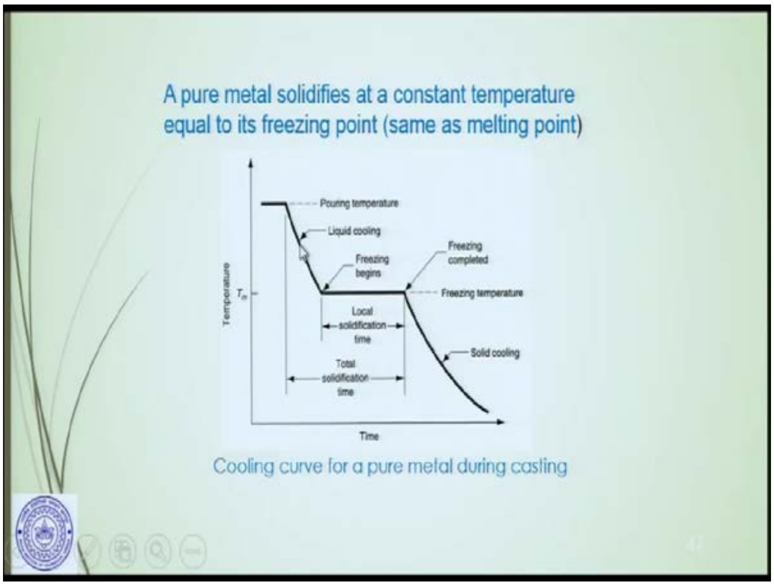
Manufacturing Processes - Casting and Joining

Prof. Sounak Kumar Choudhury
Department of Mechanical Engineering
Indian Institute of Technology Kanpur

Lecture - 07
Solidification of Metals and Alloys

Hello and welcome to the course on Manufacturing Processes Casting and Joining. Let me remind you that in our last session we started discussing on the solidification after the molten metal is poured inside the mold cavity.

(Refer Slide Time: 00:44)



A pure metal solidifies at a constant temperature equal to its freezing point (same as melting point)

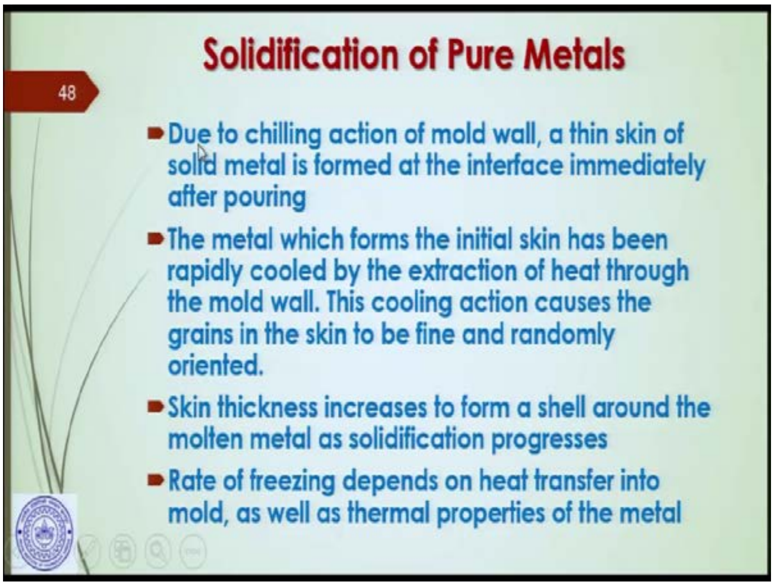
Cooling curve for a pure metal during casting

We said that for pure metal, if you look at this slide, this is the cooling curve during the casting; that means, here at this point it is the pouring temperature. This is the temperature of the molten metal at which the molten metal is poured into the mold cavity. As time elapses, the liquid started cooling off, but actually freezing begins from this point .

And from that point when the freezing begins, up to the point where the freezing completes, this is called the local solidification time. Whereas, from the time the molten metal is poured, up to the time when the freezing is complete, this is the total solidification time. The total solidification time is more than the local solidification time.

After the freezing is complete, this is the freezing temperature, then as the time elapses, the metal is already solidified. And this solid metal is cooling down; and this is the slope of the curve as shown here, it goes up to the room temperature. this is the entire cooling curve, that is the temperature versus time; as the time elapses how the temperature changes starting from the pouring to the freezing, and then till the total solidification stage.

