Welding Engineering
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Module - 08
Weldability of Metal
Lecture - 02
Reactions in Weldment

So, dear students this is the second lecture on the weldability of the metals, and in this presentation we will be mainly taking up first the different mechanisms, which are used for grain refining in the weld zone, and the different methods which are based on those grain refinement mechanisms. Then we will see that different reactions, which take place in the weldment such as, the gas metal reactions, slag metal reactions or the liquid metal reactions and the solid state reactions, and these reactions frequently lead to the development of the defect or the discontinuity of one or other kind. So, what is the mechanism behind the development of those discontinuities in the weld region and in the heat effected zone that will be taken up in these presentations.

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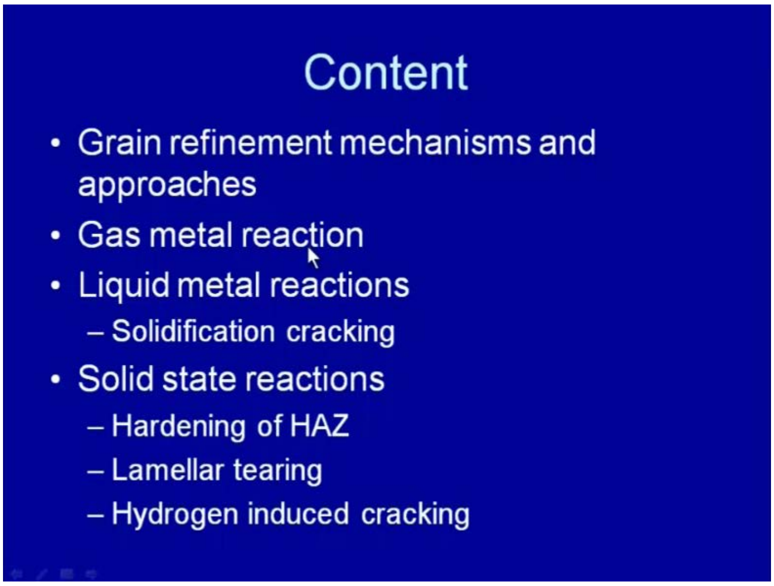

So, as far as content is concerned the grain refinement mechanisms and the approaches based on those mechanisms, then gas metal reaction, the liquid metal reaction which mostly leads to the development of the solidification cracks and many times inclusions also. And then solid state reactions, which will be involving like hardening and embrittlement of the heat effected zone, and then cracking in form of the tearing of the region very close to the fusion boundary. So, that is the hardened heat effected zone subjected to the cracking in form of this called lamellar tearing.

And then another type of cracking, which takes place in the heat effected zone again, is called hydrogen induced cracking, which is mainly promoted by the hydrogen. So, all these reactions will be occurring in the solid state while this one will be taking place in the liquid state. and this one will also be taken place in the liquid state.So, as far as the grain refinement mechanisms are concerned. We know that the refinement of the grain structure especially, the fine equiaxed grain structure is important for better mechanical performance of the weld.

And at the same time this kind of grain structure also helps in reducing the problems related with the cracking like solidification cracking in the weld zone. And therefore, it is frequently desired to have the refined very fine equiaxed grain structure in the weld region. So, in order to achieve the refined equiaxed grain structure in the heat effected zone various mechanisms are used, and these mechanisms are based on the simple approach of having the large number of the nucleants, which can be developed in the weld region. So, that during the growth stage all those nucleants, can be there in form of the individual grains.

So, basic objective is to have the large number of the nucleants in the weld region during the solidification. So, that the same number of grains can be produced in the weld zone, if we are having the fewer number of the nucleants in the initial stage during solidification then we will be having very coarse grain structure and therefore, to achieve the refined grain structure.

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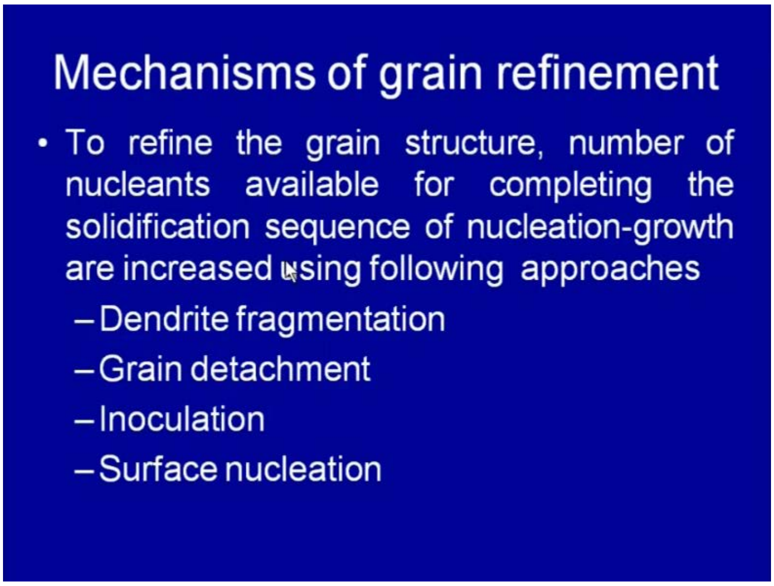

The number of nucleants present in the weld metal during the solidification is increased and for that purpose of various mechanisms, which are used or like dendrite fragmentation, brain right detachment, inoculation and the surface nucleation. These are the four different approaches, which are based on the different mechanisms just to understand, will be using this schematic diagram to understand these mechanisms.

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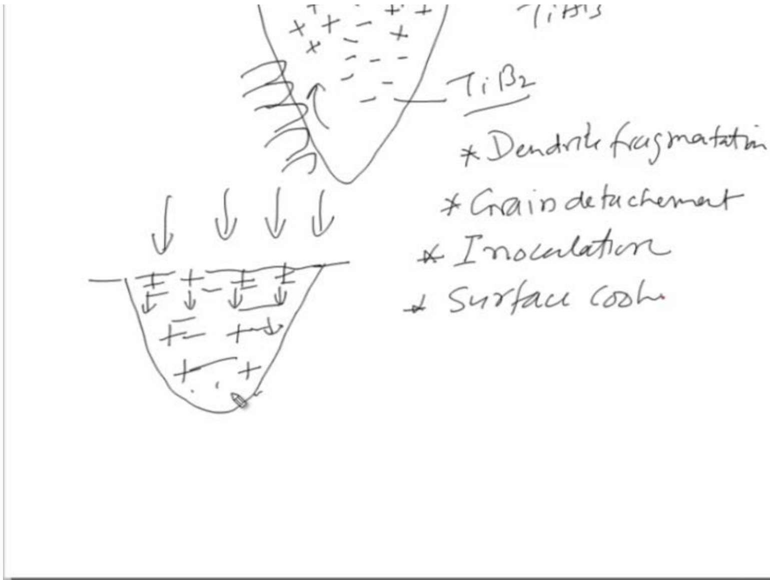

Here we know that the when weld metal solidifies this is the weld pool, which is solidifying. So, solidification will be beginning at the weld fusion boundary initially in form of the planar structure, and then some celluloid structure is developed and thereafter we get the dendrites. Dendritic structure is developed, these are present in the just after the cellular structure, and then we have very fine equiaxed grain structure. So, in order to have the very fine grain structure, it is necessary that more number of nucleants. So, to have those nucleants in this weld region somehow the grains which are in the growing growth stage? They are broken by the disturbance in the liquid metal.

So, when these grains which are growing are broken into the liquid metal then they will be present in form of very fine fragments. Here and there since these are the same metal system. So, they will be able to act as a nucleant for the liquid metal, which is still in the solidification stage. So, the break fracture of the fracture of these dendrites and the grains, which are growing in the weld zone, leads to the production of the large number of the nucleants, large number of the fragments and which are able to act as a nucleant for refining the grain structure. So, the dendrite fragmentation is one of the mechanism dendrite fragmentation.

The second mechanism is in which the dendrite or the grain detachment takes place, we know that the weld metal will be having the partially melted grains. For these partially melted grains are broken under the movement of the liquid metal in the weld poll. So, these partially melted grains when broken will be providing the fragments of these partially melted grains, and further these fragments are able to act as a nucleant. When these are present in large amount, they are able to refine the grain structure. So, the grain detachment is another mechanism which helps in refining the grain structure.

Third mechanism is that we add from outside in such a way that it is able to act as a nucleant. So, addition of the elements from the outside which are able to act as a nucleant helps in refining the grain structure. For example, addition of the Ti B 2 in aluminum weld metal, TiAl3 in aluminum weld metal frequently act as a nucleant for refining the aluminum weld structure. So, this approach when we add something from outside is called heterogeneous nucleation and this is obtained by adding something from outside in form the alloying element and this is called inoculation, where addition is wet from outside.

And the fourth approach is the surface nucleation in the surface nucleation the weld metal, which is solidifying is subjected to the liquid nitrogen or the chilled air jet is applied over the weld pool. So, at the surface some of the solidification takes place in form of the dendrites just at the surface these in the solid state and to settle down gradually towards the root of the world, when in this process these get distributed uniformly in the weld region. Since these are the dendrites which were developed in the beginning at the top level due to the application of the cold air jet.

So, they are able to get solidify only at the surface and subsequently settlement in the weld zone, leads to the develop, leads to their presence in the entire weld zone. So, they are able to act as nucleant. So, this surface cooling or surface nucleation is the another method, where jet of the chilled air is used for causing the solidification just at the surface layers in form of the dendrites. When these settled down during the course of the time they get distributed uniformly in the weld zone and they are able to act as nucleants provide the grain refinement.

