Joining Technologies of Commercial Importance

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Lecture – 36
Weldability of Aluminium Alloys

Hello, I welcome you all in this presentation. This presentation is based on the topic weldability of the aluminum alloys. In this topic we will try to talk about the properties of the aluminum alloys that govern the weldability, what are the common problems encountered during the welding of the aluminium and what we can do to avoid the same.

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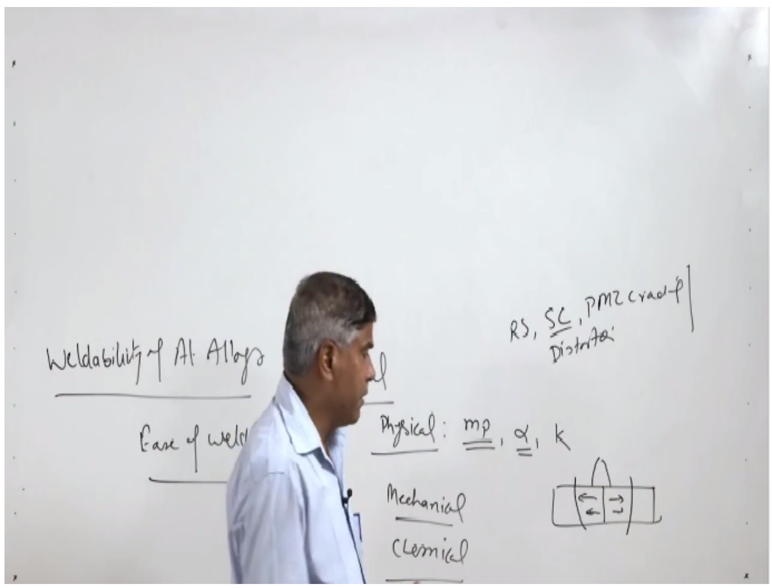

So, the topic is weldability of aluminum alloys. So as we know the weldability is defined as ease of welding a metal, so here in this case, it is aluminum and in general with the reference to the metal, various metallic properties affect the ease of welding, which primarily includes the physical properties, mechanical properties and chemical properties. So these are the 3 main ones, so in terms of the physical property. It is the melting point. Aluminum has very low melting point.

Aluminium is a low melting point material and melting point of the pure aluminum is about 662 degree centigrade, while most of the aluminum alloys melt at much lower temperature. So, it is easy to melt for producing the fusion weld joints of the aluminum alloys from the melting point of view but the problem is alpha at thermal expansion coefficient, problem is also the thermal conductivity.

It expands too much because of the higher expansion coefficient as compared to the iron, so expands much and contracts, so this sets into the higher residual stresses, increased distortion tendency and increased cracking tendency also, so the alpha is a problematic because of the higher value as compared to the other metal systems.

So it creates the problem of the residual stresses, cracking like solidification cracking, partial melting zone cracking, etc. and distortion but all are related with the like say the residual stresses, then thermal conductivity. The aluminium also has the higher thermal conductivity then the other metals like steels, so high thermal conductivity is problematic in the sense that it makes the melting difficult because whenever heat is applied for at the fink surfaces of the base metal to be joined, the heat is dissipated rapidly towards the base metal.

Like say this is the base metal and if heat is applied here, so heat is dissipated rapidly to the underlying base metal, so in turn results in the many things like wider heat affected zone and increased energy requirement or heat requirement which is to be delivered to reach the fusion conditions. So thermal conductivity is not good in that way for the weldability, from the weldability point of view.

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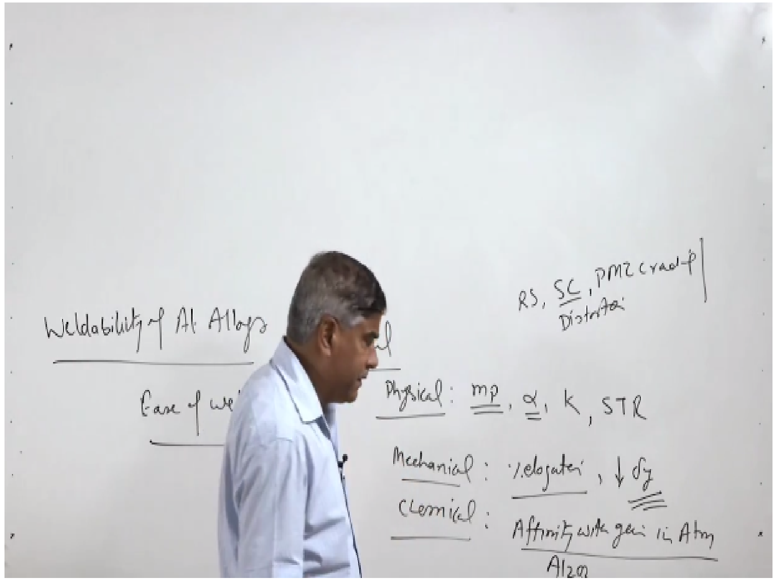

Apart from the melting point another important thing related the aluminium alloys is, the solidification temperature range which is about the temperature gap between the solidus and the liquidus and for most of the aluminium alloys it is found much wider and so whatever aluminium alloys of very much higher solidification temperature range, they will show greater cracking tendency especially the solidification cracking tendency, partial melting zone cracking tendency.

So, it like say normally it is for the most of aluminium alloys, it is found much wider and that is why it is not good from the weldability point of view because it increases the cracking tendency. Now coming to the mechanical properties, in term of the mechanical properties, percentage elongation of the aluminium alloys is much better.

So, it helps in overcoming the cracking tendency in some of the systems and it does not any problem as per as the embrittlement is concerned but mostly experiences the softening in the heat affected zone and another thing that the low yield strength, Sigma Y is less. So, low Sigma Y results reduce the magnitude of the residual stresses, so maximum magnitude of the residual stresses cannot be more than the yield strength limit or the elastic limit of the material.

