Joining Technologies of Commercial Importance
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Lecture - 30
Heat Affected Zone and Weld Thermal Cycle: II

Hello I welcome you all in this presentation. This presentation is related with the heat affected zone and the weld thermal cycle and in this presentation I will be talking about the heat affected zone characteristics related with the precipitation hardening metal systems.

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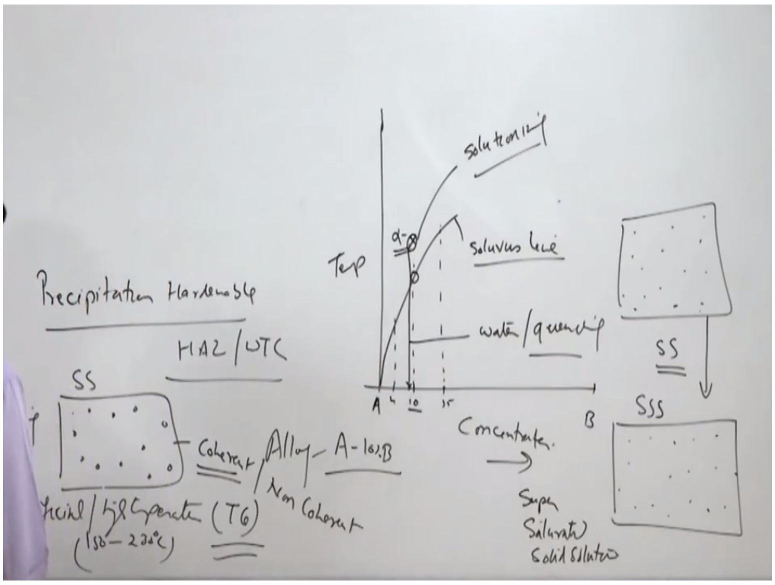

So like in the last lecture, I talked about the work hardenable metal systems in precipitation hardenable systems to understand the heat affected zone and the weld thermal cycle related aspects it is necessary to understand what the precipitation hardening is and how the metal systems are strengthened. So the requirement for precipitation hardening is that the solubility for alloying elements must increase with the temperature.

So the alloying elements say this is the metal A and the metal B and whenever a particular fraction like say 4, 10, 15 etc. The B is incorporated in A, will see that one particular solvus line and this solvus line maybe in generally is found to be like this. There can be different solvus lines like this, which shows the temperature above which the solute will get dissolve. So the 4% of the B will get dissolve above this temperature.

10% B will get dissolve above this temperature. And here it will get dissolve above this temperature, so solvus line is basically or solvus curve shows the relationship between the temperature and concentration of the alloying element here and what it shows there is increase in temperature the solubility of the element in the metrics alloying element in the metrics increases.

So what we do first say for the alloy having metrics A having 10% of the B. So this is an alloy just for an example. So here this alloy will be heated above this temperature curve on the solvus line. So that will have homogenous solid solution is formed. So we go well above this temperature to have the homogenous solid solution. So this one is called solutionizing. So heating at the temperature above the solvus line helps to achieve the homogenous solid solution, this step is called solutionizing.

And then once the homogenous solid solution of the alloy is formed then will be quenching it fast. So it is quenched by cooling rapidly in the water or oil, this is called quenching. So since during the solutionizing we have got uniform presence of the alloying element in the metrics in form of the solid solution, which maybe interstitial or substitutional and this solid solution when quenched rapidly forms the supersaturated solid solution.

Because it does not allow any diffusion to take place and the solutes will be retained wherever they are present. So this in turn results in the supersaturated solid solution wherein the solute will be present in the metrics much more than its capacity to accommodate means above the solubility limit. So the alloying elements present at room temperature in the limit above its solubility limit and that is why it is called supersaturated solid solution.

This supersaturated solid solution then subjected to the aging. Aging can be at the 2 levels, the supersaturated solid solution subjected to the aging means it will allow to hold for some time. So if this aging is done at high temperature means artificially heating is done to have the high temperature exposure means aging at high temperature is termed as artificial aging and this is typically termed as T6 treatment or temper condition.

So during this exposure at high temperature, which is normally say for aluminium alloys 150 to say 230 degree centigrade. It may be different for the different metal systems. So during the high temperature exposure, supersaturated solid solution starts forming the precipitates uniformly in the metrics. These precipitates depending upon the kind of alloy or alloying elements it will form the different types of the precipitates.

These fine precipitates, which are basically if they are coherent these can be coherent or non-coherent. So the coherent precipitates help to strength the alloy significantly as compared to the non-coherent precipitates. So in this way there are three steps in the precipitation hardening of the metal systems, one is solutionizing to form the homogenous solid solution, second is quenching to form the supersaturated and third is aging.

Aging may be done at high temperature for artificial aging or it may be done at room temperature for natural aging.

