Hello and welcome to this manufacturing process technology part –I module 23.

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We will discuss today about the various solidification processes and what are the kind of times scales which are involved and such solidification in the moulds and may be in green sand mould and then a moulds used made of metals and metals with cooling you know so these cases will try to identify to sort of cover a length of breadth of what are the different kind of processes which take place in the casting industry. So let us talk about cooling and solidification.

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Cooling and solidification

- A clear understanding of the mechanism of solidification and cooling of liquid metals and alloys is essential for the production of successful castings.
- During solidification, many important characteristics such as crystal structure and alloy composition at different parts of the casting are decided.
- Mechanism of solidification:

Pure metals:
1. Liquids need to be cooled below their freezing points before the solidification begins.
2. This is because energy is required to create surfaces for new crystals.
3. The degree of super-cooling necessary is reduced by the presence of other surfaces (particles) which serve as the initial nuclei for crystal growth.
4. When a liquid metal is poured into a mold, initially (at time t_0 in the figure below) the temperature everywhere is θ_0.
5. The mold face itself acts as the nucleus for crystal growth, and if conductivity of the mold is high, randomly oriented small crystals grow near the mold face.
6. Subsequently, a temperature gradient results within the casting, as indicated for t_1 and t_2.
7. As solidification progresses gradually inwards, long columnar crystals, with their axes perpendicular to the mold face, grow.
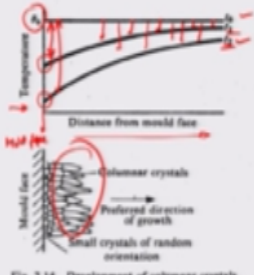
Fig. 3.14 Development of columnar crystals.

So obviously I think gates needless to illustrate that a clear understanding of the mechanism of solidification and cooling of metals and alloys very important for production of successful cast because solidification really determines the grain structure so a such the crystal structure and alloy composition are sort of decided through how it solidify and typically the mechanism of solidification in pure metals are typically when the liquid metals are cooled below their freezing points.

Before the solidification starts to take place and why they are cooled is that energy is needed to create surfaces for new crystals. So therefore you have to have a less of kinetic energy so that the such surfaces can start to get created the degree of super cooling necessary is reduced by the presence of other surfaces or particles which would surf you know as sort of nucleating sites.

So wherever there is a solidification happening you already have a seen earlier how in the polycrystalline you know material because of solidification there are different grains which have grain boundaries you know which are separated by grain boundaries which make the whole polycrystalline materials structure, so if there are certain particles which have higher thermal conductivity they may be essentially acting as the nucleation sites for development of such degree of super cooling that is necessary for crystal growth processes and let us say if there is a metal which is at a temperature θ_0 at times T_0 the temperature everywhere is θ_0 within the metal and the mould face would act as the nucleus for crystal growth.

Because that is the coolest face so let us say we are talking about the mould face along this particular line, so this is the mould face and this is corresponding to certain distance from the mould face so at different time distances as you can see the there are different temperature gradients which would result and particularly the mould face being the one where most growth would start to take place.

Because it is the cooler point in the whole casting the fall in temperature would be most at the face and then slowly if we look at how the temperature falls down you know within the mould away from the mould face the temperature differences lower if you go away from the mould face, similarly so obviously the temperature differences more as you know with time so at a certain distance of time $T_2 > T_1$ from T_0.

The total amount of temperature differences on the mould face is more and this gap grows wider and wider in comparison to if you go more towards the center of the mould away from the mould face, so mould face is really the one where makes some heat transfer takes place, so as the solidification progresses gradually inverts long columnar crystals like what has been shown here with their axis perpendicular to the mould face grow.

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Fig. 2.15 Equilibrium phase diagram of A-B alloy

And supposing if the situation was little different that we had an alloys instead of a pure phase and we can see how there would be a slight variation because of the alloying effect and let us look at this particular case where there is an alloy of temperature or between two phases A and B which is 100% A along this particular line and then 100% B along this other end and there is a liquidus and solidus temperature where the you know.

Beyond which the alloy would be completely liquid and below which there would be a solid + liquid phase which is present also in this particular zone and below the solidus line there would be solid face present, so that is how you have arrived this I think I have illustrated this how this solidus and liquidus needs to be plotted in a lot of cases before in the portion on engineering materials so during this process the solids separating out a different temperatures possess varying compositions.

