Joining Technologies of Commercial Importance
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Lecture - 29
Heat Affected Zone and Weld Thermal Cycle: I

Hello, I welcome you all in this presentation related with the joining technologies for the metals and this specific presentation is related with the heat affected zone and weld thermal cycle. How these two can be related and how the heat affected zone characteristics are affected in case of the different metal systems.

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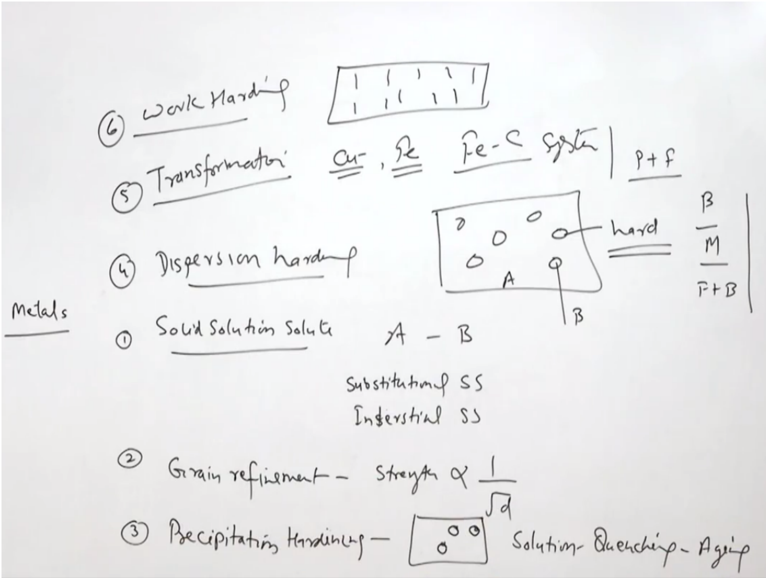

So we know that the different metal systems are strengthened using the different mechanisms and these includes solid solution strengthening where like in metal A solute B is incorporated so that the strength is achieved and the various types of solid solutions like substitutional and interstitial type of solid solutions are formed. Interstitial solid solution results in much higher strength with the addition of the solute as compared to the substitutional solid solution.

Then another mechanism this is the commonly used one like say the grain refinement. The metal systems are also strengthened by the grain refinement and here the strength, the hardness is found inversely proportional to the square root of the grain size, finer the grain higher is the strength. So whatever the factors that will be increasing the grain size either in the weld or in the heat affected zone.

They will be lowering down the hardness as well as yield strength. Third is say precipitation hardening. In this mechanism, whatever alloying elements are there, they are dissolved in the solute through the solution treatment followed by quenching so that supersaturated solid solution is formed and then aging is undertaken. During the aging, the precipitates are formed here and there.

And they impart the strength or strengthen the material by forming the precipitates in the metrics of the metal. So whatever the factors, they will either lead to the enrichment or increase in number of the precipitates, they will be strengthening the material otherwise whatever the factors they will be either causing the coarsening of the precipitates or their dissolution.

There are two aspects, either the precipitates will get be dissolved in the metrics or they will get coarsened. So both these factors due to the application of the heat will be lowering down the strength. Because these metals systems get strength from the precipitates and whenever due to the external factors like application of the heat if the precipitates either get coarsened or get dissolved then the metal gets weakened.

Then the fourth mechanism is the dispersion hardening. In case of the dispersion hardened metals, the metrics is incorporated with the certain constituents, which do not interact with the metrics itself. These are mostly hard, but they can be soft also to impart their specific properties like graphite or the lead is also incorporated, graphite is incorporated for the lubrication effect.

And the lead is incorporated for developing the free machining metal systems, but it is common to incorporate the hard constituents in the matrix so these constituents are not expecting to matrix is A and the constituents being incorporated is B. So these are not supposed to interact with each other.

Each constituent will be retaining its own identity and thereby it will be imparting either increased hardness strength or improved lubrication or improved wear resistance due to the lubrication effect by the solid lubricants like graphites or improved machinability etc. So in this case the application of the heat during the welding does not actually affect the characteristics appreciably except whatever the change in properties will be occurring that will be due to the change in grain size due to the application of the heat.

And 5th one is the transformation hardening, so transformation hardened metals like these are mostly say this maybe the copper based alloys or mostly these are the iron based alloys. So we know that iron carbon systems form a steel or the cast iron as per the concentration. So these systems result in the formation of the different types of the phases like normal carbon steels will find the pearlite and ferrite.

But when they are subjected to the specific kind of the heating and cooling cycles, we may have the bainite, we may have martensite, we may have the very fine mixture of the ferrite and the bainite etc. So various phases can be formed, which will be having their own characteristics and so accordingly the properties will be affected. Mostly in case of the welding, the heating cooling cycles are extremely fast.

So the hardenable iron carbon systems result in mostly hardening of the heat affected zone. So these are the say 5 mechanisms, which are there and their relative effect that is what will be seen in. There is one more yes that is the work hardening mechanism say six one, which is also commonly used for strengthening of the metal. So in case of the work hardening, the metal system is deformed plastically, which in turn will be producing the large number of the dislocations here and there.

And these dislocations interfere the movement of the few dislocations along the slip planes under the external stressors. And thereby so whatever the barrier whatever the new dislocations generated, they will be acting as a barrier for the movement of other dislocations and thereby it will be increasing the strength and hardness of the metal system as far as the welding and the application of the heat is concerned.

So these dislocations actually annihilate, they recover, they are lost due to the application of the heat. So work hardened metal systems under the application of the heat basically all these number of dislocations is reduced, which in turn will be softening the metal system. So as far as the heat affected zone is concerned, the different metal systems strengthened by the different approaches respond to the heat in different ways.

So what is that effect that is what will be seeing?