(Refer Slide Time: 02:38)



Solidification of Pure Metals

- Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring
- The metal which forms the initial skin has been rapidly cooled by the extraction of heat through the mold wall. This cooling action causes the grains in the skin to be fine and randomly oriented.
- Skin thickness increases to form a shell around the molten metal as solidification progresses
- Rate of freezing depends on heat transfer into mold, as well as thermal properties of the metal

After that it cools down to the room temperature, but now in case of pure metal as we said due to chilling action of the mold wall, a thin skin of solid metal is formed at the interface immediately after pouring. As you understand that during the pouring, the temperature of the molten metal is much higher than the temperature of the walls inside the mold cavity.

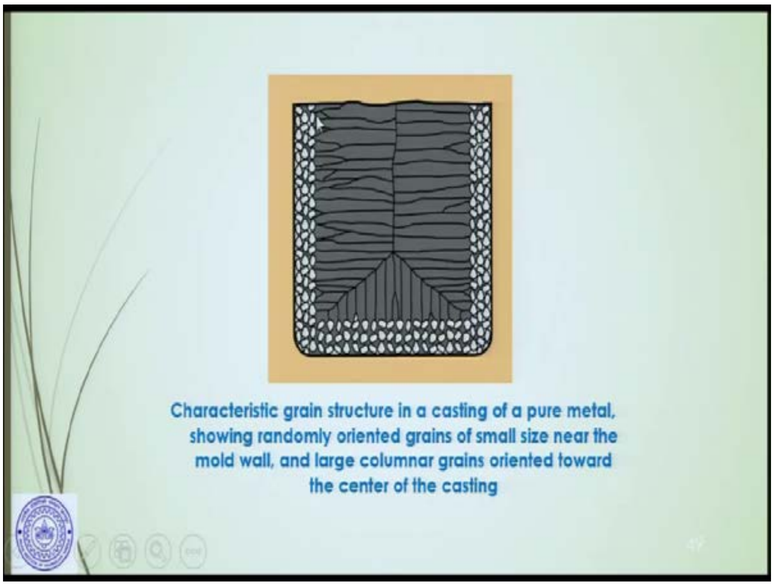
Therefore, as soon as the molten material is poured, it gets in the contact with the mold walls, and the mold walls are much cooler. So, the solidification begins at that interface to begin with. This is what is said here. Now the metal which forms the initial skin has been rapidly cooled by the extraction of the heat through the mold wall.

Now, this cooling action causes the grains in the skin to be fine and randomly oriented. Fine, because the cooling rate is very high. Since as I said that walls are cooler, so the molten metal will solidify very quickly at that interface, and therefore, the grains will be finer. And they will be randomly oriented. Now, this skin thickness increases to form a shell around the molten metal as the solidification progresses.

Once the metal is solidified, this is the solid metal around the liquid metal, and that as if is creating a kind of a shell. The thickness of the shell will be increasing as the solidification progresses, as the time elapses.

Now, the rate of freezing depends on the heat transfer into the mold as well as the thermal properties of the metal. Of course, that will depend on the heat transfer, how the heat is transferred into the mold and on the thermal properties of the metal itself, because different metals will have different rate of freezing. If it is aluminum, it is one slope; if it is cast iron, it is another slope and so on.

(Refer Slide Time: 04:58)



Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting

Now, this is what is happening. This is the molten metal; the entire mold cavity is filled up with the molten metal. As soon as it is occupying the mold cavity, it comes in contact with the mold walls, and it rapidly cools down around the wall.

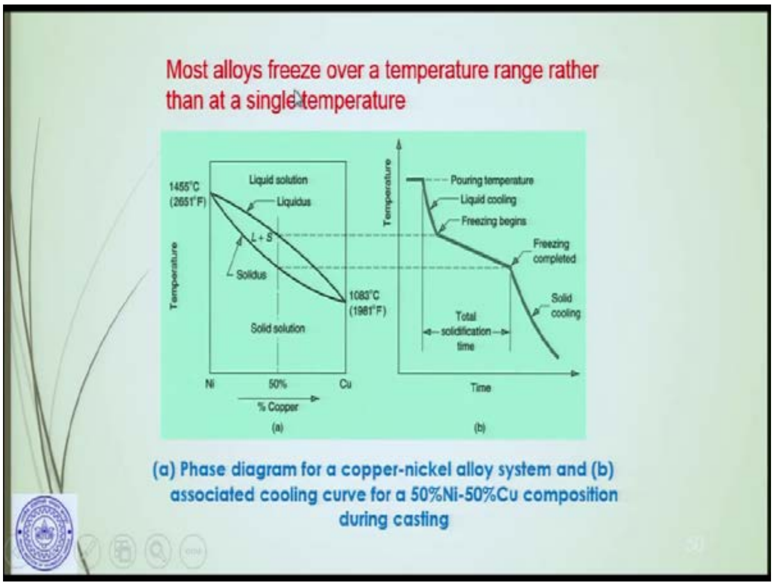
Now, since the cooling rate is rapid, so grains, as you can see, will be smaller, and they will be randomly oriented. I am repeating that once again. This is the characteristic grain structure in a casting of a pure metal showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented towards the centre of the casting;

meaning that with further cooling as the time elapses, it goes away from that wall towards the center.