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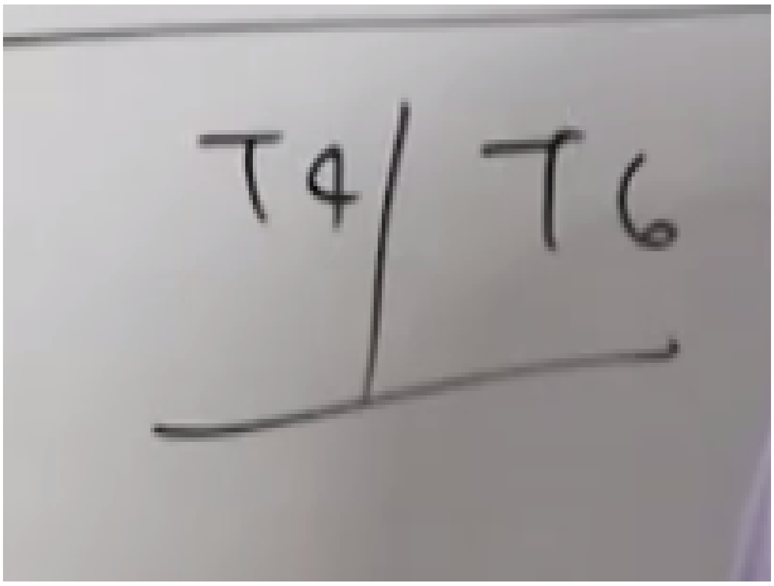

So artificial aging is normally termed as T6 temper condition while the natural aging is done by just holding the quenched samples at room temperature after solutionizing is termed as natural aging and it is given the temper T4. So T4 for the natural aging and T6 for the artificial aging.

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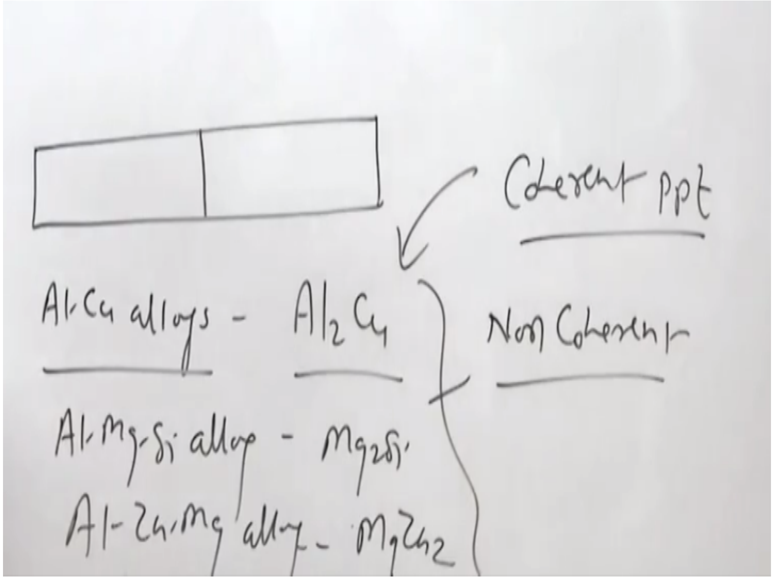

So as far as the welding is concerned when the precipitation hardened systems like this say its aluminium copper alloy. The common alloys, which are precipitation hardened is the aluminium-magnesium-silicon system or aluminium-zinc-magnesium system. These are the common precipitation hardenable systems. Copper alloy as CuAl2 Mg2Si and MgZn2, these are the kind of the precipitates, which are formed in these three types of the precipitation of hardenable alloys.

And when these are non-coherent, they result in somewhat marginal increase in strength and hardness. While in the case when they are coherent depending upon the temperature and exposure conditions, they will be resulting in the say maximum increase in the strength and the hardness. So coherent precipitates always preferred over the non-coherent and conditions are developed in such a way that the system is having a coherent precipitate.

So that typically will take one system just to explain the way by which the properties are affected when the heat is applied during the welding for the change in the properties of the heat affected zone.

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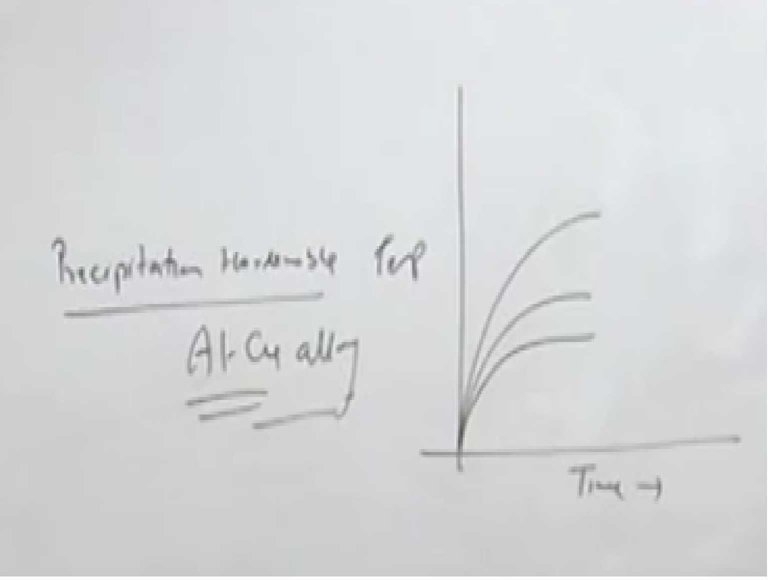

So considering this will take up one typical aluminium copper system alloy just to explain. So here if will see the aluminium copper systems have the various kinds of solvus lines for the different phases like this so here as a function of time and here in y axis we have temperature. This is what we can see clearly from these diagrams.

