Manufacturing Processes - Casting and Joining
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Lecture – 06
Aspiration Effects and Riser Design

Hello and welcome to the series of discussions on the Manufacturing Processes - Casting and Joining. Let me remind you that in the last session we were discussing the gating system design. And we said that there is one very important factor to be considered, that at any point within the molten metal, the pressure should not be negative or the pressure should not be less than the atmospheric pressure.

Now, particularly in case of the permeable molds like the sand mold, which is more popular, what may happen is that from the atmosphere the air may penetrate the molten metal and spoil the casting, because that molten metal will have the air bubbles in that case which may not be able to escape. So, there should not be any negative pressure at any level.

But now in the design the I will remind you that we have seen in the last time that if we have a vertical gating system, for example with the cylindrical sprues. In that case it may so happen that at some point the atmospheric pressure maybe the pressure maybe less than the atmospheric pressure. So, that is not acceptable that kind of a design is not acceptable.

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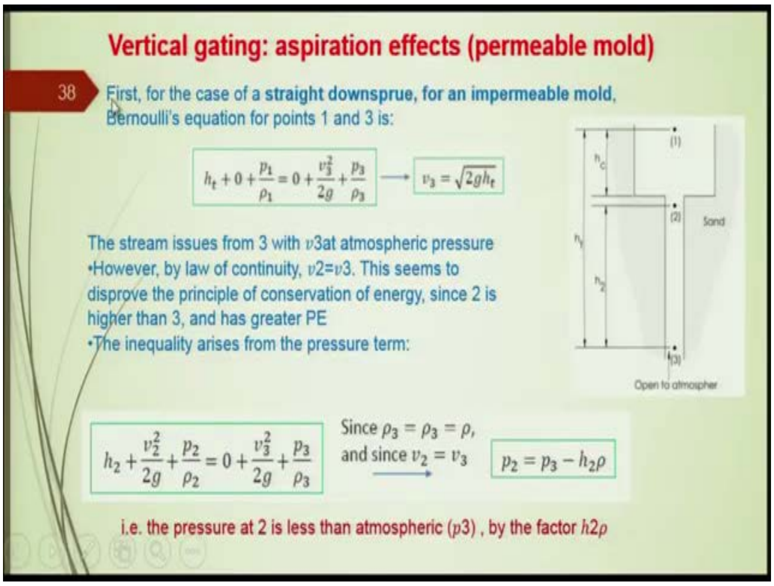

Vertical gating: aspiration effects (permeable mold)

First, for the case of a **straight downsprue, for an impermeable mold,** Bernoulli's equation for points 1 and 3 is:

$$\boxed{h_t + 0 + \frac{p_1}{\rho_1} = 0 + \frac{v_3^2}{2g} + \frac{p_3}{\rho_3}} \longrightarrow \boxed{v_3 = \sqrt{2gh_t}}$$

The stream issues from 3 with $v3$at atmospheric pressure

- However, by law of continuity, $v2=v3$. This seems to disprove the principle of conservation of energy, since 2 is higher than 3, and has greater PE
- The inequality arises from the pressure term:

$$\boxed{h_2 + \frac{v_2^2}{2g} + \frac{p_2}{\rho_2} = 0 + \frac{v_3^2}{2g} + \frac{p_3}{\rho_3}}$$

Since $\rho_3 = \rho_3 = \rho$,
and since $v_2 = v_3$ $\longrightarrow$ $\boxed{p_2 = p_3 - h_2\rho}$

i.e. the pressure at 2 is less than atmospheric ($p3$) , by the factor $h2\rho$

So, to have a recap let us look at this slide, so we are talking about the vertical system vertical gating system which is the in that case the aspiration effect. First for the case of straight down sprue; let us say this is the case where we have taken the Bernoulli's equation between 1 and 3, 2 level and we are getting that the flow velocity at this point will be equal to *2g* and the this height h_t is the height from the pouring level to that level which we are considering. That is the open you know entrance to the mold cavity.

Now, keeping that in mind the stream issues from 3 with the v 3 at atmospheric pressure, that means the with the law of continuity v_2 is should be equal to v_3. But this seems to disapprove the principle of conservation of energy since 2 is higher than the 3 , that has greater potential energy. The inequality arises from the pressure term if we compare 2 and 3, this 2 this level and this level if we apply the Bernoulli's equation you will get this equation.

