Welding Engineering

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Module - 5
Heat Flow in Welding
Lecture - 2
Effect of WTC and Cooling rate in Welding

So, dear students this the second lecture on the heat flow in welding. In this lecture we will be taking up the effect of the weld thermal cycle on the different metal systems, which are commonly used in for variety of engineering applications. Thereafter, we will take up the cooling rate related things during the welding and it is effect on the performance of the weld joint. In the previous lecture based on the heat flow in welding, mainly we have talked about the weld thermal cycle, and you know that the weld thermal cycle shows the variation in temperature of particular location as a function of time. With the change of location weld thermal cycle changes significantly.

The various parameters like the amount of the heat input, the pre heat temperature and thermal characteristics of the metal being welded, effect the weld thermal cycle being experienced by the particular point or particular location of the interest. In general increase in heat input increases, the peak temperature and the soaking time at the high temperature and the pre heat increase in pre heat temperature increases also increases the peak temperature and the soaking time at the high temperature. Because, of the reduced cooling rates and as far as thermal properties are concerned the thermal conductivity and specific heat.

Both these properties are taken care of by the thermal diffusivity. So, increase in the thermal diffusivity of the material increases the rate of the cooling, but the rate of the heating is reduced. This kind of metal systems results in the reduced temperature gradient close to the fusion boundary and which in turn helps in reducing the differential heating and differential expansion and contraction which is experienced, during the welding by the material close to the fusion boundary.

In this lecture, we will be taking up first the weld thermal cycle effect the weld thermal cycle on the different metal system's performance. Then we will be taking up the cooling rate relate issues in the welding. So, stress content is concerned effect of the weld thermal cycle on the properties of the different metal systems, we will also be taking up the need to study the cooling rate related issues during the welding, what are the kind of metals? What are the metal systems that are very sensitive to the cooling rate experienced by the metal during the welding? The significance of the cooling rate in the welding, cooling rate equations, which are commonly used for determining the cooling rate with the thin and thick plate thick plates.

Then we will be looking into the parameters, which can be used to categorize the plates as a thin or thick plates two parameters. Basically, one is the number of passes they are, two criteria's which are used normally to categorize the plates as a thick or thin plate. These are a mainly based on the number of passes required a to complete the joint, the another parameter is based on the relative plate thickness, which considers the thermal properties the thickness of the plate, the heat input being given to the plate during the welding. So, the relative plate thickness criteria is considered a as a more rational and appropriate for classifying the plate as a thin and thick plate. Further, I will be seeing that.

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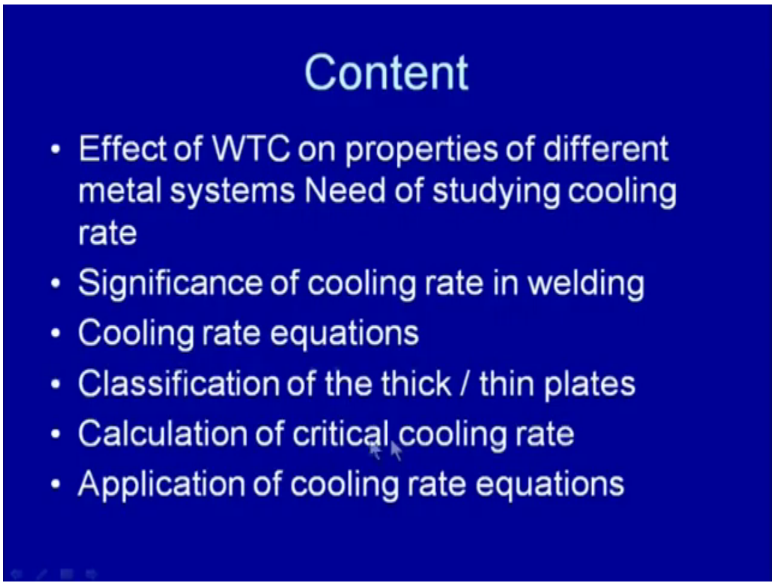

How to determine experimentally the critical cooling rate using the cooling rate equations? What are the applications of the cooling rate equations that also will be taking up? We know that the cooling rate equations are mainly used for determining the pre heat temperature, so that the critical cooling rate can be avoided, these equations can also be used to determine the critical cooling rate.

So, starting with the effect of the weld thermal cycle on the metal systems, we know that for the engineering purposes, we use variety of metal systems which are strengthened using the different mechanisms like in steels. Steels can be strengthened by the solid solution strengthening, dispersion hardening, work hardening, precipitation hardening, transformation hardening and the grain refinement.

So, depending upon the approach which is being used the effect of the weld thermal cycle will vary accordingly, like other metal systems aluminum which can also be strengthened by the solid solution strengthening or the dispersion hardening or other mechanisms which are listed here.

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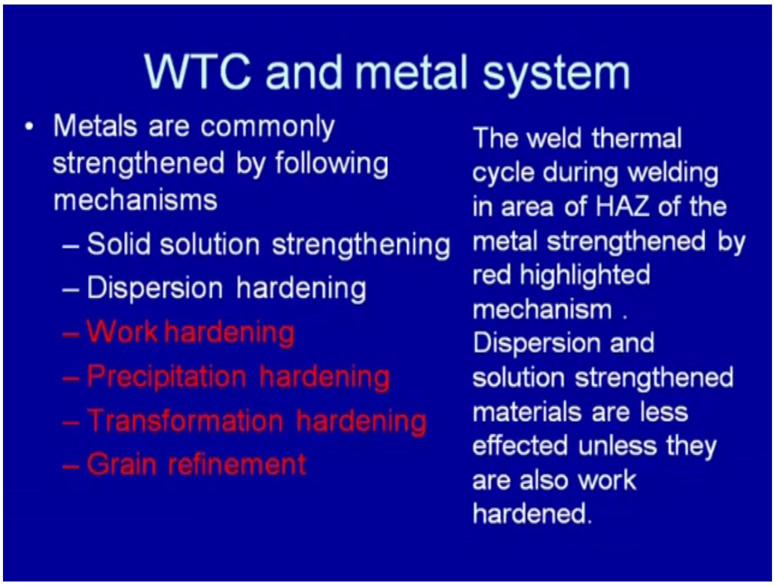

So, depending upon the kind of metals strengthening mechanism, which is being used in a particular metal system the weld thermal cycle effect is a governed by the strengthening mechanism. So, if we see here out of these mechanisms, the red highlighted mechanisms like work hardening, precipitation hardening and the transformation hardening and the grain refinement mechanism. The metal systems which are strengthened by these four mechanisms are affected most by the weld thermal cycle, because when the heat is applied during the welding the work hardening effect is lost the precipitates start getting coarsened and the strengthening effect is lost or reduced in the transformation hardening. The undesirable transformations take place during due to the application of the heat during the welding.