So, if lower is the value of Y, it will reduce the residual stress magnitude, maximum magnitude of the residual stresses. Chemical properties are important in the way that how it has affinity with the gases especially in the atmosphere. So, since aluminium is very reactive to the atmospheric gases like oxygen, so, it forms the alumina and this alumina being of the similar density as the aluminium, but of the refractory in nature aluminium melts at very low temperature around 662 but refractory aluminium melts at much higher temperature about 2000 degree centigrade.

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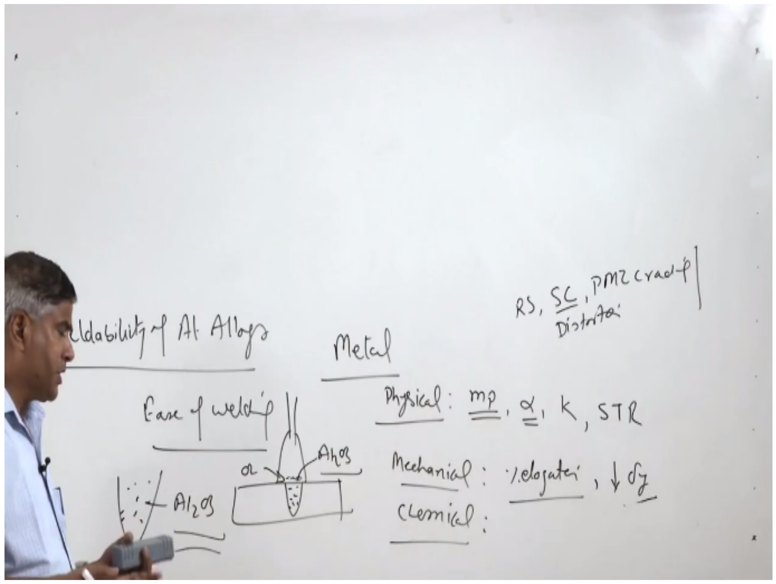

So because of this whenever during the welding if it is carried out under the ambient conditions by application of the using suitable heat source like arc or the flame then the molten aluminium reacts with the oxygen and forms the layer of the alumina over the surface, since it is of the similar density, so it tends to get distributed in the weld equally and this in turn results in the aluminium, alumina inclusions.

So these inclusions actually act as a discontinuity in the weld metal and these are act as a site of the week point and these induce or promote the formation of the whites and thereby they reduce the strength and the ductility of the weld joint of the aluminium alloy.

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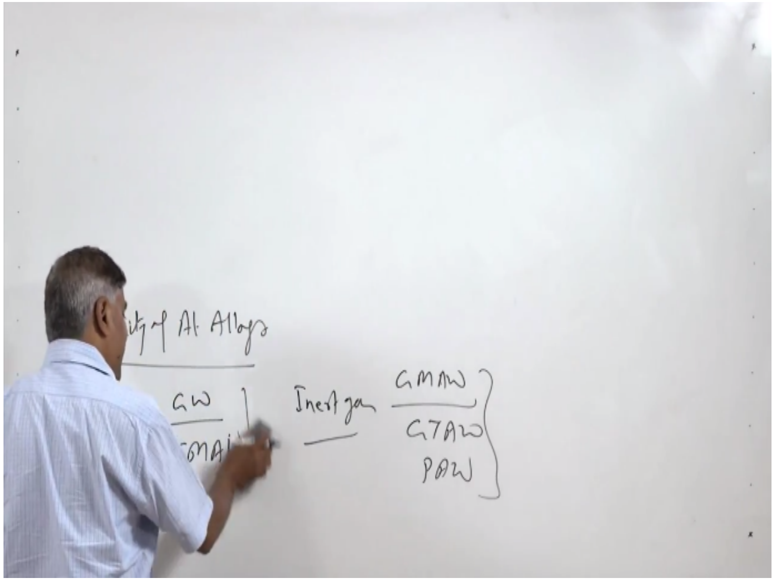

So we need to take care of this formation of the alumina, therefore to overcome the issues related with the high-thermal connectivity, higher expansion coefficient, higher solidification temperature range and greater affinity to the atmospheric gases, it becomes important to use the special processes rather than the conventional processes like gas welding or sealed metal arc welding.

These processes do not suit for the welding of the aluminium alloys because in both these cases there is no effective, the sealing is not that effective which can prevent the oxidation of the aluminium to avoid the formation of the alumina and that is why mostly the inert gas-based processes like GMAW, gas metal arc welding process and GTAW or PAW plasma arc welding process are more effective for joining of or welding of the aluminium alloys.

And since inert gases are costlier, so it requires more investment for developing the weld joints of the aluminium alloys. So with reference to the cost, the weldability of the aluminium alloys is somewhat lower than the steals. Apart from this, we need to see the kind of technological problems which are encountered during the welding of the aluminium despite of the use of those inert gas-based processes.

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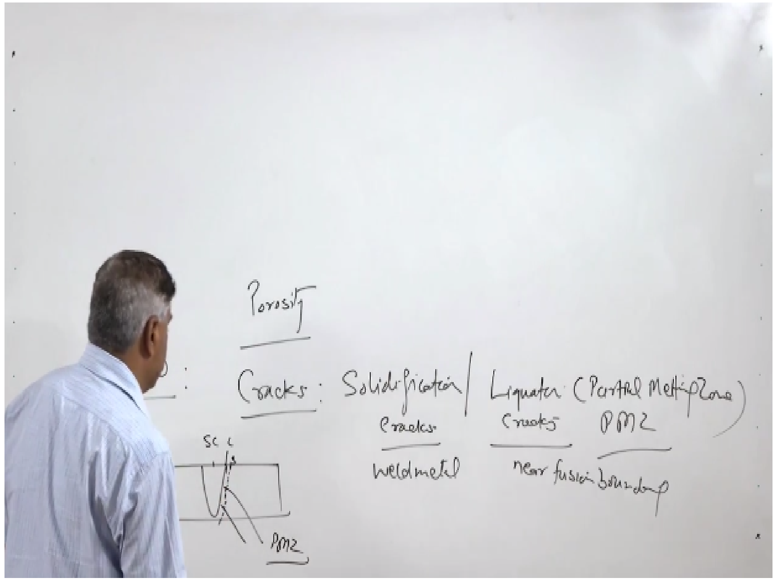

So even if we are using like GTAW which produces very clean weld, the weld joints of the aluminium alloys experience various technological issues. So the issues which are experienced by the weld joints of the aluminium alloys can be enlisted like porosity. Aluminium weld joints are very sensitive for the development of the pores or the porosity, another is the development of the cracks.