And since $\rho_2 = \rho_3 = \rho$, and since $v_2 = v_3$, then $p_2 = p_3 - h_2\rho$. If we solve this equation with these conditions, then we will have the $p_2 = p_3 - h_2\rho$, meaning that p_2 pressure here will be less than the p_3 which is atmospheric pressure by $h_2\rho$.

h_2 is the height from 2 to 3 into rho is the density of the molten metal . This is not acceptable because in that case the pressure at point 2 will be less than the atmospheric pressure and hence the air may be actually penetrating; that is what we said last time.

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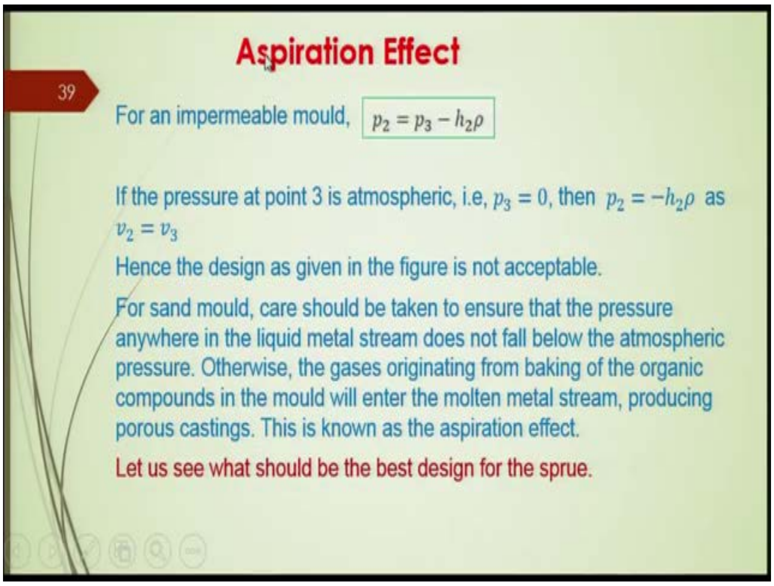

Aspiration Effect

For an impermeable mould, $\boxed{p_2 = p_3 - h_2\rho}$

If the pressure at point 3 is atmospheric, i.e, $p_3 = 0$, then $p_2 = -h_2\rho$ as $v_2 = v_3$

Hence the design as given in the figure is not acceptable.

For sand mould, care should be taken to ensure that the pressure anywhere in the liquid metal stream does not fall below the atmospheric pressure. Otherwise, the gases originating from baking of the organic compounds in the mould will enter the molten metal stream, producing porous castings. This is known as the aspiration effect.

Let us see what should be the best design for the sprue.

So, for an impermeable mould $p_2 = p_3 - h_2\rho$. If the pressure at point 3 is atmospheric pressure then $p_3 = 0$ then $p_2 = -h_2\rho$, since $p_3 = 0$ because as the v_2 is equal to v_3. Hence the design as given in the figure is not acceptable design of the cylindrical sprues given in here is not acceptable. For sand mould care should be taken to ensure that the pressure anywhere in the liquid metal stream does not fall below the atmospheric pressure .

This I already told you otherwise the gases originating from baking of the organic compounds in the mould will enter the molten metal stream producing the porous casting.

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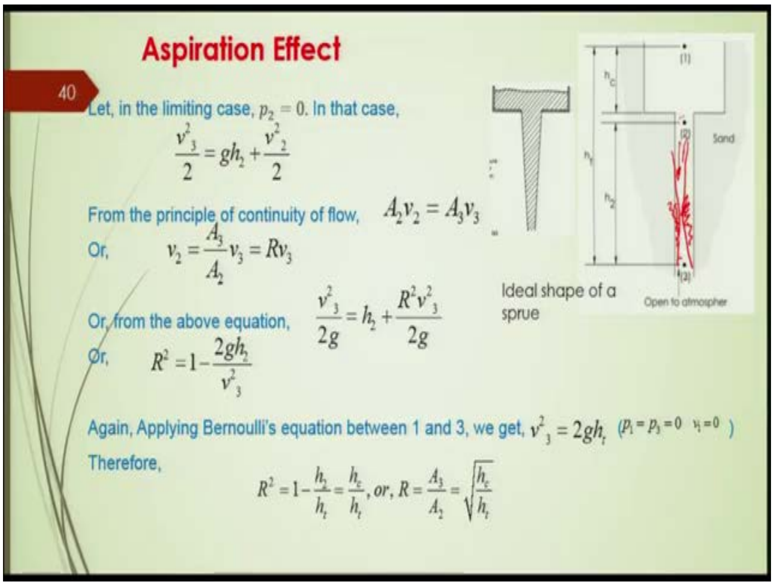

