Joining Technologies of Commercial Importance
Dr. D. K. Dwivedi
Department of Mechanical and Industrial Engineering
Indian Institute of Technology – Roorkee

Lecture - 41

Lecture 41: Weldability of Work Hardenable and Precipitation Strengthened Metals

Hello I welcome you all in this presentation and you know for the welding purpose we may use the fusion welding or the controlled plastic deformation based approach for developing the metallurgical continuity so that the required joint strength can be realized. So, you know in fusion welding process we supply lot of heat so that the fusion of the faying surfaces can be facilitated. So, in this process when the heat is supplied lot of heat is transferred to the underlying base metal. So, apart from the fusion of the faying surfaces heat is transferred to the base metal. And this heat makes lot of undesirable changes in the base metal characteristics. And if we see the variation in temperature due to the heat being supplied during the welding then this variation in temperature as a function of time is plotted for different points next to the fusion boundary.

Then we will notice that the rate of rise is very high in the zone next to the fusion boundary say the temperature variation as a function of time. If we notice the temperature variation at point 2. as a function of the time then we will find that maximum rise in temperature is reduced and it is taking longer time to reach the peak temperature. So this is for 0.

2 and 0.3 there is further reduction in the peak temperature being attained. So if there is a particular temperature value say 200 degree centigrade for copper or for magnesium 150 degree centigrade for aluminium 450 degree centigrade for iron. So, say this is the recrystallization temperature and as soon as the metal is exposed to the temperature above this temperature it will be experiencing the recrystallization by formation of the new strain free grains in case of the work hardened metals. So, the regions which are very close to the fusion boundary in case of the work hardened metals they will be experiencing very high temperature and that too for longer period this is what is evident from this diagram.

This is the temperature above which it is above the recrystallization temperature and experiencing much higher temperature while the point 2 and point 3 will be experiencing somewhat exposure to the higher temperature for somewhat lower periods and lower peak temperatures. And this kind of variation will have the direct effect on the extent of the recrystallization and the grain growth which will be happening next to the fusion boundary. And therefore there will be lot of variation in the mechanical properties of the heat affected zone of the work hardened metals and in general it is the softening which is observed. this schematically say this is the plate which is being welded through the fusion welding process. So this is the weld zone after solidification we are getting weld zone and next to the weld zone there is a weld metal and at different locations if we see 0.

1, 0.2 and 0.3 and respective Well thermal cycles if we notice then 0.1 will be experiencing very high temperature, 0.2 somewhat lower temperature, 0.3 will be experiencing further lower temperature.

And if we try to see the very rise in temperature beyond the recrystallization temperature then it will be highest. for the longest period for 0.1 then somewhat lower temperature and for shorter period for 0.2 and further lower period for 0.3 and its effect those the point which is experiencing highest temperature for longer period that will be experiencing the greater recrystallization as well as the greater grain growth and if the greater recrystallization is taking place this will be in complete annealed state.

While the locations away from the fusion boundary which will be experiencing the higher temperature or the temperature above the recrystallization temperature for shorter period they will be experiencing the partial recrystallization and that is why the hardness or strength will be somewhat more. away from the fusion boundary will be experiencing further lower temperature for shorter and exposure to the recrystallization temperature for further shorter period that will be experiencing further less adverse effect on the hardness and strength. And that is why minimum hardness will be there in the weld nugget zone, weld metal zone as well as next to the fusion boundary. And then the increasing hardness, so this increasing hardness is attributed to the reducing extent of the recrystallization and the grain growth effects. Now if metal A in form of plate is subjected to the 20% reduction like this or it is subjected to the 80% reduction.

And if we measure so the work hardening definitely work hardening effect will be more with the one will be less with one which has been reduced by 20% as compared to the another one which has been reduced. So, work harding effect will be more and if you measure the yield strength of this metal subjected to the 80% reduction will be more as compared to that of the yield strength of the metal which is subjected to 20% reduction. When both the metals are subjected to the fusion welding then how the variation will be taking place. The one which is subjected to the 20% reduction will be having the lower yield strength as compared to the one which has been subjected to the 80% reduction. So, the one which has been subjected to the 80% reduction will be having the higher yield strength like this and which is subjected to the lower percentage reduction like say 20% yield strength will be less.