It propogates in a prolonged elongated columnar grains form. This is how the picture will look like. From here, it will go to the center. And these are the grains which will be columnar.

These will be large and the columnar grains because here the cooling rate is much less than the cooling rate at the interface of the mold wall and the molten metal. However, alloys freeze over a temperature range rather than at a single temperature . Here what we have seen is a particular temperature.

(Refer Slide Time: 06:48)



Most alloys freeze over a temperature range rather than at a single temperature

(a) Phase diagram for a copper-nickel alloy system and (b) associated cooling curve for a 50%Ni-50%Cu composition during casting

In case of alloys, the phase diagram has been shown here. This phase diagram is for copper and this is the temperature, and this is the nickel, and the copper – 50, 50; 50 percent each. There is a composition of the nickel and the copper, each of them is of 50 percent volume.

And here is the phase diagram. With the temperature, here we will have the liquidus and this is the solidus. That means, in here we will have the solid solution, and in here we will have the liquid solution. In between we will have a mushy zone, kind of mixed zone. This is the liquid as well as solid phase.

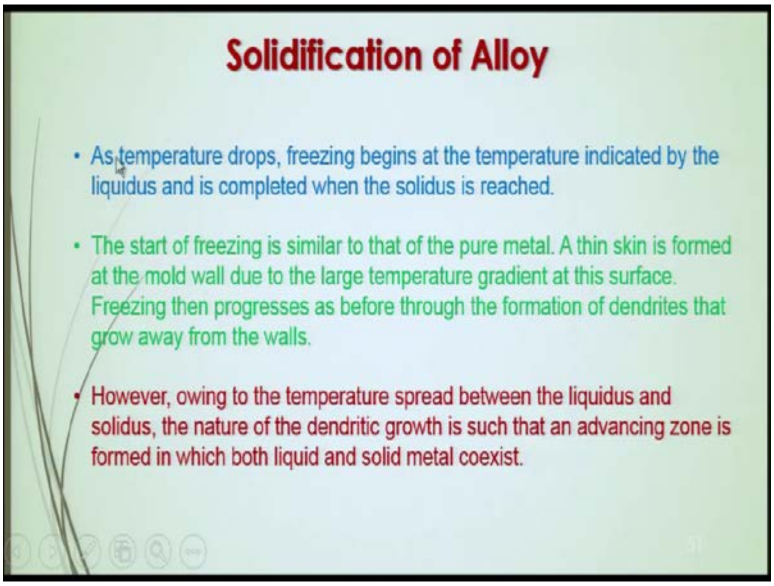
Now, here as you can see that as the liquid metal is poured, this is the pouring temperature, the liquid is cooling. And in this, freezing begins when it goes to the liquidus; it ends when it reaches the solidus point. As you can see that this is the liquidus point.

At that liquidus point, the freezing begins, and at the point where the solidus is there, there the freezing completes. This is the slope of the curve from the beginning of the freezing up to the end of the freezing. After it is solidified, solid metal cools down according to this slope.

Therefore, the total solidification time, like in the case of the pure metal, will be from the pouring temperature up to the point where the freezing is completed. So, this is what happens in case of the alloy . As I said that this happens over a temperature range, and that temperature range is from liquidus to solidus.

This is the phase diagram for a copper-nickel alloy system. Associated cooling curve has been shown here. This is the associated cooling curve, temperature versus time as we have shown in case of the pure metal.

(Refer Slide Time: 09:13)



Solidification of Alloy

- As temperature drops, freezing begins at the temperature indicated by the liquidus and is completed when the solidus is reached.
- The start of freezing is similar to that of the pure metal. A thin skin is formed at the mold wall due to the large temperature gradient at this surface. Freezing then progresses as before through the formation of dendrites that grow away from the walls.
- However, owing to the temperature spread between the liquidus and solidus, the nature of the dendritic growth is such that an advancing zone is formed in which both liquid and solid metal coexist.