So, those can adversely affect the mechanical properties and metallurgical properties of the metal systems strengthened by the transformation hardening. For example, the steel hardened and quenched by a hardened and quenched through the modesetic transformation it offers the desired strength and the hardness, but when heat is applied during the welding, the over tempering a of the steel can lead to the reduction in the hardness and the strength of the steel. So, the change in properties of the transformation hardened a component can also take place due to the weld thermal cycle and the grain refinement mechanism.

This is very commonly used mechanism used in variety of metal systems like all a means entire range of the metal systems like ferrous and non ferrous metals. When the is heat is applied during the welding, normally a the coarsening of the grains especially in the heat effected zone takes place, because of that coarsing the strengthening effect is lost so the metal systems, which are strengthened by this four highlighted mechanisms. They are adversely effected by the heat of the weld thermal cycle or the heat which is applied has been applied during the welding. While, the metal systems, which are strengthened by the solid solution strengthening and the dispersion hardening, they are least affected by the weld thermal cycle experienced by the metal during the welding.

So, this is what has been a mentioned here dispersion and solution strengthened materials are less affected unless they are work hardened. So, if the material has been strengthened by the solid solution strengthening and dispersion hardening the affect of the weld thermal cycle will be minimum, the only effect which has been offered by the work hardening a to these metals if they have been work hardened by the mechanical working. Then only that affect will be lost by the weld thermal cycle. So, the effect means this slide mainly shows that how weld thermal cycle can affect the different metal systems which are strengthened by the different mechanisms.

We know that, when exposure is given to the metal system to the high temperature the different zones are subjected to the different range of the temperatures. So, this is what we have explained in the last lecture we will again, I will try to remind this with the help of this diagram.

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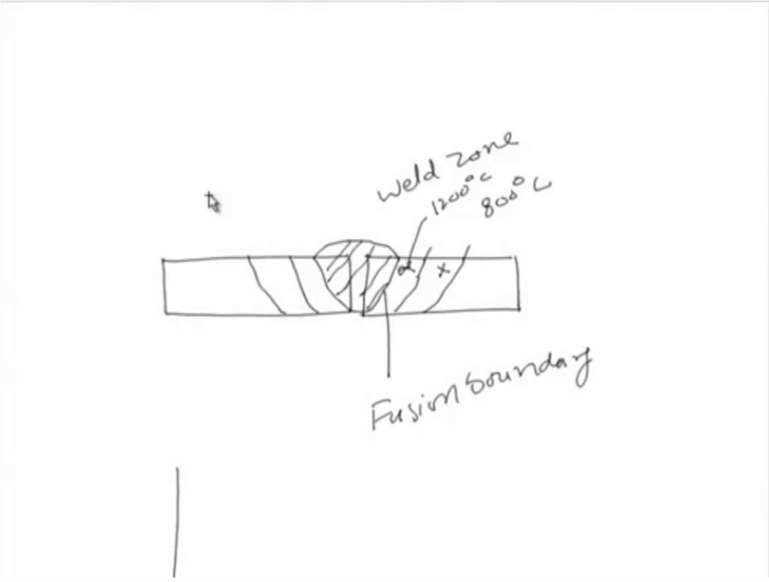

That when the two plates are being welded using the arc. So, heat of the arc will be a causing the melting of the faying surfaces and will be helping to develop the weld joint like this. So, this hedged area this is the weld zone and will have the temperature in this area will be greater than the melting point, but the other areas which are closer to the weld region will be subjected to the different temperature zones on approaching close to the a weld fusion boundary. That is this fusion boundary, if we on approaching a close to the fusion boundary the temperature will keep on increasing.

So, if we take this region say the temperature will be of say 800 degree centigrade, if we take this region temperature will be of say 1200 degree centigrade so closer. So, the area closure to the fusion boundary higher will be the temperature and if we see the weld thermal cycle corresponding to these two locations say location a and location b.

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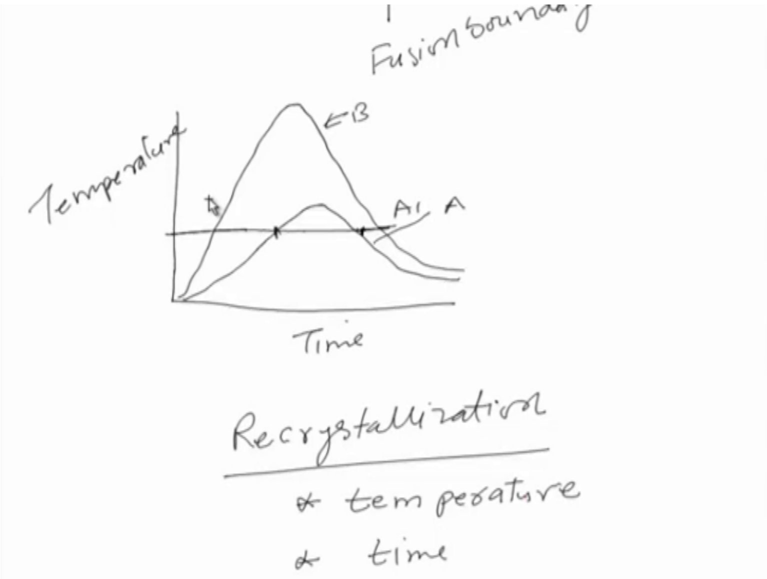

Then the weld thermal cycle corresponding to the location b will be like this which is closure to the fusion boundary and that of the location which is away from the fusion boundary will be experiencing lesser temperature. So, if this is the critical temperature so the soaking time and the temperature. If we see the exposure above the critical temperature that is say A1 will be for shorter period for location a.

In case of the location b, this will be subjected to the too high temperature and for longer duration above the lower critical temperature. Here in x axis, we have temperature and here we have time. So, on heating above this lower critical temperature there will be change in the grain structure of the material. So, that we say as so the temperature above which the new grains are formed is termed as the recrystalization temperature.