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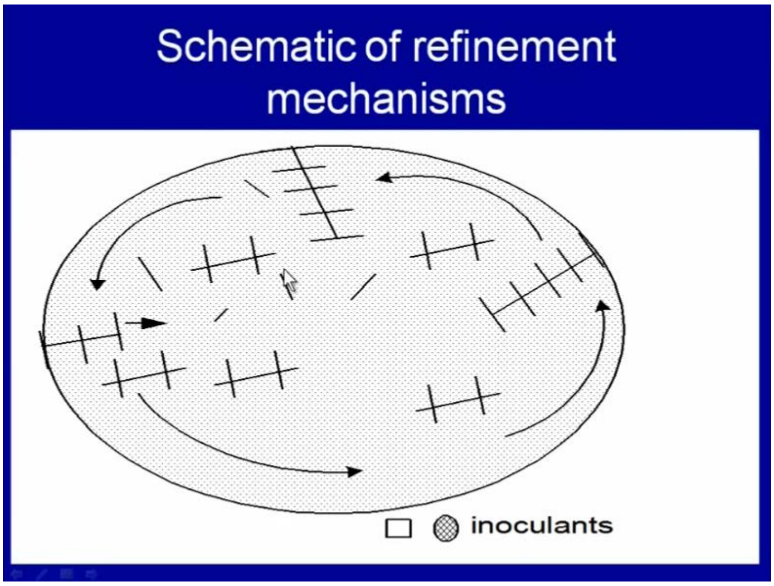

So, these mechanisms have been explained here due to the electromagnetic forces in the weld region, there is always churning of the liquid metal and because of this movement and churning of the liquid metal, whatever dendrites and the grains that are growing they are fragmented. So, the fragmentation leads to the presence of the fragmented particles here and there which are able to act as a nucleant, and then partially grains because of these forces, the partially melted grains are able to pull out of the solid near from the fusion boundary zone. When these come out further these are able to act as a nucleant and for heterogeneous nucleation, we add something from outside in the weld zone, which can act as a nucleant and for surface nucleation basically.

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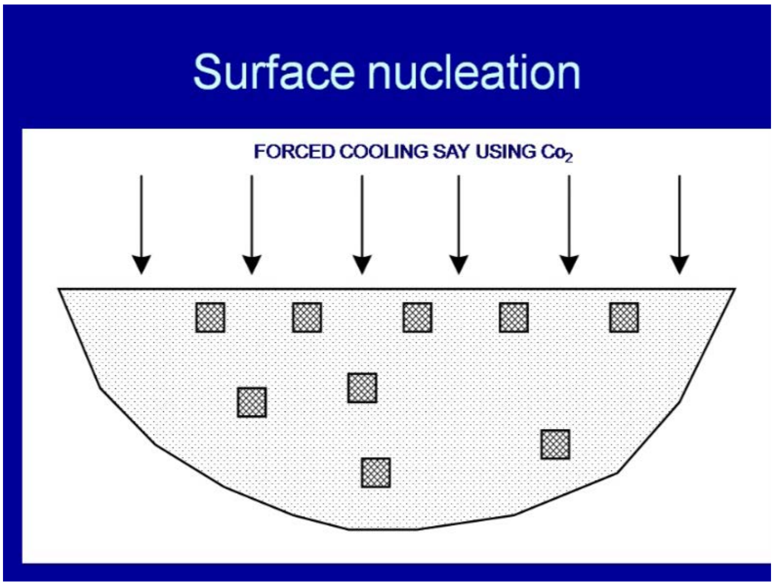

The forced cooling is done using the liquid nitrogen or the chilled air.So, that solidification just at the surface layer takes place and when the solidification has taken place there it is starts to settle down in the weld zone. So, thereby they get uniformly distributed. Since these are the same metal system present in the solid state and distributed in the mass of weld metal. So, they are able to act as a nucleant, when these are present in the large quantity, they are able to provide the desired grain refinement in the weld zone. So, based on these fundamental mechanisms various methods of the grain refinement have been developed, these are inoculation, arc pulsation, mechanical forces, electromagnetic forces, and arc oscillation.

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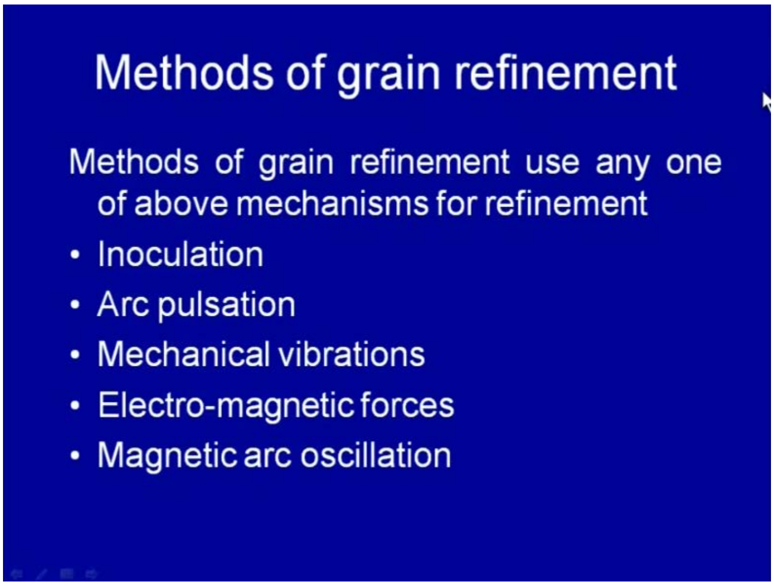

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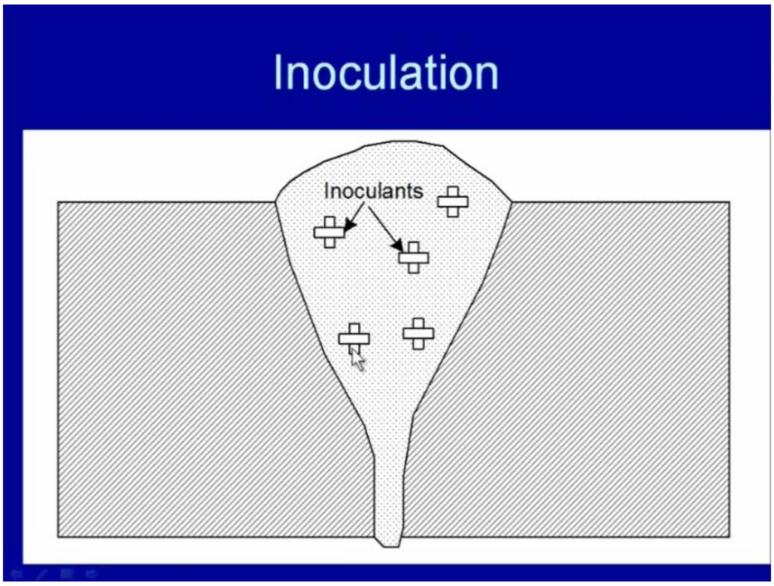

So, in case of inoculation we add from something from outside, which is able to act as a nucleant and when these are present in the large quantity. We are able to have very refined grain structure. The aluminum, vanadium, titanium, boride, titanium aluminide these are the common kind of compounds, which are added in the weld zone for refining the steel and the aluminum welds.

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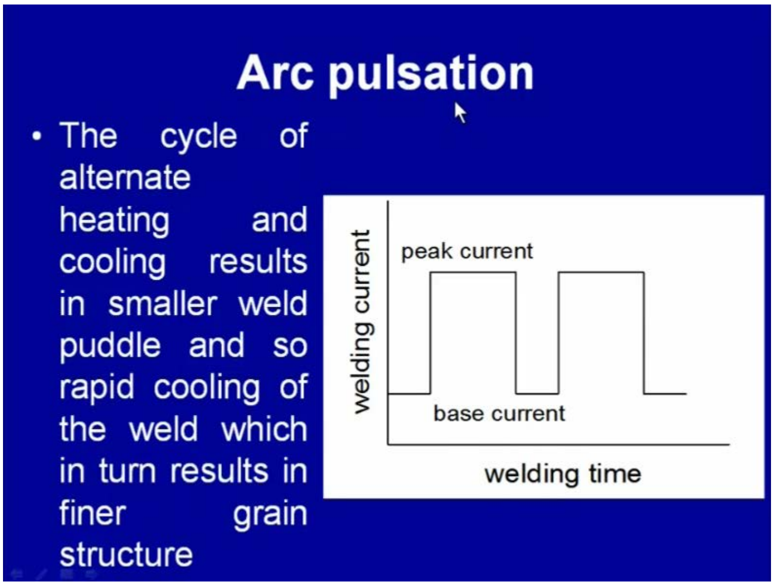

Arc pulsation is the another approach. Where every the heat input is reduced. So, reduction in heat input increase the nucleation rate and decreases the growth rate. Further, when the nucleation rate increases the nucleation rate results in the large number of the nucleants for the solidification to take place, and when these are present in the large amount they are able to refine the grain structure. Another approach is that it involves the alternate heating and cooling cycle , because once there is a peak current then base current, when no major heat is developed mainly the cooling takes place.

So, the heating and cooling cycle continues, because of this kind of feature in arc pulse, arc welding processes very small weld pool is developed, and when this solidifies very rapid solidification is also take also takes place. When the pulse arc welding is done means arc pulsation helps to develop the first smaller weld pool. So, that the grain size is limited because of the smaller weld pool and further reduced heat input increases the cooling rate helps to refine the grain structure.

So, there're two principles based on which the refinement is achieved by arc pulsation. One it reduces the size of weld pool, because each time when there is a peak current for a particular duration, the pool is developed and thereafter its solidification takes place. So, size of the pool is very small in case of arc pulsation, and second thing when arc pulsation is done. It decreases the heat input significantly which in turn increases the cooling rate being experienced by the weld pool during the solidification helps in refining the grain structure.