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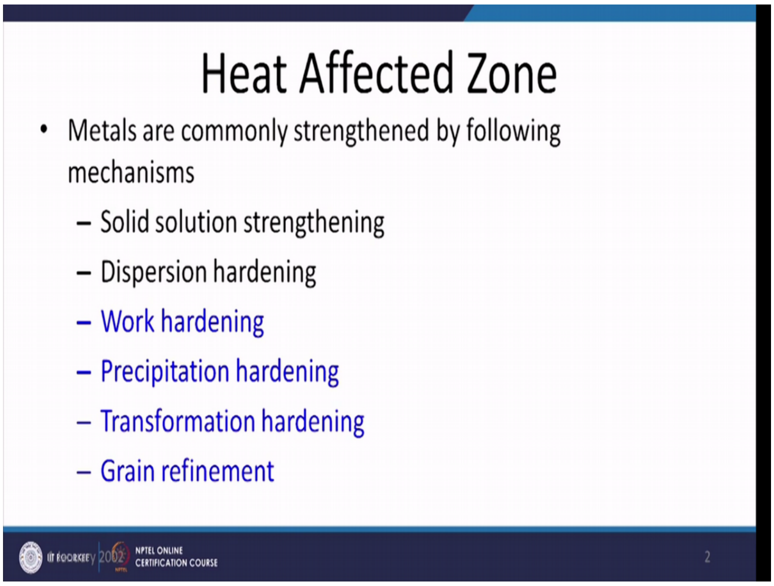

The solid solution is strengthened and the dispersion strengthened or hardened materials are somewhat less affected by the heat applied during the welding. While in case of the work hardening system, effect of work hardening is lost due to the annihilation or the recovery of the dislocations and the precipitation hardening due to the application of the heat during the welding heat affected zone near the fusion boundary.

These precipitates are either they get coarsened or they get lost or they get dissolved due to the application of heat so metal get softened. In transformation hardening mostly high rate of the heating and cooling. In case of the ferrous metal systems mostly causes the hardening despite of the grain coarsening and the grain refinement.

The metal systems which are only strengthened by the grain refinement, the coarsening in the heat affected zone will be lowering down the hardness and strength of the metal system. So this is very generic kind of the description of the different metal systems and the way by which the things will be affected with respect to the heat affected zone. Now I will be elaborating what the heat affected zone is first.

And then the way by which specific kind of metal system is affected with the application of the heat or due to the weld thermal cycle. So heat affected zone as it reflects from its name or the term, the zone or the region of the base metal which is affected by the heat applied during the welding of the given metal system is defined as heat affected zone. So in case of this heat affected zone.

Every region which is affected by the heat in terms of the structure or the mechanical properties will be falling under the category of the heat affected zone.

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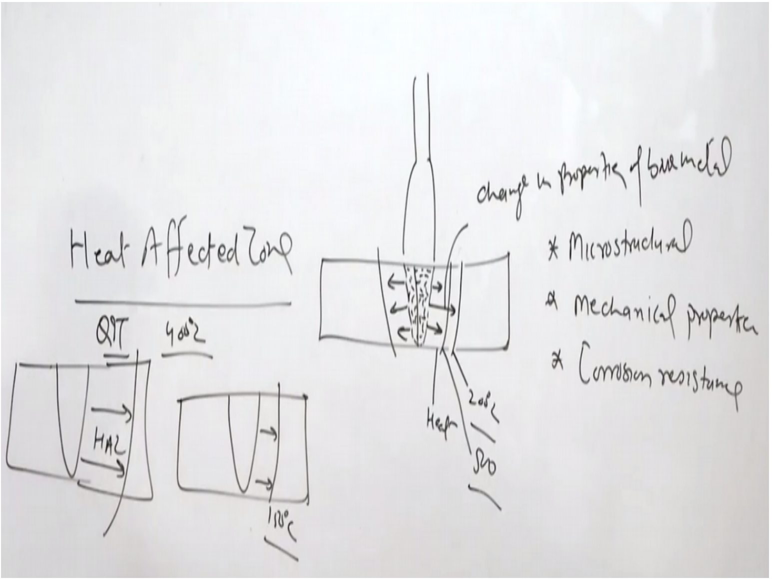

So like say during the welding the plates are being joined with the application of the heat source say suitable arc is used for the melting of the edges of the plates to be welded. So this melting will be resulting in the weld metal and when heat is applied for melting the edges of the plates, some of the heat is transferred to the underlying surfaces, underlying base metal and this heat which is transferred back to the base metal or away from the weld metal zone that is termed as the heat affected zone.

But up to what extent heat affected zone will be formed that will depend upon the distance up to which the change in properties is observed. So heat will be obviously transferred from the fusion zone to the base metal side, both side in both the directions and the distance up to which so due to this heat there will be rise in temperature. So the rise in temperature up to a particular limit for a given metal will be causing the change in properties of the base metal.

So this change in properties maybe in respect of the microstructural variation in terms of the mechanical properties wherein either hardening or softening of the metal in the heat affected zone can take place or there can be loss of the corrosion resistance, so corrosion properties can also be affected. So whenever the heat is applied to the plates for the fusion purpose, some of the heat is transferred to the base metal.

And this will be changing the underlying base metal properties in respect of structure, mechanical properties, corrosion properties either singly or in combination. So this distance up to which these properties are affected are the material specific. The properties this change may occur up to the region, which is heated above 200 degree centigrade or it may be above the region, which is heated say above 500 degree centigrade depending upon the metal systems.

For example, whenever aluminium systems are welded, will see that change whatever the regions are heated above 150 degree centigrade that will be falling in the heat affected zone. If it is the steel, so in case of the steel say carbon steels in normal conditions the regions which are heated above 730 degree centigrade like say carbon steel annealed condition and if it is in quenched and tempered conditions.

They will be like say steel Q and T steel quenched and tempered at 400 degree centigrade. So all the regions, which is heated above the 400 degree centigrade will be over tempered. So all the regions away from the fusion boundary, which is heated above the 400 degree centigrade will be falling end of the heat affected zone. So the temperature above which the heat affected zone is formed that is material specific and even for the given metal system its condition also affects at that particular temperature.

This temperature maybe 150, 200, 400, 800 anything depending upon the kind of metal systems about which we are talking. So this is how the heat affected zone is defined and heat affected zone will be experiencing the change in properties due to the application of the heat applied during the welding.