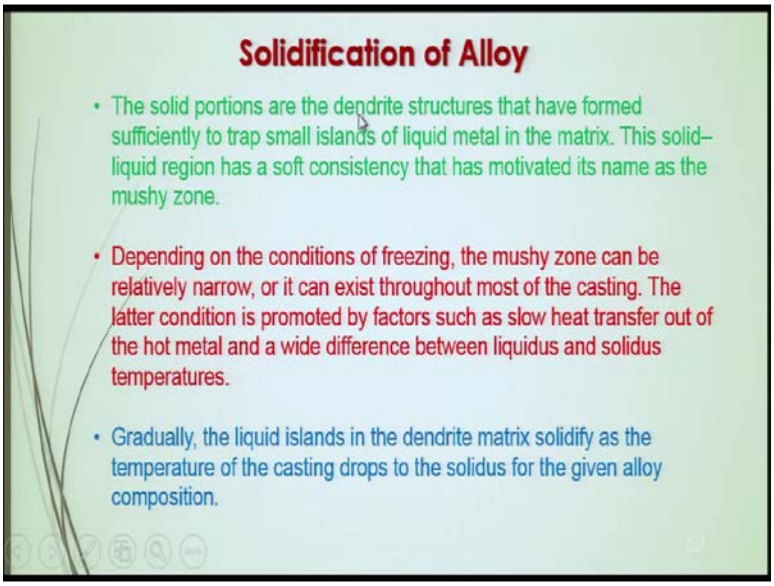
This is what happens, as I narrated to you, as temperature drops freezing begins at the temperature indicated by the liquidus and is completed when the solidus is reached. It starts when this is in liquidus state; and it completes in the solidus. The start of freezing is similar to that of the pure metal, of course. A thin skin is formed at the mold wall again due to the large temperature gradient.

Temperature gradient between the wall and the molten metal at this surface; freezing then progresses as before through the formation of dendrites, that means, after that thickness is achieved around the wall, then as the time elapses, the grains become larger, because then the rate of cooling will be more and long and the columnar grains moving towards the center will be seen in this case as well.

Those are kind of dendrites, because there are also sub divisions from them perpendicular to the direction along which columnar grain is moving. Therefore, it will look like dendrites, that grow away from the wall and moves towards the center.

However, owing to the temperatures spread between the liquidus and solidus, the nature of the dendritic growth is such that an advancing zone is formed in which both liquidus and solid metal coexist. I already told you that here we will have both the liquid and the solid state of the metal.

(Refer Slide Time: 11:12)



Solidification of Alloy

- The solid portions are the dendrite structures that have formed sufficiently to trap small islands of liquid metal in the matrix. This solid–liquid region has a soft consistency that has motivated its name as the mushy zone.
- Depending on the conditions of freezing, the mushy zone can be relatively narrow, or it can exist throughout most of the casting. The latter condition is promoted by factors such as slow heat transfer out of the hot metal and a wide difference between liquidus and solidus temperatures.
- Gradually, the liquid islands in the dendrite matrix solidify as the temperature of the casting drops to the solidus for the given alloy composition.

The solid portions are the dendrite structures that have formed sufficiently to trap small islands of liquid metal in the matrix. This solid-liquid region has a soft consistency. Therefore, it is called as the mushy zone. Since it is soft because it has the solid metal along with the liquid metal, this is called as the mushy zone.

Now, depending on the conditions of freezing, the mushy zone can be relatively narrow. If it is at a faster rate, the mushy zone will be narrower , or it can exist throughout most of the casting, when the rate of freezing is relatively higher.

Now, the latter condition is promoted by factors such as slow heat transfer out of the hot metal and a wide difference between liquidus and solidus temperatures. Meaning that, if for example, this zone is quite wide, then the temperature at this point, that is at the liquidus point, and temperature at the solidus point vary too much. In that case this is what happens.