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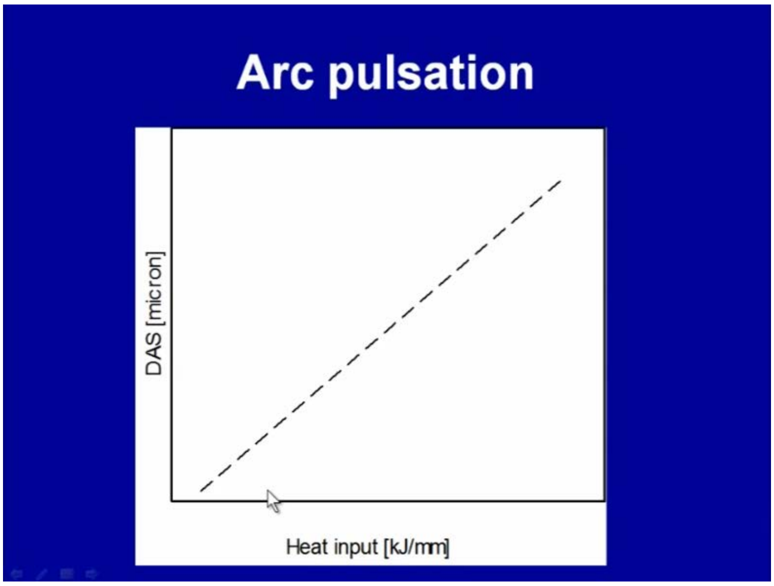

If we increase the heat input then the grain size increases in terms of the secondary dendrite arm spacing. So, we know that in case of the cast structure the grain size is measured in terms of the dendrite arm spacing. So, this spacing keeps on increasing with the increase in heat input, since in case of arc pulsation we reduce the heat input. So, this reduced heat input helps in developing the fine grain structure or very low dendrite arm spacing in during the solidification of the weld zone.

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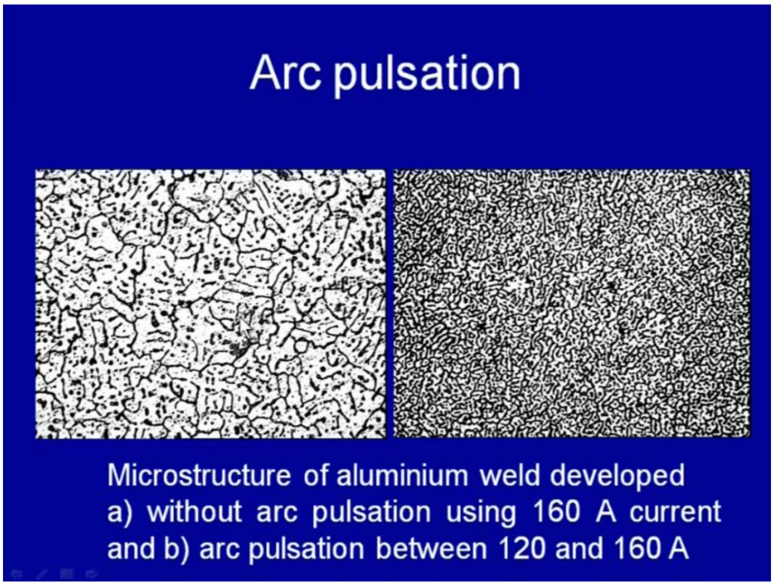

This is one typical photograph which is showing the effect of the arc pulsation. This is the microstructure of the weld, which was developed using the conventional arc welding process. In which the heat is developed continuously and thereafter according to the heat input the solidification takes place. And when the structure is means the weld is developed using the arc pulsation, where pulsing is done between the 120 to 160 ampere current.

Then it helps to refine the grain structure significantly while in case when the no arc pulsing is done under the continuous 160 ampere d c current is used it results in the coarser grain structure. So, this the refinement in the structure is attributed to somewhat higher cooling rate experienced by the weld zone as compared to the conventional arc welding process, where no arc pulsing is done.

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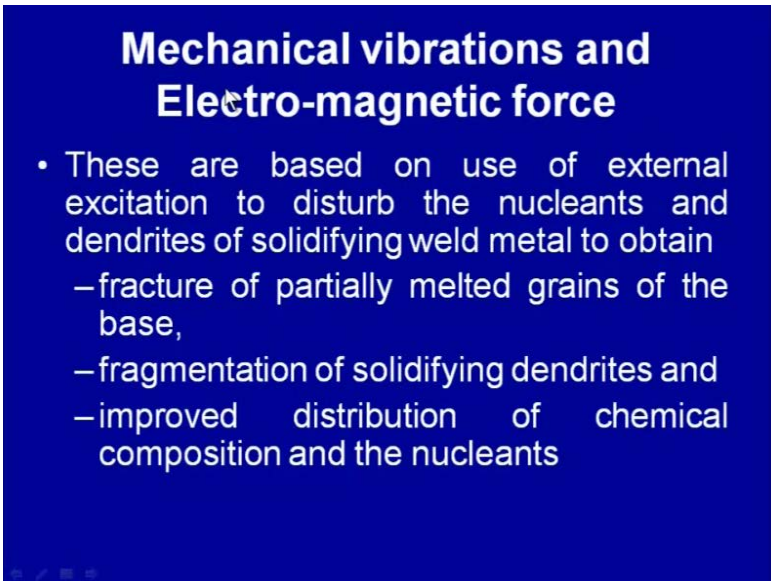

The use of the external force there are two approaches one is use of mechanical vibration, and another is electromagnetic forces. These forces are basically used to create the disturbance in the weld zone. So, that the nucleants are developed by the fracture of the partially melted grain or fragmentation of the solidifying dendrites or to achieve their improved distribution in the weld.

So, when the external force is used to create the disturbance in the weld zone using either mechanical vibrations or the electromagnetic forces. This helps in having the fracture of the partially melted grains in the solidification stage, and the fragmentation of the solidifying grains dendrites. So, both these actually effects increase the number of the dendrites which are present in the weld metal.

Since these are able to act as a nucleant for the weld metal, because they are largely similar composition as the liquid metal. That's why they are able to act as a nucleant and when these are present in the large quantity, they are able to act as a nucleant thus helps in refining the grain structure. Because more number of nucleants present in the weld zone, finer will be the grain structure. So, this is the fundamental approach, which is used when the mechanical vibrations or the electromagnetic forces are used for refining the grain structure.

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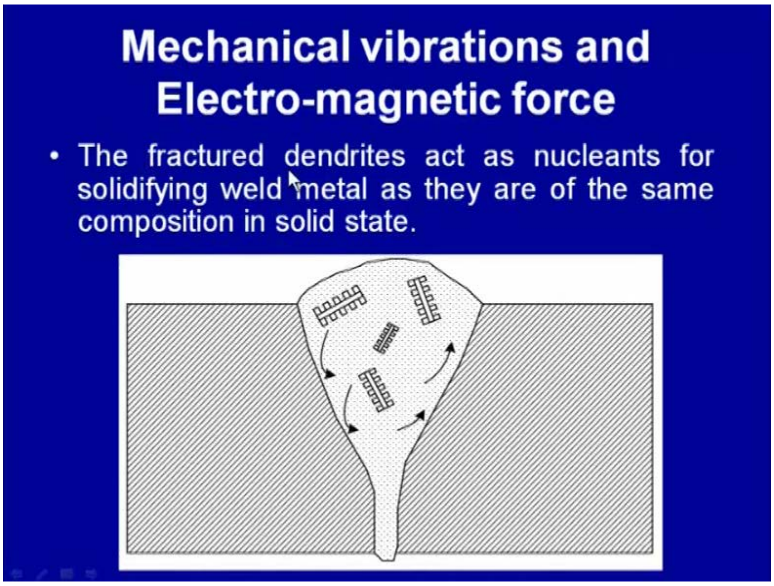

So, in case of these approaches the fractured dendrites act as a nucleant for the solidifying weld metal as they are of the same composition in the solid state. So, when this disturbance created by the mechanical vibrations or electromagnetic forces in the weld zone. Especially in the liquid metal helps to break the solidifying dendrites or the partially melted grains and thus provides the large number of nucleants for solidification.

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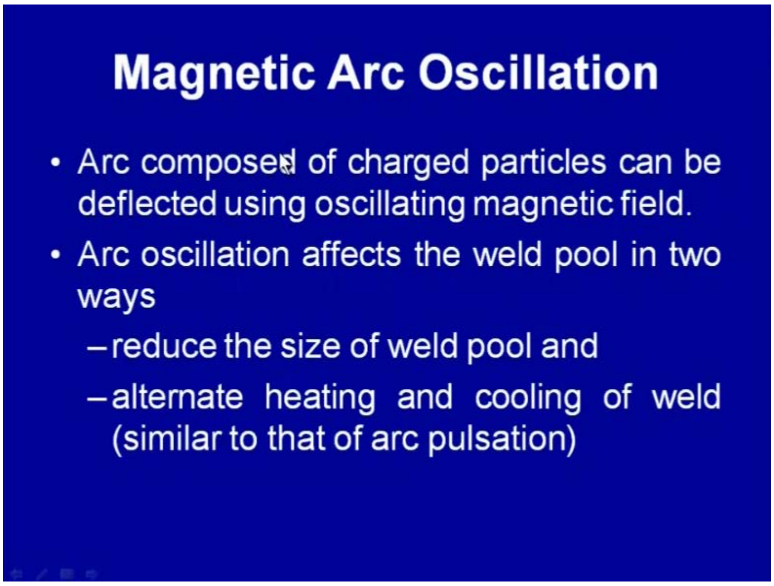

Similar to the arc oscillation, arc pulsation, and the magnetic arc oscillation works on the similar line. Because in this case the arc is deflected intentionally to provide the heat input in intermittent manner to the weld pool. So, the arc is deflected using the suitable electromagnetic field, since the arc oscillation effects the weld pool in the two ways it reduces the size of the weld pool and the alternate heating and cooling is done. In this approach basically arc is reflected from its path to such an extent that heat is provided in intermittent manner to the weld zone.