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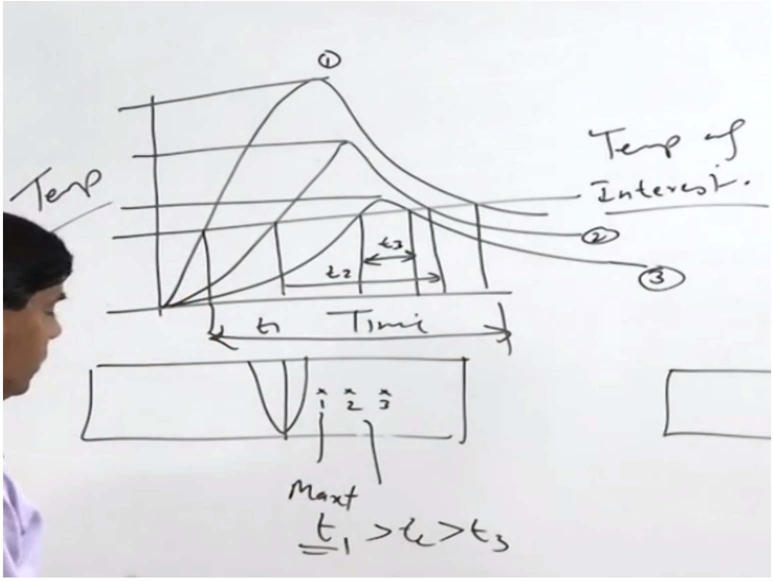

Further we know that whenever heat is applied obviously at the faying surfaces, fusion will be occurring and if we take the 3 points away from the fusion boundary then point 1, point 2 and point 3. We know that each point will be experiencing the different weld thermal cycle. One point will be experiencing the higher peak temperature and higher cooling rates.

And similarly the point 2 will be experiencing somewhat lower peak temperature and lower cooling rates and point 3 for the lower peak temperatures and lower cooling rates like this. So for point 1 this is the peak temperature, for point 2 this is the peak temperature and for point 3 this is the peak temperature. So in y axis we have temperature, in x axis we have time.

So what it reflects that if we take any particular temperature above which the 3 points will be exposed for particular duration. So if the interest of temperature is this, this is the temperature of interest above which properties will be affected. So if this is this temperature so that the duration for which the point 3 will be exposed is just this much. While the duration for which point 2, this is for point 1, this is for point two and this is for point 3.

So the duration for which the point 2 will be affected will be exposed to the temperature above the temperature of interest that will be this much. So t1, this is for t3, t2 and what will see for t1 is really very, very long this much. So the temperature t1 is really very, very long. If the temperature of interest is known, then we can see the t1 will be exposed for the maximum time, then t2 and then t3 So t1 is maximum, t2 is lesser than t1 and then minimum will be t3.

So the temperature and the time for which the particular point is exposed that governs the things appreciably. So it is important to note that the different zones will be experiencing the given temperature or will be experiencing the different temperatures. So the temperature 0.3 experiences the peak temperature very low and the duration is also very short, the peak temperature for point 3 is higher and for point 1 is further higher.

So the temperature for which particular point is exposed and the time for which above the particular temperature that location is exposed. These two factors play a big role in determining the characteristics of the heat affected zone. So considering this background now will see that how the different metal systems will be responding. So here I will be talking about first the work hardened metal systems.

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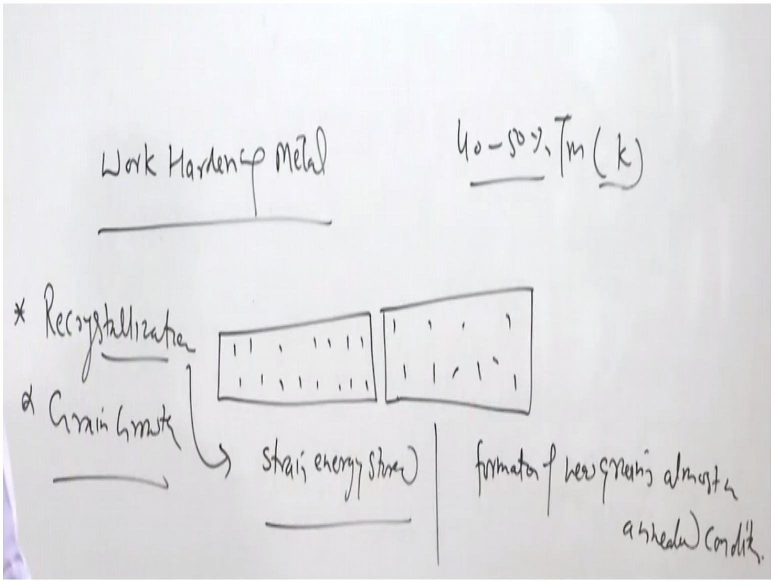

So we know that most of the metal systems during the manufacturing metal systems are deformed plastically and they get strength from that like the rolling or forging especially done under low temperature conditions. So under those conditions, plastic deformation will be developing lot of dislocations, which in turn will be increasing the strength and hardness of the metal system.

You know the work hardening metal systems are designed to be deformed for the fabrication purpose. So that during the manufacturing itself sufficient number of the dislocations are generated and these dislocations impart the strength and hardness to the metal system, but these metal systems when subjected to the welding in which way they respond that is what we can see.

There are basically the two ways by which the work hardening metal systems are affected with the application of the heat during the welding and this is about recrystallization one and grain growth is another and both these factors are dependent on means are influenced by the heat being applied and the time for which the high temperature is maintained.

So will taking up the first, the recrystallization the driving force for the recrystallization is the strain energy stored means greater the deformation greater with the strain energy stored so easier will be the recrystallization and there is particular temperature at which recrystallization takes place. So what the recrystallization is? It is about the formation of new grains almost in annealed condition means all the work hardening effect is lost and whatever new grains are formed they are in annealed condition.