So, the recrystalization the formation of the new grains, due to the thermal exposure being given to a particular location results in the recrystalization. So, the formation of the new grains take place in the recrystalization, the time and temperature are the two important parameters that effect the recrystalization process. Because, it is a diffusion based a mechanism, so the temperature and the time are the two important phenomenon parameters related with the recrystalization.

The two important things are here related with the recrystalization, one that the formation of the new grains and the second is the coarsing of the grains which are being formed. So, if the temperature e exposure is there for longer duration, then coarsing will be taking place or if the time is same. The temperature is exposure is occurring at a higher temperature or the exposure is being done at higher temperature, then also grain coarsing will be taking place. So, increase in both temperature of the exposure and the time of the exposure increase the grain size in the region, which is being subjected to the exposure of the heat above the recrystalization temperature.

Normally, the temperature about 0.5 to 0.6 times of the melting point of the metal system at which the newer grains start a form. If we a use the higher temperature for longer duration then the significant coarsing of the newer grains which are being formed will be taking place. So, if we see this aspect the regions which are closure to the fusion boundary they will be subjected to the higher temperature for longer duration. While, the regions which are away from the fusion boundary they will be subjected to the lower temperature as well as for shorter a period.

So, because of this difference in the weld thermal cycle being experienced by the metal system at different locations the difference in the grain size is observed. So, what this is what we say that due to the thermal exposure the recrystalization in the region close to the fusion boundary take place. Because, of this new grains are formed and mostly these grains are formed at a temperature around 40 to 50 percent of their melting point in the degree Kelvin.

So, that is 0.4 to the 0.5 times of the melting point of the metal in degree Kelvin, this temperature is affected by the purity of the metal and the work hardening condition. If the material is work hardened to the greater extent then recrystalization will be occurring faster and at the lower temperatures. So, this table simply shows the recrystalization temperatures for the different metal systems. and the respective the melting point.

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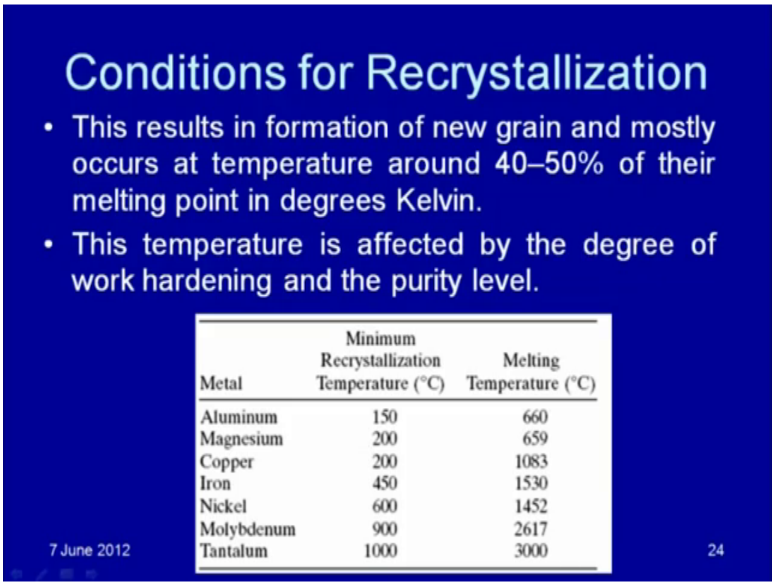

Metal	Minimum Recrystallization Temperature (°C)	Melting Temperature (°C)
Aluminum	150	660
Magnesium	200	659
Copper	200	1083
Iron	450	1530
Nickel	600	1452
Molybdenum	900	2617
Tantalum	1000	3000

So, if we see here aluminum has the recrystalization temperature 150 degree centigrade, while the melting point is 660 degree centigrade. Similarly, the melting recrystalization temperature the only crystallization temperature for the different metal systems has been given here for iron this is 450 degree centigrade and the melting point is a 1530 degree centigrade.

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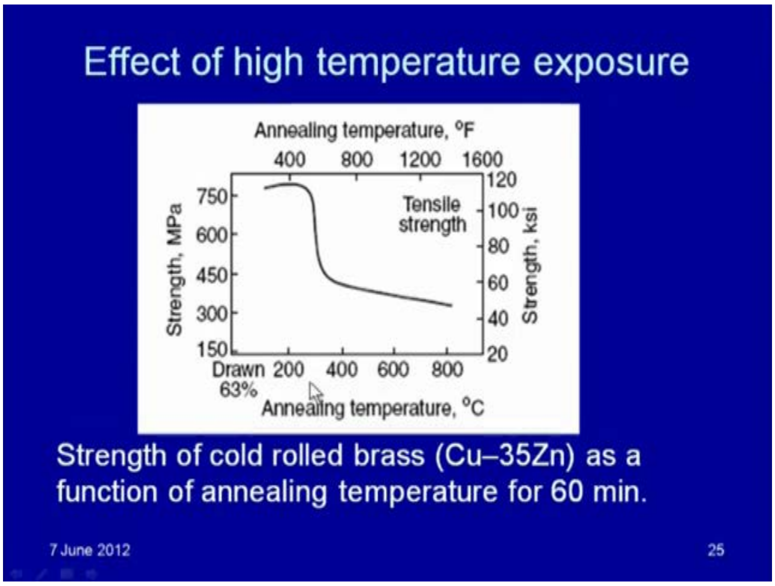

So, depending upon the metal system the different the temperatures are required for the recrystalization. If we see here if we give an exposure to the metal system at the different temperatures and for the different durations, then it be adversely effecting to the mechanical performance of the metal inquisition. Say for example, if we have the cold rolled brass with copper and 35 percent zinc then how it is strength is effected by the annealing temperature if the exposure is given for the sixty minute duration?

So, we can see here when the material is in the cold walk condition is it is strength is very good of around 750 MPa and with the increase in the annealing temperature or the increase in temperature of the exposure. We can see there the sharp drop in the strength of the metal and this sharp drop strength of the metal mainly attributed to the formation of the newer grains of the larger in size. So, grain ((refer time 16:52)) is mainly attributed to this deterioration in the strength of the metal system.

So, once the new grains are formed if the longer exposure is given at higher temperature to the grains then this will lead to the grain growth. So, upon completion of the recrystalization new means the grains begin to grow, so once the recrystalization is over, the grain growth starts and the extent of the grain growth increases with the increase of the temperature and time of exposure. So, if we increase both time of exposure or the temperature at which exposure is being given under the identical conditions, there will be a higher grain growth.