So, this reduction in heat input first increases the grain refinement due to the higher cooling rate at the same time intermittent heat input to the weld zone, further decreases the size of the weld pool. So, and this is because we intentionally deflect the arc from it's an intended path using the suitable electromagnetic field. So, arc since it is composed of the charged particles can be easily deflected using oscillating magnetic field. When the arc oscillation is achieved it affects the weld pool in the two ways, one it reduces the size of pool, and another it increases, it actually effectively decreases the heat input by alternate heating and cooling, similar to the arc pulsation. So, reduced heat input basically increases the cooling rate during the solidification and increased cooling rate helps in refining the grain structure.

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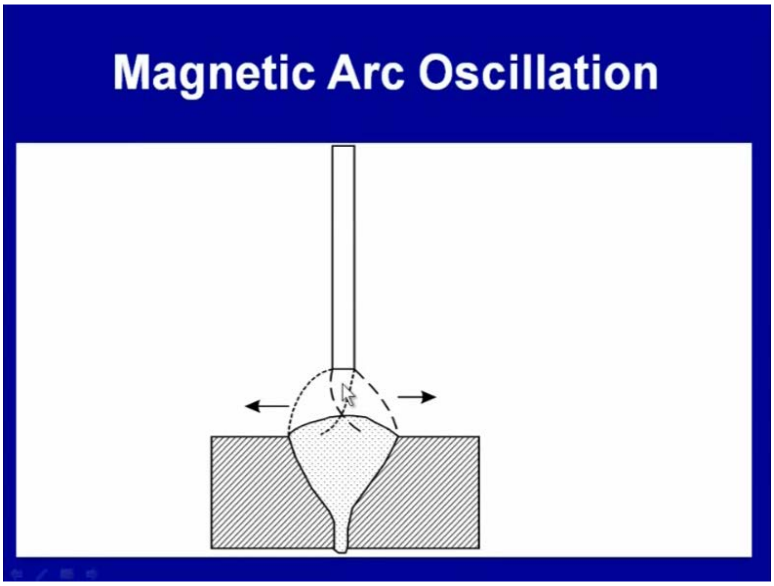

So, say this is the arc in normal position when the electromagnetic force or magnetic force is applied arc is deflected from its path from one side to another. So, this helps in reducing the net heat input as well as reducing the size of the weld pool, this process means magnetic arc oscillation and the arc pulsation these are the two approaches, which are based on the simple principle of reducing the heat input to the weld. So, that the higher cooling rate can be achieved at the same time size of the weld pool can be reduced. When this is done we automatically get the refined grain structure because of the high nucleation rate.

So, another approach based on this approach we can say that if the cooling rate is high then it will be leading to have the lower cooling rate. So, lower cooling rate we know that will be taking long time to extract the heat from the weld zone. And longer time which in turn will be resulting in the longer time to solidify the weld and the longer solidification time, because the increased time required for extraction of the heat from the weld zone. Because of this lot of time becomes available for the macro constituents to grow to the large extent due to the availability of the long solidification time and because of these grains grow to larger extent.

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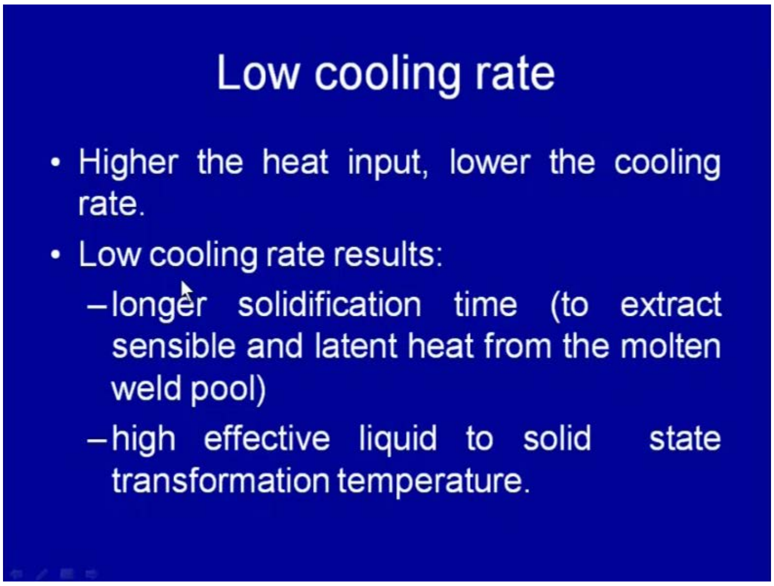

So, when the low cooling rate is experienced by the weld pool, we find that solidification is long means solidification takes place for the longer duration. Basically the liquid to solid state transformation takes place at the higher temperature. So, when the liquid to solid state transformation temperature is high means the nucleation rate will be low and the growth rate will be high under these conditions, and the low nucleation rate and the high growth rate facilitates the coarser grain structure. So, when the cooling rate is high our effective liquid to the solid state transformation decreases, which in turn helps in increasing the nucleation rate and decreasing the growth rate. So, increase in nucleation rate and reduced growth rate helps in refining the grain structure.

This is what we can see that we can compare that if the heat input is change from say in one case this submerged arc welding process. So, the still joint developed using the submerged arc welding process with the help of the two types of the heat inputs. One is 3.0 kilo joule per mm, and another 6.0 kilo joule per mm. So, here when the weld joint is developed using the low heat input, we get the finer grain structure as compared to the case when the high heat input is used, and very coarse columnar grains can be observed in the weld region across from the weld centre to the fusion boundary while such kind of structure is not visible from the photographs, which are shown here.

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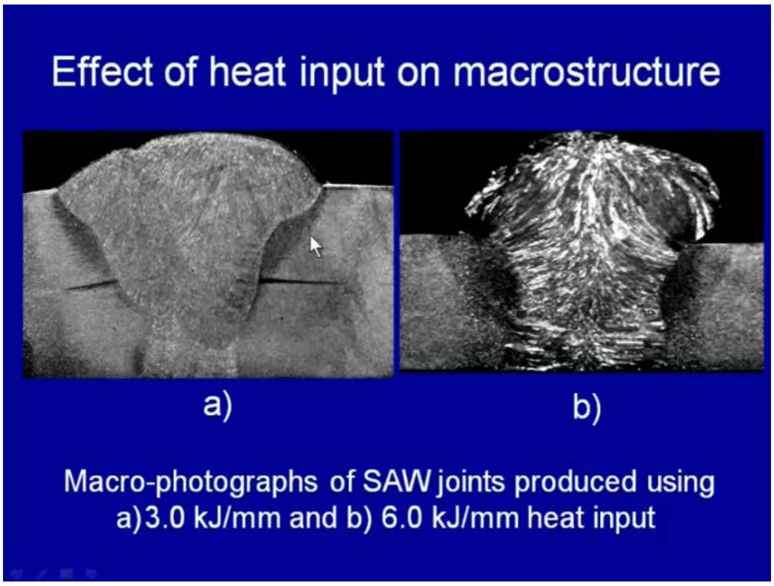

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Now, we will be talking about the different reactions which take place in the weld zone. Basically the three types of the reactions, which are commonly encountered in the weld zone and in the heat effected zone. And these, are basically the gas metal reaction liquid metal reaction and solid state reaction. Gas metal reactions basically occur due to the presence of the gases in the arc region and liquid metal reactions basically take place due to the formation of the low melting point phases in the weld zone. While the solid state reactions are encountered in the solid state whether these are happening in the weld zone or in the heat effected zone, but most of the solid state reactions happen or take place in the heat affected zone.

Where and there are three types of the common solid state reactions, one is the martensitic transformation leading to the embrittlement or hardening of the heat effected zone and the second is the lamellar tearing, where the cracking just below the heat effected zone, just below the fusion boundary takes place, and the third is the hydrogen induced cracking, which is also commonly encountered in the heat effected zone especially in case of the hardenable steels.

So, we will be talking about these reactions one by one in the coming slides. Here starting with the gas metal reactions, we know that the any metal system is brought is heated to the high temperature and brought to the molten condition. it becomes very active and tends to react with the gases present all around it. So, when the gases present in the weld zone due to the poor protection of the weld pool gases like hydrogen oxygen and nitrogen in the weld pool react with the molten weld metal, and produces number of undesirable effect.

So, when these gases are present in the weld region or in contact with the molten weld pool. They form, they lead to the development of the porosity and the formation of oxides nitrides and the hydrogen induced cracking, and embrittlement of the weld due to the formation of nitrides. So, there are various kinds of the effects, which are observed when these gases are present in the weld zone.

But the commonly the two types of the effects are observed one is that when these gases are present in the large quantity with the molten weld pool, then due to the entrapment of the these gases porosity is developed in the weld region. Because, when these gases are present in the large amount with the molten weld metal. If they do not get enough time for escaping from the weld zone due to the high cooling rate encountered during the welding.

