 is a human statue, a soldier that is there. Seven is an ingot, which is like a lump of material. Eight is a tripod concept, which has been used, where they have kept liquid there. Nine is a circulated foot cauldron.

So, these are the other things that are there. So, 1 to 4 is from the Bronze Age, and 5 to 9 is from the Iron Age. So, bronze to iron started the development of casting.

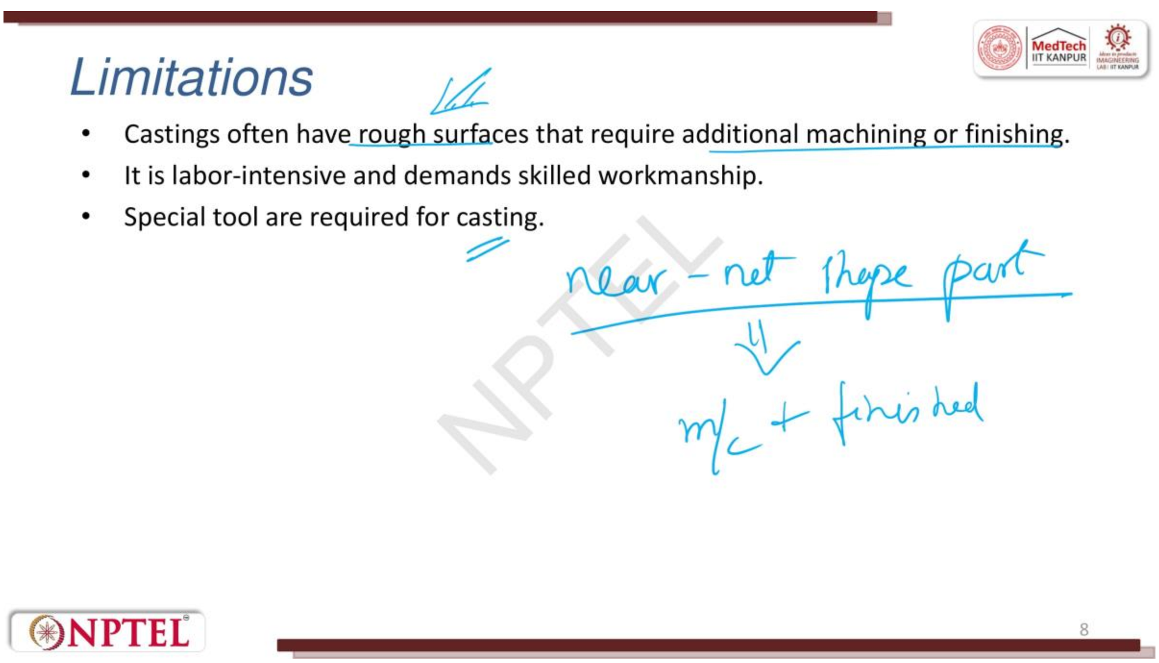


So, what are the advantages of casting? Casting can produce very complex parts, including internal cavities.

Now, complex parts and features. Your face, nose is a feature, complex part and features which are both external and internal. Now, internal cavities are very important. It is very difficult to make them through other processes. Casting can be used to make parts ranging from small to very large sizes. That means to say, from a few hundred grams, a few milligrams like gold ornaments, which can be made in milligrams to a large size, it can be used for making a church bell. So, church bells, some of the church bells are made out of 1,000, maybe 2,000 or 5,000 kgs.

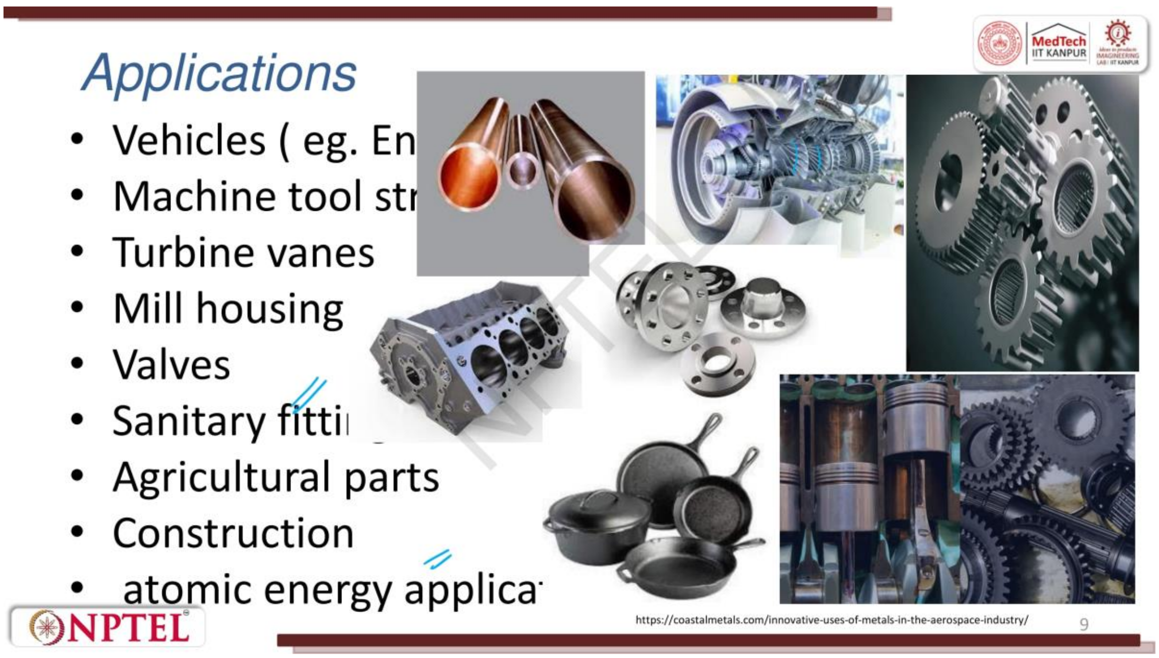
It is hung and it produces a wonderful sound when it is hit. Any intricate shapes can be produced which is internal cavity. Any material can be cast. It can be ferrous as well as non-ferrous. For example, you can also try to do by silicon mold, you can try to make silicon parts which are like toys, you just try to open and then close. It is economical and has very little wastage, so it is otherwise called a constant volume process. I start with one liter of liquid and then I end up getting a solid of equal 1 liter or 1 kg, whatever it is equal to that. The extra metal in each of the castings is remelted and it is reused.

The cast iron produces an isotropic property. That means, if I take an object and cut it in this direction or in that direction, I will get the same mechanical response, and it is called isotropic. Many of the processes lead to anisotropic behavior, meaning that along one direction, the mechanical properties will be different. The necessary tools required for casting are economical and simple. Certain metals and alloys are produced only by casting; no other technique can be used. They are produced by casting. For example, if you want to have exotic materials wherein it is too difficult to machine or too difficult to deform, then casting is the only route they can take.



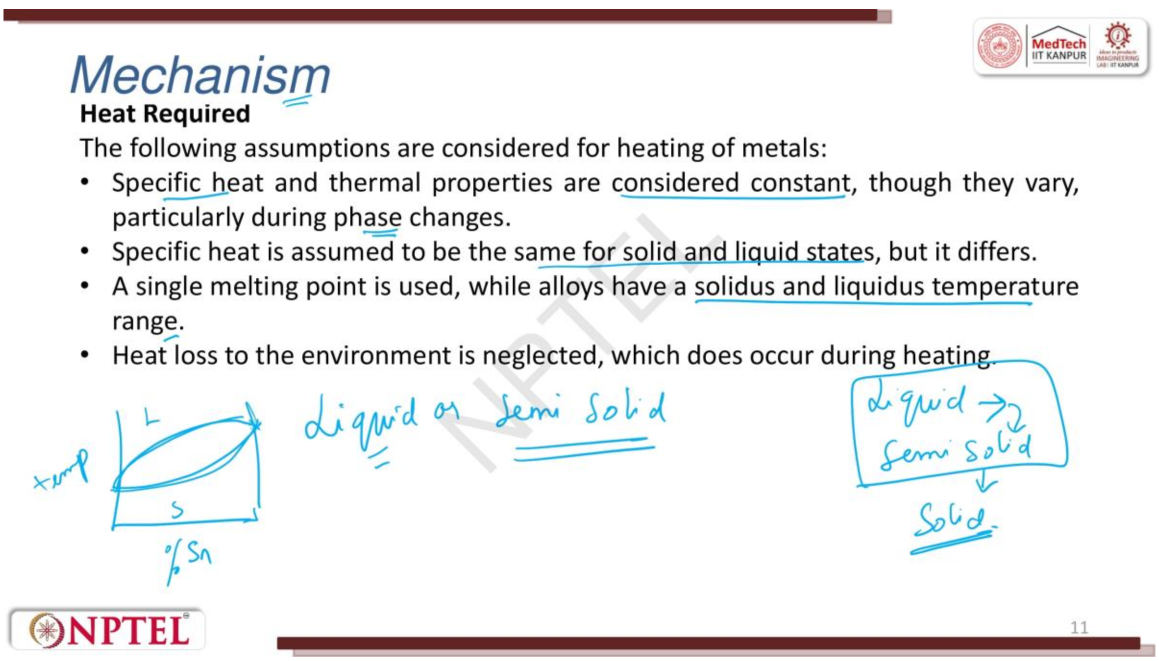
What are the limitations? Every process has limitations. The limitations are that it always tends to produce a rough surface, and sometimes it needs finishing or machining to get the final part. The roughness today can be improved to a large extent. It is labor-intensive when you are trying to make a mold; yes, it is labor-intensive. Special tools are required for casting.

In sand casting, when you try to remove mold material, special tools are used. But these are not so great a limitation. But one of the biggest limitations is that it produces a near-net-shape, near-net-shape part. So, if you want to go for assembly, it has to be machined and finished or it has to be finished alone.