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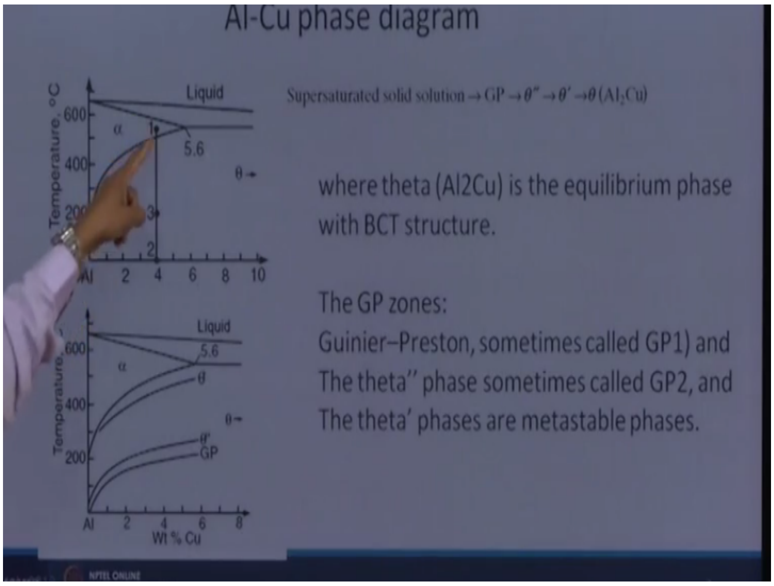

Al-Cu phase diagram

Supersaturated solid solution → GP → θ'' → θ' → θ (Al_2Cu)

where theta (Al2Cu) is the equilibrium phase with BCT structure.

The GP zones:
Guinier–Preston, sometimes called GP1) and
The theta'' phase sometimes called GP2, and
The theta' phases are metastable phases.

So for the aluminium copper systems, this is the typical phase diagram for aluminium copper systems. Solute that is copper in x axis and temperature in y axis, this is the solvus line and here it indicates that first heating is done in this alpha region so that solutionizing takes place. Then it is quenched back quickly so quenching results in the supersaturated solid solution and thereafter third step is the heating artificially at about 200 degree centigrade so that the precipitates can be formed.

The different types of the precipitates are formed in these systems and that is what we can see supersaturated solid solutions in course of the aging it will be resulting in the GP zones that is called Guinier-Preston zones, theta double dash, theta dash and theta. These are the different precipitates. The Guinier-Preston it is also called GP1, theta double dash also called GP2 and the theta dash phases all these are metastable phases.

Theta is the equilibrium phase that is the CuAl2 and it has the BCT crystal structure. So if will see this diagram the solvus line for the GP phase Guinier-Preston 1 is the minimum, this is solvus line for the GP phases and then theta double dash then theta dash and thereafter the one solvus line for the aluminium and copper system where the homogenous solid solution of the alpha or the alpha aluminium is formed.

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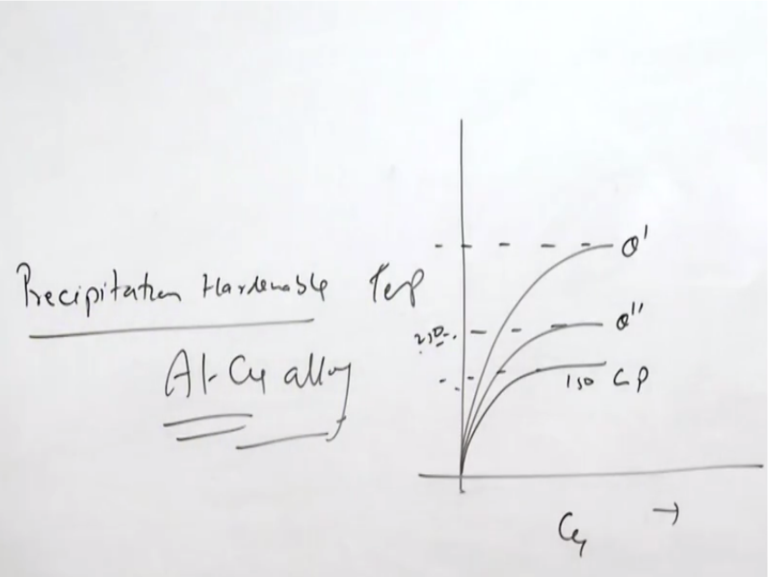

So what it shows that the GP, theta double dash and theta dash, here we have the concentration of the copper so copper and the temperature. So here it occurs around say 150 to 200 degree centigrade then the 250 degree centigrade and likewise so higher temperatures. So if we see the GP and theta dash phases will get dissolved as per the concentration of the copper they will get dissolved above the particular temperature say 200 and above.

So the GP and the theta double dash phases are the metastable while the theta is stable or equilibrium phase and similarly theta dash is also unstable and above the particular temperature these get dissolved. It is always desirable to have a particular kind of phase so that the maximum strength can be achieved. So what we can see the different phases are formed after this during the precipitation, during the aging.

And some of these phases are coherent, some of these phases are non-coherent and accordingly they will have effect on the hardness.