Aspiration Effect

Let, in the limiting case, $p_2 = 0$. In that case,

$$\frac{v_3^2}{2} = gh_2 + \frac{v_2^2}{2}$$

From the principle of continuity of flow, $A_2 v_2 = A_3 v_3$

Or, $v_2 = \frac{A_3}{A_2} v_3 = R v_3$

Or, from the above equation, $\frac{v_3^2}{2g} = h_2 + \frac{R^2 v_3^2}{2g}$

Or, $R^2 = 1 - \frac{2gh_2}{v_3^2}$

Again, Applying Bernoulli's equation between 1 and 3, we get, $v_3^2 = 2gh_t$ $(p_1 = p_3 = 0 \quad v_1 = 0)$

Therefore,

$$R^2 = 1 - \frac{h_2}{h_t} = \frac{h_c}{h_t}, or, R = \frac{A_3}{A_2} = \sqrt{\frac{h_c}{h_t}}$$

Ideal shape of a sprue

Let us see what should be the best design. So, here we have discussed it last time and we have applied Bernoulli's equation between 3 and 2 and principle of continuity of flow is equal to $A_2 v_2 = A_3 v_3$. So, from here we can find out that the $v_2 = \frac{A_3}{A_2} v_3$, v_3 is the flow velocity at point 3, and v_2 is flow velocity at point 2. From this equation you can find out that $R^2 = \left(\frac{A_3}{A_2}\right)^2 = 1 - \frac{2gh_2}{v_3^2}$.

Again, applying Bernoulli's equation between 1and 3, we will get $v_3^2 = 2gh_t$ and then R which is $\frac{A_3}{A_2}$ this will be equal to $\sqrt{\frac{h_c}{h_t}}$. This is what is most important here to be considered that the ratio of A_3 and A_2 should be maintained as $\sqrt{\frac{h_c}{h_t}}$ h_c is the height between 1 and 2 and h_t is the total height as I said .

So, if it is not maintained and if the design is this, that is A_3 is the same as A_2, then the aspiration will happen. We have to have $\frac{A_3}{A_2} = \sqrt{\frac{h_c}{h_t}}$ and this is supposed to be the ideal shape of a sprue, not the cylindrical.

But actually, it should be spherical, but this is difficult to make and therefore for the for easier design and the manufacturing the ideal design is the tapering here . So, if you , from point 2 to point 3, the velocity is increasing. Let me draw that curve . At point 2 the flow of the material will be like this (as shown in the figure) and as it is flowing down, the velocity is increasing because it is gravity feed.

In that case what will happen is that as the molten metal comes closer to the 3, the velocity increases and the pressure drops. So, the pressure curve will be something like this (as shown in the figure). In that case, these are the pockets where the pressure drops and the air can actually penetrate .

Once again, the velocity increases from 2 to 3, so pressure will be dropped and the curve will be different than the straight curve. So finally, what we are saying is that the ideal design will be a tapered design of the sprue and not the cylindrical one. Well, this is the conclusion that we draw for the aspiration effect.

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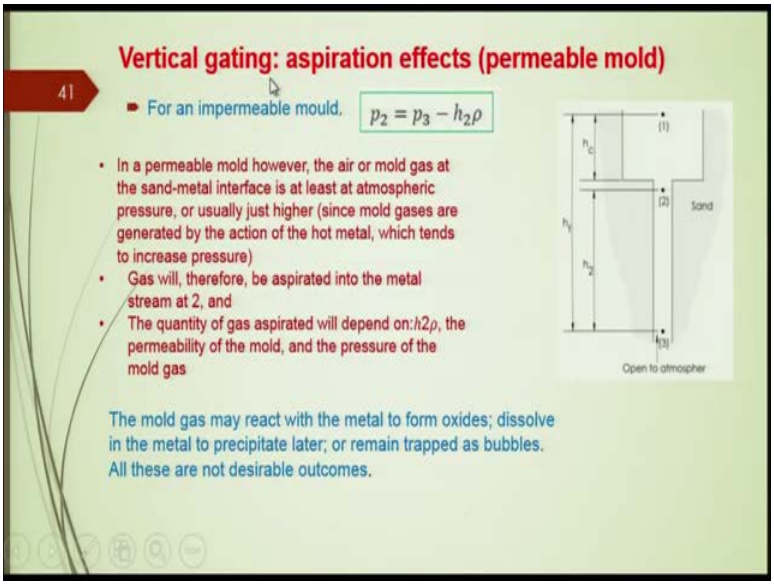