So, you can see here a wide spectrum of engineering applications. It is used in vehicles, machine tool structures, turbine vanes, milling housings, valves, and sanitary fittings. Sanitary fittings like pipe fittings are very costly and made through casting. It is also used in agricultural parts and the construction industry. In atomic energy applications, you can see large diameter pipes being made. Gears, flanges, vessels, utensils, and sometimes pans are also made out of it. So, all these things give you a clear understanding that it can be used in high engineering applications, domestic applications, entertainment applications, and exotic applications. So, in all the fields, the casting process plays a very important role. Some more, you can see all these things are attached to the same group.

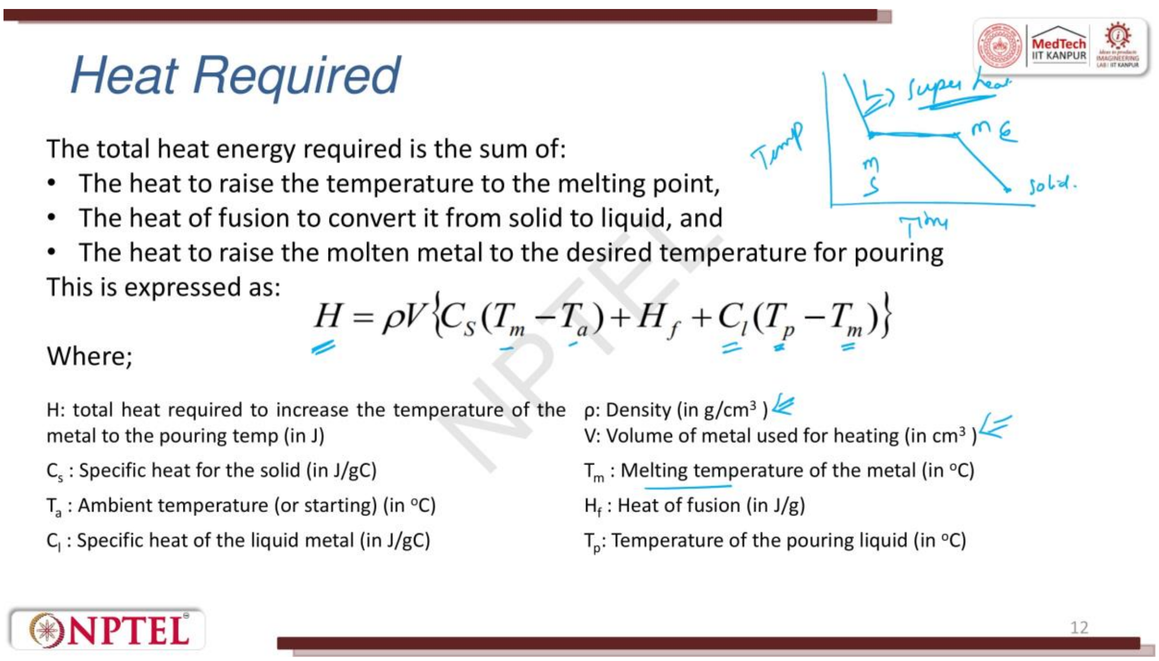
The rim of a car can be made, and large turbines can be made. These are all parts used for making things like handles or mugs. The engine block is cast.



Now, let us understand the Mechanism. In casting, as I told you, there can be only two possibilities. One is you start with a liquid, or you would start with a semi-solid form.

So, where is the semi-solid coming from? So, when metal is in a liquid state, it undergoes a mushy zone, which is a semi-solid state, and then it solidifies. These two stages are used in casting. So, we use liquid or we use semi-solid mushy zone material, which has lower viscosity as compared to very high applied heat. So, the specific heat and thermal properties are considered constant. You should understand we are not changing it. They vary particularly during the phase change.

Next, specific heat is assumed to be the same for the solid and liquid states, but in reality, it is different. A single melting point is required, while in alloys, there is a solidus and a liquidus line in the temperature. Remember, we had a graph like this: solidus line, liquidus line. This is temperature, and this is some percentage; maybe let's take Sn (tin), right? So, this is liquid, this is solid, this is the liquidus line, and this is the solidus line. The heat loss to the environment is neglected, which does not occur during heating. These are some of the assumptions and the heat requirements.



So, the total heat energy required is the sum of the heat to raise the temperature to the melting point. So, if you remember, in a temperature versus time graph, it looks like this: this is liquid, this is the melting start, this is the melting end, and this is solid. The heat is required to raise the temperature to the melting point. This is where melting starts, and then the heat of fusion is needed to convert it from solid to liquid. And then, the heat to raise the molten matter to the desired temperature for pouring.

So, you try to heat it to a little higher temperature. Why? Because when you try to pour, the liquid should flow easily into the pipes. So, the pipes are nothing but sprue, runner, gate, all those things it has to smoothly flow. So now, keeping all these things together, the equation is written as

$$H = \rho V \{ C_S (T_m - T_a) + H_f + C_l (T_p - T_m) \}$$

What is ρ? ρ is the density of the material. V is the volume of metal used for heating. Cs is the specific heat for a solid times the melting point - the ambient temperature. Tm is the melting temperature of the metal, and Ta is the ambient temperature. Then, Hf is the heat of fusion plus Cl.

Cl is the specific heat of the liquid metal, multiplied by Tp minus Tm, where Tp is the pouring temperature and Tm is the melting temperature. So, that is the melting temperature. So, by doing this calculation, we try to determine the total energy required to convert a solid into a liquid before pouring it into the mould.

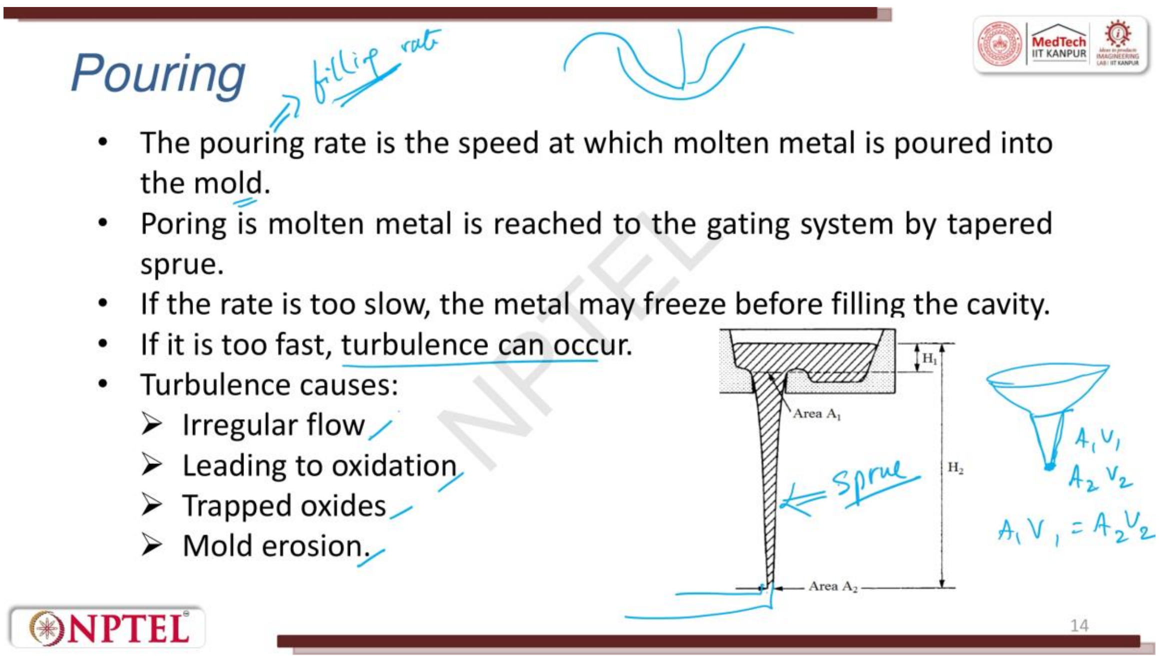
Pouring

- After heating, the metal is ready for pouring. Introducing molten metal into the mold involves:
- Control of pouring temperature
- Rate of filling
- Turbulence to ensure complete mold filling before solidification.
- The difference between pouring temperature and freezing point, known as superheat, indicates the heat to be removed before solidification begins.

https://makeagif.com/gif/melting-pure-gold-sponge-and-pouring-a-gold-bar-y2VXkR

Now, let us try to understand the Pouring process. After heating, the metal is ready for pouring. Now, what this gentleman is doing is trying to pour the material into the sand casting or into a mould. He is trying to take it into a mould and then allows the hot metal to get solidified, cooled, and solidified. So, after heating, the metal is poured. Introducing the molten metal into the mould involves controlling the pouring temperature and the rate at which it is filling. So, the temperature is one factor.

The other thing is when you try to pour, the rate of filling and simultaneous solidification. The rate of filling and the turbulence ensure complete mold filling before solidification. The difference between the pouring temperature and the freezing point is known as superheat, which indicates the heat that must be removed before solidification begins. This is called superheat. The difference between the pouring temperature and the freezing point, known as superheat, indicates the heat to be removed before solidification. This is a crucible; he holds it through an iron rod and then tries to pour it.



So, the pouring rate is the rate at which the metal is poured, and the filling rate is the rate at which the mold is filled. So, the filling rate depends upon the viscosity, and the pouring rate also depends upon the viscosity. So, the pouring rate is the speed at which the molten metal is poured into the mold. If you pour too slowly, the metal may start solidifying during the pouring process itself.

So, that leads to defects; maybe half of the mold will be filled with metal, and it will start solidifying, or it will start solidifying while pouring itself. So, in the end, we will try to do one or two experiments so that you can learn. The molten metal reaches the gating system through a tapered sprue. So, this is the pouring basin. Here, fortunately, the metal is poured directly into the mold. But many times in reality, we will try to pour the metal into a pouring basin.

This is the pouring basin. The funnel, which is connected to the other part between the pouring basin and the rest of the mould, leads to the area called the sprue. The sprue is a pipe that is tapered. Why is it tapered? The same concept applies—if you look at funnels, they are tapered, right? Why are they tapered? Because it allows proper flow and prevents air locking.