So this is you can say the base metal strength subjected to the 20% reduction and the base metal yield strength of metal subjected to the 80% reduction. So obviously one which is subjected to 80% reduction will have the higher yield strength but when we see this is about the distance from the weld centre and this is about the hardness or yield strength variation. So both the metals. are having approximately similar kind of the hardness and yield strength in the weld zone or next to the fusion boundary. So, while if we see the base metal one which has been subjected to 80% reduction is having much higher yield strength as compared to the one which has been subjected to 20% reduction.

Since the minimum since the weld metal or the hardness of the metal next to the fusion boundary in both the cases almost same. So greater reduction we can notice in case the metals which has been subjected to the greater strengthening by work hardening as compared to the one which has been subjected to the lesser strengthening by work hardening. Because all the work hardening effects will be eliminated by the recrystallization and grain growth effects. So that is why harder the metal strengthened by work hardening greater will be the magnitude of the strength loss. So in this case the strength loss will be this much say for metal subjected to the 20% reduction for a strength hardening.

On the other hand metal strengthened by work hardening with the 80% reduction. So this will be experiencing the greater reduction in the yield strength as well as hardness. Now this we will see with this schematic the yield strength of the metal one which is subjected to the greater strength through the more work hardening base material of course will have the greater yield strength but after the welding. They will have approximately similar yield strength as that of the one which has been less work hardened. So, the one which has been more work hardened will be experiencing the greater strength loss as compared to the one which has been less work hardened.

Now coming to the grain growth in the heat affected zone, we have seen that in the near fusion boundary the temperature exposure is higher and that is also for the longer period and so both combination of the high temperature as well as longer period exposure leads to the greater grain growth. in the region next to the fusion boundary. While those zones which are away from the fusion boundary they will be experiencing lower temperature rise and that too for shorter period and that is why the grain growth will be lower in case when the point is located away from the fusion boundary or the heat input is very limited for development of the weld joint. This is what we can see here the similar kind of the logic the weld has been made this is the weld metal. The point next to the fusion boundary away from the fusion boundary and further away from the fusion boundary and respective weld thermal cycles 0.

1, 0.2 and 0.3. So 0.3 is experiencing lower temperature rise and 0.1 is experiencing the maximum temperature rise for longer period. So, higher temperature retention for longer period is available with the 0.1 and that is why it experiences the greater grain growth as compared to the points which are located away from the fusion boundary. So, the finer grain structure will be there away from the fusion boundary while the grain growth maximum grain growth will be observed next to the fusion boundary.

fusion boundary and we know that from the hull patch relationship the yield strength or the hardness of the material is found inversely proportional to the average grain size of the material or the average grain diameter. So, greater is the grain diameter lower will be the yield strength, lower will be the hardness and that is what will be reflecting when we see the variation in the hardness of the material as a function of distance from the fusion boundary. So in this case also if we notice that this is the fusion boundary the 0.

1, 0.2 and 0.3 and the respective hardness if we plot hardness will be minimum 0.1 somewhat higher for 0.2, 0.3 and 0.4 say this is in base metal, this is partially affected zone.

So this we can say H3, H2 and H1 heat affected zone 1, 2 and 3 and the base metal. So, the point 1 is next to the fusion boundary will be experiencing the much higher temperature for longer period. So, it will be experiencing the complete recrystallization and the significant grain growth while the point 2 experiences somewhat lower temperature for shorter period. So, the grain growth will be limited recrystallization will be. Then further lower temperature for 0.

3 and further lower temperatures for 0.4. Thereafter there would not be any change, so this gradual increase in the hardness or of the metal on moving away from the

fusion boundary is attributed to the increasing grain growth. So those metals which are primarily strengthened through the work hardening effect or the grain refinement effect. So, this kind of the variation is true for variation in hardness of the properties due to the recrystallization and grain growth is true for them.