Because obviously there is also a concept of or there is also an additional constraint of a solubility of the solid in the liquid phase as a function of temperature, so the solid phase may not be always 100|% soluble and there may be certain critical solubility beyond which you know the one of the phases may not go into the solid phase okay one of the phases may not go into the solid crystal,.

And in the liquid form their solubility may be different so in that kind of a situation obviously the point where the solidification is taking place which is also known as the liquid solid front it the composition would be a function of time because obviously if supposing the solid phase is

rejecting a part of the or the solid state is rejecting a part of the phase B for example okay because it cannot contain B beyond a certain percentage.
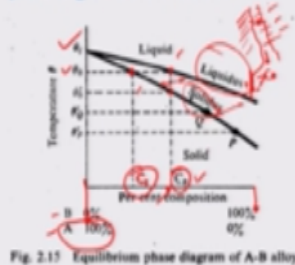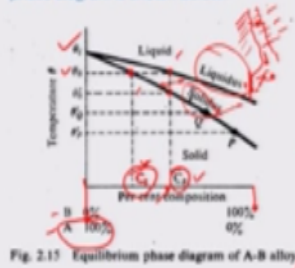
So immediately in the near vicinity of that solid liquid interface the composition of B or the percentage of B would get higher because of this throughout of the solid crystal into the liquid,. So therefore there are several such compositional changes which are at that solid liquid interface which may result in a lot of problems in this particular case for example the let us let the liquid alloy have compositions C_0 Of B in A. so you can see here that at this particular point for example composition of B is C_0 and that of A is 100 minus C_0 so also let θ_F be the freezing point of the pure metal at A so this is θ_F right here and θ_0 and θ_0' are the respectively the liquidus and the solidus temperatures so you can think of at C_0 composition θ_0 is the liquid does temperature and θ'_0 is the solid does temperature corresponding to this composition C_0.

So as the liquid alloy is cooled down to the temperature θ_0 so from here you are basically trying to cool it down to a temperature θ_0 and the solid starts to separate out and the concentration of B in this solid is now only reduced to C_1 . so if you want to really make a situation where the further cooling of the liquid alloy is done and it is cooled down to the temperature θ_0 as you can see here the solid would start to separate out and because now it cannot hold beyond C_1% composition in the solid phase, okay.

So as a result the concentration of B in the liquid near the solid liquid interface as I had just mentioned increases to the value more than C_0 because obviously whatever part has been thrown out of this solid liquid interface because it cannot get accommodated within the solid just goes in the near zone you know I mean this is the solid formation and this is may be the liquid and so if the solid cannot hold anymore the composition of B. That B is precipitated into very near to the solid liquid interface . so the percentage here would definitely go above C_0 so it will be somewhat greater than C_0 whatever be the % composition near in this particular zone.

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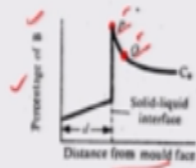Fig. 2.16 Variation of concentration of B with distance from mould face.

Alloys

- The figure on the left shows this situation where the solidification front has progressed upto some distance 'd' from the mold face.

- Now, let us consider two points P and Q within the liquid alloy, P being just beyond the solid-liquid interface, as indicated in the figure.

- The solidus temperatures, corresponding to the compositions at P and Q are θ_p' and θ_q'.
- Let θ_p and θ_q be the actual temperatures at the points P and Q, respectively. $\theta_q > \theta_p$, due to the thermal gradient within the casting.
- If both θ_p and θ_q lie in the range θ_p' to θ_q', then the liquid at Q is supercooled, whereas that at P is not.
- This implies that the crystallization starts at Q sooner than at P.
- If this difference is very prominent, then the columnar growth of crystals starting from the mold surface is hampered.

And because of that the if you look at how the % of B is varying as a function of distance from the mould the figure on this left shows the situation where the solidification front has progressed upto some distance d for example from the mould face, so now let us consider two points P and Q within the alloy within the liquid alloy and P being just beyond the solid liquid interface.