So, here, A1V1 = A2V2. A1 is the area at the top, V1 is the velocity with which it comes, A2 is the area which is more, and the velocity will be high. So, the continuity equation will be A1V1 = A2V2. So, the velocity will be very high, such that it can go through a longer distance. So, if the rate is too slow, the metal may freeze before filling the cavity. If the pouring is very fast, it can create turbulence while pouring.

What is turbulence? It occurs when the metal is poured, causing it to splash out. So, turbulence causes irregular flow, leading to oxidation, trapped oxides, and mold erosion. The mould is made out of sand. Till now, we have seen only sand casting. So, that will try to ensure that the irregular flow is there.

Then the trapped oxides can be there, and mold erosions can happen. So, for analyzing what should be the pouring time or the pouring temperature. So, what we do is we always try to do a test which is called the spiral mold test. So, this will try to tell us the rate at which you have to allow the liquid to flow such that it gets properly filled in the mold.

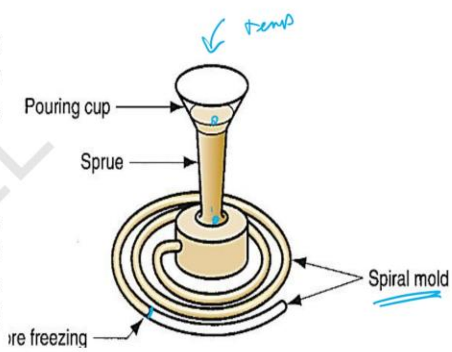
Analysis of Pouring

The flow of molten metal through the gating system into the mold is influenced by key principles, including **Bernoulli's theorem** and the **continuity law.**

Bernoulli's Theorem:

This theorem states that the sum of head, pressure, kinetic, and friction energies/heads remains constant at any two points in a flowing liquid. The flow of molten metal is considered as ideal fluid flow. It is expressed as:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + h_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + h_2$$



For a simplified case where Point 1 is at the top of the sprue and Point 2 at its base.

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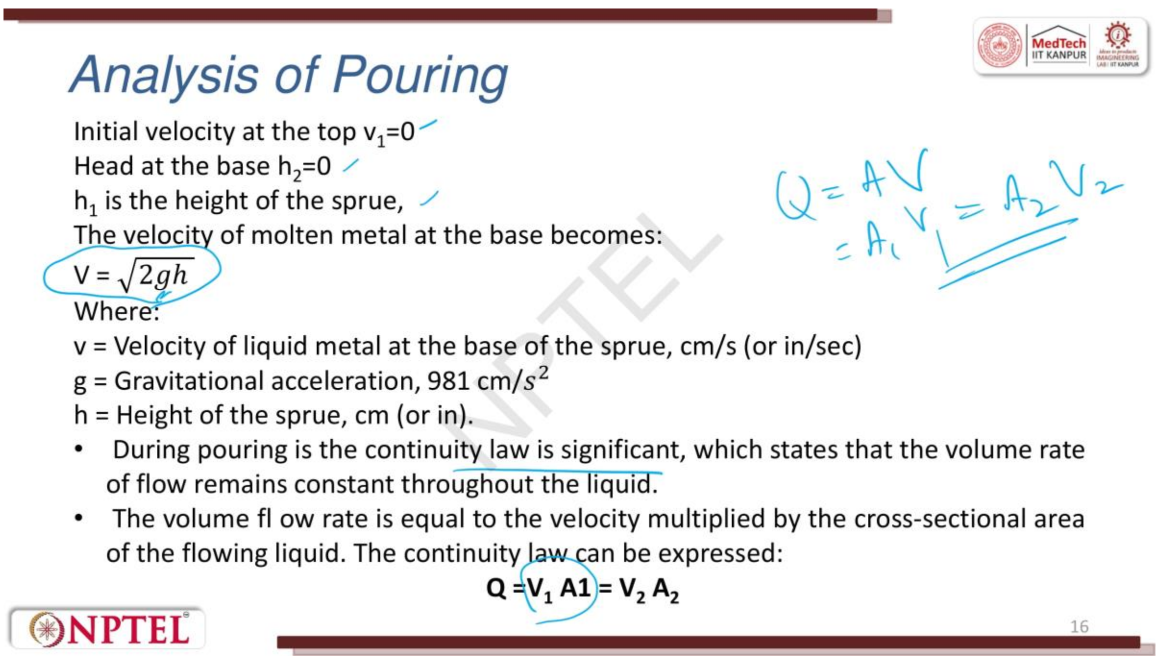
The flow of molten metal through the gating system into the mold is influenced by a key principle called Bernoulli's theorem and the Continuity Law.

So, we use Bernoulli's theorem to determine how the liquid fills the mold when poured at a given temperature. So, what is the distance it can travel? And then, where does it start freezing? So, Bernoulli's theorem states that the sum of pressure head, kinetic head, and friction energy head remains constant at any two points in a flowing liquid. The flow of molten metal is considered as an ideal fluid, and this is how we write Bernoulli's theorem.

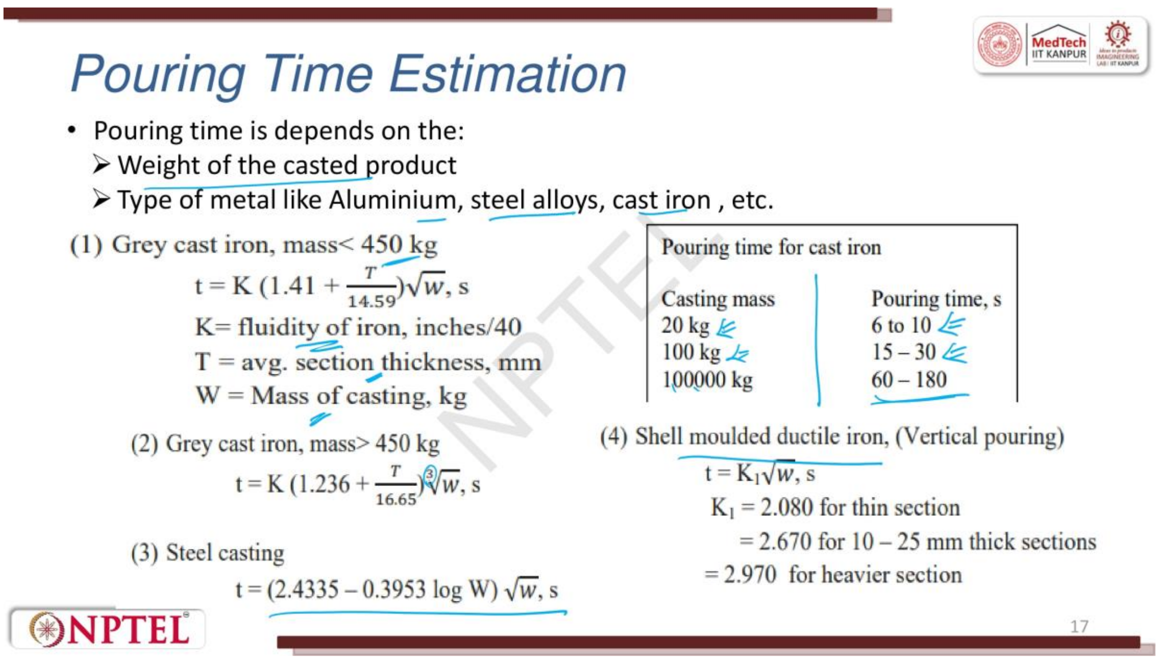
$$\frac{P_1}{\rho g} + \frac{V_1^{\,2}}{2g} + h_1 = \frac{P_2}{\rho g} + \frac{V_2^{\,2}}{2g} + h_2$$

So, many times when you start at the pouring basin, the velocity will be atmospheric, the room velocity, and so this becomes 0. So, we can do all sorts of calculations and try to figure out what the pouring speed should be, ok. For a simplified case, where point 1 is at the top of the sprue and point 2 is at the base of the sprue.



So, here the initial velocity v1 is 0, and the head at the base h2 is 0. So, h1 is the height of the sprue. So, now if you try to play with it, we try to get the velocity of the molten metal to fill at the base becomes v = √2gh. You can try to equate it from Bernoulli's equation, where g is the velocity of the liquid metal at the base of the sprue, g is the gravitational force, and h is the sprue height. During pouring, the Continuity Law is significant, which states that the volume flow rate remains constant throughout the liquid.

The volume flow rate is equal to velocity multiplied by the cross-sectional area, which is nothing but this. So, Q equals A multiplied by V. So, now we say A1 V1 equals A2 V2. So, from there, we can try to calculate the pouring time.



The pouring time is dependent on the weight of the cast product, the type of metal like aluminum, steel alloy, cast iron, etc. When the mass is less than 450 kg, the equation is assumed to be like this.

$$t = K\,(1.41 + \frac{T}{14.59})\sqrt{w},\ s$$

K will be the fluidity of the iron, T is the average cross-sectional thickness, and W is the mass of the casting.

So, when the gray cast iron and the mass is greater than 450, the empirical equation changes like this.

$$t = K\,(1.236 + \frac{T}{16.65})\sqrt[3]{w},\ s$$

So, you can see the numerator, you can see the denominator, then you can see the cube root; the rest is the same.

$$t = (2.4335 - 0.3953 \log W)\sqrt{w}, s$$

So, when you are trying to do steel casting, you get the equation like this, and when you try to do shell mold ductile iron, you have the equation like this.

$$t = K_1\sqrt{w}, s$$

$K_1 = 2.080$ for thin section

$= 2.670$ for 10 – 25 mm thick sections

$= 2.970$ for heavier section

So, this is a thumb rule which has been generated from a table.