So, if we see here are the identical temperature conditions, if we increase the growth means exposure time then the how the growth in the grain size takes place? So, this is in the increasing order of the exposure time this simply shows that with the increase of the exposure time there will be a significant increase in the grain growth. This is the another diagram which is further showing the effect of the duration when the exposure is given at the different temperatures.

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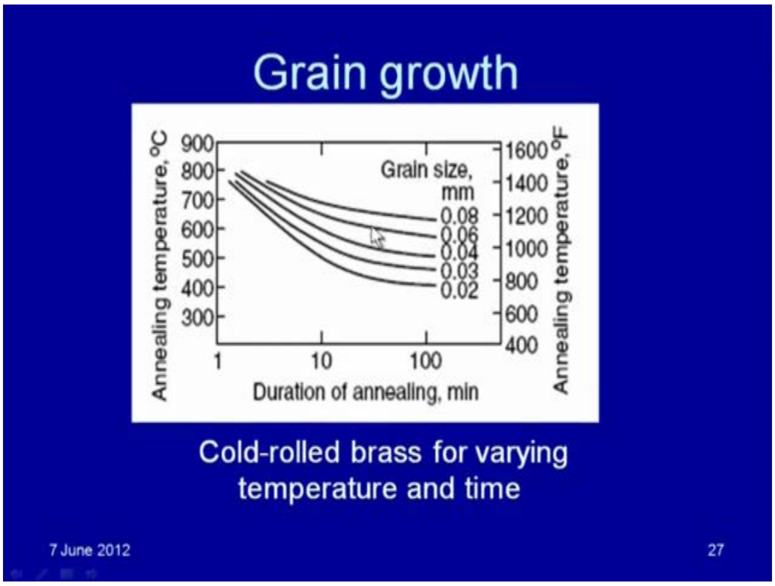

So, we know that if the both exposure temperature and the time significantly affect the grain size. So, if we take up again the case of the cold rolled brass for varying temperature and durations, then simply reduction in the exposure temperature helps in a decreasing for identical time helps in decreasing the grain size or for the given a exposure temperature, increase in the duration increases the grain size. So, these different lines are corresponding to the different grain sizes.

So, we can see that for a given duration of the 10 minutes if we increase the temperature from say 500 degree centigrade to the 800 degree centigrade, then there will be increase in the grain size from 0.02 millimeter to the 0.08 millimeter, that is the average a grain size. So, this diagram indicates that for a given temperature increase in the duration increases the grain size or for given duration of the exposure increase in annealing temperature or the exposure temperature increases the grain size. So, this grain size variation significantly dictates the mechanical performance of the metal system especially close to the fusion boundary that is the heat affected zone.

So, as far as the effect of the weld thermal cycle is concerned, the work hardening effect after the exposure of the material to the heat, due to the weld thermal cycle work hardening effect is completely eliminated from the fusion zone, because of the melting. This work hardening effect is partially lost from the heat effected zone, because the new grains are formed means the recrystalization takes place, the grain growth occurs in the heat effected zone. So, these strength losses must be taken into account when considering the weld joint for the structural designs or the joint is to be made using the welding. Then these strength losses must be considered in a structural design.

We know that further the fracture toughness of the heat affected zone which is close to the fusion boundary, having the coarse grains offers the poor fracture toughness as compared to the base material. So, the fracture toughness is usually found poor with the coarse grains in the heat effected zone and if also the coarse grains are formed in the fusion zone. Just an example, if we see here this diagram with the exposure of the weld thermal cycle or the heat during the welding, how the grain size is affected for the orsanatic steel AISI 304.

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So, if we can see here the base metal having very finer grained structure and as we come closer to the fusion boundary, the coarsening of the grains take place. This is the fusion boundary and beyond this we have the ((refer time 21:39)) grain structure, where significant grain growth a can be observed. These grain coarsening a deteriorates the strength as well as hardness of the work hardened material means the metal system, which has been work hardened by the mechanical working like a using operations like rolling forging etcetera. The strength important by the strain hardening effect is lost or the reduced by with the application of the heat or the weld thermal cycle, which is experienced by the metal during the welding in specially the heat effected zone.

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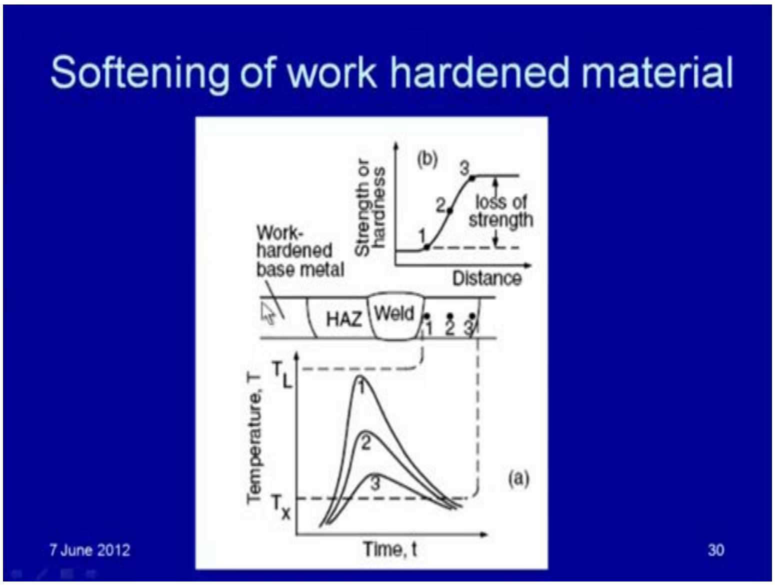

So, if the work hardened material system say having this base material the weld is made will be having a the weld joint this centre and the heat effected zone close to this. So, if we consider the two or three points close to the weld fusion boundary the one is closest to the weld, two slightly away and the three farthest away from the weld. If we look into the weld thermal cycle corresponding to these three locations the point a or point one will have the highest peak temperature and will have the longer and it will be very close to the fusion boundary. So, point one will have a it is since it is very close to the fusion boundary, so the temperature will be close to the melting point.

Also, if it considers the point second the significantly lower peak temperature is observed and the temperature exposure at high temperature is also for the shorter duration. Further, point three is at further lower the peak temperature is further lower and the exposure duration is also shorter. So, the steepness of these slopes of slope during the heating stage and the cooling stage of the weld thermal cycles is also higher, for the point one and these are lower for the point two and point three. So, which are indicating that the point one will be subject to the higher heating rate and then the point two and point three and at the same will be subjected to the higher cooling rate a as compared to the other two points that is two and three.