The two types of cracks are usually formed in the weld joints of the aluminium alloys, one is the solidification crack and another is the liquation crack which occurs in the partial melting zone commonly known as PMZ, partial melting zone, so solidification cracks or liquation cracks occurring in the so this typically occurs in the weld metal and this occurs near fusion boundary. Okay, so if we take the schematic of the aluminium weld joint.

So the solidification cracks will be appearing along the centerline of the weld while the partial melting zone cracks will be appearing next to the fusion boundary, it is a very narrow zone which will be falling between the liquidus and solidus. So, those the falling on the liquidus that will be forming the fusion boundary, liquidus and solidus, so between this zone only, these liquation cracks are observed and this is also known as partial melting zone.

Because the low melting point face in the PMZ region is brought to the molten state while other face remains in the solid state.

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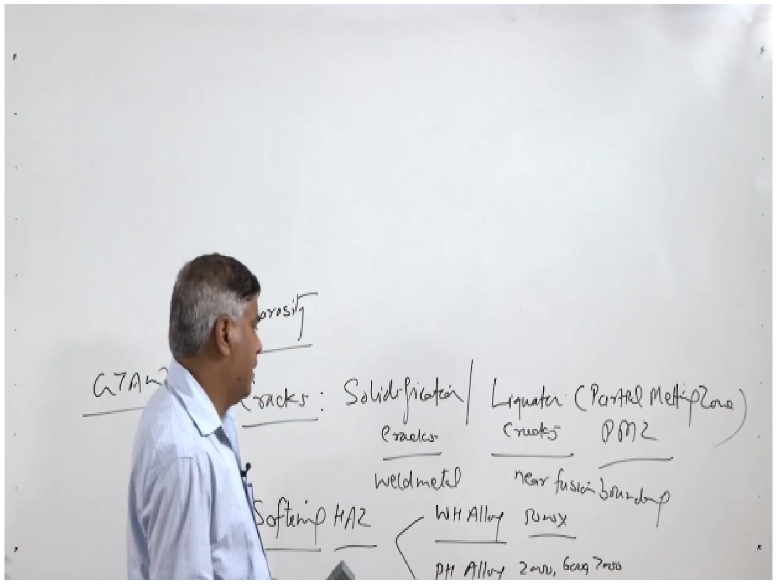

So the solidification crack occurring in the weld metal and liquation cracks will be occurring next to the fusion boundary in the heat affected zone then we also experience the problem of the softening of the HAZ. So, in both the cases whether it is the work hardened aluminium alloys like 5000 series aluminium alloys or precipitation hard enable aluminium alloys like 2000,6000 and 7000 series aluminium alloys, both type of the aluminium alloys experience the softening of the heat affected zone, this must be taken care of properly.

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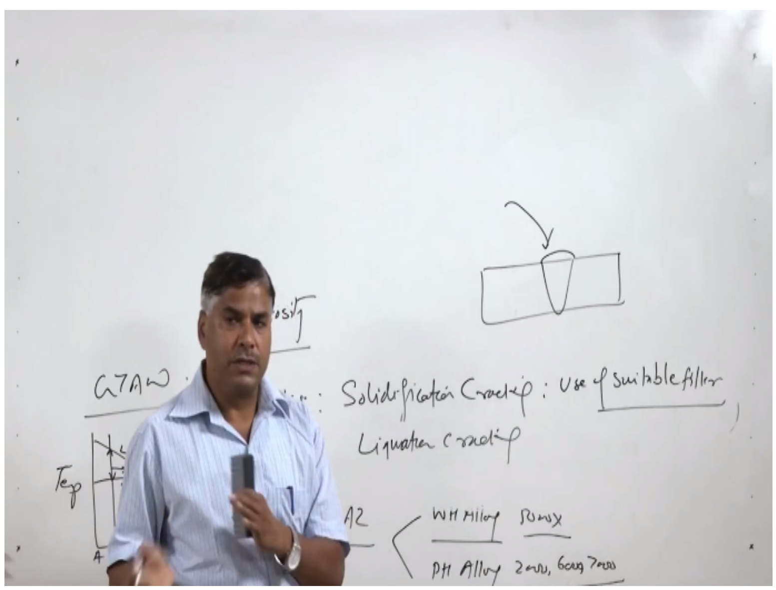

So as far as the approaches are concerned to overcome these problems so in brief I will mention here that how to overcome the problems related with these, so here cracking and the liquation cracking. So for the solidification cracking, it is basically the solidification cracking is due to the high solidification temperature range. So the weld metal composition is adjusted by using the suitable filler in such a way that the solidification temperature range is reduced.

Like if we consider the typical aluminium alloys, it goes in like this, so here the A and the B so this is a particular composition say 8 and 10% B resulting in the much wider solidification temperature range. This is a liquidus and this is solidus and this is temperature, right. So the wider solidification temperature range promotes the solidification cracking tendency. So what we do we select the filler in such a way that the weld metal composition is shifted towards the eutectic point.

So this shifted helps to reduce the solidification temperature range of the weld metal and thereby it will help in controlling the solidification cracking.