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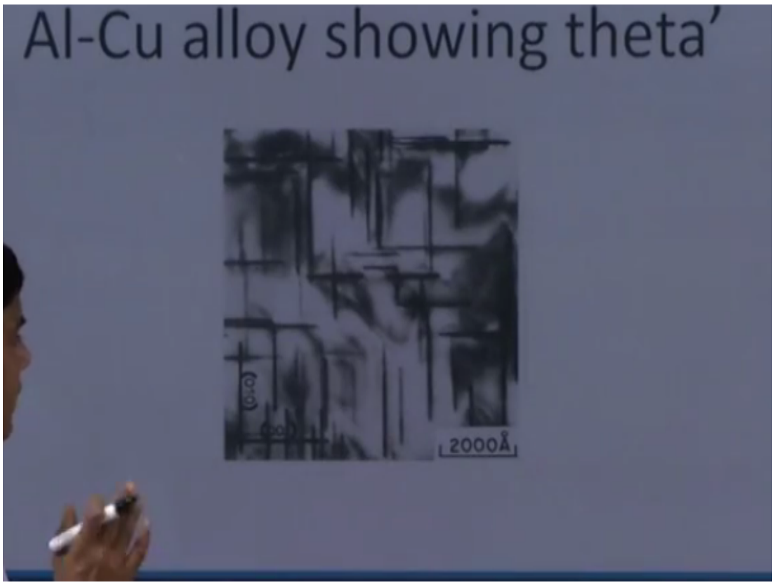

Al-Cu alloy showing theta'

This is the typical photograph showing the precipitates, which are formed. These are very fine in size say the dimensions are in like say 10 of the angstrom to the 100 of the angstrom in the thicknesses and the diameter of these precipitates can vary from say 500 to 2000, 3000, 4000 angstrom. So these are very fine in size, normally these are not dissolved, resolved under the optical microscope, so transmission electron microscope is used for this purpose.

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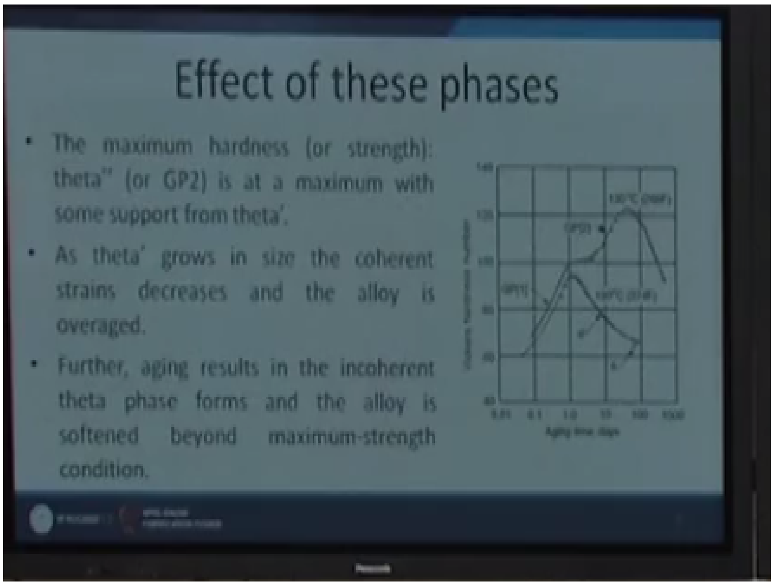

Effect of these phases

- The maximum hardness (or strength): theta'' (or GP2) is at a maximum with some support from theta'.
- As theta' grows in size the coherent strains decreases and the alloy is overaged.
- Further, aging results in the incoherent theta phase forms and the alloy is softened beyond maximum-strength condition.

If we see this diagram, what it shows that as a function of the time how the properties or the hardness of the particular alloy varies in course of the aging.

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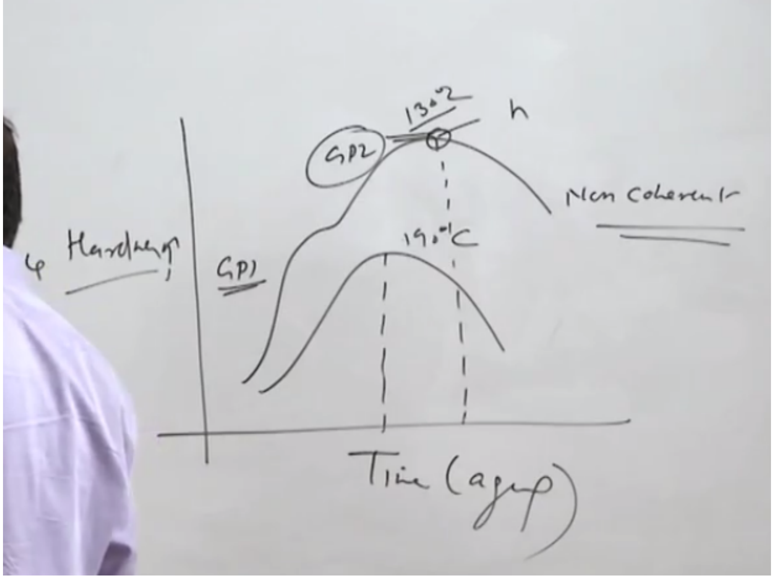

So if we see this diagram typically here in x axis it has the time and in y axis it is temperature. So time is about the aging time and in y axis it is the temperature so how the property change takes place when the exposure is given at the different temperatures. So in one particular case like say it goes in like this here when the exposure is at 130 degree centigrade and when it is done at higher temperature then peak is achieved earlier like say it is 190 degree centigrade.