Pouring time for cast iron

Casting mass	Pouring time, s
20 kg	6 to 10
100 kg	15 – 30
100000 kg	60 – 180

Pouring Time Estimation

(5) Cu alloy castings

$$t = K_2\sqrt[3]{w}, s$$

K_2 = constant given by

Top gating – 1. 30

Bottom gating – 1.80

Brass – 1.90

Tin bronze – 2.80

(6) Intricately shaped thin walled casting – upto 450 kg

$$t = K_3\sqrt[3]{w'}, s$$

W' =mass of casting with gates and risers, kg

K_3 = constant

T (mm)	K_3
1.5 – 2.5	1.62
2.5 – 3.5	1.68
3.5 – 8	1.85
8 – 15	2.2

(7) Above 450 kg &upto 1000 kg

$$t = K_4\sqrt[3]{w'}, s$$

T (mm)	K_4
Upto 10	1
10 – 20	1.35
20 – 40	1.4
Above 40	1.7

for mass< 200kg; avg.section thickness – 25mm

grey cast iron	40s
steel	20s
brass	15 – 45s

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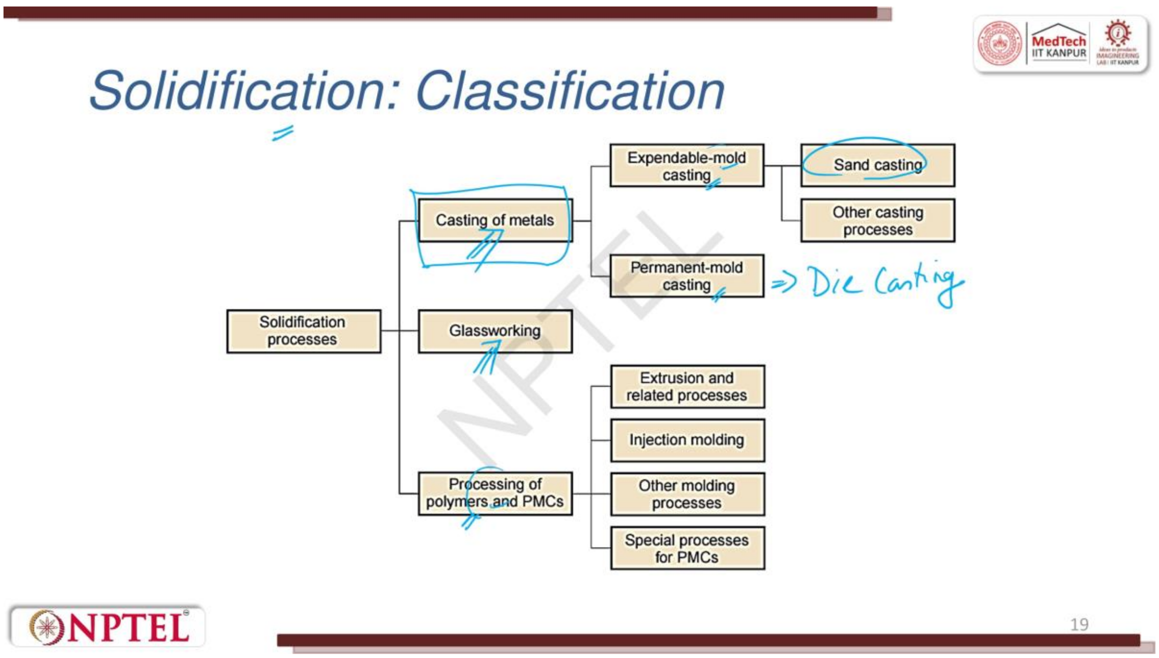
So, for copper, the time is given by: $t = K_2\sqrt[3]{w}, s$. For intricate, thin-walled castings up to 450 kg, this equation applies. When casting above 450 kg, a different equation is used, depending on the intricacy of the shape and the average cross-section.

So, this is how it will take for various materials. So, you don't have to memorize these numbers or formulas. This is just for understanding how the equation looks and how it changes. By using Bernoulli's theorem and the continuity equation, you can estimate the pouring time.



Now, let us get into the casting process in detail. So, the process of solidification can be divided into three stages. One, it can be used for casting metals, then it can be used for glass working, which also involves solidification. For glass, you don't reach a melting point; instead, you go to a glass transition point and then deform it—that's glass working, where solidification is involved. In polymer and polymer matrix composite processing, solidification is also used. Common processes include injection molding and compression molding.

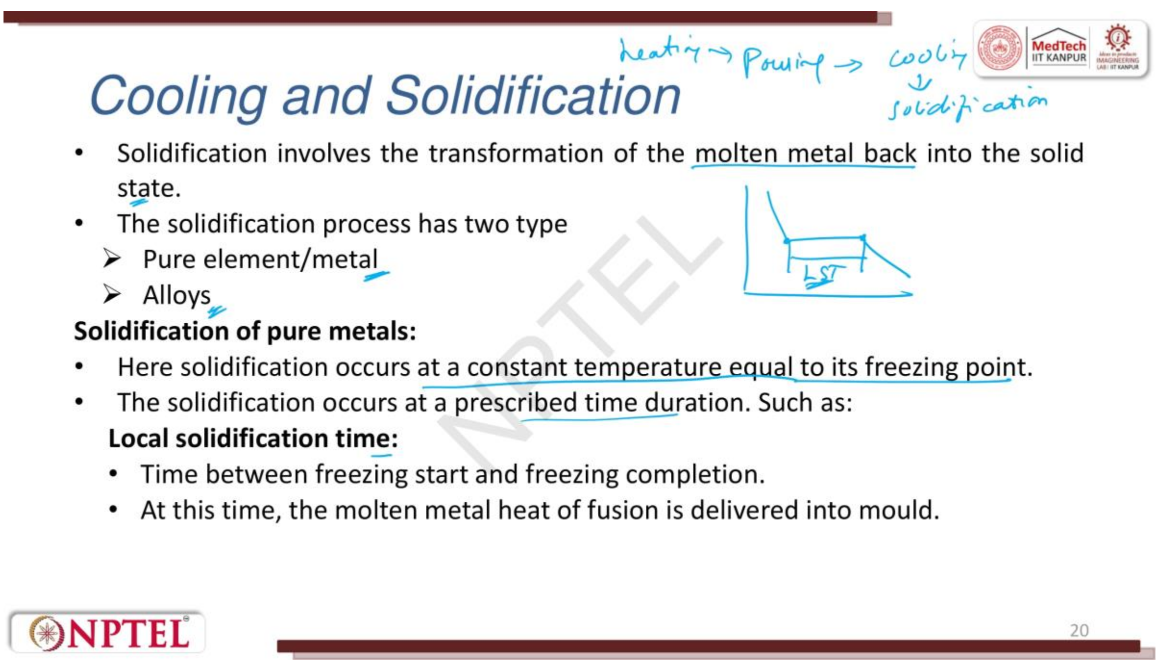
So, here what we do is: we again do not take it completely to liquid. We try to take it to the glass transition temperature and slightly above, then try to deform the polymer. When I say polymer, it includes thermoset, thermoplastic, and elastomer. So, now let us look into casting. Our focus in this chapter is the casting of metals.

So, now the casting of metals can be divided into two parts. One is called Expendable Mold Casting, and the other is Permanent Mold Casting. What is Expendable Mold Casting? Whenever I take a cast product out of the mold, I destroy the mold. So, that is called Expendable Mold Casting.

For example, you can assume you have an ice cream cone wherein the ice cream is on the top. So, when you eat the ice cream, you also eat the cone. So, now the cone cannot be reused. So, now the cone becomes the expendable mold. Permanent mold is like the ice cubes you keep in the refrigerator.

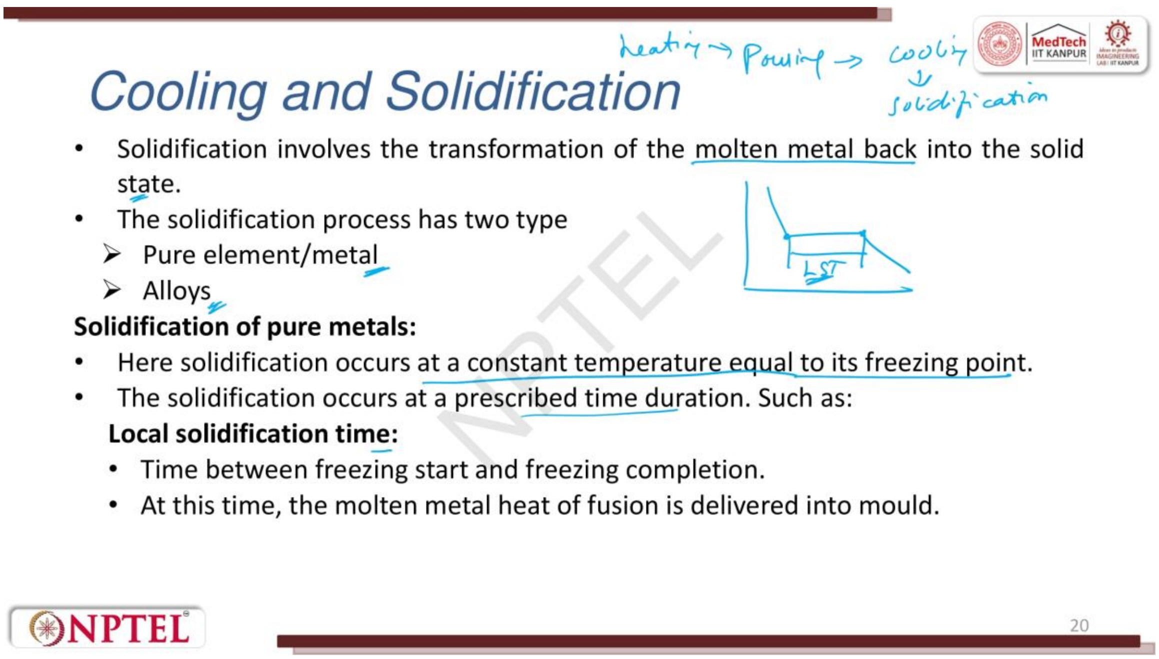
There is a mold; you fill it with water, and then the water gets solidified, and you get cube ice. Then, you remove the ice from there and pour another setup. So, the mold is fixed. For example, if you want to make popsicles, the mold is a plastic cone. You pour the milk with all the ingredients, place a stick in it, and allow it to solidify. Then, once it solidifies, you remove the kulfi stick along with the ice cream, but the mold remains unchanged.