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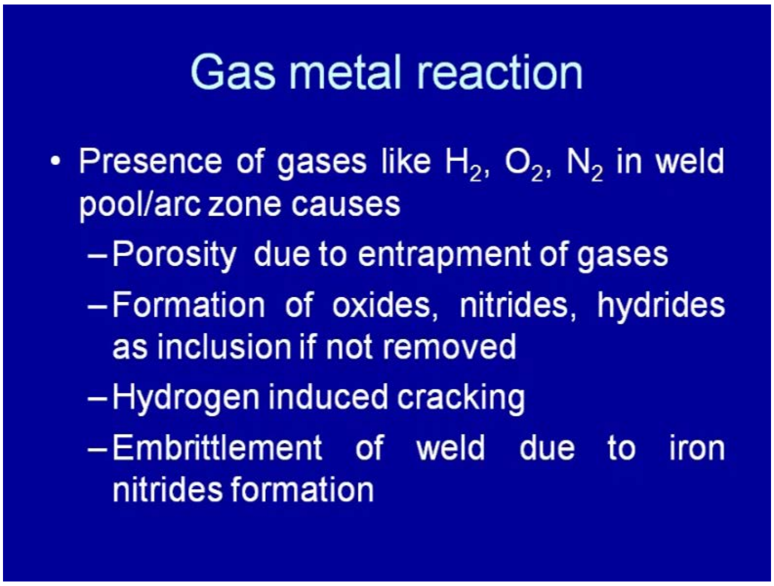

So, this leads to the entrapment of these gases with the weld metal and produces the porosity, the second is these gases are very reactive in the sense these liquid metal becomes very reactive at a high temperature, and tends to react with these gases. When the molten weld metal reacts with these gases forms the oxides nitrides hydrides, and if these are not removed way by proper reactions between the flux and with these impurities, and then these may be left in the weld zone itself as inclusion. If they are not removed from the weld zone and when these are present in the weld zone as inclusion these will be acting as a sight for the stress concentration and thus weakening the weld joint.

Therefore it is always desired to avoid the presence of these gases in from the weld zone by providing the proper protection to the weld pool. The second means, the third important effect as far as the gas material reactions is concerned, when the hydrogen is present in the large amount either, it can get entrapped to develop the hydrogen induced porosity or it can form hydrides or it can get diffused into heat effected zone, and increase the cracking tendency of the heat effected zone and that happens at very low temperature.

Because of that, it is also termed as cold cracking, but it is always assisted by the hydrogen. So, the cracking which is experienced in the heat affected zone is encouraged by the presence of hydrogen. So, if the gases are present in the weld zone these will get diffused into the heat affected zone through the liquid metal, and will increase the cracking tendency in form of the hydrogen induced cracking. When there is another side of the presence of these gases is that. When the nitrogen is present in the large quantity in the weld zone nitrogen will be reacting with the liquid iron and forming the iron nitride.

Since the iron nitride is very hard and brittle micro constituents and it is the needle shaped. When it is present in the large quantity it decreases the ductility, toughness of the yield strength of the material to the greater extent; however, hardness and the tensile strength of the material increases with the presence of these iron nitrides. So, just to show the effect of these, we know that is important that the weld zone is well protected from the presence of all these gases. So, to have the protection of the weld pool from these gases of the atmosphere, the weld pool is protected by the different approaches in the different processes. For example.

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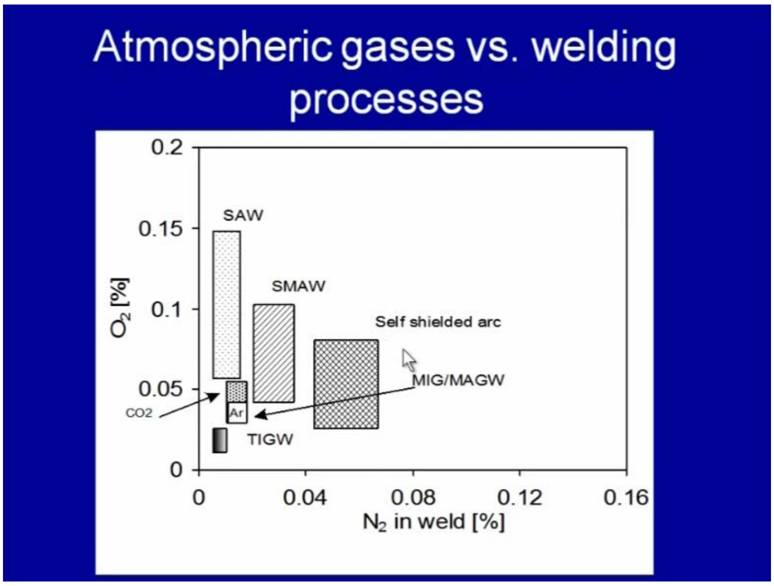

in the gas metal and the tig g m a w and g t a w processes inert gases are used to shield the weld pool from the atmospheric gases, while in case of the submerged arc welding molten fluxes is used in case of the submerged arc welding the decomposition of the flux develops the inactive gases for protecting the weld pool. So, the different processes use the different approaches for protecting the weld pool, but even after that they have the different means the concentration of the oxygen and the nitrogen, which in the weld zone. Which has been developed, using a particular process, varies significantly with the process being used.

So, means the concentration of the oxygen and nitrogen in the weld zone and the weld metal will be affected by the process ,which is being used in general the submerged gas welding process has the higher percentage of oxygen and the self shielded arc processes have the higher percentage of the nitrogen. So, when these gases, whether it is oxygen or nitrogen they are present in the large quantity. They will be reacting with the weld metal, will be forming their nitrides and oxides and when these are present as inclusion, they will be deteriorating the mechanical performance of the weld region, just for an example.

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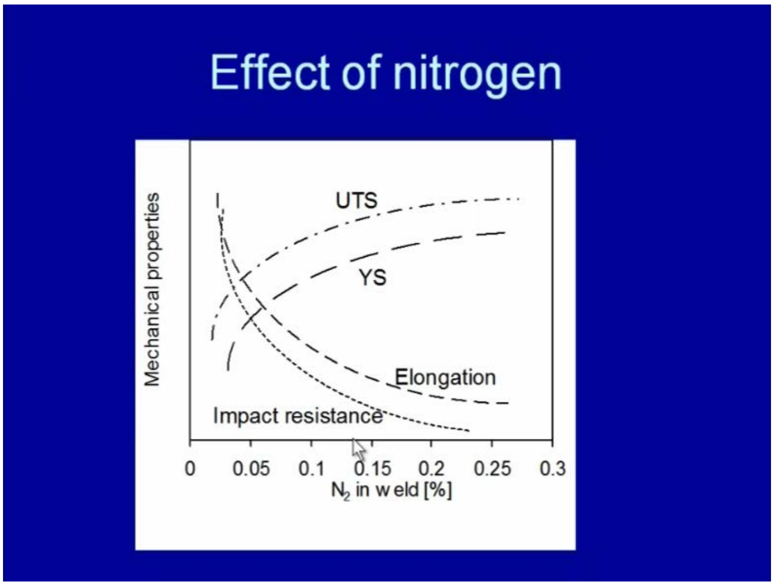

When the nitrogen is present in the large amount as I said nitrogen reacts with the iron to form iron nitrides in form of needles, which adversely effects the elongation and the resistance that is impact resistance in form of toughness. While the yield strength and the ultimate strength increases with the increase in the nitrogen content and this is mainly attributed to the formation of the iron nitride and when these gases are entrapped in the weld zone. We know that,

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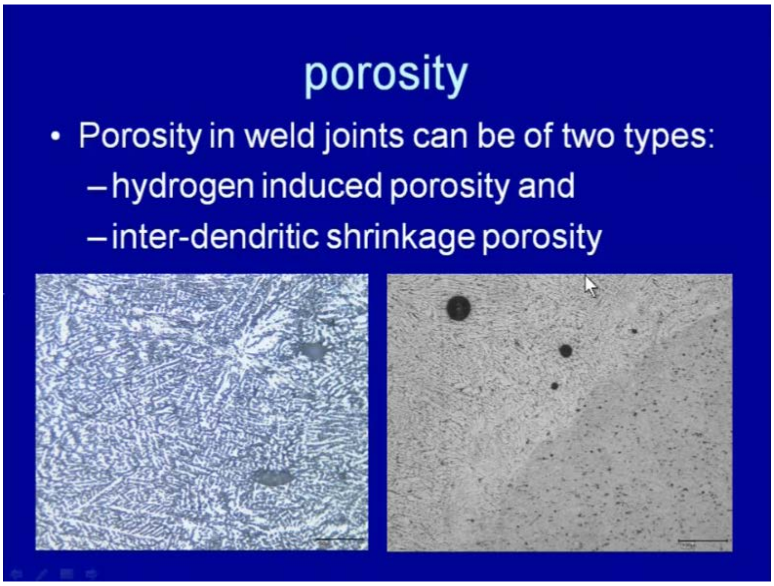

The entrapment of the gases present in the weld zone due to the higher solidification rate during the welding results in the porosity. Basically two types of the porosities are observed in the weld zone, one is the hydrogen induced porosity when the gas is entrapped in the weld zone, another is inter-dendritic porosity. Inter-dendritic porosity is basically due to the poor fluidity and the low heat input being provided to the weld. So, that in the inter-dendritic zone due to the shrinkage liquid metal is not able to reach in those areas, and this happens especially when the some of the shrinkage leads to the development of the vacant spaces, and which are found difficult to be filled in by the liquid metal due to its poor fluidity.

So, the low heat input and poor fluidity of the material basically leads to the inter-dendritic porosity. So, proper correction of the alloying composition and the heat input helps in controlling the inter-dendritic porosity and here in case of inter-dendritic porosity. We are clearly able to observe that how the grains and the grain structure is very clear while in case of the porosity, which is developed with the presence of the gases. It is mostly spherical in nature. What is been shown here,

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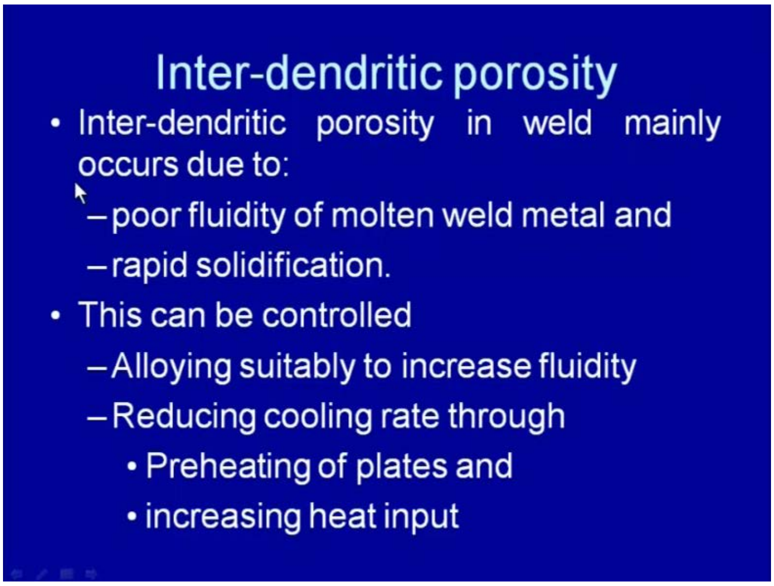

So, inter-dendritic porosity in the weld mainly occurs due to the poor fluidity of the molten weld metal, and the rapid solidification this happens because of the low heat input. So, this can be controlled by suitably adjusting the composition of the weld zone. So, that fluidity increases at the same time cooling rate is decreased, and for decreasing the cooling rate we can use the approach of either preheating the plate.