So what it shows for the peak hardness it takes longer as compared to the peak hardness at the high temperature and the different phases, which are formed like say the GP1, GP2 and here thereafter non-coherent phases are formed once the over aging starts. So what we can see here are the initially with the aging, there is formation of GP1 and then GP2 phases and if this high temperature exposure is continued for longer period.

Then the non-coherent phase formation results in the drop in hardness. So this one is hardness not the temperature so it is the hardness. If the exposure is given at 130 degree centigrade for the different increasing periods for the different aging times will see that initially the GP1 is formed, then GP2. GP2 will result in the maximum increase in hardness and thereafter due to the formation of the non-coherent phases hardness starts dropping.

So this is the stage when we need to stop for achieving the maximum hardness and strength. Similarly, when further high temperature exposure is given then the peak hardness is achieved in much shorter period as compared to that at low temperature. So always target is to have GP2 phases in the maximum amount so that the maximum strength and the hardness can be achieved.

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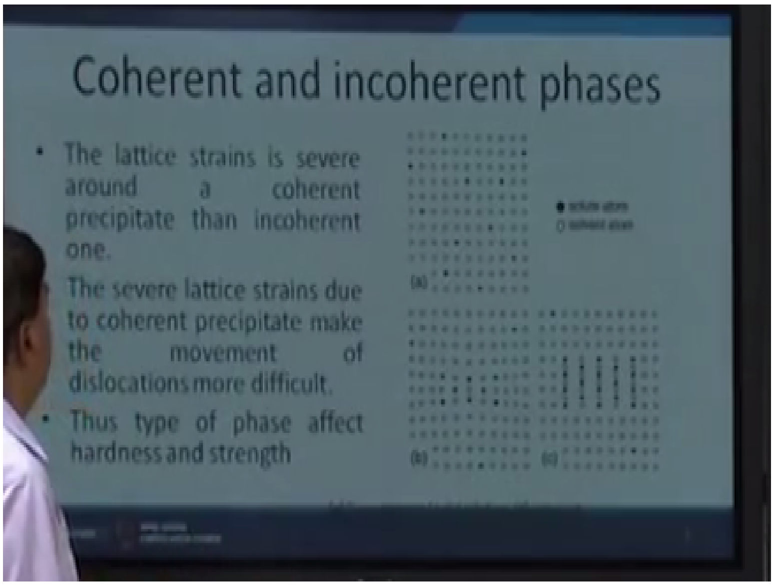

Coherent and incoherent phases

- The lattice strains is severe around a coherent precipitate than incoherent one.
- The severe lattice strains due to coherent precipitate make the movement of dislocations more difficult.
- Thus type of phase affect hardness and strength

And how do these phases offer the strength? Let us say strain is very severe around the coherent phases like this. So this schematic diagram shows the supersaturated solid solution and when the aging is achieved or when aging is performed, coherent phases result in the distribution of the solute in the metrics like this and the distribution of the solute in the metrics is like this for the non-coherent or incoherent phases.

Coherent phases result in the maximum strain around the region where these are present as compared to that of the incoherent phases. So that is why the maximum strain around the coherent phases result in the increased barrier for the movement of the dislocations and which in turn increases the strength and hardness of the alloy significantly. While the strain around the non-coherent phases is very less.

And that is why barrier to the movement of dislocations is very limited and which in turn does not result much increase in the strength and hardness. So according to the type of the phases, which are present like if the non-coherent phases are formed then strength and increase in the strength and hardness is not much as compared to the coherent phases.

And this is what is observed that after the peak hardening or after the peak strength exposure to the exposure of the alloys at high temperature for much longer period causes the over aging due to the formation of the non-coherent phases and that is why reduction in strength and hardness is observed.

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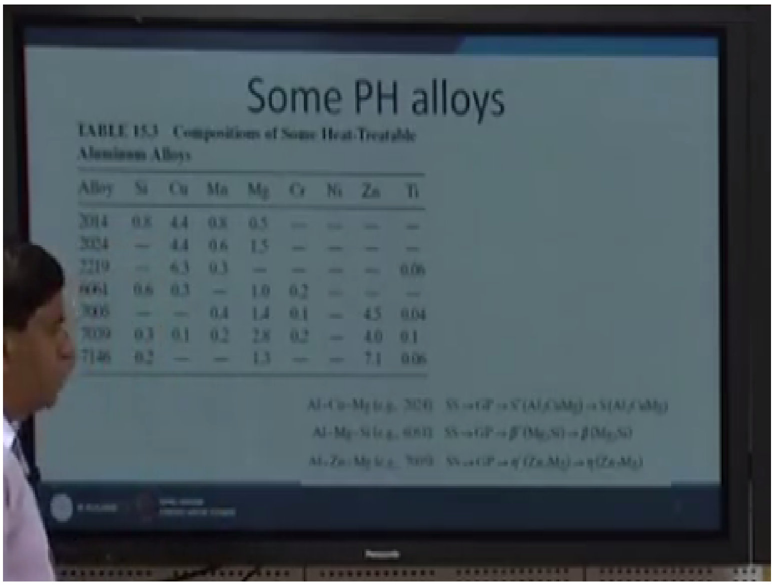