If the temperature Tx is the decreased ((refer time 23:59)) in temperature at which the grains are newer grains are formed, then the point three will be subjected to the minimum change in a for the lower temperature of the exposure for shorter duration. While, the point three will be subjected to the higher the temperature exposure for longer duration and point one will be subjected to the highest temperature and for the longest period of the exposure, above this critical temperature or the this a specific temperature above which recrystalization take place.

So, considering this the point one will be subjected to the highest the temperature exposure for longest duration. While, point three will be subjected to the minimum temperature means the lower temperature and for the shorter period as compared to the point two and point three . Accordingly, the maximum grain coarsening will be occurring at point one and the minimum will be occurring here in this case at the point three in the in the region, which is being affected by the heat and accordingly the loss in strength will be maximum in case of the location one. Then somewhat the lesser loss in case of the point two and the loss will be minimum in case of the point three.

This will have a strength almost same as to that of the base material, so this is how we can say the work hardening strength of the work hardened material is significantly affected by the weld thermal cycle, and it decreases in especially in the regions close to the fusion boundary. So, just to describe the effect of weld thermal cycle recrystalization, during the welding usually occurs at high temperature due to the higher heating rate. Meaning of this, if the temperature of the recrystalization temperature for iron is at 450, but during the welding since the cooling a heating rate is very high. Then this recrystalization temperature will not exactly be a starting at 450, but it will occur at the higher temperature, because it is the diffusion based phenomena, which requires the time and temperature.

So, just at 450 when the things are heated at high rate recrystalization will not be occurring. So, under the high heating rate conditions, which are experienced during the welding recrystalization usually occur at the higher temperature, but not exactly at the temperature at which recrystalization can take place under the equilibrium heating conditions and the strength of the work hardened material, a decreases with the increase of the annealing temperature and the time. Therefore, strength of the hardness of the HAZ decreases as we approach towards the fusion boundary.

Further, harder the metal system and will be experiencing hard metal systems experience greater loss in strength than the soft one, as far as work hardening wok hardened metal systems are concerned. If we do more work hardening to strengthen the metal system, then they will be experiencing greater loss after the welding. So, now we will see the heat how the grain growth occurs in the heat affected zone? The region closer to the fusion boundary subjected to the higher peak temperature for longer duration, because of this like the point one being subjected to the higher temperature and for longer duration, then it will be having the maximum grain size and as we move away from the fusion boundary. That is point two will be subjected to somewhat lower peak temperature for shorter duration, then it will be experiencing somewhat smaller grain.

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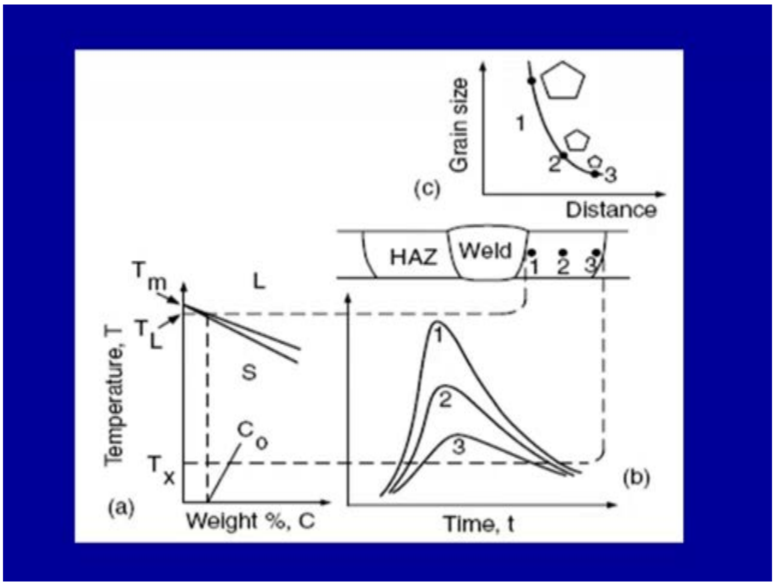

If we talk of the point three it will be having then it experiences the weld thermal cycle, which is having peak temperature for the lower value. The exposure duration is also shorter and that is why it results in the finest grain structure as far as the grain size in the heat affected zone is concerned. So, this is what we say that since the point one subjected to the higher temperature for longer duration that is why the grain size is found maximum in the region close to the fusion boundary

So, this in turn causes the grain growth and the coarsening increases in the heat effected zone, on approaching from a on approaching to the fusion boundary, so on approaching from base material side to the fusion boundary side. Then continuous growth in the grain size is observed, because of the difference in the peak temperature and the duration of exposure at the higher temperature.

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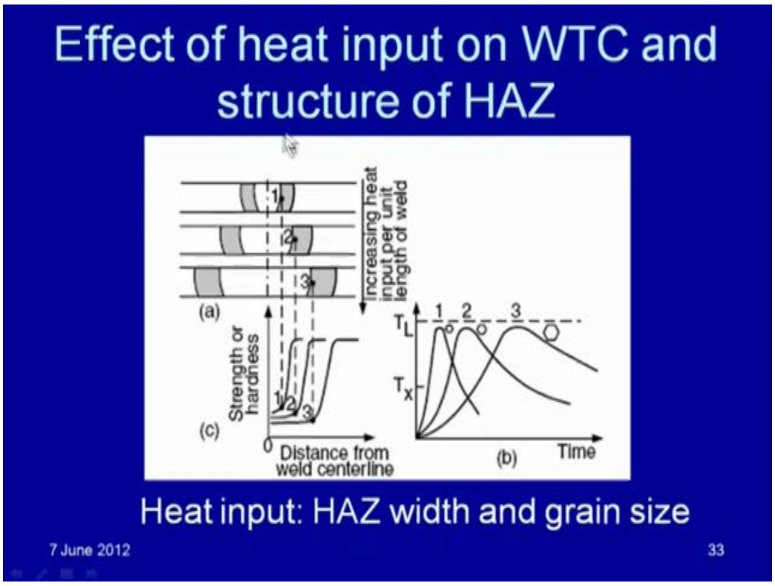

Now, this diagram shows the effect of the heat input on the weld thermal cycle and the structure of the heat effected zone. How the heat affected zone is affected? if we consider the first diagram the top one, this shows that the heat input is minimum and this is the somewhat higher heat input and the maximum heat input. So, these three diagrams are in the increasing order of the heat input if we say the weld joint made using the minimum heat input will have the smaller weld zone.