Vertical gating: aspiration effects (permeable mold)

- For an impermeable mould. $p_2 = p_3 - h_2\rho$

- In a permeable mold however, the air or mold gas at the sand-metal interface is at least at atmospheric pressure, or usually just higher (since mold gases are generated by the action of the hot metal, which tends to increase pressure)
- Gas will, therefore, be aspirated into the metal stream at 2, and
- The quantity of gas aspirated will depend on: $h2\rho$, the permeability of the mold, and the pressure of the mold gas

The mold gas may react with the metal to form oxides; dissolve in the metal to precipitate later; or remain trapped as bubbles. All these are not desirable outcomes.

Now, in the vertical gating aspiration effects for an impermeable mould we said that the p_2 is equal to $p_3 - h_2\rho$. In a permeable mould; however, the air or mould gas at the sand metal interface is at least at atmospheric pressure or usually just higher since mould gases are generated by the action of the hot metal which tends to increase the pressure.

Now gas will therefore be aspirated into the metal stream at 2 and this we have already seen . The quantity of gas aspirated will depend on the $h_2\rho$, because the p_2 is less than p_3 by this value, the permeability of the mould and the pressure of the mould gas, so these are the factors .

Of course, if the permeability of the mould is more then, the gas will be coming out and the pressure of the mould gas is less. In that case it will not be able to penetrate into molten metal. The mold gas may react with the metal to form oxides, dissolve in the metal to precipitate later or remain trapped as bubbles - all these are not desirable outcomes.

This I have already told repeatedly that we have to avoid having at any point the pressure less than the atmospheric pressure because, otherwise from the atmosphere the gas or the air will penetrate and it may stay. It may be trapped inside the molten metal and it will create the air bubble air pockets air bubbles.

Those air bubbles will create the defect in the casting and sometimes it is difficult to detect, because it remains trapped inside the casting .

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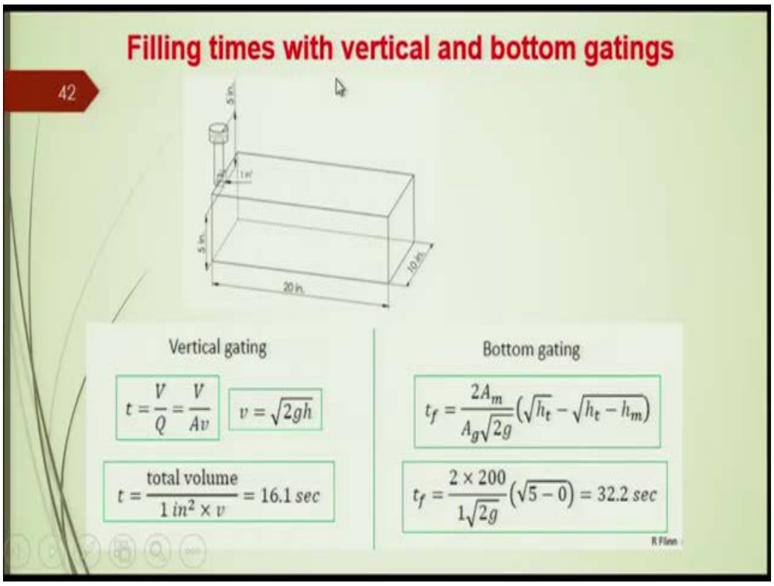

Filling times with vertical and bottom gatings

Vertical gating

$t = \frac{V}{Q} = \frac{V}{Av}$

$v = \sqrt{2gh}$

$t = \frac{\text{total volume}}{1\,in^2 \times v} = 16.1\,sec$

Bottom gating

$t_f = \frac{2A_m}{A_g\sqrt{2g}}\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)$

$t_f = \frac{2 \times 200}{1\sqrt{2g}}\left(\sqrt{5} - 0\right) = 32.2\,sec$

R Flinn

Filling times with vertical and bottom gating is just for your idea so that you could understand. Let us say if according to this design these are the sizes, unfortunately these are given in inches. So, the length is 20 inch, breadth is 10 inch, height is 5 inch and so on.