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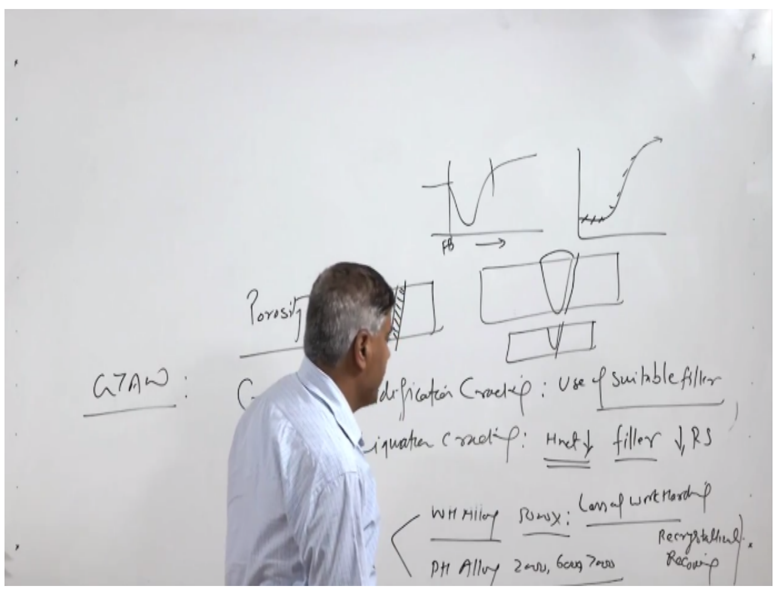

So the point is basically use of suitable filler so that it will help to reduce the solidification temperature range of the weld metal and the liquation cracking, liquation cracks are observed in the heat affected zone so the attempts are made in the two ways, let us say the liquation cracks are being observed in the heat affected zone of this metal so what we do by reducing the H net, net amount of the heat by reducing the heat input we will try to reduce the heat affected zone size.

So, if the heat affected zone is much wider, PMZ region will also be wider so large cracks will be formed so HAZ size is reduced by reducing the net heat input, this is a point one, and the second any kind of the cracking will be occurring due to the residual stresses only. So efforts are made to reduce the residual stresses and for that purpose filler metal is selected in such a way that partial melting that the heat affected zone solidifies first.

And thereafter the weld metal solidification takes place. So the filler is selected in such a way that the weld metal is a still in the liquid estate and before that the PMZ region solidifies. So, the solid region can sustain the stresses in much easier way as compared to the case when it is having the liquid. So another thing is select the filler in such a way that it reduces the residual stresses as well as it solidifies after the solidification of the PMZ region or the liquation whatever is taking place next to the fusion boundary.

As far as softening of the heat affected zone is concerned only efforts are made like work hardened aluminium alloys like 5000 series aluminium alloys, the softening in the heat affected zone is basically due to the loss of work hardening effect and this happens due to the recrystallisation and recovery mechanisms which will be operational during the welding in the heat affected zone.

So this loss will be simply resulting in the significant reduction in the hardness of the weld in the heat affected zone. So this is the variation, this is the fusion boundary and this is the distance from the fusion boundary and you will see that there is sudden drop in the hardness of the alloys, sudden drop in the strength of alloys, even in some cases this drop happens like this where the hardness is very low in the heat affected zone.

And then it starts increasing away from the fusion boundary.

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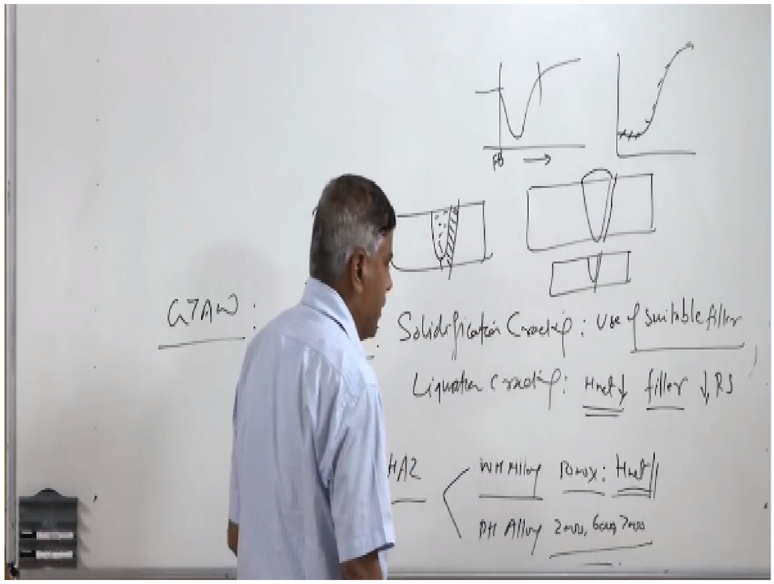

So loss of the work hardening effect it can be reduced, this happens due to the recovery in recrystallisation so in order to reduce the loss of the strengthen in the heat affected zone of the work hardening aluminium alloys mainly we try to reduce the H net and for this purpose we primarily use the high-energy density processes so that the faying surfaces of the base metal can be brought to the molten estate without applying much of the heat

So that net heat input can be reduced and so the related effect of the softening in the heat affected zone can be reduced. Another thing in this case PWHTR, post weld heat treatment is not possible because these systems are designed to be strengthened by the work harding not by the precipitate formation.

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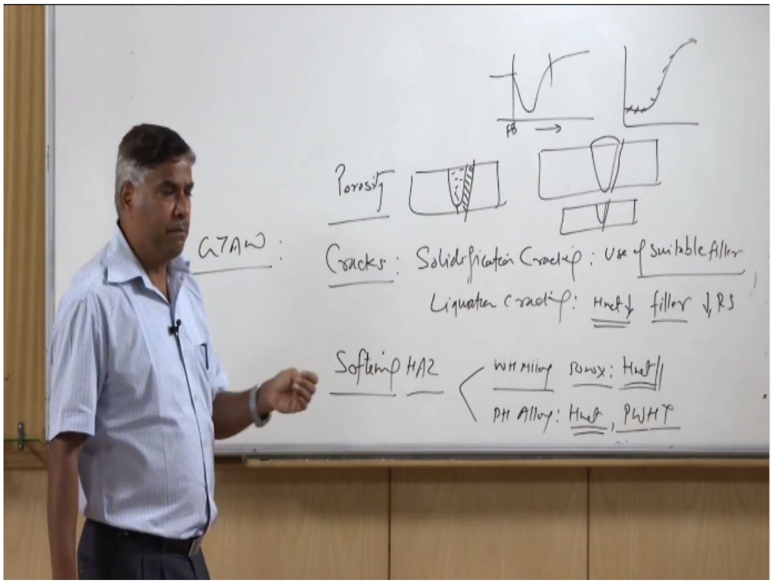

Another one softening in the heat affected zone, the control of the softening of the heat affected zone control of the of the softening in the heat affected zone of the precipitation hardenable aluminium alloys again the same thing reduced heat input or the post weld heat treatment. So that whatever precipitates get dissolved, whatever reversal takes place in the heat affected zone contributing to the softening of the heat affected zone.