This is the another schematic which is showing the variation in the weld properties and heat affected zone properties as a function of the heat input. We know that for fusion welding we have to supply lot of heat so that the melting of the faying surfaces can be facilitated. Different processes require different amount of the heat to be supplied for ensuring the fusion of the faying surfaces. Low energy density processes like gas welding, shielded metal arc welding processes require higher energy, higher heat input as compared to the high energy density processes like laser and electron beam. So low energy density processes like shielded metal arc welding it will be required to supply lot of heat.

to facilitate the fusion of the faying surfaces and it forms the very large weld metal zone and large heat affected zone. On the other hand if we use high energy density process then it will require lesser heat input, weld zone size will be limited and the heat affected zone size will also be limited. And then that is what we can see these are the 3 different 3 plates of the same thickness same material when subjected to the different heat input. The minimum heat input in this case weld zone size is limited, heat affected zone is limited then wider heat affected zone and as well as the weld metal zone and further wider weld metal zone and the heat affected zone and corresponding variation if we see in the first case next to the fusion boundary what we will notice that the weld thermal cycle is of this kind where the exposure to the higher temperature for any temperature if we will take. Exposure if we take any point away from the fusion boundary or next to the fusion boundary what we will notice that when the heat input is minimum the weld thermal cycle is corresponding to this point 1 which shows that high temperature exposure for any temperature is shorter for the case 1 when well heat input is less and the high temperature exposure is increasing with the increase of heat input and in this case the high temperature exposure at a high temperature is maximum.

So when the heat input is high, high temperature exposure above the given temperature will be high. and that will be increasing the grain growth. So greater is the heat input greater will be the time for which the high temperature exposure will be there and that will be in turn will be increasing the grain growth tendency. So if you will notice the schematically this one the grain size corresponding to the temperature Heat input 1 the grains are very fine corresponding to the 2 grains are somewhat coarser and further coarser for the case 3 when the heat input is maximum. So, increasing heat input per unit length of the weld means it is net heat input that is given in terms of kilo joule per mm.

So, if we try to see this with respect to the process like as I said gas tungsten arc welding process is somewhat low. energy density process as compared to that of the laser or electron beam welding process. So electron beam welding will require lesser heat to be supplied for facilitating the fusion of a given metal as compared to that of the gas tungsten arc welding process. So GTAW in case of the GTAW we have to supply more heat. So, the weld thermal cycle will be less favourable with regard to the heat input as compared to that of the electron beam welding process.

So, if we compare the weld thermal cycles corresponding to these two processes we may have the weld thermal cycles like this. The other one this one is for the GTAW and this one is for the electron beam welding process. So, this weld thermal cycle here we have temperature and here we have time and if we take any temperature above which exposure is observed then this will be for shorter period as compared to the one for the GTAW process. So, for GTAW the high temperature exposure will be for longer period as compared to that So, this is the you can say the fusion boundary grain structure of the work hardened metal of the aluminium copper alloy when it is subjected to the welding by electron beam welding The structure is like this and when it is subjected to the gas tungsten arc welding the structure is coarser. So, if we see this GTIW is also the coarser grain structure as compared to that of the electron beam welding which will be resulting in the finer grain structure.

And this is directly attributed to this case where the heat input is less the weld thermal cycle is more favourable with regard to the grain size as compared to the case when the heat input is more and weld thermal cycle is unfavourable with respect to the grain size and this will be leading to the greater Greater grain sizes will be leading to the greater reduction in the hardness and the yield strength of the metal. Now we will see another metal system which is not strengthened by the work hardening but strengthened by the precipitation hardening. There are many steels. copper, aluminium, titanium alloys which are designed to get strength from the development of fine precipitates which are hard, well distributed.

in the completely soft and tough matrix. This is how the strength is imparted and the general principle for imparting the strength in all these cases is that such kind of the metals say A and the solute. So, these metals show the variation in the solubility to the solute as a function of temperature say this is temperature, this is the solvus line showing the solubility limit for metal B in A. So all the metals which show this kind of the tendency they will have the tendency to show the precipitation hardening behaviour. So this is a prerequisite for precipitation hardening that the solubility limit for solute should vary as a function of the temperature. So, here what we can see like say if we take any alloy A with 2% of the B.