In that case, if you put these values in the equations that we have already derived, then you will see that for vertical gating the time taken is exactly twice less than for the bottom gating. This is also very obvious because in case of the vertical gating, it is quickly filled up because it is poured by gravity .

In the bottom gating, as we have seen that the mould filling will take more time because it is coming from the bottom and it is coming not because of the gravity, but because of the pushing behind from the flow of the molten metal. So, as you can see that here the in the vertical gating the *t* is equal to this volume divided by cross sectional area into the flow velocity , put the values here; total volume divided by 1 inch square area into *v*, so this will be 16.1 second.

You will see *v* is equal to root over *2gh* for the vertical gating system and in the case of the bottom gating, similarly if you calculate with the values given, this will be equal to 32.2 which will be exactly double the vertical gating .

So, this is the conclusion that can you can draw. You can take other examples yourself and find out how much time it takes for filling up the cavity for the bottom gating and the vertical gating systems .

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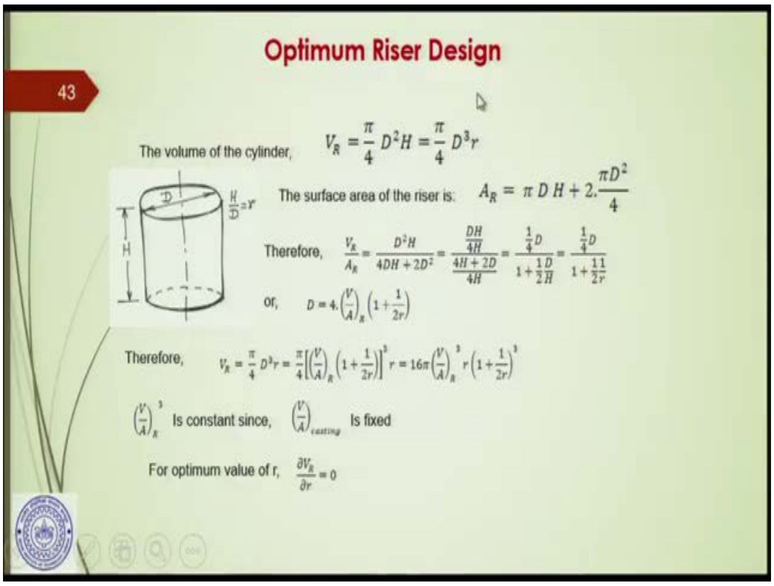

Optimum Riser Design

The volume of the cylinder, $V_R = \frac{\pi}{4} D^2 H = \frac{\pi}{4} D^3 r$

The surface area of the riser is: $A_R = \pi D H + 2.\frac{\pi D^2}{4}$

Therefore, $\frac{V_R}{A_R} = \frac{D^2 H}{4DH + 2D^2} = \frac{\frac{DH}{4H}}{\frac{4H + 2D}{4H}} = \frac{\frac{1}{4} D}{1 + \frac{1}{2}\frac{D}{H}} = \frac{\frac{1}{4} D}{1 + \frac{1}{2}\frac{1}{r}}$

or, $D = 4.\left(\frac{V}{A}\right)_R \left(1 + \frac{1}{2r}\right)$

Therefore, $V_R = \frac{\pi}{4} D^3 r = \frac{\pi}{4}\left[\left(\frac{V}{A}\right)_R \left(1 + \frac{1}{2r}\right)\right]^3 r = 16\pi \left(\frac{V}{A}\right)_R^3 r \left(1 + \frac{1}{2r}\right)^3$

$\left(\frac{V}{A}\right)_R^3$ Is constant since, $\left(\frac{V}{A}\right)_{casting}$ Is fixed

For optimum value of r, $\frac{\partial V_R}{\partial r} = 0$

Now, let us see the optimum riser design . Once again, I will remind you that the risers are made as a reservoir of molten metal which can feed the molten metal to the casting after it get solidifies. So, it is required because during the 3 stages of solidification thatI already discussed with you, there will be shrinkages . The shrinkages have to be compensated for with the molten metal and that molten metal can come from the riser .