So, those things are called permanent molds or die casting when somebody says it is going to be a permanent mold. So, expendable casting means the mold is destroyed, and permanent casting means it remains the same. So, now in this, sand casting is one major process in expendable molds. Die casting, centrifugal casting, all these things are permanent mold castings.



Cooling and solidification. Solidification involves the transformation of molten metal back into a solid. So, the first step is heating, followed by pouring. Then, cooling and solidification. Solidification involves the transformation of molten metal back into a solid state. The solidification process is classified into two types: pure metals and alloys, but no pure metal has engineering value.

So, we always try to work on alloyed metals only. So, the solidification of a pure metal occurs at a constant temperature equal to the freezing point.



The solidification occurs over a pre-described duration known as Local Solidification Time. This is the graph for Local Solidification Time. The time between the freeze start and the freeze end is called Local Solidification Time.

At that time, the molten metal's heat of fusion is delivered into the mold, which is also called Local Solidification Time. I drew this figure, and we saw this in the phase diagram also; this is for a pure metal. You can see there is a superheat, which we always do above the melting point. So, you can try to have a proper pouring. So, viscosity plays a very important role. So, this makes your pouring temperature very high, and the time duration is very small.

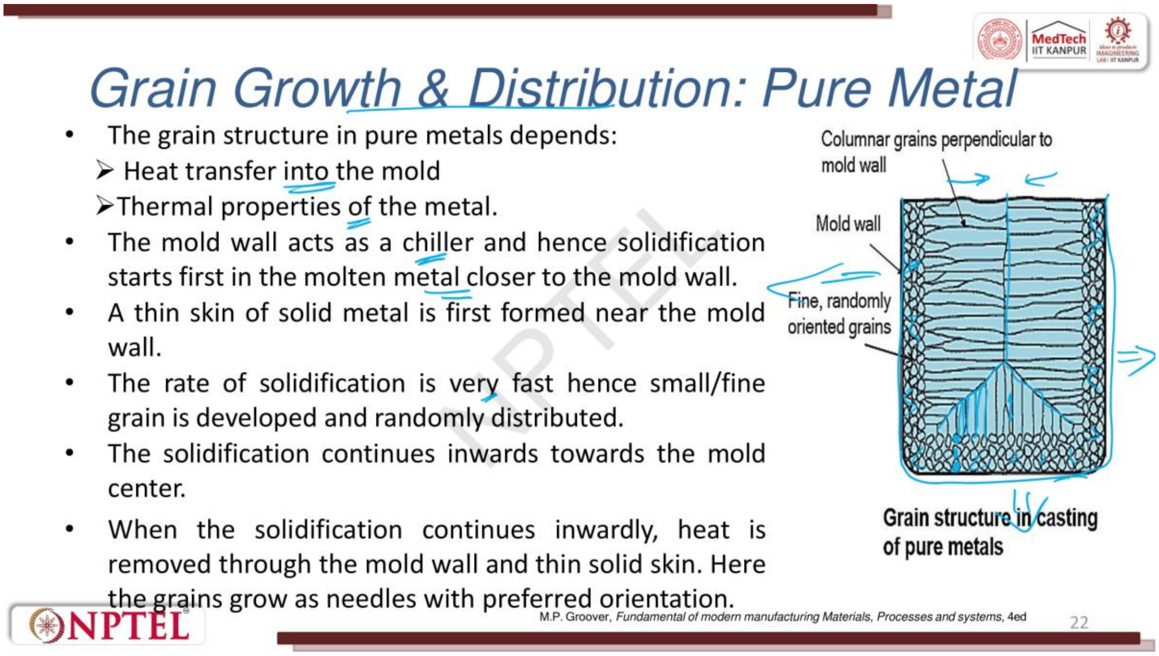
Next, you try to pour; the moment you pour, there is a step down in the temperature. Why is there a step down? Because until here, you are heating; the moment you pour into the mold, there is heat extraction through the mold. If the mold is metal, heat extraction will be faster; if it is sand, it will be slower. However, in both cases, heat is extracted, leading to the beginning of freezing. At the freeze beginning, it starts solidifying, and at the freeze complete, it ends solidification.

So, this point is called Local Solidification Time. From the start of pouring to the end of freeze completion is called Total Solidification Time. After the end of freezing, there is again a downfall in the temperature here, which is called Solid Curing or Solid Cooling. So, these are very important steps. The time between pouring and final solidification is called the Total Solidification Time. The first liquid cooling occurs until the freeze starts, then solidification occurs for a time duration until the freeze is complete.

Even after solidification is over, there is some small amount of liquid, and then it starts pouring into it. Once it is poured, there is heat extraction. Now, when the heat extraction starts, solidification begins. When solidification starts, what happens? The structure gets formed, and grain growth and distribution start happening.

This is the grain growth that is seen when a pure metal is poured into a mold and the heat is extracted. So, you can see this is the mold wall. Around the mold wall, there will be a sudden extraction of heat, which leads to the formation of equiaxial grains. After the equiaxed grains, columnar grains begin to grow. Heat is extracted from multiple directions because the metal is poured into a mold. So, the heat gets extracted from all sides. So, along the sides, instantly what gets formed is the equiaxial grains.

Then, you can see the columnar grains growing toward the center. So, this one grows, this one grows, and this one grows too. They all meet along a line. So, this is also called a Grain Boundary. So, today we talk about grain engineering by playing with the grain structure; you can try to play with the mechanical properties.



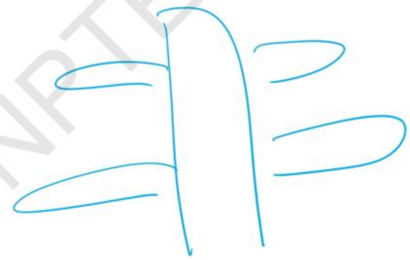
The grain structure in pure metal depends on heat transfer into the mold and the thermal properties of the metal, thermal properties of the liquid, plus the heat transfer in the mold. So, why? Because there is a gradient of heat, so you have to be there. The mold wall acts as a chiller. What is a chiller?

It gives a sudden cooling. So, chiller. And hence, solidification starts first in the molten metal close to the walls, forming a thin shell. The thin skin of solid metal is first formed near the mold wall. The rate of solidification is very fast. Hence, small or fine grains develop along the boundary.

The solidification continues inward toward the mold center. When the solidification continues inward, the heat is removed through the mold walls and thin solid skin. So, the heat will be extracted through the solid skin only. Here, the grains grow like needles along a preferred orientation. That is very important.

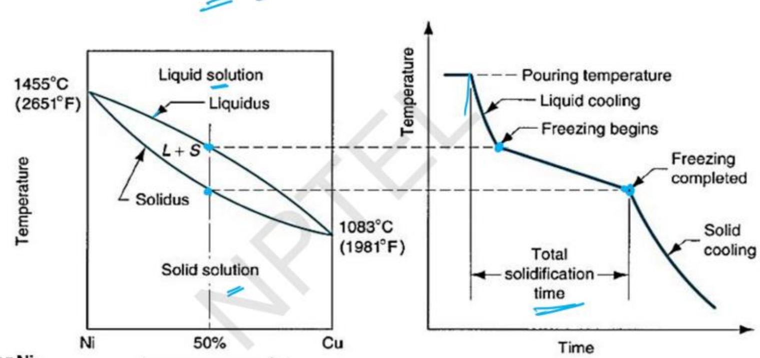
Grain Growth & Distribution: Pure Metal

- As these needles enlarge, side branches develop, and as these branches grow, further branches form at right angles to the first branches.
- This type of grain growth is referred to as dendritic growth. It occurs at the freezing of pure metals and in alloys.



These needles enlarge, side branches develop, and as these branches grow further, branches form at a right angle to the first branch. So, they are saying it like this. This type of grain growth is referred to as dendritic growth. It looks like dendrites. It occurs during the freezing of a pure metal and its alloys.

Solidification: Alloys



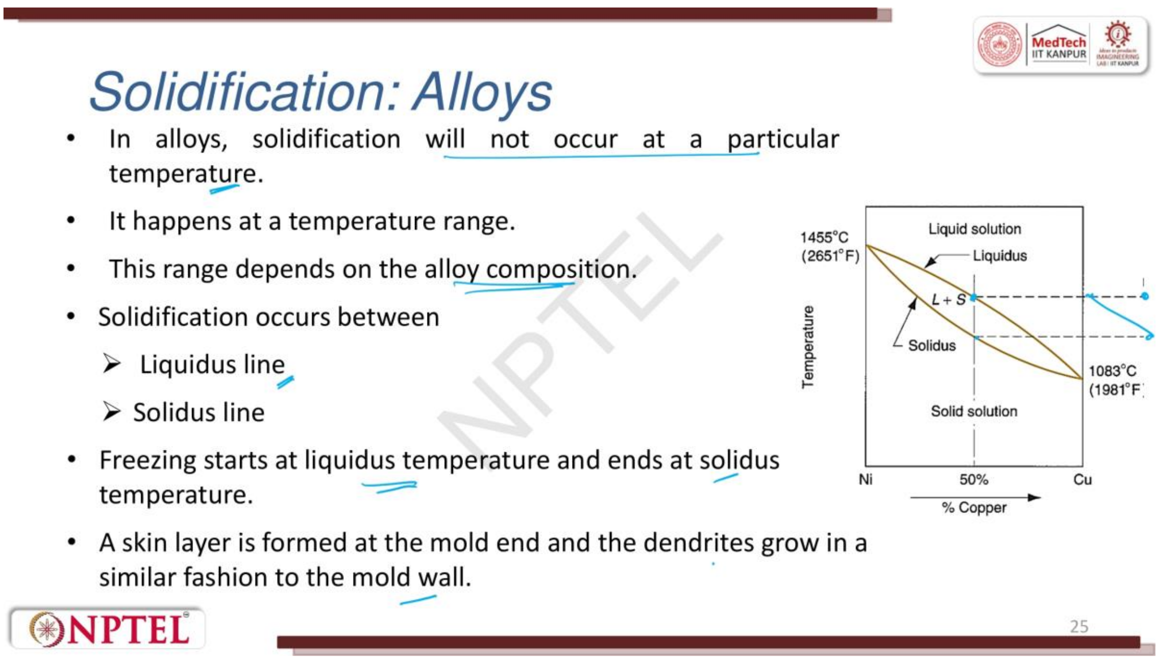
Phase diagram for Ni-Cu alloy system

Cooling curve for 50%Ni-50% Cu during casting

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

So, this diagram clearly shows how solidification happens for the alloys. So, here it is very clear that the start of freezing and end of freezing do not happen in a single line. It happens on a taper. When you extrapolate the taper to a phase diagram, you can see this is where the liquidus line is, and then that meets this point. So, there is a liquid solution on the top and a solid solution at the bottom. This is the liquidus line, and this is the solidus line. The point where they meet is the freezing start, and the point where it exits is the freezing end.