Some PH alloys

TABLE 15.3 Compositions of Some Heat-Treatable Aluminum Alloys

Alloy	Si	Cu	Mn	Mg	Cr	Ni	Zn	Ti
2014	0.8	4.4	0.8	0.5	—	—	—	—
2024	—	4.4	0.6	1.5	—	—	—	—
2219	—	6.3	0.3	—	—	—	—	0.06
6061	0.6	0.3	—	1.0	0.2	—	—	—
7005	—	—	0.4	1.4	0.1	—	4.5	0.04
7039	0.3	0.1	0.2	2.8	0.2	—	4.0	0.1
7146	0.2	—	—	1.3	—	—	7.1	0.06

Al-Cu-Mg (e.g. 2024) SS → GP → S'(Al$_2$CuMg) → S(Al$_2$CuMg)

Al-Mg-Si (e.g. 6061) SS → GP → β'(Mg$_2$Si) → β(Mg$_2$Si)

Al-Zn-Mg (e.g. 7075) SS → GP → η'(Zn$_2$Mg) → η(Zn$_2$Mg)

So the different type of the precipitation hardenable alloys and the kind of phases which are formed in case of the aluminium alloys that is what has been shown in this diagram

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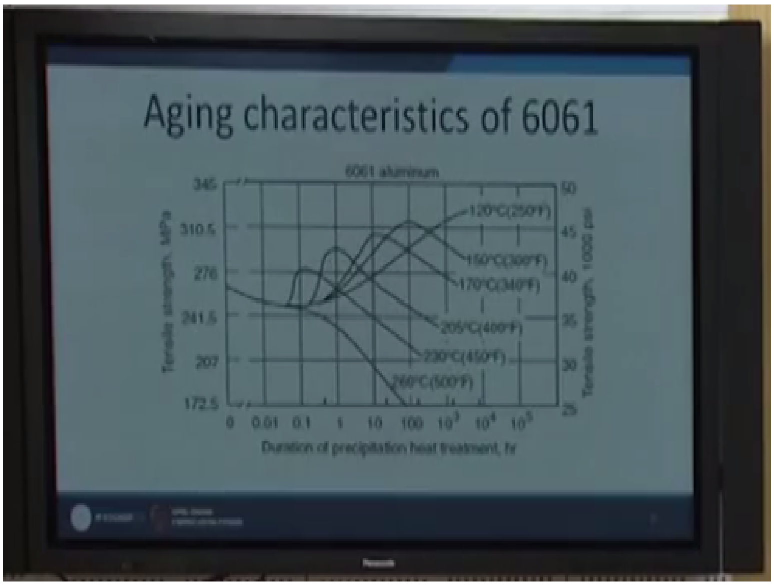

Aging characteristics of 6061

Now we will see the kind of behavior which is observed as a function of the aging time and the strength.

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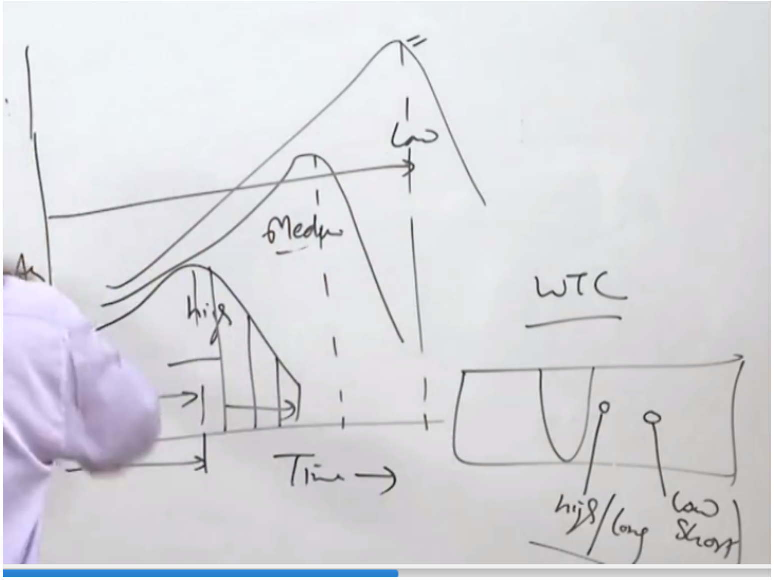

Normally the trend is like this, when the strength and hardness in y axis, aging time in the x axis and what will see that if the temperature is high then this is observed very quickly otherwise it takes longer time like this. So what we can see here if this is the high temperature somewhat low medium and low temperature. So low temperature exposure results in the higher increase in the strength.

But after a longer time while medium temperature results means peak hardening occurs after very long time at low temperature while that in case of the medium temperature it takes shorter time and for the high temperature it takes very short time. So it is important that if the temperature of the exposure is high, then the softening will start much earlier while if the temperature of the exposure is low, then it will take long time for softening to occur.

This is important with respect to the weld thermal cycle. So the zones of the weld, which are very close to the fusion boundary like this they will be subjected to the high temperature as well as for longer period and that is why will be getting the softening or over aging much earlier as compared to the case when the point is located away from the points, which are located away from will be experiencing the lower peak temperature for shorter periods.

So both these things are favorable it will be having the minimum effect of the over aging or over aging effect will not be that apparent and visible. So the over aging or the formation of the non-coherent phases or the dissolution of the phases will primarily be observed next to the fusion boundary since the precipitation hardenable alloys are strengthened by the precipitates.