Therefore, one of the most important phenomena or important criteria is that the molten metal which is in the riser should solidify later. First, the casting that is in the mould cavity, that is the molten metal should solidify. While solidifying,it will have shrinkage and then the molten metal should come from the riser, provided that the solidification takes place later than the solidification took place in the mould cavity. This is very important in the riser design.

So, the solidification at the riser should be at a later stage. Let us see how it is done. Let us say we have a cylindrical riser like this where the height is *H* and the diameter is *D*. So, the $\frac{H}{D}$ ratio is let us say *r*. Now the volume of the cylinder is $\frac{\pi}{4}D^2H$ this is given by $\frac{\pi}{4}D^3r$.

So, *H* by *D* is equal to *r;* putting this value, the surface area of the riser which is A_R which is $\pi DH + 2.\frac{\pi D^2}{4}$, this is cylindrical. Therefore, $\frac{V_R}{A_R}$ value can be obtained as $\left[\frac{\frac{1}{4}D}{1+\frac{1}{2}\frac{1}{r}}\right]$.

From here we can find out the value of the D which is the diameter of the cylinder, as shown in the slide above as $D = 4.\frac{V_R}{A_R}\left(1+\frac{1}{2r}\right)$. Putting this value of *D*,we get the value of V_R as shown in the slide above.

Now, $\left(\frac{V}{A}\right)_R^3$ is constant, since $\left(\frac{V}{A}\right)_C$ of the casting is fixed. What I mean to say is that the in the riser the ratio of the volume and the area is constant, since the volume by area of the casting is the same. For optimum value of the r that is $\left(\frac{H}{D}\right)$,we will take the first derivative of the V_R, with respect to r and we will get the optimum value of the r as 1 as shown in the slide below..

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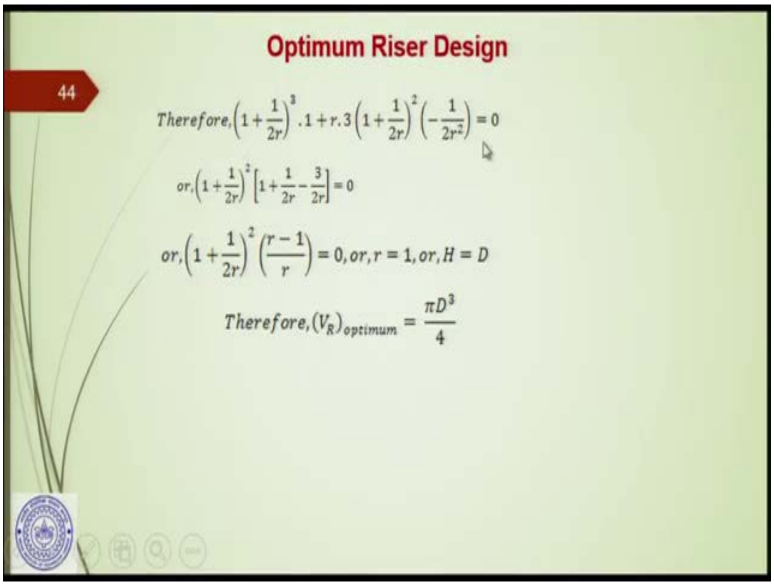

Optimum Riser Design

$$Therefore, \left(1+\frac{1}{2r}\right)^3 .1 + r.3\left(1+\frac{1}{2r}\right)^2\left(-\frac{1}{2r^2}\right) = 0$$

$$or, \left(1+\frac{1}{2r}\right)^2\left[1+\frac{1}{2r}-\frac{3}{2r}\right] = 0$$

$$or, \left(1+\frac{1}{2r}\right)^2\left(\frac{r-1}{r}\right) = 0, or, r = 1, or, H = D$$

$$Therefore, (V_R)_{optimum} = \frac{\pi D^3}{4}$$

Now, let us take the first derivative. So, the expression will be as shown in the slide which is equal to 0.

If we simplify you can get that r is equal to 1. Since r we have taken as $\left(\frac{H}{D}\right)$, So H is equal to D because $\left(\frac{H}{D}\right)$is equal to 1 and the V_R optimum will be $\frac{\pi D^3}{4}$, putting the value of the r equal to 1.

So, this is the optimum volume of the riser, $\frac{\pi D^3}{4}$. So, if we consider this and if we stick to this, i.e. the volume of the riser, in that case we can make sure that the solidification of the molten metal inside the riser will be at a later stage than the solidification taking place in the molten material inside the mould cavity.