All that can be restored after the post weld heat treatment reduction in H net will simply helping to reduce the kind of damage to the precipitates will be taking place in form of the reversion and resolution. So these are the approaches which are tried for overcoming the problems related with this. Now one by one we will try to see why these problems are encountered and what are the main contributors to the problems related with the welding of the aluminium alloys.

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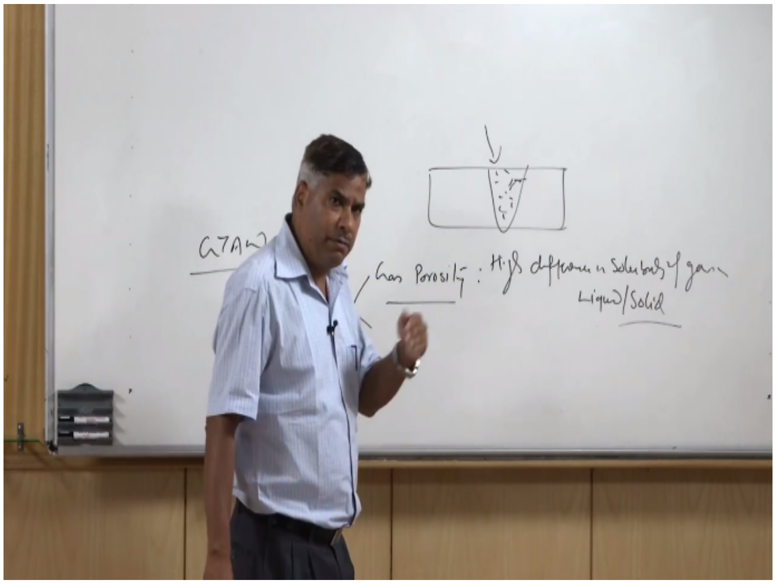

We will start with the porosity. Porosity wherever it is formed either in the casting or in the welding the two types of the porosity is normally observed, one is the gas porosity, gas porosity will be occurring due to the high difference in solubility of gases in liquid and solid state, this is one reason like when things are brought to the molten state the gases get dissolved.

These gases get dissolved in the molten state due to the high solubility but when the things solidification starts due to the rapid cooling all these gases due to the limited solubility in the liquid solid state. In the solid state these gases are rejected at the solid liquid interface and the rejected gases since the cooling rate is high during the welding so they do not get enough time to reach up to the surface and they get interrupt.

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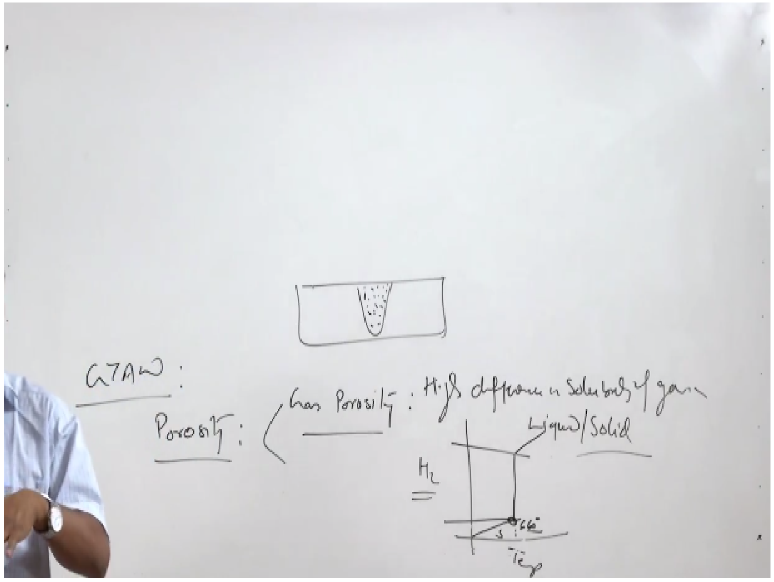

So the main reason here is the gases in the liquid state they get dissolved. These gases are rejected subsequently in course of solidification and because as these gases have limited solubility in the solid state so the rejection of these gases occurs during the solidification since solidification occurs very fast so these gases do not find enough time to come up to the surface and so they get interrupt and that is why the gas porosity is formed and that is what we will see also here as a function of the temperature if we see solubility of the hydrogen in aluminium.

In solid state solubility increases gradually, this is solid state and as soon as there is a transformation to the liquid estate, solid to the liquid state express there is sudden increase in solubility and then again it starts increasing slowly in the liquid state, so this is the temperature say for pure aluminium, it is around 6, 60 degree centigrade to a sudden change in the solubility of the hydrogen in aluminium will be occurring.

So there is a large difference in the solubility of the hydrogen in aluminium in solid state and the solubility of the hydrogen in the liquid state. Because of this large difference in course of solidification the hydrogen is rejected and as the hydrogen is rejected due to the high cooling rate, limited time availability for escaping of all these gases, these gases get interrupt in the weld metal and they result in the pores.