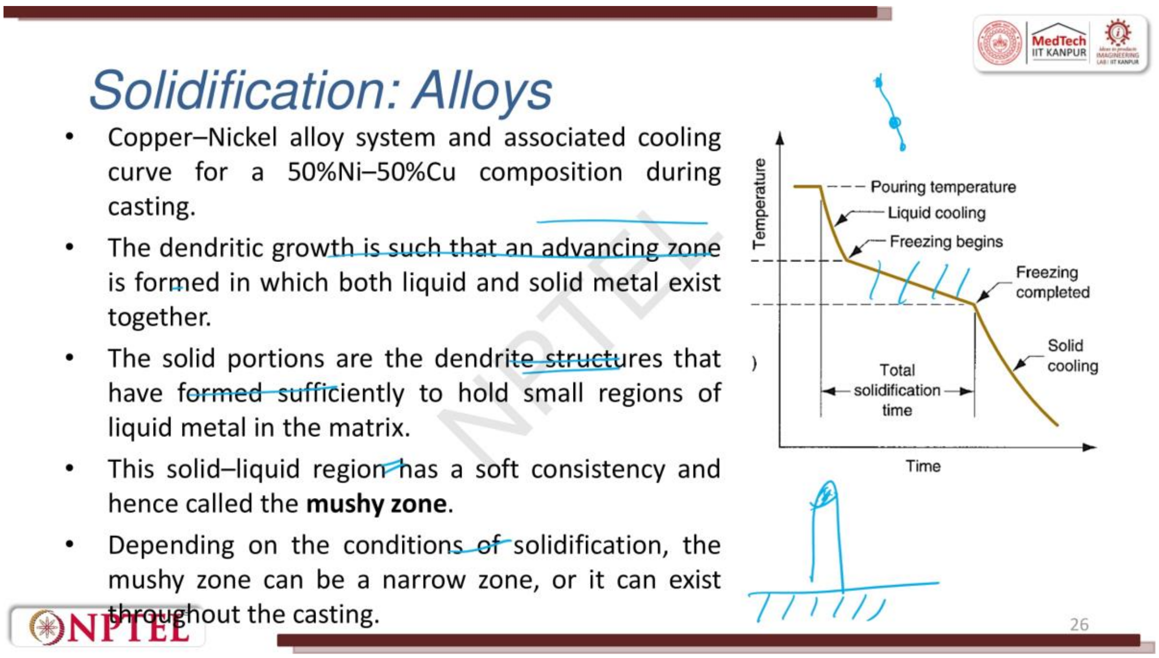
So, now the total solidification time will be here; this is called the total solidification time. So, solidification in alloy.



In alloy, solidification will not occur at a particular temperature; that is what I said. There is a point on the liquidus line and a point on the solidus line. So, this will be the start, and this will be the end. So, in alloy, solidification will not occur at a particular point. So, it will always be a slope.

It happens over a temperature range: a start range and an end range. The range depends on the alloying composition. You can shift it depending upon the composition. The solidification occurs between the liquidus line and the solidus line. The freezing starts at the liquidus temperature and ends at the solidus temperature.

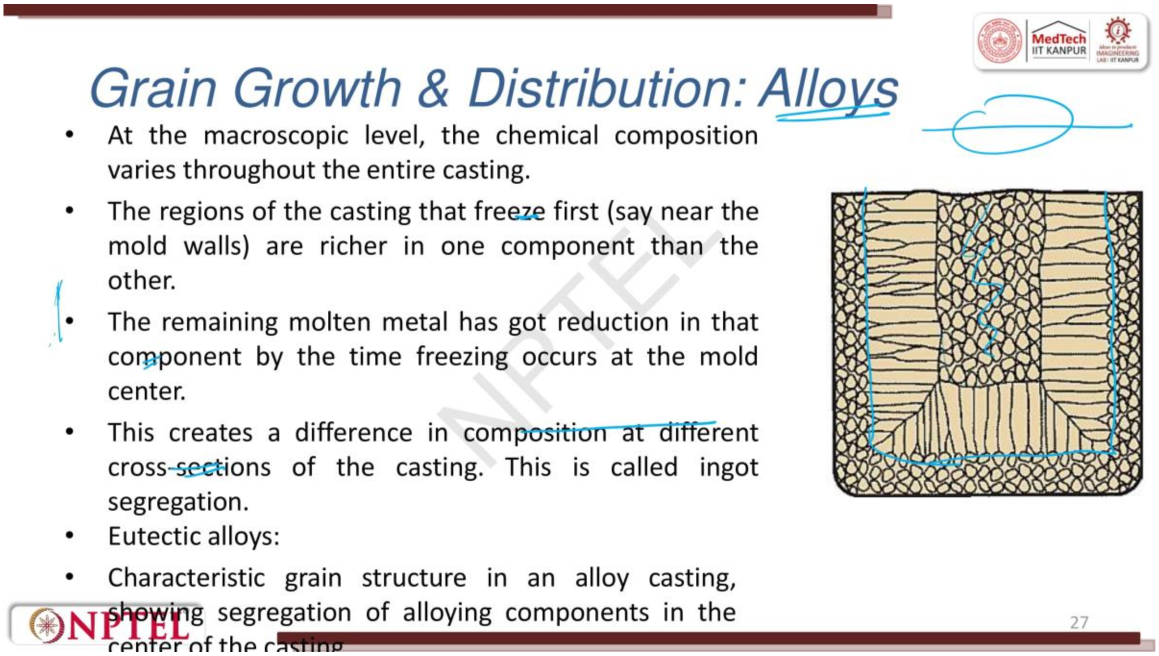
A skin layer is formed at the mold, and the dendritic growth is in a similar fashion to the mold walls.



So, when we take the example of a copper-nickel alloy with a 50-50 composition and its associated cooling curve during casting, the dendritic growth forms an advancing zone where both liquid and solid metal exist together. So, basically, if you go back to your heat treatment, you can see along the grain; you can see some hard precipitates, right? So, how are these getting formed? Basically, the precipitates are hard elements that are moved towards the grain, right.

So, in the same way, here the dendritic growth is such that an advanced zone is formed. So, a dendrite in an advanced zone, right. This is how it is growing. So, dendritic growth is such that an advanced zone is formed in which both the solid and the liquid metal exist together. The small portions are the dendritic structures that have formed sufficiently to hold small regions of liquid metal in the matrix.

This solid-liquid region is called the Mushy Zone. The solid-liquid region has a soft consistency and hence it is called the Mushy Zone. Depending on the conditions of solidification, the mushy zone can be a narrow zone and it can exist throughout the casting. So, this is what happens when you have an alloying element.



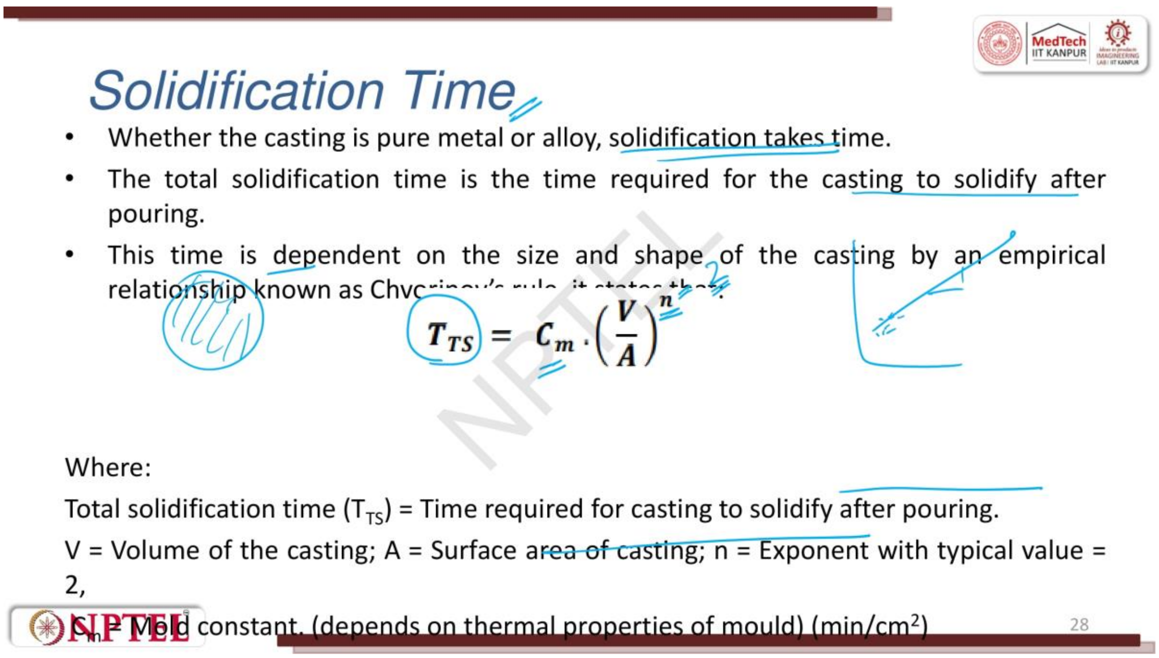
At the macroscopic level, the chemical composition varies throughout the casting. When you have an alloy, because you have said the dendritic growth will have a mixture of both. The region of the casting that first freezes is rich in one component than the other. The remaining molten metal has a reduction in that component by the time freezing occurs at the mold center. This point is very important. The remaining molten, the region of the casting that first freezes, say near, so this one, right?