So the formation of the new grains and this happens at particular temperature like say 40 to 50% of the melting point temperature in kelvin of the given metal and this temperature sometimes decreases with the increase in the strain energy stored or due to the kind of the deformation for which material has been subjected. So what we will see here the strain energy stored affects at temperature at which recrystallization will be occurring.

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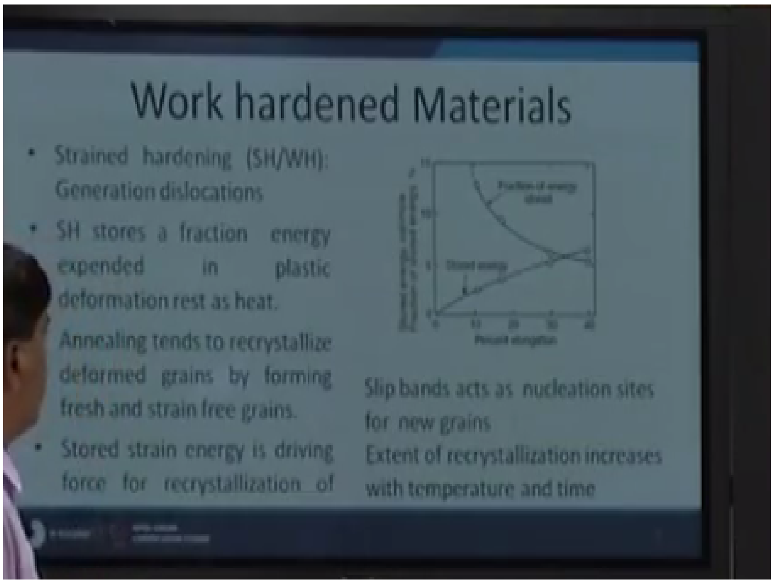

So here we know that as we increase the deformation, increase in elongation takes place say, increase in strain is taking place. So the stored energy increases continuously and the fraction of the energy stored out of the energy supplied keeps on decreasing. So this is what we can see strain energy stored increases with the strain or the deformation which is being applied.

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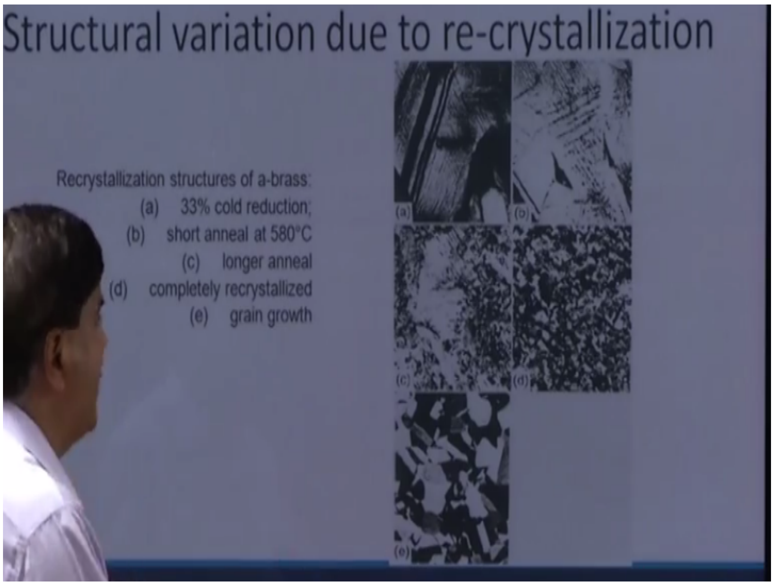

And whenever the heat is applied what you will see the material in very strained condition offers large number of the dislocations which we can see and when material is annealed for a short period, some of these dislocations are lost or these dislocations annihilate and further longer annealing results in the loss of this dislocations completely.

And then complete recrystallization formation of new grains take place with the continuous exposure at high temperature that is called annealing. And after the complete recrystallization if further exposure at high temperature during the welding if continues then it results in the coarsening of the grains. So material right from it is in original condition in deformed state showing large number of dislocations.

And these dislocations will keep on decreasing with the increase in time at a particular temperature during the annealing and over exposure causes the grain growth. So this is the third or last stage so first the recrystallization and thereafter the grain growth takes place.

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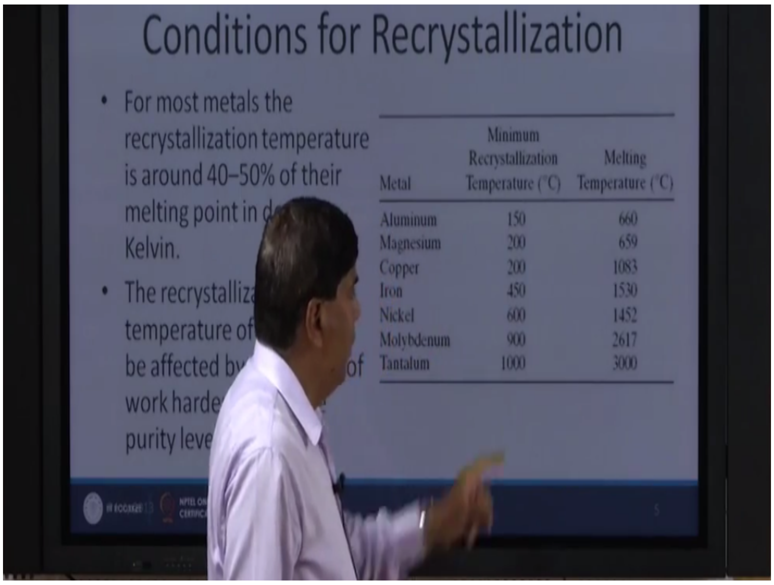

So the different metal systems show the recrystallization tendency at the different temperatures so with respect to the metal systems what we can see here the aluminium recrystallizes above 150 degree centigrade while its melting point is 660 degree centigrade. Similarly, magnesium recrystallizes above temperature 200 degree centigrade while its melting point is 569.