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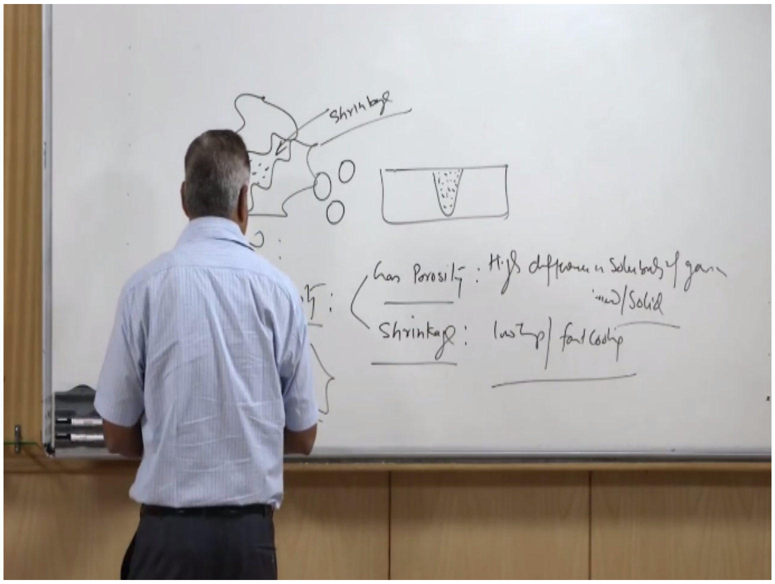

So mostly the gas porosity is of the circular family it is very easy to identify and recognize. Another is the shrinkage porosity, shrinkage porosity happens due to the limited fluidity of the molten metal and whenever it happens and this limited fluidity may be due to the low temperature or the fast cooling, so under these conditions whatever gap is created due to the shrinkage that is not filled in and the gap is left unfilled due to the absence of the liquid metal

and that in turn forms the shrinkage porosity and this is typically of like say this is one dendrite and this is the another dendrite being formed so the gap between the two dendrites is left unfilled and it leads to the formation of the shrinkage porosity. It happens especially when the grains are very course and they interrupt the flow of the molten metal and whatever gap is created between the dendrites that is not filled in due to the limited fluidity or blocked channels for the flow of the liquid metal that in turn leads to the shrinkage porosity.

So it is typically the feature if we see the shape of the shrinkage porosity is the dendritic one like which will be having like two sides of the dendrites and between them there will be a gap which will appear in form of the shrinkage porosity and if whenever there is a fracture of weld or of the casting having the shrinkage porosity, the surface exposed or surface that we can see after the fracture that will have the typical dendritic features on the fracture surface if it is having the shrinkage porosity.

So improving the fluidity of the molten metal, refining the grain structure are some of the approaches, which are used for overcoming the problem related with the shrinkage porosity and to overcome the problem related to the gas porosity. Normally the degassing is done in case of the welding, proper cleaning of the base metal filler or the hydrogen free, the gases or the consumables are used so availability of the hydrogen to the aluminium can be reduced.

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So this is what we can see here, this diagram shows the solubility of the hydrogen and this as a function of the temperature so there is a sudden increase in solubility at the melting point and it increases as soon as the solid to the liquid state transform is under influence there is a sudden increase in the solubility.

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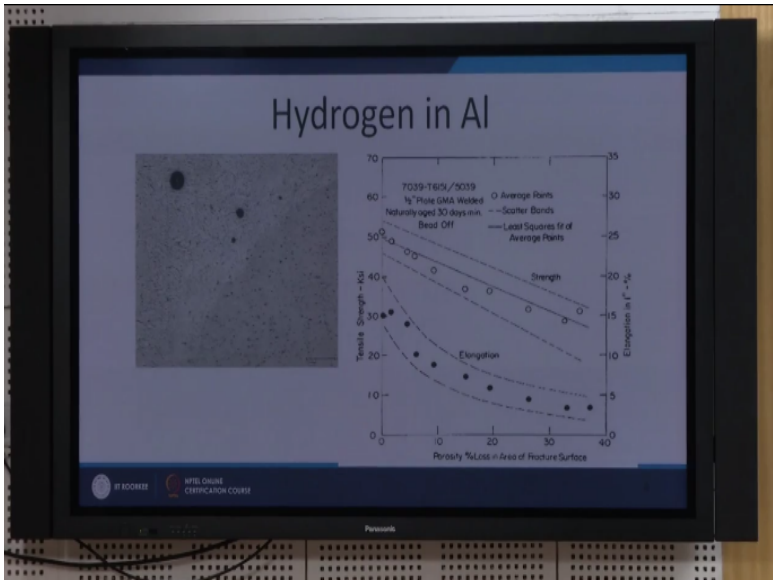

And because of this only we find that the gas porosity which is of spherical family is observed. So increase in porosity we know that there is a reduction in the ductility and reduction in the strength because the porosity actually reduces the net load resisting cross-sectional area of the weld joint.

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Let us consider this example, here this is a weld and if we have pores like this so these porosity will be reducing the load resisting cross-sectional area and reduction in road resisting cross-sectional area of the weld will actually be reducing the load carrying capacity and so the tensile strength of the weld joints. Apart from that like the solidification cracking partial melting zone and the softening of the heat affected zone.

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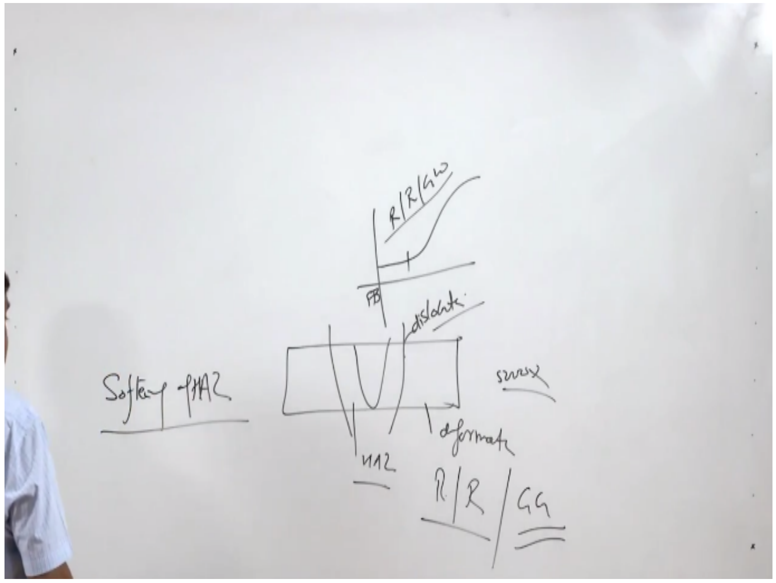

So I will take up the softening of the heat affected zone. Softening of the HAZ like say this is the weld of the aluminium alloys of say 5000 series so since the 5000 series aluminium alloys are strengthened by the deformation or strain hardening so it will have a lot of dislocations which will be contributing towards the strength and whenever heat is applied all these dislocations whatever were there.