So, that heat extraction rate is decreased or the heat input is increased. So, increase in heat input will be reducing the cooling rate which in turn will be increasing the solidification time. So, that the liquid metal will have enough time to settle down and take care of the shrinkage in the liquid state, which is taking place in order to overcome the inter-dendritic porosity.

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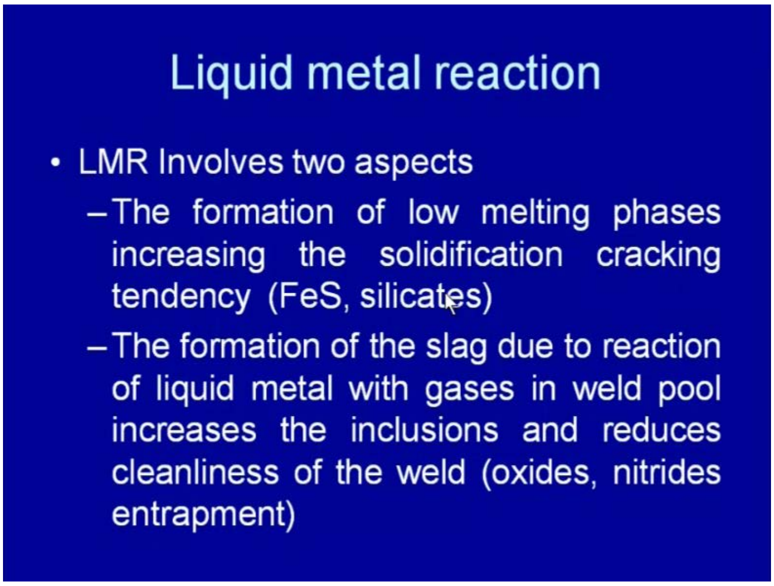

Now, we will see the liquid metal reactions they are two main aspects related with the solidification, we know that it is frequently the phosphorous and the sulphur concentration in the weld zone, and in the steel is controlled within the limit of 0.05 percent, it is not allowed to have the phosphorus and sulphur greater than 0.05. But if the sulphur is present in the steel greater than 0.05 then it increases the tendency of the solidification cracking primarily, because of the fact that, when sulphur is present in the large quantity it forms the iron sulphide, and which solidifies at very low temperature.

Since the pure iron solidifies it around 1540 degree centigrade while the iron sulphide melts around or solidifies around 730. So, because of this huge difference in the solidification temperature leads to the development of the solidification cracking, and another aspect related with the liquid metal reaction is the formation of the slag. Due to the reaction of the liquid metal with the gases present in the weld zone increases the inclusion and reduces the cleanliness of the weld.

So, when there is a presence of the large amount of the gases in the weld zone forming the large amount of the slag and low melting point slag, which is the weld metal. If it does not get enough time to come up to the surface or if it is being formed in the very large quantity, then it will have the increased tendency to get interrupted in the weld region and these will be present in the form of the inclusions.

So, it will be decreasing the cleanliness of the weld. So, there are two important aspects, one is the formation of the low melting point phases, and another is the formation of the large amount of the slag, which will be increasing the tendency to get entrapped in the weld zone. And thus increasing the inclusion forming tendency in the weld metal and these inclusions may be in form of oxides nitrides and when these are present in large amount.

They will be adversely affecting the cleanliness of the weld and when these are present in the large amount, they will be deteriorating the mechanical performance of the weld zone. Because these will be frequently acting as site for the stress concentration site of the weakness and will be easily facilitating the crack nucleation and growth from these locations, and facilitating the premature failure of the component under the external load conditions especially, under the fatigue load conditions.

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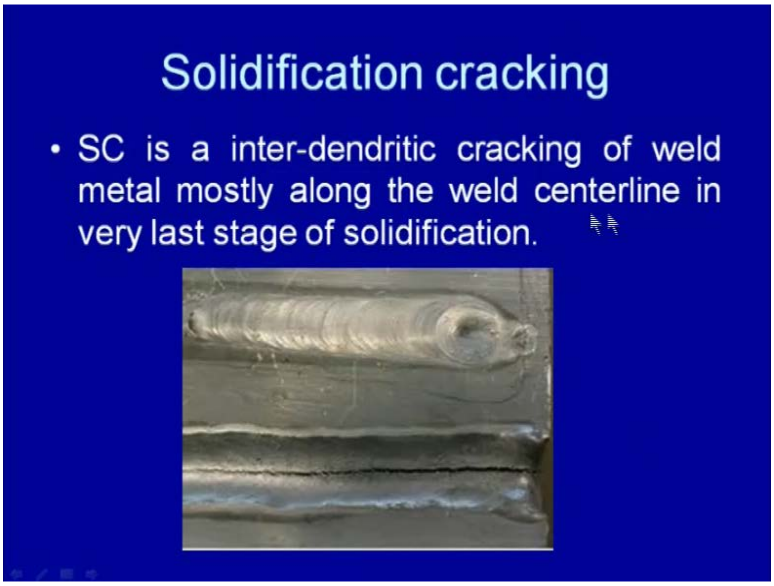

So, the solidification cracking is one of the very important aspects related with the weld metals we know that, solidification cracking is the inter-dendritic cracking of the weld metal, mostly along the weld centre line and it occurs in the very last stage of the solidification. So, here to understand this we know that, if the entire weld pool solidifies at one temperature then there would not be any problem. Because in the situation when everything is solidifying and transforming from the liquid to solid state then all the things will be in the solid state, and then it will be coming down to the room temperature.

But in the situation when some of the micro constituents or some of the things are solidifying at high temperature while others are solidifying at low temperature. So, the portion, which is already been solidified will be subjected to the residual tensile stresses while the portion, which is already in the liquid state will not be able to take up these tensile residual stresses, and when this continues for long time in the large amount then this leads to the development of the crack.

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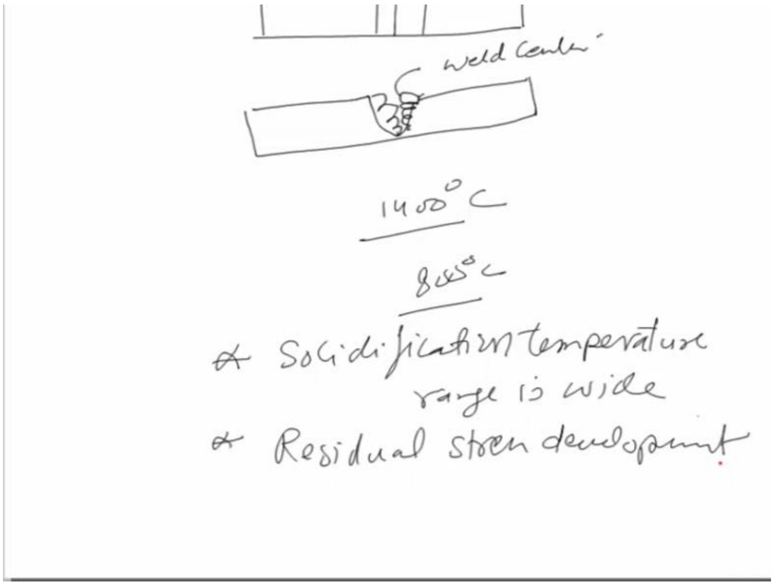

So, they are two basically regions behind the solidification cracking one is say this is the plates, these are the weld centre line and this is the portion, which has been welded, and we have here arc this is the weld zone. So, and if we see it in the front view then we will able to have it view like this. So, if this base metal is having the micro constituents such that the few are solidifying at high temperature and other are at low temperature.

So, say most of the metal systems is, if it is solidifying at high temperature say around 1400 degree centigrade and developing the solid like this from both the sides. So, whatever the low melting point phases are present they will be posted to the weld centre. So, one solidifying at high temperature say 1400 degree centigrade and if the low melting point phases are being formed they will post along the weld centre. So, and say another is solidifying at 800 degree centigrade then the low melting point phases will remain along the weld centre line until the 800 degree centigrade temperature is achieved.

But we know that since the remaining portion has already been solidified. So, it will keep on cooling down from say 1400 degree centigrade to the 800 degree centigrade and during this cooling process it will try in to contract. This contraction will lead to the development of the tensile stresses and when this tensile stresses are set up. They will be basically acting on the weak zone. And a weak zone is one where still we have the liquid metal to solidify, and therefore most of the stresses tend to localize along the weld centre line. Where we have the liquid metal still solidify and because since, the liquid metal cannot sustain any kind of the tensile residual stresses and therefore.

The cracks are developed basically along the weld centre line, and this kind of crack development tendency will be more when especially in the cases. Where solidification temperature range is very wide something is solidifying at very high temperature and temperature range is very wide or the second thing, even if we are having a very wide solidification temperature, the cracks will not be developing until the residual stresses are developed. So, for development of the cracks it is necessary that the residual stresses are present.