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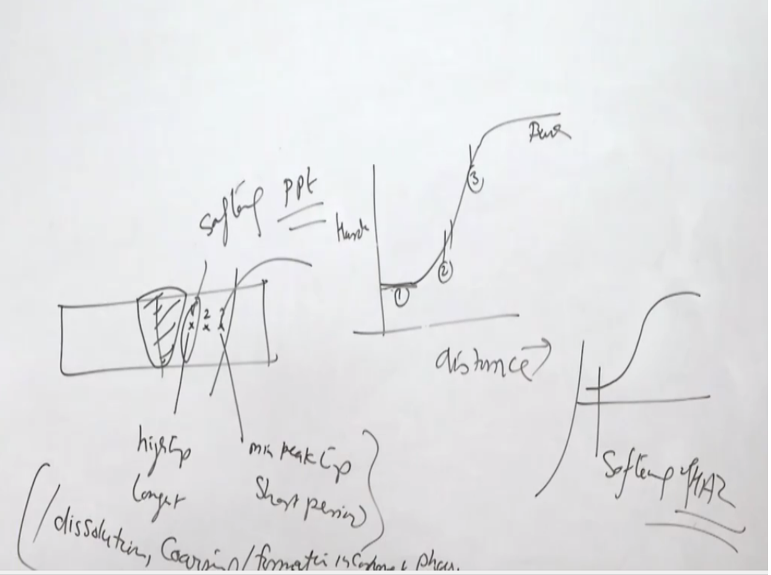

So with the application of the heat like say this is the weld with the heat, the weld joint is formed and next to the fusion boundary, we have 1, 2 and 3 points obviously each will have its (()) (21:21). This will have the highest temperature and for longest period while the point 3 will have the minimum peak temperature and for very short period. So what will see that at the point 1, there will be the dissolution coarsening as well as the formation of incoherent phases.

So fine phases either they will dissolve or they will convert into the incoherent phases or their coarsening will take place. So all these phenomena will be leading to the softening of the precipitation hardenable alloys in the zone next to the fusion boundary while its effect will be less away from. So if will see the hardness variation from the fusion boundary hardness will be minimum next to the fusion boundary and then it will keep on increasing.

So hardness of the zone 1, hardness of the zone 2 and hardness of the zone 3 so we may have like this, this is for the base if here this is the hardness curve, and this is the distance from the fusion boundary, so the zone which is very next to the fusion boundary will be experiencing the maximum dissolution, coarsening and formation of incoherent phases and that is why will have very low hardness.

While as the distance increases, the extent of dissolution, formation of incoherent phase precipitates and the coarsening will be limited that is why somewhat higher hardness and somewhat more hardness and then it is corresponding to the base metal. So this is the typical behavior, which is observed next to the fusion boundary what we get in like the hardness is minimum and then it increases.

So this reduction in hardness is called the softening of the heat affected zone and this softening is invariably observed in the weld joints of the precipitation hardenable alloys.

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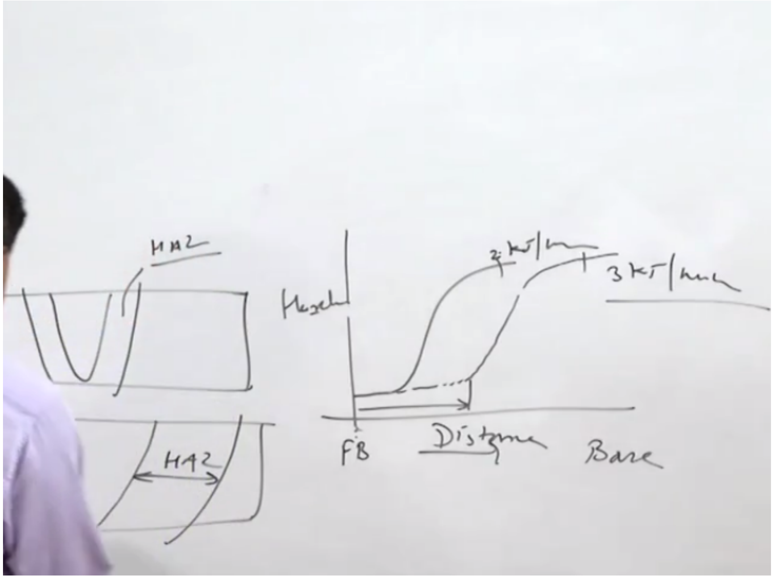

Now if we try to relate it with the heat input and other conditions related with the welding then what will see with the increase in heat input simply the effect of heat input is what say the plate is welded using 2 kilojoule per mm heat input then the weld zone size will be this much and heat affected zone is this much and if the same thing is welded using 3 kilojoule per mm.

Then our weld zone will be wider because of the more heat input and the heat affected zone will be further wider. So heat affected zone since the width up to which increase in heat input increases the width up to which the temperature rises above the critical temperature increases which in turn increases the width of the heat affected zone while this width is limited.

So basically HAZ size is directly related with the amount of the heat input or more is the heat input wider will be the heat affected zone, larger will be the cross sectional area of the weld and this in turn will have the more adverse effect. So if we try to replicate this in terms of the hardness variation from the fusion boundary to the base metal side then increasing distance from the fusion boundary will be showing that for 2 kilojoule that variation in hardness is like this while say 2 kilojoule per mm hardness variation.

And the extent of the hardness loss will be much more for the 3 kilojoule and this is the extent of the softening which will be occurring in corresponding to the region which is very close to the fusion boundary. And then wherever the drop in hardness is taking place that will be the part of the heat affected zone and increase in heat input will simply be increase in the width up to which the softening is taking place.