They will be annihilating complete recovery and recrystallisation in the heat affected zone will be taking place and therefore the recrystallisation and the recovery both will be reducing the hardness and its strength and they will be annihilating the dislocations. Apart from that green growth in the heat affected zone is also observed, so all three factors actually cause the softening of the heat affected zone and if we see this is the fusion boundary and away from the fusion boundary, there may be continuous.

There is a sudden drop in the hardness next to the fusion boundary and then as we move away from the fusion boundary there is a increase in the hardness, so this loss of the hardness is attributed to the recovery, recrystallisation and the green growth. This is what I have already explained in the earlier lectures regarding the effect of the weld thermal cycle on the HAZ.

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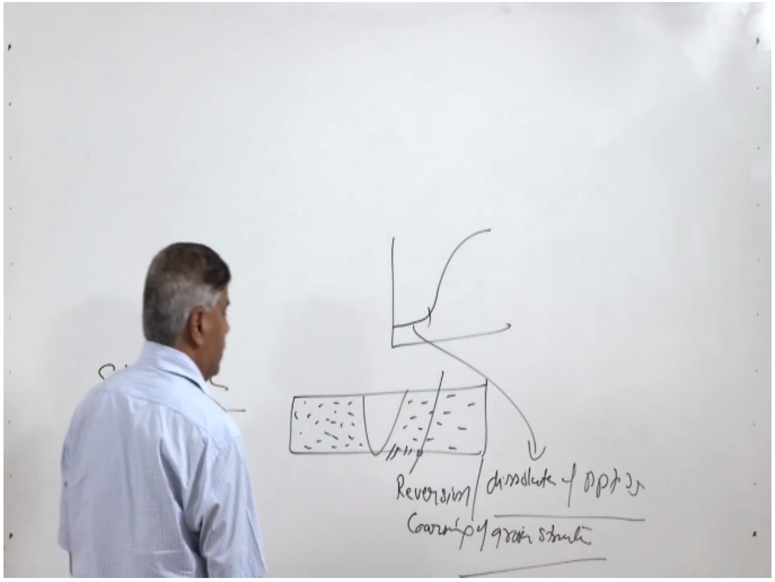

As far as the second point is concerned like the softening in the precipitation hardenable systems about this also I have talked here where the systems are strengthened by the presence of the precipitates in the entire mass. So these precipitates get dissolved at the different temperatures especially when they are heated above the 150 or 200 degree centigrade, so these precipitates when they get dissolved under the influence of the weld thermal cycle.

Dissolution will be more complete next to the fusion boundary somewhat less away from and further lesser away from the fusion boundaries. So because of the like say the technical term is reversion which is basically dissolution of precipitates so in precipitation hardenable system these precipitates get dissolved under the influence of the weld thermal cycle.

And since these precipitates are main strength contributing factors main factors which are contributing towards the strength of the base metal and wherever from these get dissolved that zone experiences the loss of strength, loss of the hardness and that is why in this case also the loss of strength is observed next to the fusion boundary and this loss is attributed to the dissolution of the precipitates or the reversion at the same time coarsening of the grainy structure in the heat affected zone will also be taking place.

So all these factors contribute towards the loss of the hardness and its strength so that that is what we can say. To reduce these in case of the work hardenable systems as I have explained only way is that reducing the net heat input so that the region which is experiencing the softening can be reduced and in case of the precipitation hardenable systems apart from reducing the heat affected zone subsequently after the welding we can do the post welding treatment.

So whatever reversal has taken place, the precipitates can be restored after the relevant post weld heat treatment process. It may be T6 or the T4 as per the kind of alloy which is in question.

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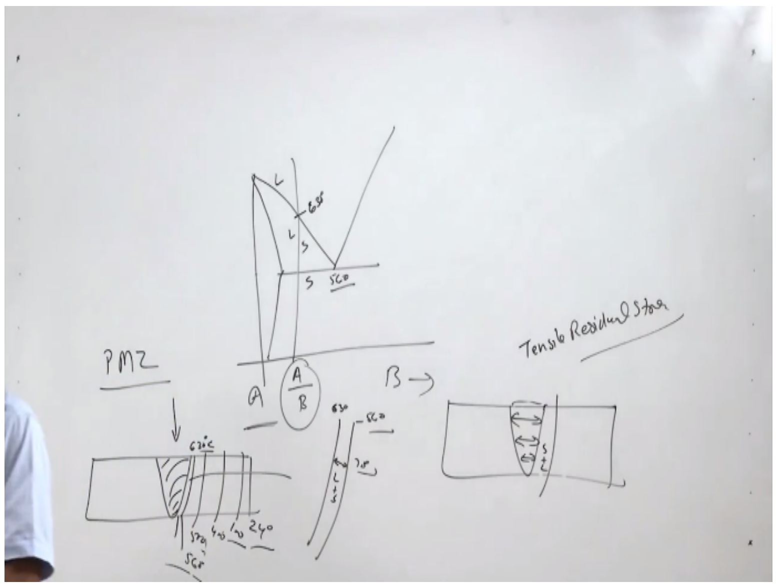

Now we will see the partial melting zone problem. Partial melting zone problem, this is basically related with the aluminium alloys which are having the much wider solidification temperature range, so let us say most of the aluminium alloys they show the typical phase diagram of this kind say or there maybe other also which will have the partial solid solubility like this also, so depending upon the case like the aluminium alloy is of this composition say this side we have B, this is A and composition is this A for a given percentage of the B.