This is called the skin. The region of the casting that freezes first is rich in one composition than the other because of solidus liquidus, right. So, the remaining molten metal has got a reduction because it is rich in one, so the other will. The balance will be there. So, the remaining molten metal has got a reduction in that component by the time freezing occurs at the mold center.

So, this is what the mold center is. This creates a difference in composition at the cross-section or in the casting. This is called ingot segregation or eutectic alloy formation. If you have an alloy, ingot segregation happens. You have a component; when you cut it across, there is a compositional difference.

This creates a difference in composition at different cross-section areas. The characteristic grain structure in an alloying casting shows segregation of alloy composition in the center of the casting. So, you see the big difference between alloy and pure metal. Now, comes the next thing: what is the solidification time? First was heat pouring, then cooling and solidification.

Now, I should try to find out what the solidification time is when I have a mould like this. Why is it important? Because correspondingly, I will try to pour, and I will also try to have the other systems in place.

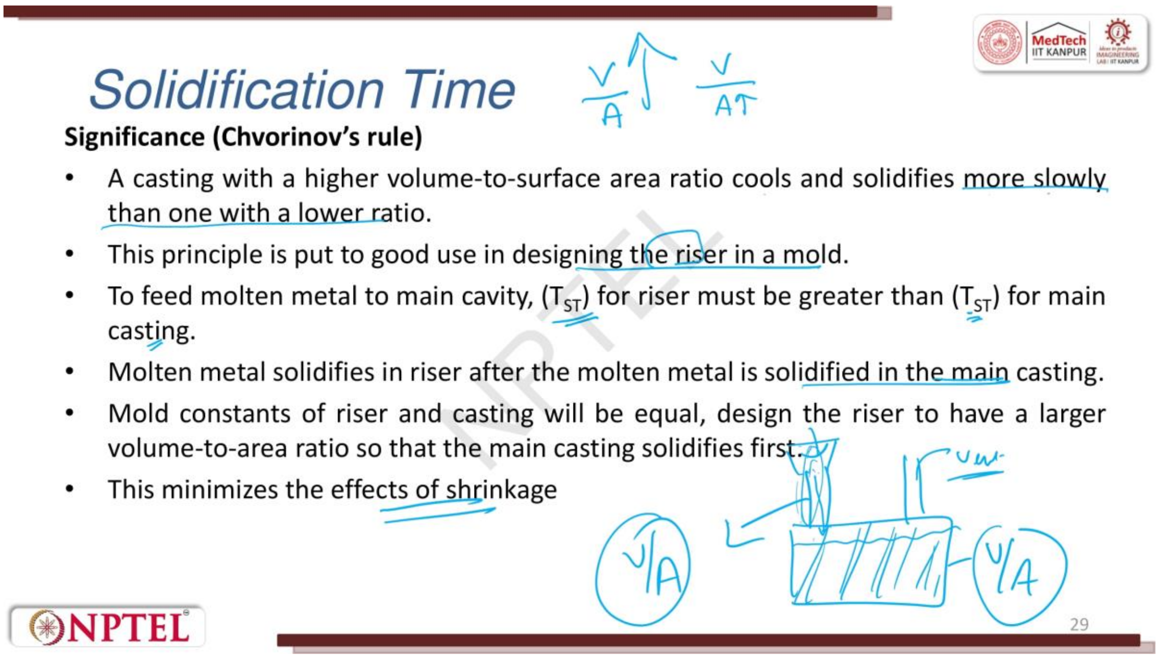


When the casting is a pure metal or alloy, the solidification takes time. The total solidification time is required for a casting to solidify after pouring.

So, the time which is required for solidification can be figured out through Chvorinov's rule. So, Chvorinov's rule clearly states that there is a mold constant multiplied by volume divided by area to the power n. 'n' is an exponential where the value of n is generally taken as 2 based upon empirical experiments. What are empirical experiments? They did so many experiments, so there is no proof they did experiments, and they collated the data n.

They could have plotted several points, and then they would have drawn a straight line, and then they would have taken a slope. So, all these things are possible. So, these things are called empirical. Cm is a constant which is the mold constant. This mold constant depends upon the thermal conductivity of the mold.

It can be a metal mold or it can be a sand mold. So, it depends on that. And V is the volume, A is the surface area. So, you know if you have a sphere, you know the volume of the sphere and you know the surface area of the sphere. So, from this, you can try to calculate what the solidification time is. Based on the solidification time, you can try to play with the volume-to-surface area ratio.



So, what is the significance of Chvorinov's rule? A cast with a high volume-to-surface-area ratio cools and solidifies more slowly than one with a lower ratio. Higher V to A volume is more compared to the surface area, the solidification is very slow. If the surface area is high and the volume is very low, then it is faster cooling. The principle is put to good use in designing the riser in the mold.

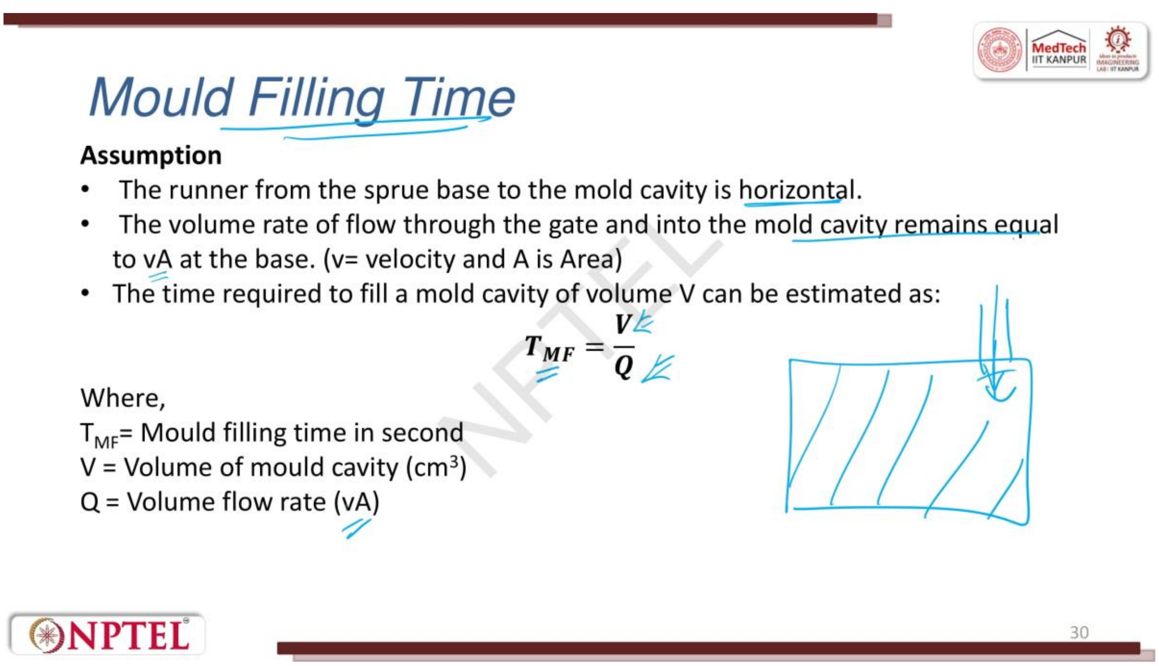
Riser is one term, please hold it. We will get back to it later. If you want to see the riser, the riser was there in the first slide, mold, and then they had an open riser. This was there. Here there was a vent and this was a riser.

The feed of molten metal to the main cavity for the riser must be greater than the solidification time for the main casting. So, that means to say the solidification rate of this liquid should be slower as compared to that of the solidification which happens here. Why? It is because if everything gets solidified here and there is a small shrinkage, then the liquid metal from the top can pour into the mold such that the mold is filled and you get a sound part. So now what happens is this has a volume surface to volume ratio, and this has a surface to volume ratio.

So, if you can play with this volume ratio, a higher volume to surface area ratio cools and solidifies more slowly. So, if I play with this, this material over here slowly cools as compared to that of this. So, to feed molten metal to the main cavity, the Ts of the riser must be greater than the Ts of the main casting. The molten metal solidifies in the riser after the molten metal solidification in the main casting. So, please keep that in mind; the riser is always used because once the material is poured into the mold, while solidification, there is going to be a shrinkage.

You know, in the phase change, liquid to solid, there is going to be a shrinkage. So, once there is a shrinkage, there will be improper mold filling. So, now excess metal has to come from the riser to the So, the riser will always solidify last as compared to that of the mold. The mold constant of the riser and the casting will be equal.

The design of the riser has a larger volume-to-area ratio so that the main casting solidifies first. To minimize the effect of shrinkage, we always use the riser.