Similarly, iron recrystallizes above 450 degree centigrade while its melting point is 1530 degree centigrade. This likewise each metal will be recrystallizing as soon as the exposure above particular temperature is given and this is found to be significantly lower than its melting point. So we know that these metals get strength from the dislocations and in course of the exposure these dislocations are lost.

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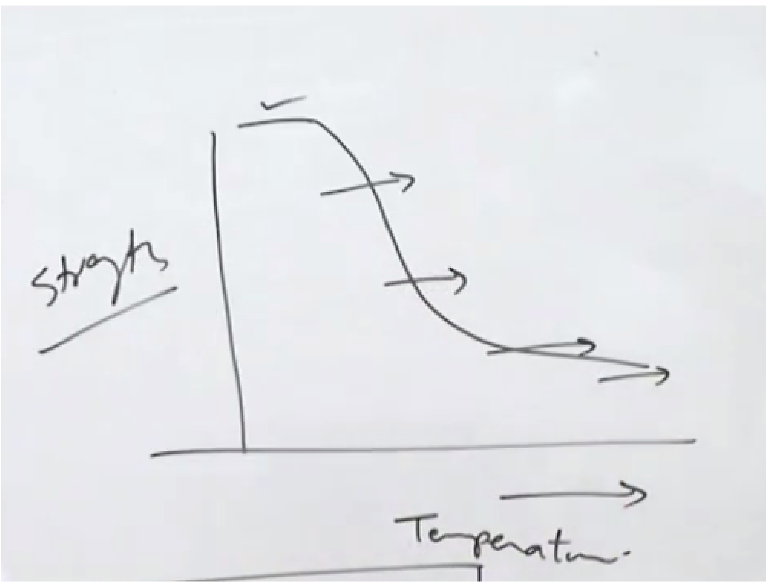

So which in turn will be lowering down the strength of the metal system say the temperature of exposure here if we have temperature of exposure as the temperature of exposure increases then the metal which is in work hardened conditions will be offering higher strength and as the temperature of exposure is increased will see there is a significant reduction in its strength of the metal system.

So this is the strength of say cold world metal offers the very high strength as it is exposed at the different temperatures so this is the increasing temperature of exposure or increasing annealing temperature, the extent of recrystallization will be increasing and it will be lowering down the strength of the metal system.

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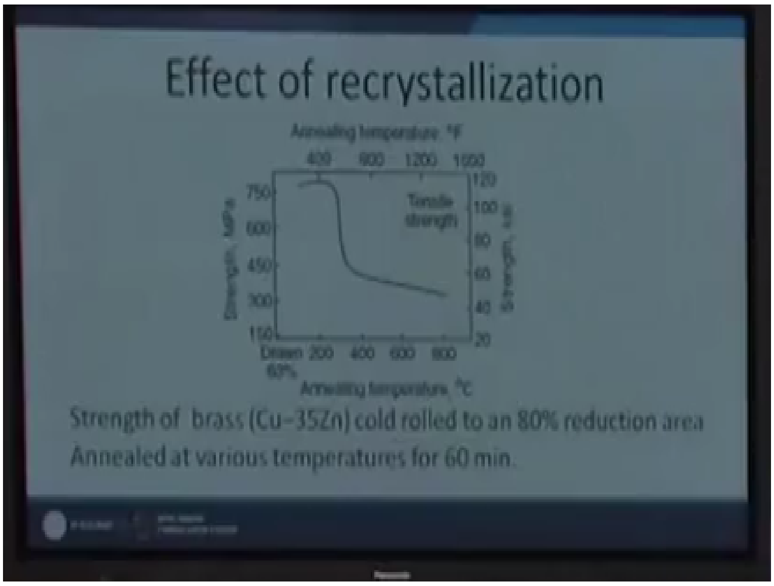

Say for this example, the material cold drawn up to 63% when it is given exposure to the higher temperature say 200 degree centigrade, there is no major drop in hardness, but as the exposure temperature is increased to 400, 600, 800 degree centigrade so there is a sudden drop in the strength of the brass, which has been cold drawn. This reduction in the strength takes place and this sharp reduction is attributed to the complete recrystallization, which is occurring for the brass.

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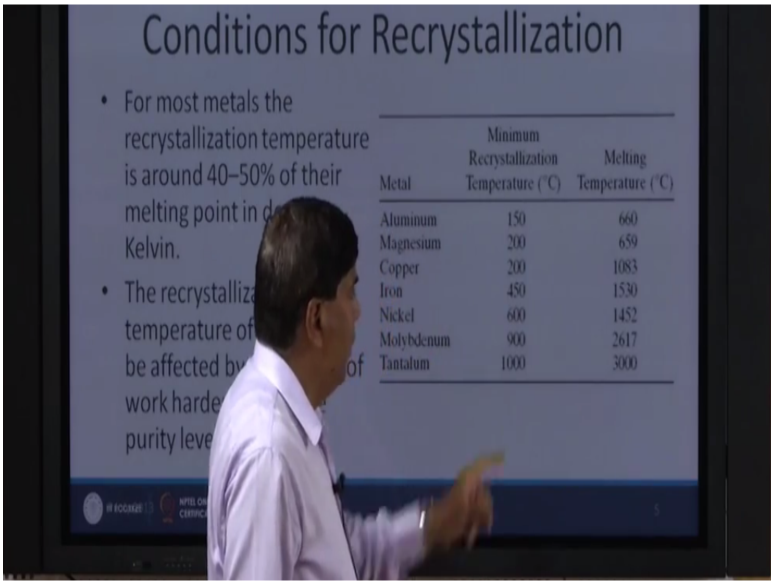

Since that recrystallization temperature for the brass is say around this what we have seen in the previous slide it is 200 degree centigrade so as soon as it is exposed very quick and rapid recrystallization takes place and this results in the significant drop in the strength of the brass as the exposure at high temperature takes place.