In that case of course, the problem is solved because in that case the molten metal will be available in the riser to be fed to the shrinkages which took place during the solidification.

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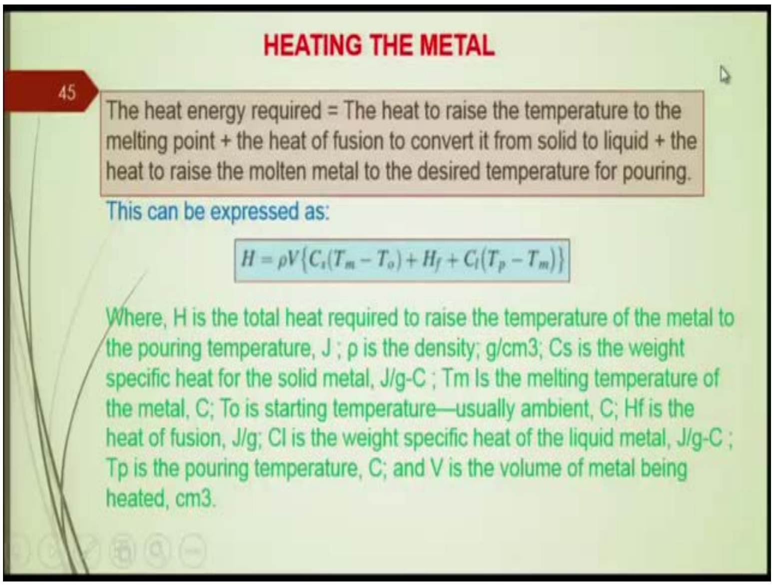

HEATING THE METAL

The heat energy required = The heat to raise the temperature to the melting point + the heat of fusion to convert it from solid to liquid + the heat to raise the molten metal to the desired temperature for pouring.

This can be expressed as:

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

Where, H is the total heat required to raise the temperature of the metal to the pouring temperature, J ; p is the density; g/cm3; Cs is the weight specific heat for the solid metal, J/g-C ; Tm Is the melting temperature of the metal, C; To is starting temperature—usually ambient, C; Hf is the heat of fusion, J/g; Cl is the weight specific heat of the liquid metal, J/g-C ; Tp is the pouring temperature, C; and V is the volume of metal being heated, cm3.

Let us see now the heating the metal. If you remember, initially I discussed that although the casting process looks very simple because, normally it consists of melting the metal then pouring the molten metal in the cavity; let it solidify and you get the casting. In each stage of this process, however, we need to be very careful and the design has to be very carefully made.

Then only the casting could be obtained as a defect free casting. Some of them we have already discussed, for example the riser design, the design of the sprue . So, initially of course, it look very simple that we will pour the molten metal, so whether it is a cylindrical or it is a tapered how does it matter?

But if we apply science, in that case you will find out that it is actually not the case and many things may go wrong and the casting may not be obtained nicely; I mean it should not be the defect free one.

Another reason for which the casting may be defective is the heating of the metal. This I already said in brief that metal should be heated up at a particular temperature. If not, in that case the flowability will be less, and the metal flow will not be sufficient to cover all the areas inside the mould cavity.

Particularly when the mould cavity is very intricate. Before covering the intricate shapes and all corners in the mould cavity, the molten metal actually may get solidified because the initial temperature or the heating temperature is less or the pouring temperature is less.

Therefore, we have to really find out how much we have to heat the metal. Let us see this. The heat energy required this is actually defined by the heat to raise the temperature to the melting point plus the heat of fusion to convert it from solid to liquid plus the heat to raise the molten metal to the desired temperature for pouring.

So, if we see this it is not really so simple that the temperature is raised to the melting point , here we have to add these 2 factors so to get the actual temperature in the molten metal. So, this can be expressed as H, this is the heat energy required this is equal to as shown in the slide above.

First term is the heat to raise the temperature to the melting point, second term is the heat of fusion to convert solid to liquid and then the third term is the heat to raise the molten metal to the desired temperature of pouring.

Now, here in this equation H is the total heat required to raise the temperature of the metal to the pouring temperature, this is in Joule; ρ is the density in gram per centimetre cube; C_s is the weight specific heat for the solid metal in Joule per gram centigrade, Tm is the melting temperature of the metal these in centigrade, T_0 is the starting temperature; usually this is the ambient temperature in centigrade.