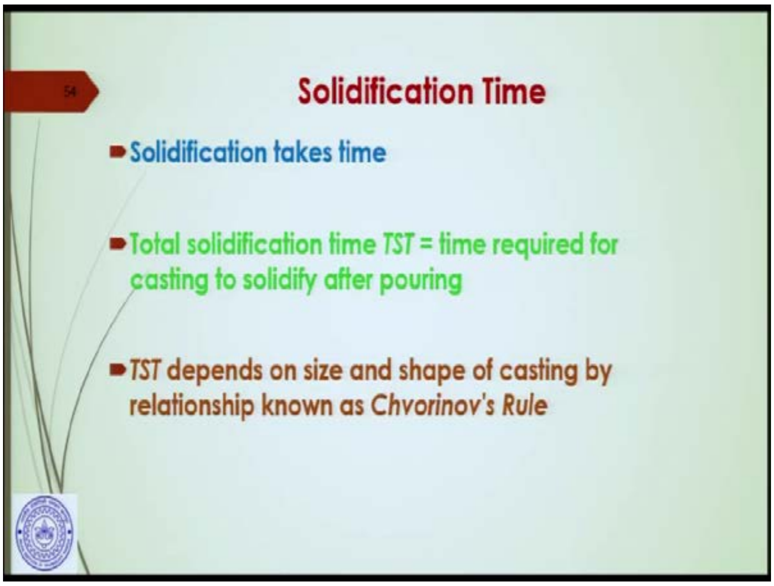
Gradually, the liquid islands in the dendrite matrix solidify as the temperature of the casting drops to the solidus for the given alloy composition. So, this is in brief what happens - that freezing starts with the liquid and the solid both together, then it goes up to the freezing point where the freezing completes, and then it becomes solid. During that period, the temperature gradient between the liquidus and the solidus could be narrower or it could be wider.

If it is narrower, in that case the mushy zone will be narrow or it exists for less time. And it will exist for longer time, it will be more if the temperature gradient is more; and if this is not so narrow, the liquidus and the solidus temperature gradient is higher.

So, this is what we can see. And inside you can see that this is the mushy zone. This is the characteristic grain structure in an alloy casting showing segregation of alloying components in the center of casting. These are the alloying components which will be segregated.

Here similar phenomenon happens like in the case of the pure metal, that means, there will be smaller grains at the interface of the wall, and then the grains become larger, and they get elongated and prolonged moving towards the center, away from the wall. And here you will have the segregated alloying components. This is the difference in the characteristic features between the pure metal and the alloys while solidifying.

(Refer Slide Time: 14:38)



Solidification Time

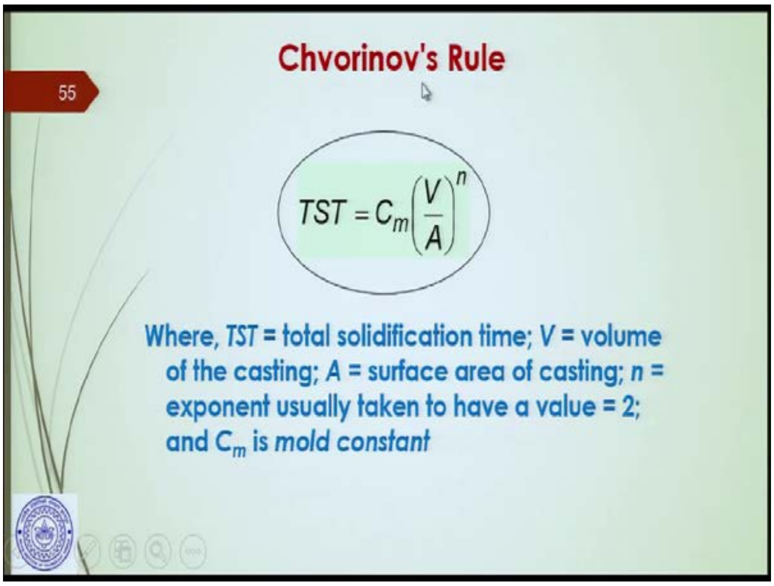
- Solidification takes time
- Total solidification time *TST* = time required for casting to solidify after pouring
- *TST* depends on size and shape of casting by relationship known as *Chvorinov's Rule*

Now, let us talk about the solidification time, because solidification time is very important, and we will see how important this is. We should have the ability to determine the solidification time and should have the provision to control it. Let us see how to control that .

Solidification of course, takes time. Total solidification time is the time required for casting to solidify after pouring, that means, where the freezing ends. From the pouring temperature up to the freezing ends is the total solidification time. Let us designate that as the TST.

Now the TST – Total Solidification Time depends on size and shape of the casting of course. If it is bulky, if its mass is more, it will take more time to solidify. And if it is less bulky, it will take less time. Now, even in one casting, if there are thinner wall and thicker wall, then the thinner wall will solidify at a faster rate than where the mass of the material is more, where the thicker portions are there. There is a relationship, known as Chvorinov’s rule.