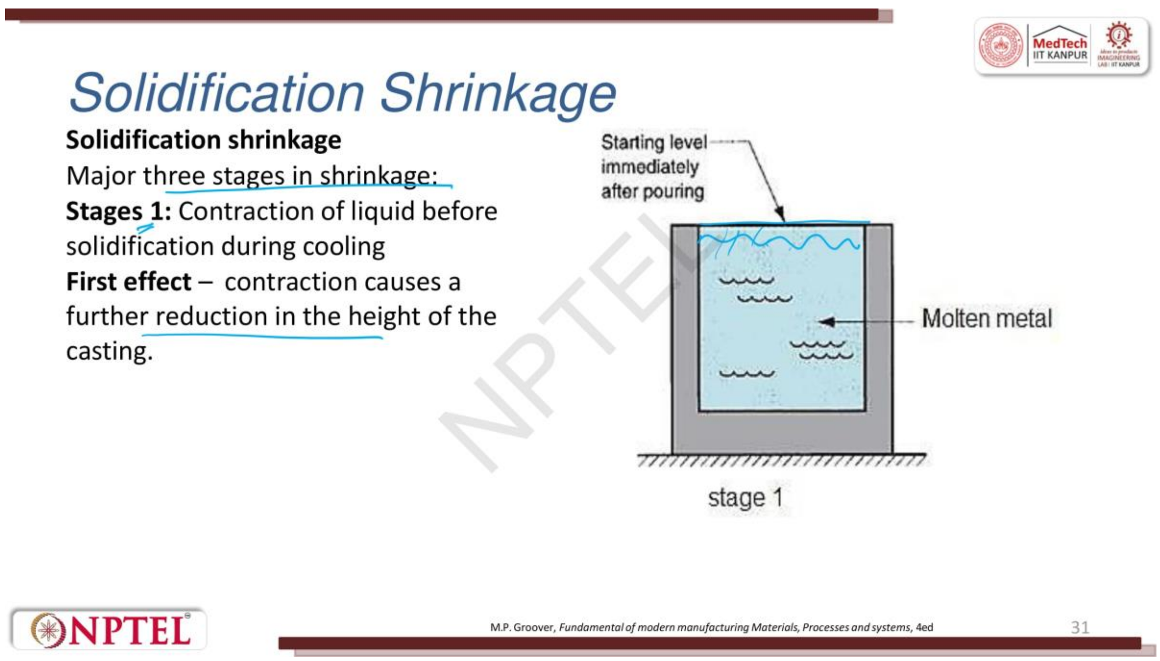


Mold filling time: what is mold filling time? You have a dubba, then you have liquid coming from here. So, what is the time required to fill it?

Fill, so this is mold filling time; this is mold solidifying time. How do you calculate the mold filling time? Mold filling time is the volume of the mold divided by the flow rate. The section from the sprue base to the mold cavity is horizontal. The volume rate through which the gate into the mold cavity

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

So, the filling time will be V divided by the flow rate. So, mold filling time is equal to the volume of the mold divided by the flow rate VA. What is VA? VA is calculated from here, which is nothing but the mold cavity remains equal to VA, the gating area.



So, let us try to look into solidification shrinkage. So, solidification shrinkage happens in stages. There are three stages of shrinkage. It is not just one; there are three stages. Stage 1 is the contraction of the liquid before solidification during cooling. So, this is the full pore level you have done, and these are molten metal. In stage 1, what will happen is there will be a contraction of the liquid before solidification during cooling.

The first effect is contraction, which causes a further reduction in the height. This is stage 1, right? It reduces the height. So, from here, it is reduced. So, reduction in the level of the liquid contraction is stage 1.

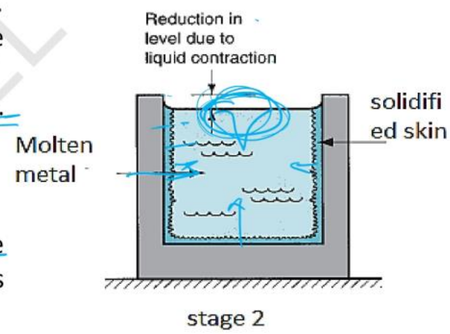
Solidification Shrinkage

Stage 2:

- Contraction during liquid-to-solid phase change
- Solidification front has started at the mold wall.
- The level of liquid metal has reduced at the open surface due to liquid contraction.
- The amount of liquid contraction is approx. 0.5%.

Second effect –

- The top center portion is the last to get frozen.
- The amount of liquid metal present to feed the top center portion of the casting becomes restricted.
- The absence of metal in this region creates a void in the casting.
- This will be converted into a 'shrinkage cavity'



Then, stage 2, what happens? There is contraction during the liquid-to-solid phase change. The solidification front has started from the mold cavity, so from the edge walls. The level of the liquid metal has reduced at the open surface due to liquid contraction. First, there was liquid contraction, then because of this solidification, further reduction happens.

The amount of liquid contraction is approximately 0.5 percent. Then the second effect is the top center portion; this portion is the last to solidify because it starts solidifying from here. It starts solidifying, it starts solidifying. So, the last portion to get solidified will be here. The center portion is the last to solidify.

The amount of liquid metal present to feed the top surface portion of the casting becomes restricted because from here it is done, here it is done, here it is done. So, this point is very important. The amount of liquid metal present to feed the top center portion of the casting becomes restricted. So, the absence of metal in the region creates a void. So, you will have a void.

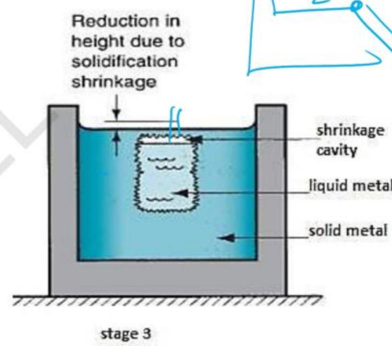
So, this one is converted into a shrinkage cavity. Look at this shrinkage cavity, right. The solidification happened here, from the top, then there is a void which is there.

Solidification Shrinkage

Stage 3: Contraction of solid metal during cooling to Room temperature

Effect:

- This shrinkage is determined by the solid metal's coefficient of thermal expansion.
- Which in this case is applied in reverse to determine contraction.



The last stage is going to be the contraction of the solid metal cooling to room temperature. From here to here, we are saying right, stage 3, stage 1, stage 2, stage 3.

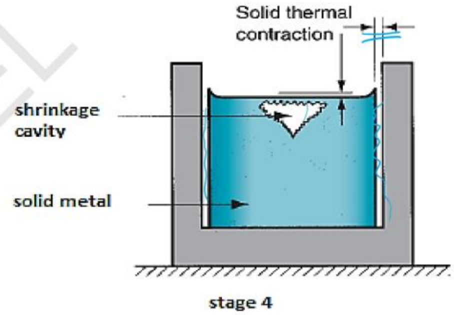
Contraction of solid metal during cooling to room temperature is determined by the solid metal's coefficient of thermal expansion, which in this case is applied in reverse to determine the shrinkage. So, solidification can happen in three stages. The first stage is from the top. Then, further from the top, because the solidification is there, and because of this, you have solid everywhere, and then there is a small shrinkage cavity. So, now, this cavity is further increased, and we have to fill it up with the metal.

So, in this, we try to put a riser and then we try to make sure the excess metal flows to take care of this shrinkage.

Solidification Shrinkage

Stage 4:

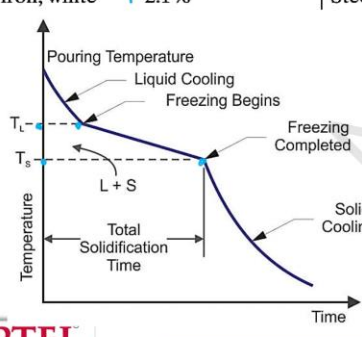
- Once solidified, both height and diameter contracts resulting in shrinkage cavity at the top centre.
- This will be seen as a 'Pipe', in case casting is done in a tube like container which does not have mold wall at the bottom.
- Solidification shrinkage occurs almost in all metals because the solid phase has a higher density than the liquid phase.

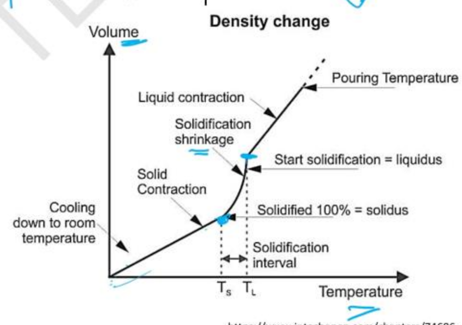


The fourth stage is going to be one where solidification occurs, and both height and diameter contract, resulting in a shrinkage cavity at the top. This is known as the pipe. In the case of casting, it is done in a tube-like container which does not have the mold wall at the bottom. The solidification shrinkage occurs in most metals because the solid phase has a higher density than the liquid phase. So, you can see here that they get detached from the mold. So, solid thermal contraction happens. So, it gets detached, and then you try to remove it.

Solidification Shrinkage: Examples

Metal	Linear shrinkage	Metal	Linear shrinkage	Metal	Linear shrinkage
Aluminum alloys	1.3%	Magnesium	2.1%	Steel, chrome	2.1%
Brass, yellow	1.3%–1.6%	Magnesium alloy	1.6%	Tin	2.1%
Cast iron, gray	0.8%–1.3%	Nickel	2.1%	Zinc	2.6%
Cast iron, white	2.1%	Steel, carbon	1.6% – 2.1%		





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So, solid shrinkage is a pretty interesting phenomenon in which there are four stages. There are three major stages, and the last one is the fourth stage.

The first stage is top shrinkage. In the second stage, as solid forms, shrinkage continues. The third stage involves trapped shrinkage. In the fourth stage, a pipe formation occurs, followed by solid thermal contraction. So, the solid is removed from the mold.

So, when solid shrinkage examples are there, you have linear shrinkage for various alloys I have given, then for various metals I have given, and then the other things are given. So, if you look into it, this is temperature versus time, this is the pouring temperature, it is liquid cooling, then freeze beginning because it is an alloy, freeze end. This is the liquidus and solidus line. From there, it comes back to room temperature cooling. So, when I try to plot it with respect to volume. And with respect to here, I take temperature, volume, and temperature. Please make a note, you try to have from here, let us go from here.

So, the cooling down, let us start from the top. So, pouring temperature, from the pouring temperature, the volume reduces with respect to time up to the start of the liquidus line. Then, the start of solidification is equal to the liquidus line, then there is a sudden reduction in the volume up to the solidus line, okay. So, here there is solid solidification shrinkage, then after this, at room temperature when it comes, it is solid contraction, this happens at room temperature, right. So, the volume reduces as and when the temperature reduces.

Thank you very much.