The narrow heat effected zone that is shown by the shaded area and corresponding to the zone means the weld one. It will have the sharper weld thermal cycle and the finer grain size if we talk of the second weld made using somewhat more amount of the heat input higher amount of the heat input. It will have the wider means the larger weld zone size and the wider heat effected zone and corresponding the weld thermal cycle will have the somewhat slower the heating rate. The slower cooling rate, but the exposure duration is more due to the longer duration of exposure grain size is somewhat larger.

Then in third, the weld thermal cycle corresponding to the a point close to the fusion boundary, which has this joint, which has been joint three, which has been developed using further higher heat input. The weld zone is the larger further larger size and the heat effected zone is also a the wider, this a if we consider this case for as far as the grain size weld thermal cycle is concerned, we can see that exposure to a particular temperature will be there for longer duration with the higher heat input.

The grain size will also be the larger that is what has been shown. So, if we see here the how the strength and the hardness is effected of the heat affected zone strength and hardness of the heat affected zone is affected, with the variation in the heat input being given. So, the corresponding to the weld one, which has been developed using the minimum heat input will have the somewhat the lesser a reduction in the strength. The width of the heat affected zone, which is being affected by the strength loss, will also be shallow or it will be narrow.

If we talk of joint two, which is being made, which has been made using somewhat higher heat input, the strength loss will be up to the greater distance from the fusion boundary or from the weld center and the distance up which is effected by the strength loss, due to the excessive heat input in case three, this distance increases further from the weld center. So, if we see increasing the heat input increases, the weld zone size increases, the width of heat effected zone increases, the distance up to which strength loss takes place increases, the strength loss which will be occurring in the heat effected zone and it will be in increasing the soaking period, above the recrystalization temperature or particular temperature.

Further, it will be increasing the grain size, because of these changes in the metallurgical properties of the material in the heat affected zone. The mechanical properties of the weld joint are very adversely affected with the increase of heat input. In general, the larger the grain size and the poor the mechanical properties, simply increase in the grain size, decreases the strength of the material that is ultimate strength and the ((Refer Time 33:07)) strength both it decreases the ductility. It also decreases the hardness and the toughness of the material resistance to fracture is also adversely affected by the increase in the grain size.

So, it is not desirable to have the larger grains, especially the heat affected zone. Because, the properties of the heat affected zone are very adversely effected by the application of the higher amount of the heat. That is why; efforts are always made to reduce the heat input, so that the adverse effect of the heat input on the properties of the HAZ can be reduced.

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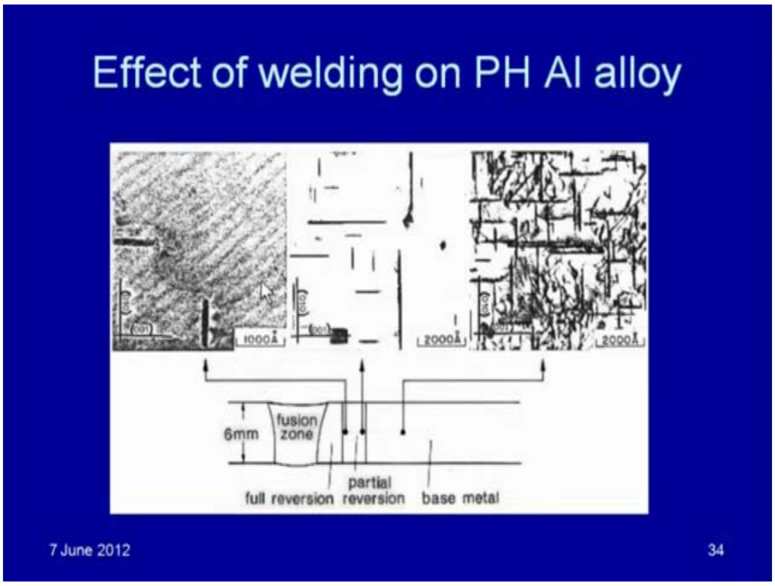

Now, if we consider so far we have talked about the work hardened metal systems, where the effect of the work hardening is reduced with the application of the heat. If we consider the case of the precipitation harden able aluminum alloys like a the aluminum alloys of the 2000 series, which are aluminum copper based systems or a aluminum or the 6000 series, which is aluminum zinc aluminum magnesium silicon system or the 7000 series, which is aluminum zinc magnesium based system. In all these three series of the aluminum alloys the strength is important by the development of the fine precipitates strengthening precipitates and these strengthening precipitates are adversely affected by the application of heat during the welding.

In the base metal these precipitates of very of the disc shape of very small sizes and thicknesses when these are present and uniformly distributed in the metal system, very good strength is obtained, but when the exposure of the heat is given during the welding. Especially, in the region close to the fusion boundary in the heat affected zone these precipitates are dissolved and these and these get mixed with the matrix material that is aluminum and forms the solid solution, so precipitation effect is lost. Solid solution strengthening is offered, but we a so if we see this diagrams corresponding to location, this in base metal then a the closer to the fusion boundary and very close to the fusion boundary.

So, if we see here lot of precipitates are present in the base material, offering the desired strength to the base material, when we move closer to the fusion boundary the number and size of these precipitates reduced, this in turn decreases the strength of the metal system. So, this the de solution of this precipitates a is called the reversion effect.

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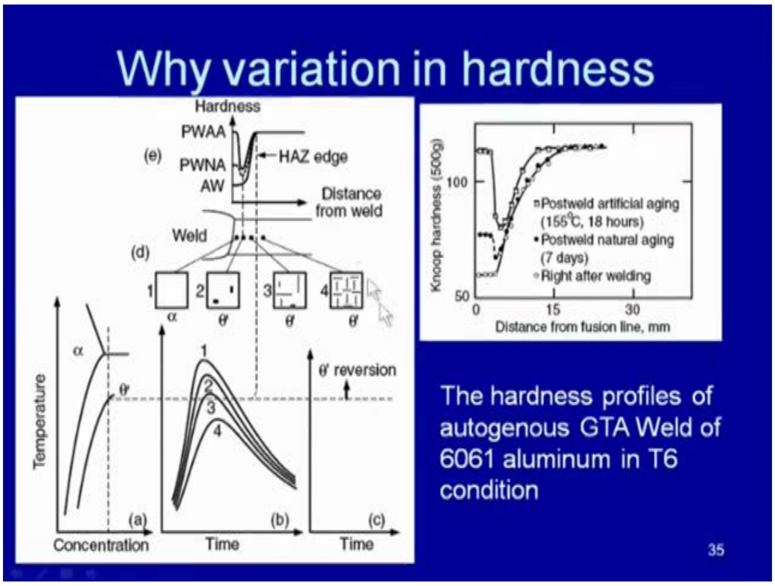

Here we have a partial reversion and as we move further closer to the fusion boundary that is this point, then we can see that only very few precipitates are left in the matrix and most of the precipitates have dissolved. So, we can say that full reversion or almost full reversion has taken place in the region very close to the fusion boundary. So, we know that since these precipitations harden able alloy systems are strengthened by the precipitates, if these get dissolved by the application of the heat. Due to the weld thermal cycle experienced by this metal systems during the welding, then there will be loss in strength of the metal in the heat effected zone.