So, if they are no tensile residual stresses then they would not be any cracking. So, the even if the solidification temperature range is wide if we can control the development of the residual tensile stresses then it will help in controlling the solidification cracking. So, all the factors that increase the residual tensile stresses especially along the weld centre line they will be increasing or they will be affecting the solidification cracking tendency. So, among of those factors that affect the development of the solidification, development of the residual stresses, they will be affecting the solidification cracking tendency, but important thing is that residual stress development, no residual stress, no cracking.

So, all the factors like the thermal expansion coefficient of the metal or the size of the weld zone, which is being developed or the kind of restraints which have been put in all those factors will be affecting the residual stress development. So, they will be affecting the solidification cracking tendency. So, important thing is that for solidification cracking to take place residual stress should be present and the very wide solidification temperature should be there. If the metal further in some of the cases even when the solidification temperature range is not very wide, but at a high temperature material is very weak and it is low ductility.

Then also the solidification cracking is observed because most of the stresses tend to localize along the weak zone, which is mostly at the weld centre along the weld centre line, and because of that also the solidification cracking tendency is observed. So, we can see here this is the typical the weld joint of the aluminum, where the solidification crack is running along the weld centre is the fusion boundary and this is the weld zone. So, at the weld centre only the crack is running this is one form of this is also called hot tearing and it is mainly encountered in terms due to the presence of sulfur and the lead in case of steels.

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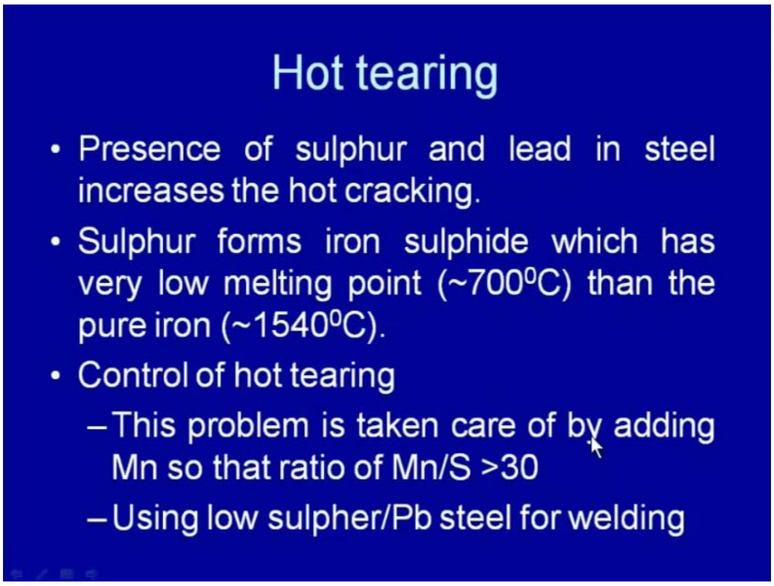

So, in the steels when sulphur and lead are present in the large amount these increase the tendency of the solidification cracking tendency or hard tearing and sulphur, because the sulphur forms the iron sulphide, which has very low melting point around 700 degree centigrade. Then the pure iron, which is around 1540 and to control the solidification cracking tendency. It is necessary that the adverse effect of the iron sulphide is reduced and to reduce the adverse effect of the iron sulphide on the cracking tendency means, which is increasing the cracking tendency normally. Manganese is added, when the manganese is added it forms the manganese sulphide, which solidifies at much higher temperature then the iron sulphide.

And further the iron sulphide, which is formed in form of the thin films, which further increases the cracking tendency. While when a manganese is added it forms the manganese sulphide, which solidifies at high temperature, and another it forms manganese sulphide in form of the globules, which further decrease the cracking tendency. So, another aspect is that use the low sulphur and the low Pb steel for the welding purpose. So, these are the two things which can be done as far as the control of the hot tearing is done apart from this there are many other aspects, which can be tried for controlling the solidification cracking about that we will be talking subsequent slides.

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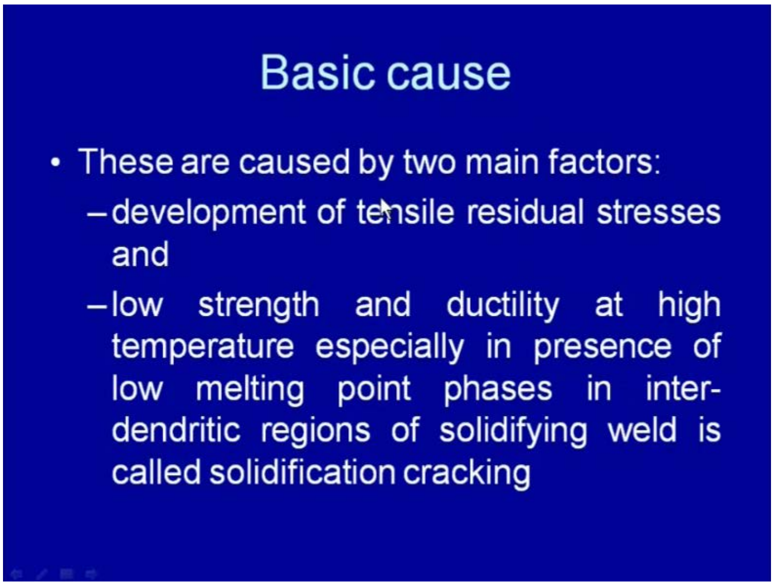

So, from the above it is clear that there are two mean factors that contribute towards the development of crack at high temperature during the solidification cracking. One is the development of the tensile residual stresses, and second is that material is having the low strength and ductility at a high temperature, which is mostly due to the presence of the low melting point phases in the inter-dendritic region. Especially near the end of the solidification or the last stage of the solidification and this is called solidification cracking. Now, we will see the cold cracking this is another type of the cracking, which is observed.

This is one type of the solid state reaction. So, we have talked about the gas metal reactions and then liquid metal reactions in the gas metal reactions. Where effect of oxygen nitrogen and in the liquid metal reactions, we have seen the solidification cracking. Now we will see the solid state reactions solid state reactions occur in three forms, one is very embrittlement and hardening of the heat effected zone due to the martensitic transformation and the second is the cold cracking which mainly occurs in the presence of the hydrogen, and the third one is the lamellar tearing. So, these will be described one by one.

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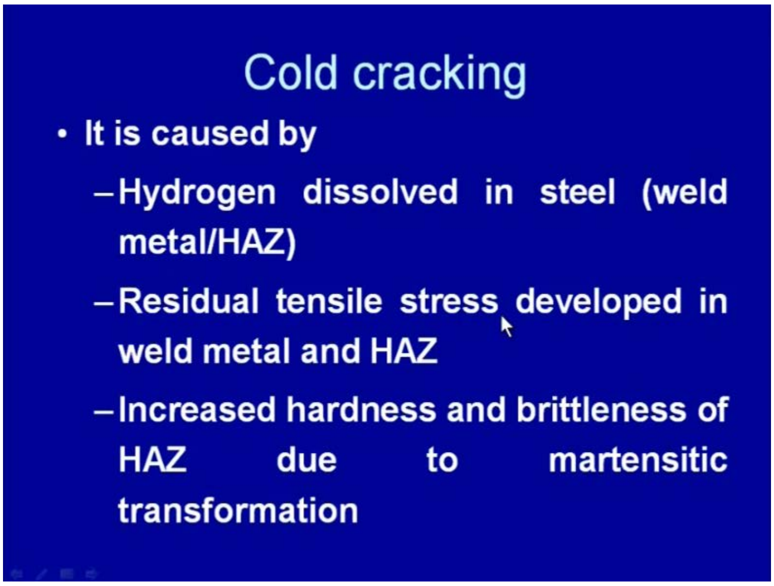

Now, cold cracking since it occurs at very low temperature after completion of the weld when it comes down to the room temperature because of that it is called cold cracking. Since it is mainly caused by the presence of hydrogen that's why it is also called hydrogen induced cracking, and it occurs after sometime of the welding therefore it is called delayed cracking. And main reason for that hydrogen is dissolved in a steel in the weld zone and the heat effected zone. At the same time tensile residual stresses are also developed in the weld zone and the heat effected zone.

The very crack sensitive, the structure like the martensitic transformation leads to the development of the very high hardness and the brittleness. So, these are the three deadly combination factor of the combination of these three factors like development of the tensile residual stresses presence of the hydrogen and the embrittlement due to the martensite crack sensitive structure like martensite. When these three are present the weld tends to weld joint tends to crack from the heat effected zone.

After the welding depending upon the severity of these components like the how much amount of the hydrogen is present? How much residual stresses are there, and how much increase in the hardness and the brittleness is taking place. Due to the martensite transformation that will directly be affecting the cold cracking larger is the amount of the hydrogen more the tensile stresses are being developed and increased embrittlement. If taking place that will be adversely, that will increasing the tendency of the cold cracking.