So what we will have this is the liquidus and this is solidus and between these two we have both solid and liquidus and this temperature say for example its 630 degree centigrade and this is 560 degree centigrade so these are the two temperatures, solidus, liquidus at 630 where above which it will be in completely liquid state and just for example solidus is occurring at 560 degree centigrade.

So when such kind of system when welded what we will see, so the weld metal with the application of the external heat source what we will be doing we will be simply applying the heat so the things will be brought to the molten state so any region which is heated above 630 degree centigrade that will be forming the portion of the weld metal and away from that definitely.

We will be having the different zones of the temperature which will be heated to the different temperature and those which are located far away from the fusion boundary. There will be another room temperature condition, say 24 degree centigrade, 100 degree centigrade, 400 degree centigrade, likewise so 500 degree centigrade like this and there will be one region which will be heated up to 560 degree centigrade.

So this region, this is the boundary for 560 degree centigrade, say for this example, so the fusion boundary will be experiencing the temperature of 630 and above and just below that we will have the region which will be heated up to the 560 degree centigrade and between these two. So this narrowband which one upper one corresponding to 630 and below one 560 so the temperature band is of 70 degree centigrade and in this gap what we will have, we will have both, liquid as well as solid.

So in this case the zone there will be one phase which will be in the solid state, another phase in the liquid estate so during the welding, what will happen like the weld metal produced, liquation zone is formed, solid plus liquid. So during the heating it will brought to the molten state nearby areas will be expanding and during the cooling this weld metal will solidify and then after solidification it will be cooling down to the room temperature.

Similarly, the zones which were heated to high-temperature, they will be cooled down so they will be sinking so these heating and cooling results in the development of the tensile residual stresses especially due to the shrinkage of the weld metal. So the tensile residual stresses being set in due to the weld metal they cause the suppression of the liquid metal especially in the partial melting zone.

And this separation results in the development of cracks especially in the PMZ region.

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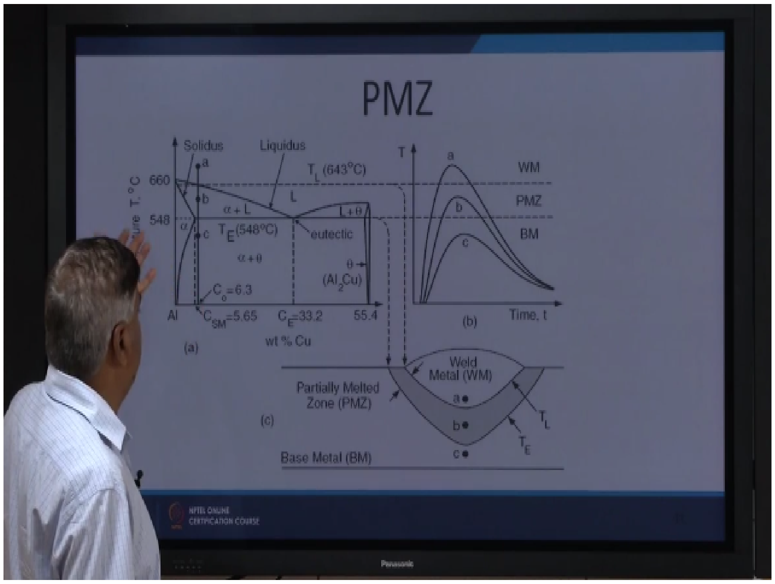

This is what we can see here as far as the PMZ problem is concerned. This is what I have said like say this is the aluminium alloy, one typical aluminium alloy. A is in the liquidus, B in the two-phased zone and C is in the solid state it is below the eutectic point so A is in the weld metal, B is in the partial melting zone having both solidus and liquidus, L is the liquidus and TE is the solidus and C is the in the solid estate. So this entire band will be in the two-phase zone.

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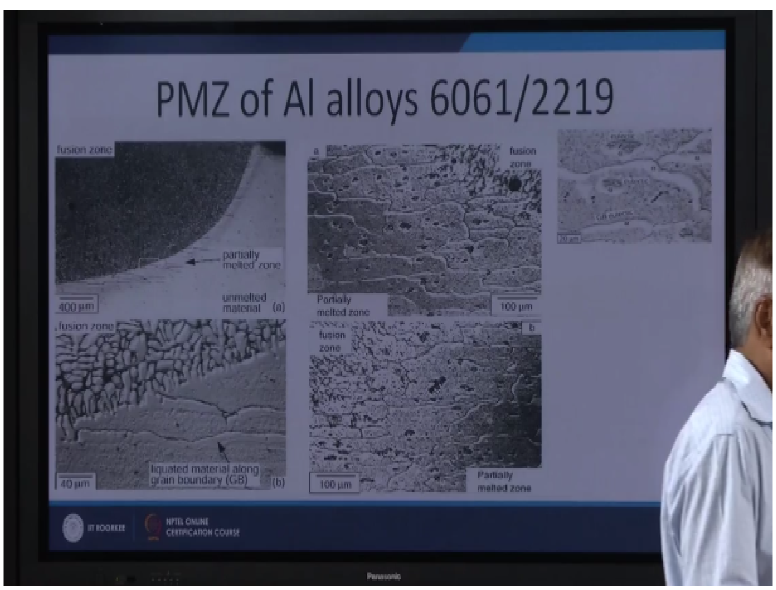

So when subsequently this weld will solidify then what we will that the tensile residual stresses will be set in. We can see one very narrow zone here is having number of cracks, it will be having the partial, this is zone corresponding the partial melting zone where both solid and the liquid will be present and this zone will be very sensitive for development of cracks especially in presence of the residual recesses.

Liquid metal tends to get separate from the solid-phase and produces the cracks and that is why we will see that number of cracks next to the fusion boundary are formed. So now here I will conclude this presentation. In this presentation I have talked about the weldability of aluminium alloys, we have seen that what are the different properties of the metals related with aluminium alloys that affect the weldability.

And we have also seen the commonly encountered problems related to the welding of the aluminium and what are the important causes of the problems commonly encountered like porosity, softening of the heat affected zone and partial melting zone problem and solidification cracking problem is another big one about which I will be talking in the next lecture, so thank you for your attention.