So, this is a about the main ah adverse effect of the weld thermal cycle on the precipitation harden able metal system. If we have to see that how the strength is adversely affected and the hardness is affected by the weld thermal cycle of these systems. So, the region say this is the weld and this is the base material they are four different locations in the location, we have the number of theta ((refer time 37:20)) phases and these when these are present in large number we get very good strength in the base material, that is just close to the heat effected zone. So, a presence of large number of precipitates offers the good strength, but on approaching closer to the a fusion boundary that is the location three, we can see the fewer percentage of this precipitates there will be reduction in strength.

Further, on approaching towards the fusion boundary further reduction and minimum hardness is obtained here in very close to the fusion boundary. This is a mainly attributed to the reversion or the de solution of the precipitates, which is a taking place close to the a fusion boundary. So, this reduction in the hardness of the metal in the heat effected zone is mainly attributed to this reversion effect and this is termed as softening of the metal systems. So, a we have to regain these this lost hardness and strength due to the reversion effect then the weld joints are normally given the precipitation hardening treatment once again, which will be involving the solutionizing to dissolve all this precipitates first.

Thereafter rapid quenching to have the super saturated solid solution of the metal in the heat affected zone. Finally, the artificial easing or the natural easing effect is done to have the development of these precipitates, so that the initial strength and the hardness can be important to the various zones of the weld joint to have the uniformity in the properties. So these diagram simply shows the variation in the hardness profiles for the metal systems, which a weld joint say 6061 metal system in the T6 condition will reducing the GTAW process for the autogenously weld is made.

Now, we will be looking into the another important aspect of the heat flow in the welding that is the cooling rate. We know that that during the welding when we apply heat initially, the heat application increases the temperature rises to the peak value in weld region, it increases it goes above the fusion temperature or the melting point. While, in the heat effected zone it becomes closer to the fusion a temperature or the melting point. Thereafter, a reaching to the peak temperature the heat is extracted continuously by the low temperature base material cooling starts.

So, depending upon the way by which the rate at, which heat is extracted the different zones of the weld joint like the weld metal and the heat effected zone will be experiencing the different cooling rates and based on the kind of cooling rate which is being experienced by them a during the welding different metallurgical reactions occur.

So, it is important to see that what kind of cooling rates are experienced by the metal in the weld region and in the heat effected zone.

Cooling rate during the welding is important, especially in case of the hardenable steels, because these result in the huge difference in the kind of phases, which are formed due to the difference in the cooling rate. So, the metal system the steels harden able steels which are subjected to the different cooling rates will be having the different phases. Accordingly, lot of difference in the mechanical properties is found, while in case of the aluminum alloys this cooling rate does not affect the properties of the heat affected zone appreciably, but the cooling rate being experienced by the weld metal.

The heat affected zone significantly affects the weld soundness of the weld and the properties of the heat affected zone. Especially, in case of the harden able steels and the ferrous metal ferrous metal systems. So, as far as the effect of the cooling rate on the soundness of the weld joint is concerned, mainly we need to see that the how cooling rate will be affecting to the time required for the solidification. In general, if the cooling rate is high then the time required for the solidification will be less for a typical weld the solidification time may vary from say 0.5 second to the 2 to 3 second, depending upon the size of the weld metal or it can be further larger in processes like the electro slag welding and the submerged arc welding, which are the high heat input process.

So, for the process like GTAW the solidification time may be as low as less than one second, while it can be significantly more in case of the high T heat input processes. So, depending upon the time available for the solidification to take place the time available for escaping the gases from the weld zone and a will be affected like if we have longer solidification time. Then the more time will be available for the gases, which are dissolved with the molten metal and the inclusions to come out of the weld metal in order to sound weld joint.

So, in the in the welding processes, where solidification time is very less, so the these inclusions and the gases will have more tendency to get interrupt in the weld metal and lead to which can lead to the development of the unsound weld joint where lot of porosity and inclusions can be present in the weld metal. So, the cooling rate can affect the soundness of the weld joint in the way it effects the time required for solidification, which in turn can affect the time available for this impurities to come up of the molten metal and to develop the sound weld joint.

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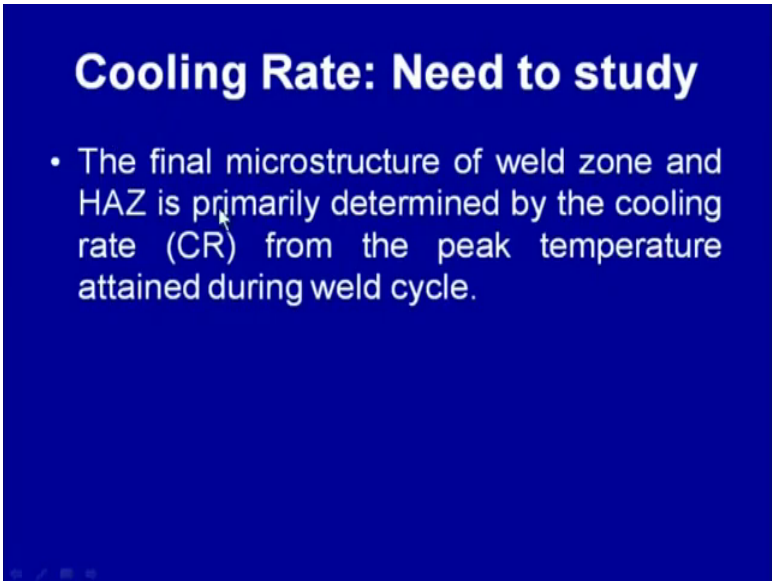

So, if we see here the final structure of the weld zone and the heat effected zone in the weld joints is primarily determined by the cooling rate, which is being experienced by them from the peak temperature during the welding, so if we have to see this we can see this in the next diagram.