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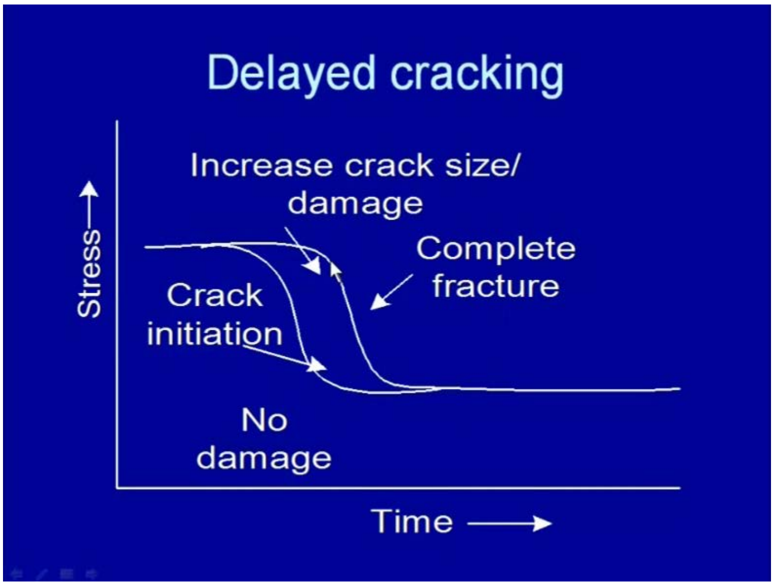

So, here we know that it is delayed cracking because it occurs after some time of the weld. So, depending upon the kind of the stresses, which are tensile residual stresses which are there or externally applied stresses are present. The time required for fracture to take place or this delayed cracking to take place will be governed by the kind of the stresses which are there. So, if we see here these are the typical diagram showing that how the stress or the tensile stresses acting in the weld joint will be affecting the time required for fracture or time required for initiation of the crack by the delayed cracking. We can see the lower areas the stresses higher is the stress lower time it will take to initiate.

So, this is the no damage zone, here the damage is initiated where crack grows gradually and here complete fracture takes place. So, if we can see for a given stress that time required for damage. So, if this is the stress level then this is the time when crack will initiate then it will grow in this period, and then fracture will take place after this much time. So, if further we can see that, if the tensile stresses are below certain level then there would not be the nucleation and growth of the crack by this delayed cracking and if the stresses are above certain level then immediately after the welding, we can see that the cracking has taken place and fracture has taken place.

So, this stress versus the time relationship for development of the delayed crack and the fracture is shown from this diagram. Further if the hydrogen concentration is varying in the weld zone then for the low concentration. It will for a given stress level low hydrogen concentration weld will be surviving for longer period as compared to the medium, and the high hydrogen concentration. So, with the increase in presence of the hydrogen in the weld region under the identical conditions the weld joint will be performing for longer period, and if the hydrogen content is too high at the too high stresses.

It the fracture will be occurring immediately after the development of weld. So, in order to control the cold cracking various approaches are used. We have seen that there are three factors which contribute in big way on the development of cold crack, one is tensile residual stresses, two is the presence of the hydrogen, and three is embrittlement due to the crack sensitive structure like marten site. So, efforts are made in order to avoid the presence of these three factors.

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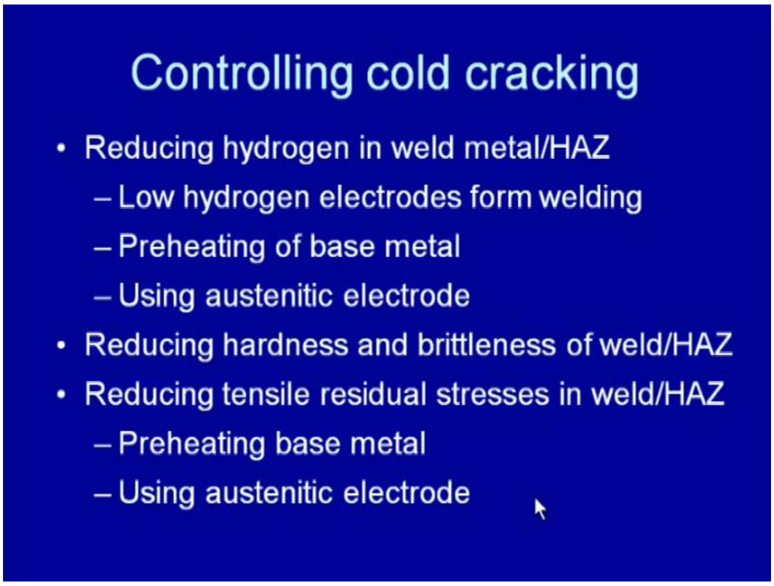

So, the first one like the hydrogen presence is avoided or reduced by using the low hydrogen electrode. So, that the hydrogen concentration presents in the weld zone and the heat effected zone can be reduced. Preheating of the base metal helps in reducing the cooling rate encountered by the weld zone, and the heat effected zone during the welding. Reduced cooling rate decreases the martensite transformation tendency and it forms the soft phases in the larger amount. So, the hardness is reduced and the crack sensitive structure is also avoided, and the use of the low hydrogen. Further preheating also increases the time available for the hydrogen to come out at high temperature.

Because most of the high temperature transformations will be occurring with the increase of the preheat. So, pre heating having the high temperature transformation of the austenite to the softer phases like pearlite and bainite at the same time. It will have the higher means longer period for stay at a higher temperature that will further help in release of the hydrogen dissolved in the heat effected zone and in the weld metal. Then the use of the austenitic electrode, since the austenitic can dissolve large amount of the hydrogen in it. So, the when it is present, and further it is softer also.

So, there it will decreasing the tensile residual stresses and it will be decreasing the amount of hydrogen going towards the heat effected zone, and thereby it will be reducing the cracking tendency. So, reducing the hardness and the brittleness of the heat effected zone is then another approach for this purpose basically the preheating is done, and reducing the tensile stresses in the weld zone, basically heating is done. So, that most of the things cool down means the temperature gradient from the weld zone to the heat effected zone is reduced by preheating, and because of that the tensile residual stresses are reduced and use of the austenitic electrodes.

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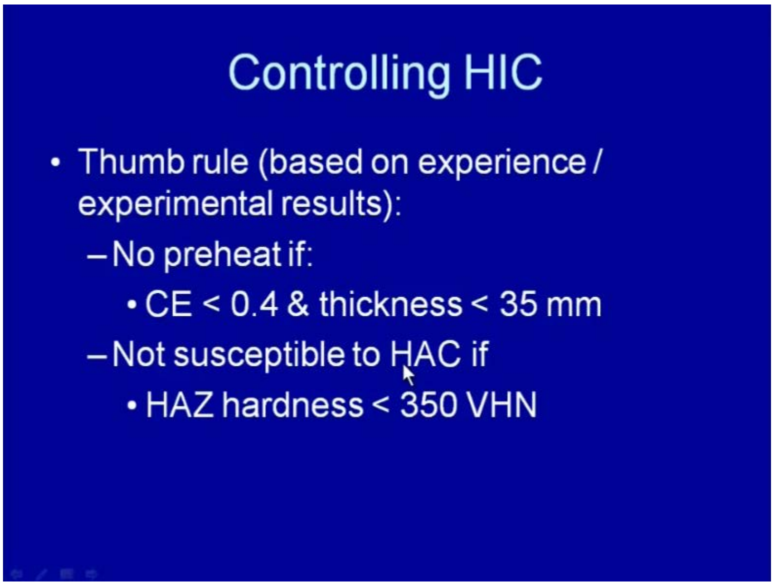

Since the austenitic electrodes are of the lower yield strength as compared to that of the hardened steels. So, when the electrode itself means weld metal, itself is of the lower yield strength that helps to reduce the localization of the tensile stresses in the weld zone and in the heat effected zone. Because when these stresses are setup the weld zone itself undergoes the deformation and thereby helps in reducing the magnitude of the tensile stresses, which are being developed. So, in order to control the HIC.

As a thumb rule no preheating is done to control the HIC up to the carbon equivalent of 0.45 and thickness below 35 mm and the system is not considered to be the hydrogen assisted cracking, if the hardness is below 35 VHN. Now, lamellar tearing is another solid state reaction, which occurs in the heat effected zone.

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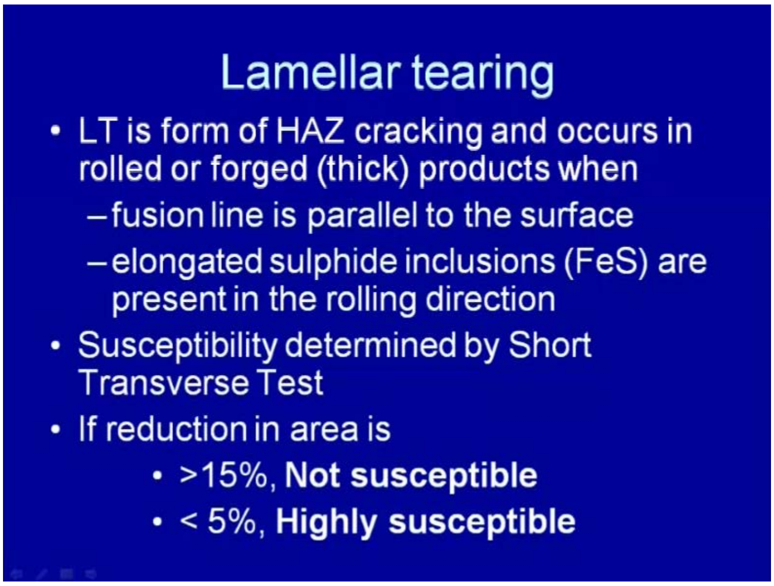

It is form of the HAZ cracking, which occurs in the rolled and forged product especially in the direction parallel to the fusion line along the fusion line parallel to the surface or elongated sulphide inclusions are present in the rolling direction. So, these are the two things, that the HAZ cracking takes place in the rolled or forged products especially. When the fusion line is parallel to the surface or elongated sulphide inclusions are present in the rolling direction. Susceptibility for this kind of cracking is found to be more when the reduction in area that is the ductility short transverse direction or there is a through thickness direction ductility is in terms of the percentage. Reduction in area is greater than 15 then the weld zone is not found susceptible for the lamellar tearing and it is found highly susceptible, when the reduction in area is lesser than the 5 percent.

So, this kind of the cracking is mainly observed in the heat effected zone and it occurs to decohesion of the sulphide inclusions in presence of the tensile stresses. Other aspect related with this we will be taking up in the next presentation. In the next presentation we will also talk about the weldability of the aluminum alloys and that what are the important factors that should be kept in mind while the welding aluminum.

So, thank you for your attention.