So it is just the state where solidification has happened as indicated in the figure and the solid does temperature corresponding to the composition at P and Q are respectively θ'ₚ and θ'_Q. So Q is somewhere in the near vicinity so it is actually in the liquid phase so you have P as a point and again Q as another point very close to each other, so you can see that the composition of Q the composition of you know this zone P which is near to the solid liquid point is % of B is slightly higher in comparison to that of Q,. So obviously they will have different solidus temperatures.
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Fig. 2.15 Equilibrium phase diagram of A-B alloy

Let us just go back to see what so you know the solidus temperature for example at a lower concentration is higher in comparison to a higher concentration the solidus temperature is lower okay.
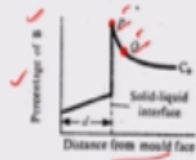
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So therefore the θ' P and θ' Q which are the solidus temperatures at P and Q are quiet variant because of the change in the % composition so there may be case where actually the θ_P and θ_Q are the sort of the you know actual temperatures as P and Q respectively and θ_Q is obviously more than θ_P because the θ that point Q is far away into the mould then P is more closer to the phase okay.
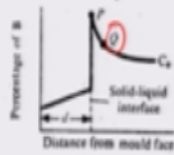
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Alloys

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So if both the $\theta_Q - \theta_P$ this temperature range, it basically lies within the range of the $\theta_Q' - \theta_P'$ so there is a case where lets say because of the varied solid does temperatures now there is a wide range which has been introduced here because obviously the θ_P did not you know because it is into the solid it has a lower concentration and θ_Q' is a higher concentration because of which the solidus temperature has come down.
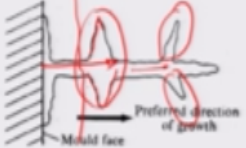
So still there is a case where this θ_P- θ_Q actual temperature difference between the point Q and P are lesser in compression to θ_Q'- θ_P ' so this can only be sort of working out if θ_Q is lower you know and then θ_Q' or θ_Q' is higher than θ_Q. So very importantly if such a situation happens when θ_Q' is higher than θ_Q than we can say that the liquid at has started to solidify because it is being super cooled, okay.

So Q is super cooled whereas P is not because probably the range of P or the θ_P is probably higher than θ_P' that is the only way that this you know this condition of the range $\theta_Q' - \theta_P$ ' $> \theta_Q - \theta_P$, so whereas the Q is super cooled the P is not because P the actual temperature is higher than the solidus points so still it is in the liquid phase whereas the still you know it is in the sort of it is not yet solidify completely.

So it is in-between and this θ_Q' because the actual temperature is lower than that there is a sort of a degree of super cooling which is there in the phase Q, so what is happening now because of this that the columnar orientation of the crystal is hampered because of this and there is a side growth of the crystal at the point P.

So it in effectively turns out that the although the preferred growth directions is from the mould phase onwards but in because of the effects of concentration changes near this area where it is solidifying let us say this is the solidification front there is going to be a side wise growth okay and this is also known as the dendrite growth of the crystal structure, so the crystal growth in such a situation may appear as on the figure dendrite structure is produced if the crystallization at Q gets completed before it starts at P.

Due to very small thermal gradient within a high concentration difference and very sloppy solidus line, then randomly oriented crystals would appearance side the casting okay and because of this randomly appearance oriented crystals you may not have a single direction long direction growth anymore and the presence of these solid crystals ahead of the solid liquid interface makes life more difficult.

Because now you know beyond the point where you are estimating the solid to happen actually the solidus getting formulated, okay. So therefore feeding the liquid metal becomes more difficult because of such solid liquid interface and it also implies a greater risk of having voids within the casting normally referred to as central line shrinkage, so one remedy to avoid the aforesaid problem is to produce a larger thermal gradient within the mould by providing a chill at the moulds end.

So that the gradient is increased so much that this value $\theta_Q - \theta_P$ produced by the chill becomes automatically elevated from $\theta_Q' - \theta_P'$ so that once again the normal C returns and there is a uni directional growth prominently happening, so that can already happen when you chill the mould and by putting some kind of a metal insert which would be formulating the rapid heat transfer from that particular point.

So you can create various temperature gradients which are large in nature so that the Q does not get solidify before P because of the concentration variation problem. so if θ_P is considerably below Q then the degree of super cooling is not significant whereas the significantly different at P and Q gradual progress of solid liquid interface can be ensured in that case. So the problem is obviously let critical for alloys having a smaller temperature difference between liquidus and a solidus.

So having said that you have some idea now about how the grain growth would start to happen or how the crystallization will take place, I would like to sort of end this session here but in the next section I am going to give you a more fundamental introduction into how to find out or estimate the temperature within the casting given a certain boundary condition based on simple heat transfer criteria, thank you so much.

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