(Refer Slide Time: 16:15)



Chvorinov's Rule

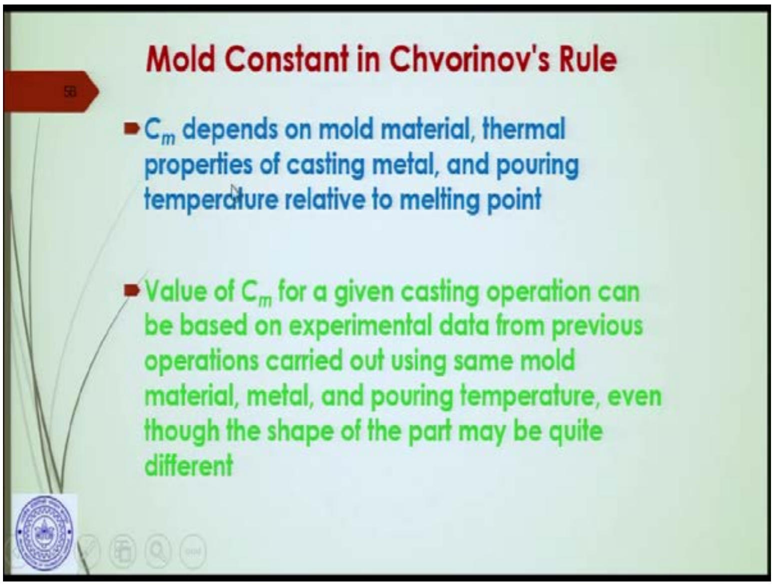
$$TST = C_m \left(\frac{V}{A}\right)^n$$

Where, TST = total solidification time; V = volume of the casting; A = surface area of casting; n = exponent usually taken to have a value = 2; and C_m is *mold constant*

So, what is that Chvorinov's rule? Chvorinov's rule says that the total solidification time is equal to a constant C_m into $\left(\frac{V}{A}\right)^n$. C_m is the constant and that is called the mold constant. Now, the TST is the total solidification time. This is the mold constant C_m; V is the volume of the casting ; A is the surface area of casting, and the n is the exponent; usually that is taken as 2.

Normally if you see in the textbooks, you will find that the formula is given as $TST = C_m \left(\frac{V}{A}\right)^2$. That is, the value of the n is normally taken as 2 .

(Refer Slide Time: 17:13)



Mold Constant in Chvorinov's Rule

- C_m depends on mold material, thermal properties of casting metal, and pouring temperature relative to melting point
- Value of C_m for a given casting operation can be based on experimental data from previous operations carried out using same mold material, metal, and pouring temperature, even though the shape of the part may be quite different

Now, this C_m, that is the mold constant in the Chvorinov's rule, depends on the mold material, thermal properties of the casting metal and pouring temperature relative to the melting point.

Of course, it is obvious that it will depend on the mold material, what kind of mold material is there, either it is a sand mold or it is a permanent mold, where the material is metal. You understand that the property of the mold is different in case of the sand mold or the metal mold. Therefore, mold material is important here.

Then the thermal properties of the casting metal. How much heat is transferred, heat is taken out. And the pouring temperature relative to the melting point. Obviously, these are the factors on which the mold constant will depend. Now, the value of mold constant for a given casting operation can be based on experimental data from previous operations.

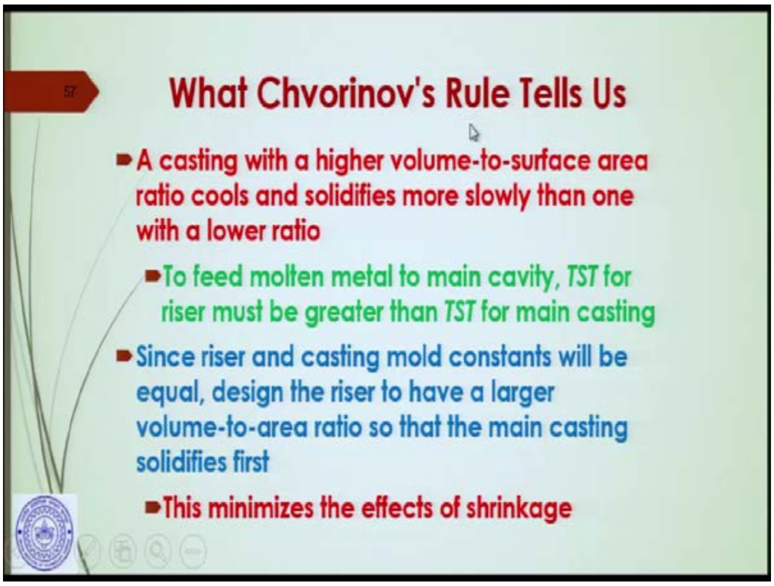
In one word, what is said is that the C_m, mold constant can be tabulated depending on the previous experience. That means, if we have a particular sand of a particular composition or a particular metal, mold made of a particular metal, the C_m can be calculated or C_m can be measured, and this can be tabulated. If you are using the similar or the same kind of material, then you can take the value of the C_m from the hand book.