And that in turn will be weakening the material and will be leading to the reduction in strength of the metal system.

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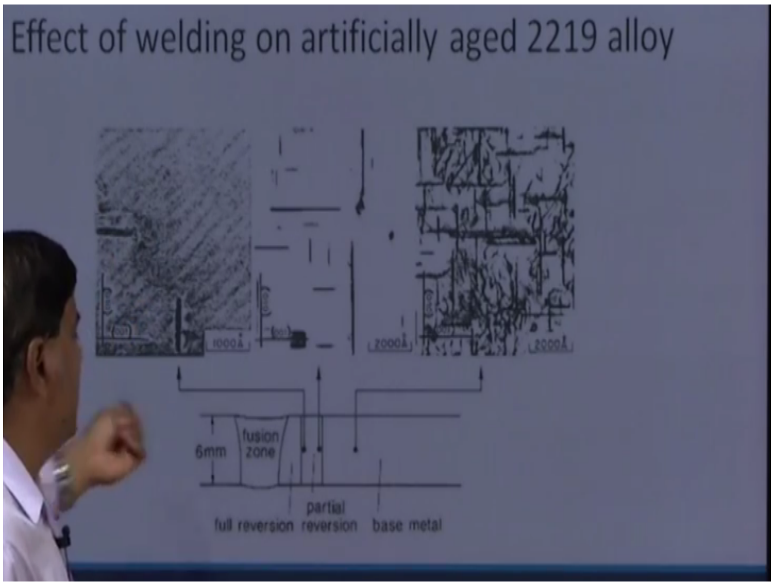

Effect of welding on artificially aged 2219 alloy

So this is what is about the effect of the weld thermal cycle. This is what we can see here when the material is in the precipitation hardened condition like in the base metal condition, it has large number of the precipitates as we approach towards the fusion boundary the number of precipitates have reduced because some of them will get dissolve and as we further approach towards the fusion boundary these have got almost completely dissolved.

So this dissolution is also termed as reversion. Full reversion is taking place close to the fusion boundary leading to the maximum reduction in the hardness while the partial reversion or the dissolution will be taking place away from the fusion boundary so somewhat more precipitates can be seen in the heat affected zone so it will have somewhat higher hardness and maximum hardness in the base metal.

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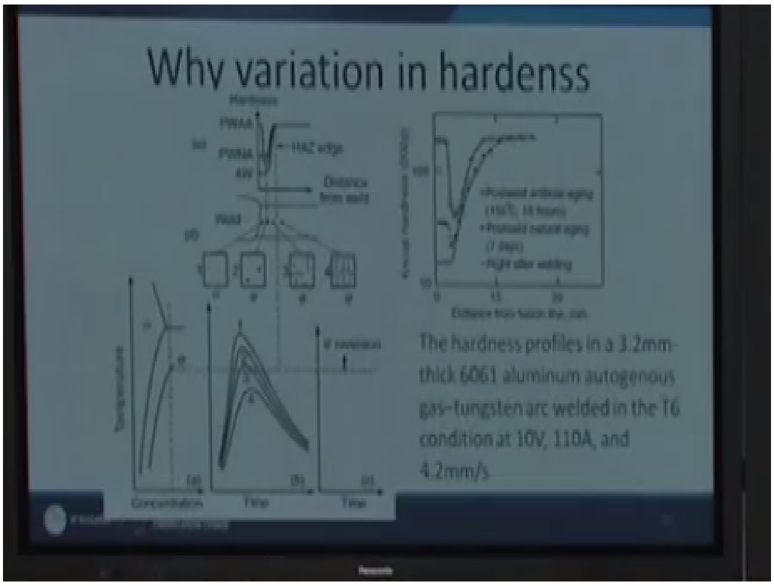

Why variation in hardenss

The hardness profiles in a 3.2mm-thick 6061 aluminum autogenous gas-tungsten arc welded in the T6 condition at 10V, 110A, and 4.2mm/s

So this is what it reflects in this diagram also in the zone 1 corresponding to the next to the fusion boundary experiences the maximum softening, the zone 2 is having somewhat more precipitates than zone 1. So this diagram shows the location 1 weld thermal cycle experiencing in maximum temperature for longest period so it will have the complete reversion or complete dissolution of the precipitates will be leading to the minimum hardness.

While away from this what we can see somewhat less reversion is taking place so the hardness will be somewhat more as compared to the location 1. So increasing number of the precipitates as we are moving away from the fusion boundary and the reduction in peak temperature, reduction in the time for which high temperature is retained. So the reduction in temperature for shorter period above particular temperature will be leading to the limited reversion, somewhat more reversion and full reversion.

And this in turn will be leading to the reduction in hardness of the aluminium alloys or the precipitation hardenable systems next to the fusion boundary. So now I will conclude this presentation. In this presentation, I have talked about the strengthening mechanism of the precipitation hardenable alloys and how the strengthening mechanism can be related to the heat affected zone properties when the metal systems are welded.

So the application of the heat in these alloys basically causes the three things, one is the dissolution of the precipitates also called reversion, coarsening of the grains and third is formation of the non-coherent precipitates and these 3 phenomena, these 3 effects result in the reduction in the hardness and the loss of the strength of the metal system, which is also termed as softening of the heat affected zone in precipitation hardenable alloys. So now thank you for your attention.