H_f is the heat of fusion in Joule per gram; C_l is the weight specific heat of the liquid metal in Joule per gram centigrade, T_p is the pouring temperature centigrade and V is the volume of metal being heated in cm^3. So, all these factors will give us the total heat required to raise the temperature of the metal to the pouring temperature.

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Solidification

Now, the solidification; this is again a very complicated issue because we said that when the metal gets solidified after pouring, it goes through 3 stages. Let us see what are those 3 stages and in each of these 3 stages the metal gets a contraction.

So, there should be some sort of worry for us that there should be some defect until unless those shrinkages are taken care of and one of the processes, one of the easiest ways is the proper riser design. The riser is the reservoir of the molten metal which will be able to feed the molten metal to the shrinkages after it is getting solidified.

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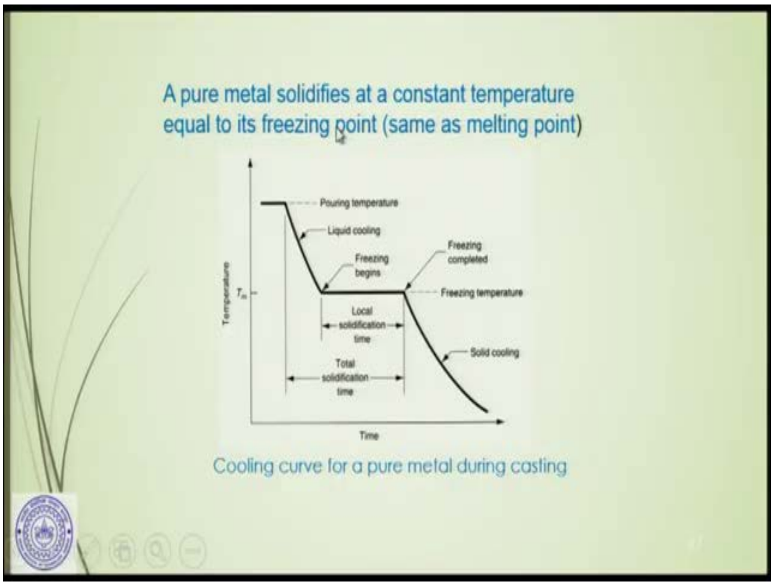

A pure metal solidifies at a constant temperature equal to its freezing point (same as melting point)

Cooling curve for a pure metal during casting

So, let us see. Pure metal solidifies at a constant temperature equal to the freezing point same as the melting point. Now, here is the temperature versus time curve and as the time elapses what happens to the temperature is shown here. So, let us say here we have the pouring temperature, mind it this is for a pure metal; this is not for all metals and you know that metals are not really pure, they always come with imperfections, with defects.

So, but we have to find out that what happens to the solidification of the pure metal, then I will tell you that what happens to the alloys and other factors. In pure metal, when the metal is supposed to be pure, then the pouring temperature here let us say. So, it remains the pouring temperature for some time, then it started as the time elapses; this is solidifying.

So, it is cooling but the molten metal is still in the liquid stage. Some time elapses from here to here, during this time the cooling takes place. But the molten metal is still liquid, from this point the freezing begins and the local solidification continues up to this. Let us say here at this point as the time elapses the temperature does not change, because here this is the cooling period and here the freezing begins, at the same temperature freezing completes.

Here at this point the freezing completes. From here when the pouring starts, up to this point, where the freezing completes, is called the total solidification time.

Whereas, the freezing time as the freezing begins up to the freezing ends this is called the local solidification time. Now after the freezing completes then the temperature goes down and from the freezing temperature this is the solid already and this is cooling; the temperature of the solid metal will be falling, and it will come to the ambient temperature once again.

So, this is the entire curve that when the molten metal is poured at this temperature, from here the liquid cooling, freezing up to this point; this is the total solidification time, then the metal has been solidified. It is supposed to be solidified at this point and then the solid metal will cool down, because the temperature is still very high it is not liquid but temperature is high and that temperature goes down, it cools down from freezing temperature.

So, this is a solid cooling and it comes down to the ambient temperature. This is the entire curve for the temperature versus time for the pure metal , as the pure metal solidifies. The rest of the material we will be discussing in our next discussion session.

Thank you for your attention.