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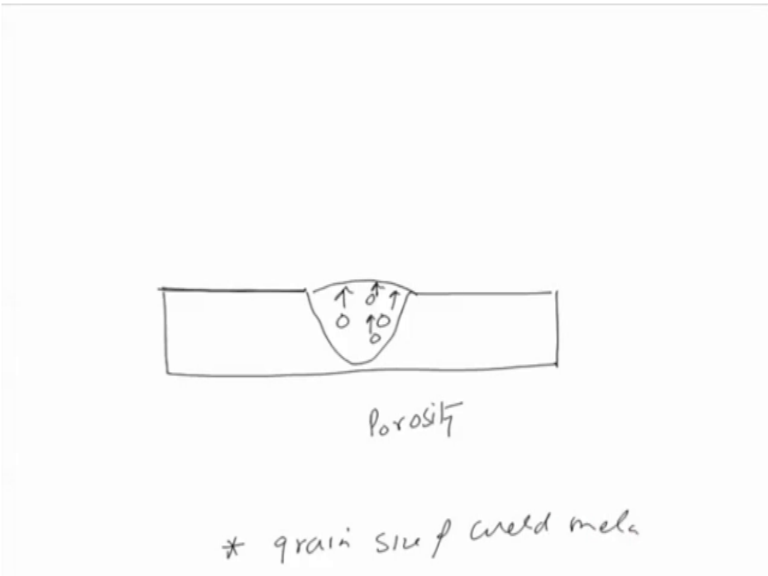

If we have this weld and here we have the gas packets in the dissolved state if the solidification of the weld metal is occurring fast, then this gases will not be able to come out of the molten weld region. So, this will be interrupt and will result in the porosity. Similarly, this can be inclusions, which can be formed due to the interaction between the different elements present in the weld metal or a reaction between the gases present in the arc environment and the metal in the molten state.

So, these inclusions and impurities and the gases should have enough time to come up of the molten metal. So that a they can a get automatically removed another important aspect apart from the soundness is that a the grain size of the weld metal the grain size of the weld metal is directly affected by the cooling rate being experienced by the weld metal. So, the finer is the grain size, fine grain size is obtained, if the weld metal experiences the higher cooling rate in the welding processes, like the tungsten inert gas plasma arc or the laser beam processes laser beam welding processes, where the heat input is very less the weld metal experiences the high cooling rate and in general fine grain structure is obtained.

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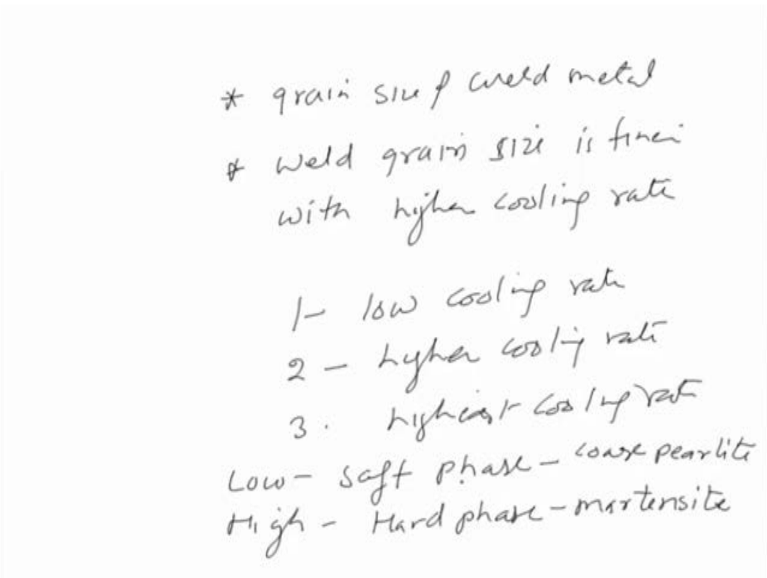

So, the weld metal having the finer grain structure will be offering the better mechanical properties, so this is one that the weld the grain size of the weld metal is affected and the weld grain size is finer with higher cooling rate. Another important aspect is that, say the region which is a being affected by the heat called heat affected zone, say that is this region having the different zones subjected to the different peak temperatures. All zones say zone one, two, three will be experiencing the different cooling rates. So, the zone one farthest away say in the heat affected zone from the fusion boundary, so zone one is subjected to the low cooling rate, because it is located away from the fusion boundary somewhat zone two will be subjected to the higher cooling rate and zone three will be subjected to the highest cooling rate.

So, in case of the hardanable steels, especially this cooling rate is very crucial, because it directly dictates the kind of phases which will be formed. So, at a the low cooling rate in general results in soft phases, while the high cooling rate results in the hard and brittle phases, soft phases like coarse pear lite. While, hard phases are formed due to the high cooling rate liken marten site so formation of the hard and brittle marten site in the region very close to the fusion boundary like in location three will be leading to the imbrittlement of the weld zone. So, while if the zone one where cooling rate is low can have the soft phases like coarse pear lite.

So, this difference in the kind of phases which are formed results in the significant variation in the properties of the heat affected zone. This property variation is especially encountered in case of the hardanable steels, so to have the uniformity in the properties as well as to avoid the development of the excessive hard and brittle martens tic structure in the heat affected zone. It is necessary that the cooling rate in the heat affected zone is controlled properly, so how can we control? What are the conditions which can help in controlling? The heat input properly that will be looking into the detail. We need to see that what heat input we should give during the welding or for given heat input.

What pre heat temperature is to be used so that the formation of the hard and brittle martens tic structure can be avoided in the weld joint? So, how to calculate the cooling rate during the welding? What are the equations, which are normally used for calculating the cooling rates in case of thick and thin plates? How we can distinguish between the thick and thick plates? What are the various applications of the cooling rate equations? That a will be taking up in the next lecture. So, now I will summarize this presentation, in this presentation mainly we have seen the effect of the weld thermal cycle on the different the properties of the different metals systems like the work hardened, the precipitation hardanable metal systems. We have also seen the importance of the cooling rate in the welding and will see in detail in the coming lectures about the methods, which are used to calculate a the cooling rate and the application of the cooling rate equations for developing the sound weld joint.

Thank you for your attention.