This can be based on, as I said, experimental data from previous operations carried out using same mold material, metal and pouring temperature, even though the shape of the part may be quite different. Because as we said that C_m is a mold constant that does not depend on the shape of the part, either it is a bigger part or it is a smaller part or it is a complicated part.

Most important should be those three parameters, that is the mold material, thermal properties of the metal, immaterial of the shape, and the pouring temperature relative to the melting point. So, this is about the mold constant which is one of the most important parameters in the Chvorinov's rule as we understand that, because this total solidification time is directly proportional to C_m .

C_m varies from mold material to mold material, because as we said that this basically depends on the mold material. This is the first in this sequence. Therefore, if it is the metal mold, this will be of a particular value, and if it is the sand mold then this value will be different. As you understand that total solidification time, TST will be decreased if the mold material is metal because the solidification is faster.

(Refer Slide Time: 20:33)



What Chvorinov's Rule Tells Us

- A casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio
  - To feed molten metal to main cavity, *TST* for riser must be greater than *TST* for main casting
- Since riser and casting mold constants will be equal, design the riser to have a larger volume-to-area ratio so that the main casting solidifies first
  - This minimizes the effects of shrinkage

Now, what then Chvorinov's rule tells us, let us see. This equation, that is total solidification time as per the Chvorinov's rule is equal to the mold constant multiplied by

$\left(\frac{V}{A}\right)^2$. So, this says that a casting with a higher volume to surface area $\left(\frac{V}{A}\right)$ ratio cools and solidifies more slowly than one with a lower ratio.

This is understood; because, once again, this total solidification time is directly proportional to $\left(\frac{V}{A}\right)^2$. Therefore, the casting with the higher volume to surface area ratio cools and solidifies more slowly than one with a lower ratio because the total solidification time will be more if the $\left(\frac{V}{A}\right)$ is higher.

To feed molten metal to main cavity, total solidification time for riser must be greater than the total solidification time of the main casting. this is one of the most important parameters or most important statement that can be concluded from the Chvorinov's rule, that when you are feeding the molten metal to the main cavity, the total solidification time for the riser must be greater.

Meaning that the molten metal in the riser should solidify later than the molten metal in the mold cavity; and this I repeatedly I kept telling you in my previous lectures also that the purpose of a riser is to feed the molten metal to the metal which is poured in the mould cavity after the mould cavity metal is solidified because after the solidification there will be shrinkages.

To compensate for those shrinkages, we should have some liquid metal present in the riser, so that, that liquid metal can be fed to the to the mold cavity. That is why we call the riser as the reservoir of molten metal. Therefore, it is obvious that the liquid metal in the riser should not solidify at a faster rate than the liquid metal inside the mold cavity. This is important.

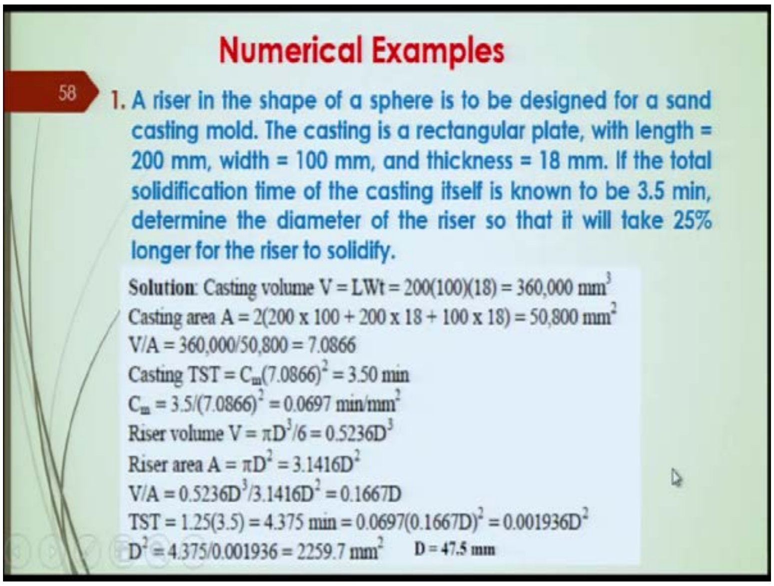
And that the Chvorinov's rule says how to design the riser because it already says that the it depends on the $\left(\frac{V}{A}\right)^2$. So, you manipulate the $\left(\frac{V}{A}\right)$ in the riser with respect to the mold cavity, and you can actually make sure that the molten metal in the riser solidifies later than that of the mould cavity.