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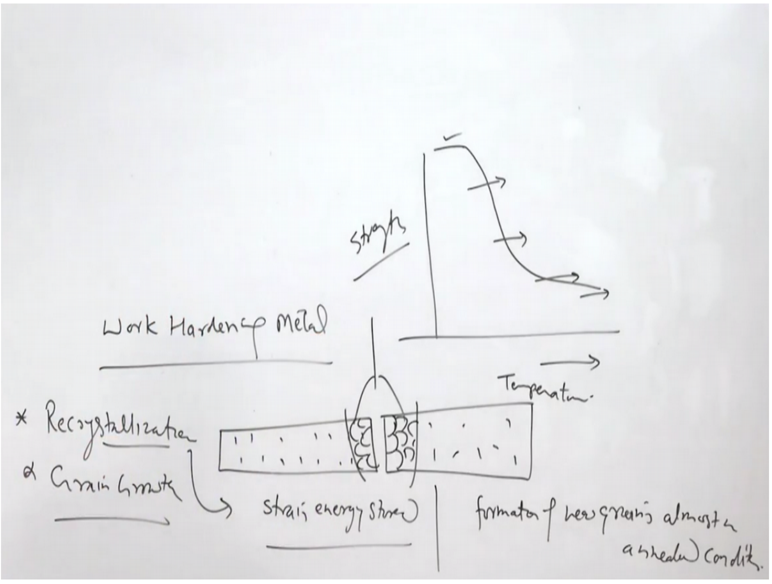

This is what we can see whenever the work hardening metal systems exposed to the external heat the metal systems near the heat affected zone recrystallize and formation of the new annealed grains lower down the strength of the metal as compared to that of the work hardened condition. So basically effect of the work hardening is lost due to the recrystallization.

And if further this application of the heat in high temperature exposure is continued then it will be causing the growth of the grains. Growth of the grains again will be causing the reduction in the strength and hardness because of the grain coarsening so the approach for the grain coarsening is different from which the driving force for the grain coarsening is different from the recrystallization so that is what will see now that the factors governing the grain growth.

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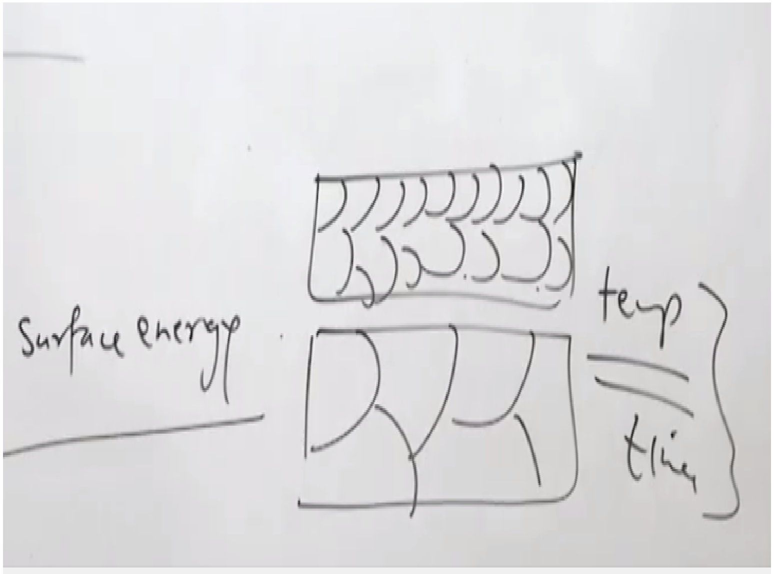

So driving force for the grain growth is the surface energy not the strain energy like the recrystallization and most of the metal systems made of large number of the grains, more number of the grains, large will be the grain bound area, more will be the grain bound area, great will be the surface energy related with that. So all metal systems try to attain the minimum energy for the maximum stability.

And therefore the metal systems under the favorable conditions tend to attain the larger grain size. So that fewer grain boundary area can help to reduce the surface energy associated with them. So for this purpose what is needed, the high temperature since this process is governed by the diffusion, it is diffusion dependent so it needs enough temperature and time so that diffusion can facilitate this change in grain size for the maximum stability of the system.

So because systems tend to have reduced their surface energies and because of this since strain energy does not play any role in the grain growth it is the surface energy that governs the grain growth aspect. Therefore, the grain growth phenomenon is not limited to the work hardening materials only, but it is limited to all kind of the systems because most of the metal systems they will be of the polycrystalline structure and they will tend to attain the minimum surface energy by the grain coarsening.

So whenever favorable conditions for diffusion exist, the high temperature for sufficient time is present then it will be causing the grain growth.

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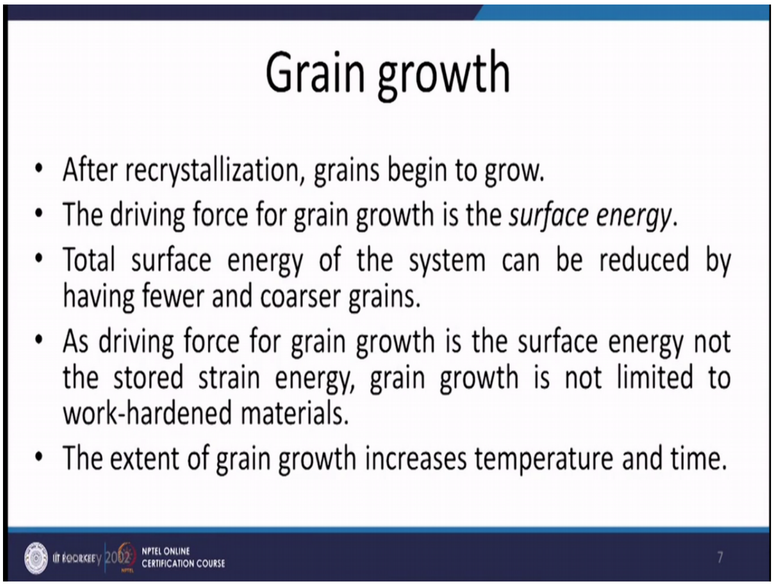

So grain growth will see now the way by which the grain growth is affected so this is what we can see. Driving force of the grain growth is the surface energy not the strain energy. So grain growth is not limited to the work hardened metal systems, but it is applicable in all the cases.