Since riser and casting mold constants will be equal, design the riser to have a larger volume to area ratio, so that the main casting solidifies first. This I told you already that the idea is that the molten metal in the riser should solidify later. Therefore, it will be riser to have the larger volume to area ratio that will actually solve the purpose.

Because the same molten material is poured inside the cavity and the riser, the riser and the mold cavity C_m is the same, riser and the casting mold constants will be the same.

This minimizes the effect of the shrinkage, because it will be always ensured in that case that the molten metal will be present in the riser and it can be fed to the shrinked portions of the main cavity, the cavity where the casting is to be formed.

(Refer Slide Time: 24:38)



Numerical Examples

1. A riser in the shape of a sphere is to be designed for a sand casting mold. The casting is a rectangular plate, with length = 200 mm, width = 100 mm, and thickness = 18 mm. If the total solidification time of the casting itself is known to be 3.5 min, determine the diameter of the riser so that it will take 25% longer for the riser to solidify.

Solution: Casting volume $V = LWt = 200(100)(18) = 360{,}000\ \text{mm}^3$

Casting area $A = 2(200 \times 100 + 200 \times 18 + 100 \times 18) = 50{,}800\ \text{mm}^2$

$V/A = 360{,}000/50{,}800 = 7.0866$

Casting TST $= C_m(7.0866)^2 = 3.50$ min

$C_m = 3.5/(7.0866)^2 = 0.0697\ \text{min/mm}^2$

Riser volume $V = \pi D^3/6 = 0.5236D^3$

Riser area $A = \pi D^2 = 3.1416D^2$

$V/A = 0.5236D^3/3.1416D^2 = 0.1667D$

$TST = 1.25(3.5) = 4.375\ \text{min} = 0.0697(0.1667D)^2 = 0.001936D^2$

$D^2 = 4.375/0.001936 = 2259.7\ \text{mm}^2$ $\quad D = 47.5$ mm

Now, I would like to discuss some of the numerical examples in which it will be very clear how the theory that has been told to you, particularly the Chvorinov’s rule, the riser design, how the riser can be designed in an appropriate way. How they can be implemented in the in practice ?

Let us discuss few numerical examples towards this. Example number 1, riser in the shape of a sphere is to be designed for a sand casting mold. This is the example. The casting should be a rectangular plate let us say with length of 200 millimeter, width 100 millimeter, and thickness of 18 millimeter. This is the casting, final casting which is the rectangular plate.

If the total solidification time of the casting itself is known to be 3.5 minute, let us say from previous practices, determine the diameter of the riser, so that it will take 25 percent longer time for the riser to solidify. Here this is the application of the theory in the riser design area. You have to design the riser knowing that riser should be solidifying 25 percent time later. Let us see how to do that.

Now, we know that the casting is the rectangular plate. The casting volume we can find out. This will be length into width into the thickness. So, this will be 200 length, 100 millimeter is the width, and the thickness is 18 millimeter. So, this will be 360000 mm^3.

The volume being determined, the casting area has to be found out. Since it is a rectangular plate, we can find out the area by 2 into 200 we have the length into 100 is the width plus 200 into 18 is the thickness plus 100 width and the thickness 18 because it is a rectangular. So, the area we can find out this way. This will be equal to 50, 800 mm^2. All dimensions are in millimeter and they are getting added up. Therefore, it will be mm^2.

Now, $\left(\frac{V}{A}\right)$ ratio will be 360000 divided by 50800, and it will be equal to 7.0866 let us say about 7.09. This is unit less because this is a ratio of V and A.

Now, the casting total solidification time can be found out using the Chvorinov's rule that is the mold constant into $\left(\frac{V}{A}\right)^2$, $\left(\frac{V}{A}\right)$we found out for the casting as 7.0866, C_m into $(7.0866)^2$. If the total solidification time of the casting is known, so the total solidification time is equal to $C_m\left(\frac{V}{A}\right)^2$ which is equal to 3.5.

Now, from here, we can find out the value of the mold constant C_m which is equal to 3.5 minute divided by $(7.0866)^2$. it will be 0.0697 min/mm^2 because 3.5 is given in the minute. Now, that C_m has been found out, we will use it at a later stage and the riser volume you can find out.

Now you have to find out the riser volume. We said that the riser in the shape of a sphere. Therefore, the riser volume will be $\frac{\pi D^3}{6}$ for sphere. D is given. We can find out this volume and we can find out the area. About this in more detail, I will discuss in my next lecture session.

Thank you.