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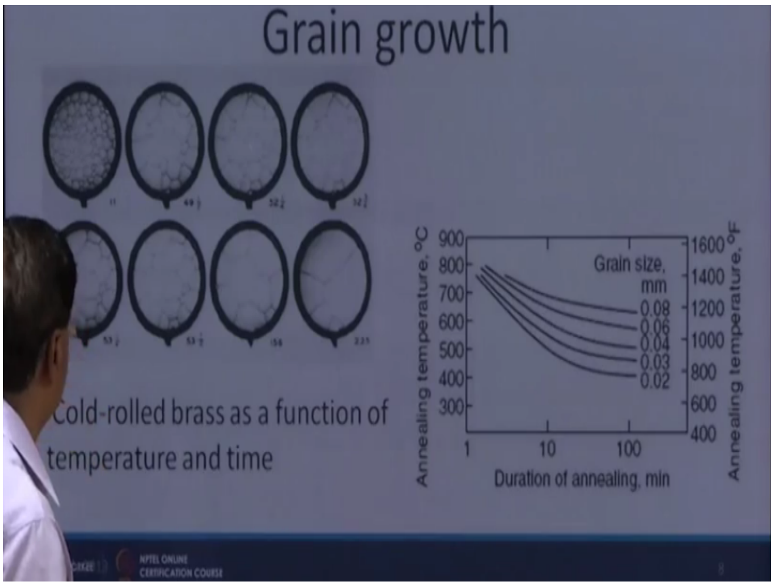

Say cold drawn metal system, how the grain size is affected as a function of the time and temperature this is what we can see. Work hardening metal systems having very fine grains as the exposure keep on increasing in terms of the time. We will see if there is continuous increase in the grain size. This is the same thing what we can see from this diagram also annealing temperature versus the annealing time, so temperature versus time.

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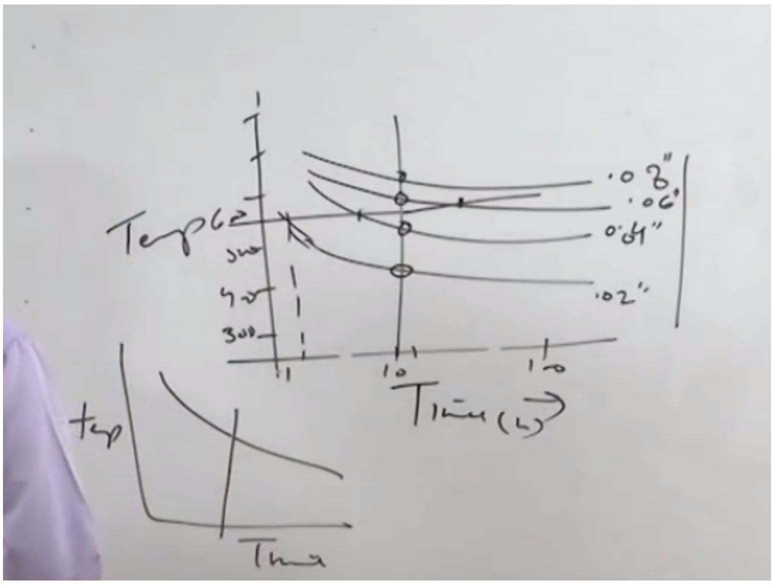

So this is what we can see here. In x axis we have time and in y axis is the temperature, so how the grain size like say this is for one, this is another and this is another like say if we consider 3 grain sizes, so for 0.02, 0.04 and 0.08 like this or we can have one more 0.06. This is in inches the grain size and typically the temperature values from 300, 400, 500, likewise and the time in log scale 1, 10, 100, 1000 like this.

So here it will be further longer like say 10 and 100 in hours. So what we can see here for the given grain size let say for 0.04 inch like say how the grain size changes that is what we can see as a function of the time. If the exposure is given say 600 degree centigrade then how the grain size will change, grain size will be like say after 1 hour, this is 0.02, then after 10 hours or 8 hours it will be 0.04, then 0.06.

So as a function of time means the increase in time coarsens the grain. And similarly for the given time, increase in temperature also increases like say 10-hour exposure at 450 degree centigrade leads to the 0.02-inch grain size then the grain size will keep on increasing with the increase in temperature for a given period. So basically the thing is so the grain size variation is like this temperature and time in simple form.

So if we increase for a given temperature for a given time increase in temperature increases the grain size or for a given time, given temperature increase in time increases the grain size. Now we have to relate this with the weld joints. So we know that the point is closer to the fusion boundary.

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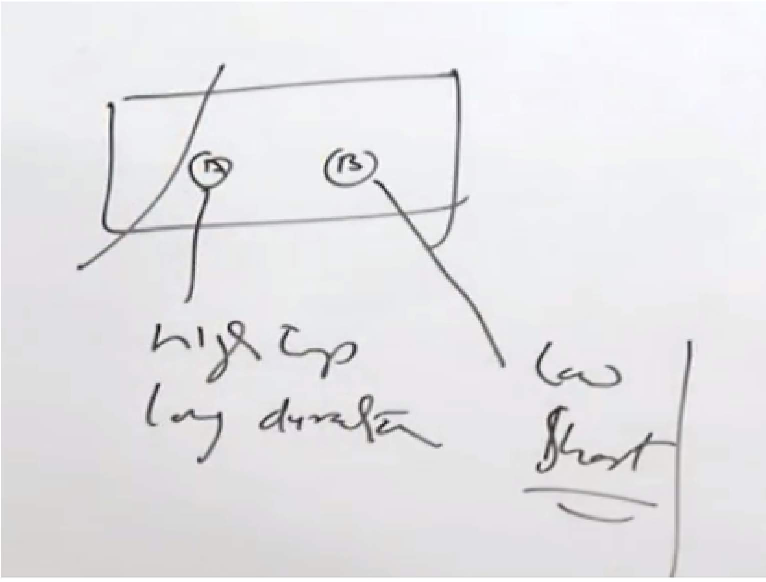

So the points close to the fusion boundary will have higher temperature like say A and B, A will have high temperature and long duration at high temperature as we have seen from the weld thermal cycle while the low temperature and short high temperature exposure so this is just opposite and this in turn will be reflecting in the weld thermal cycle so this is what the effect of weld thermal cycle.

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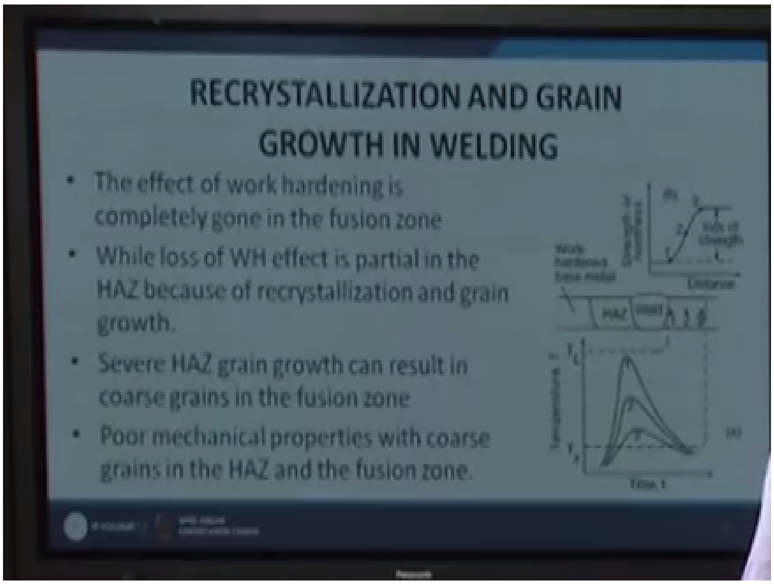

So when the point is very close to the fusion boundary, peak temperature is high and also duration for which high temperature exposure is given is also long as compared to the point 2 and point 3. Accordingly, will see that the loss of strength due to the recrystallization and grain growth is maximum with the point 1 and then loss of strength and hardness will keep on increasing as the distance from the fusion boundary increases.

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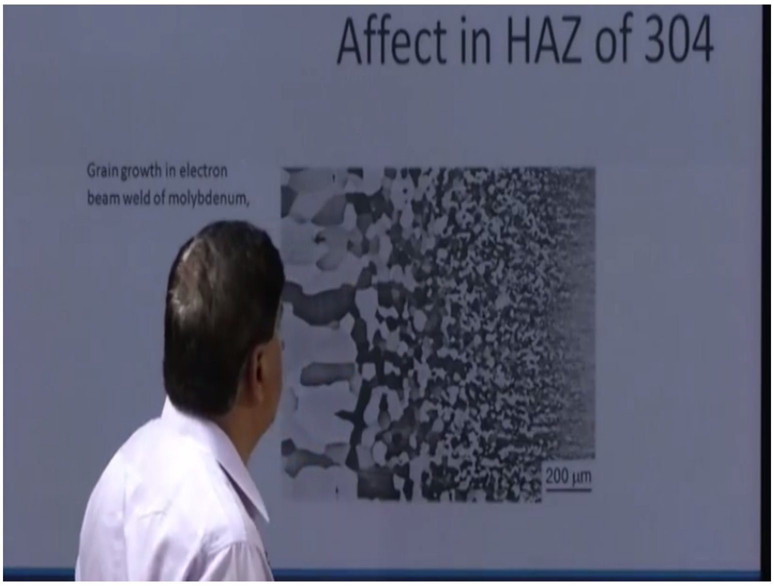

This is what we can see here the points which are very close to the fusion boundary will have the coarser grains and as we move away from the fusion boundary this will keep on decreasing the coarsening.

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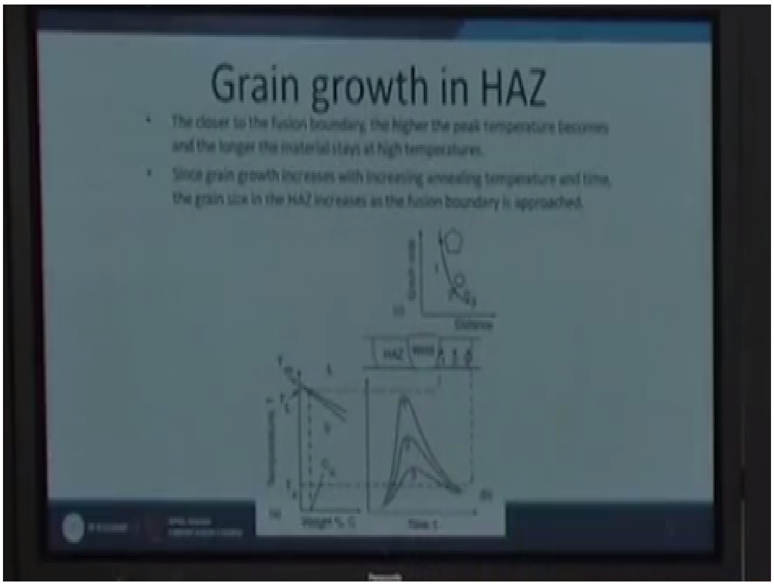

Same thing can be seen from here the point 1 very close to the fusion boundary as compared to the point 2 and point 3. So the point 1 will be experiencing the more grain growth as compared to the point 2 and point 3. Point 3 will be having the minimum grain coarsening as compared to the point 2 and point 1. And the main reason for this is what the difference in the peak temperature and the duration for which higher temperature exposure is given that will be higher.

The temperature will be higher and it will be for longer periods for the point A as compared to the point B. So that is why will see that the maximum coarsening takes place near the fusion boundary as compared to those away from the fusion boundary. So now here I will summarize this presentation. We have seen the different mechanisms that are used for strengthening of the metal systems.

And the way, by which the heat of the welding can affect the properties of the metal system strengthened by the different approaches and especially in detail I have talked about that how the weld thermal cycle will be affecting the heat affected zone characteristics and accordingly it will have the effect on the grain size and the properties of the heat affected zone especially of the work hardened metal system. Thank you for your attention.