So, at room temperature it may be supersaturated or it may be in form of a intermetallic compounds or it may be in form of precipitates. But when the alloy is heated to the high temperature the B is dissolved completely into A and this is the limit the maximum amount of B can be dissolved in the A as a function of the temperature below which it will be supersaturated and above which means above this temperature it will be under saturated. like a metal having elements A and B which is designed to get strengthened through the precipitation hardening. When such kind of the metal is subjected to the heating above the solvus line it forms the solid solution. And the process of forming the solid solution through the heating is called solutionizing, so this is first step solutionizing.

Homogeneous solid solution of the different elements present in the metal is formed and once the homogeneous solid solution is formed through the solutionizing step. we follow the quenching. So heating to the high temperature for solutionizing we follow rapid quenching. So that supersaturated solid solution is formed and whatever solutes were there they could not find enough time to diffuse out. So they will be in the supersaturated solid solution state.

thereafter ageing is performed. Now ageing is the third step which can be performed by heating the supersaturated solid solution to the high temperature in range of like say 150 to 250 degree centigrade depending upon the metal or higher temperatures or it can be performed under the ambient condition. like room temperature. So accordingly whenever artificial heating is carried out it is termed as artificial ageing otherwise it is termed as natural ageing when after forming the supersaturated solid solution the component is left at a So, this one is called artificial ageing and designated by the T6 and when ageing is carried out without any external heating it is called natural ageing and the metal is designated as T4. So, one of the typical precipitation hardenable aluminium copper alloy which shows the formation of the different types of the precipitates what we can see here the aluminium with the different percentages of the this is aluminium copper phase diagram and this is the solvus line. So when the and what it shows that the aluminium copper in aluminium can be dissolved maximum up to 5.

6% at temperature at this temperature around 500-550 degree centigrade. And so say this alloy is having say 4% of the copper whenever it is heated to the high temperature corresponding to the 0.1 it forms the supersaturated solid solution alpha. homogeneous solid solution followed by the rapid cooling to the stage 2. So, it forms the supersaturated solid solution, it forms the homogeneous solid solution and then natural ageing is performed or artificial ageing is performed, so during the artificial ageing or natural ageing the different types of the precipitates are formed.

So, this is the sequence in which these precipitates will be formed from the supersaturated solid solution. First the GP zones or the Guinier-Preston zones are formed. Then the theta double dash precipitates which are GP2, Guinier-Pristons II precipitates are formed. Then theta dash precipitates are formed and all these 3 types of precipitates are the metastable in corrector. And then the stable phase which is theta, theta is formed this is of the body central tetragonal structure.

And further what we can see here this is about the formation of the Gp Guinier-Friston phases as a function of temperature and the copper concentration. So if we notice this. These are the temperature values up to which the GP1 will be stable thereafter it will get destabilized or will get dissolved. So, the first on the heating like say a precipitation strengthened aluminium copper alloy whenever it is heated above these temperature lines.

this line above which it gets dissolved. So heating above this say 200 degree centigrade GP phases will be dissolved and thereafter theta double dash phase will be dissolved and then theta dash phase will be dissolved. So, there will be these precipitates will be getting dissolved with the increase of temperature and these are the hard precipitates which will be imparting the desired strength to the aluminium copper alloys. Likewise the similar types of the precipitates like Mg2Si in aluminium magnesium silicon system. and MgZn2 is formed in case of the aluminium zinc magnesium system. So different types of the precipitates are formed with the different kind of the metal systems and these will be stable.

at room temperature or the temperature up to a particular limited value and thereafter these precipitates will tend to get dissolved. These precipitates are extremely fine in size and their size is measured in angstrom. What we can see these are the fine precipitates. of aluminium copper showing the theta does precipitate and these are of the different sizes and thicknesses. This is what we will see in this next slide like the GP zone phase which are formed very next to the very low level then GP theta double dash then theta dash, so GP theta double dash and theta.

So, these are the stable, these are the different types of the precipitates and these are stable up to the different temperatures. So, here we have copper, here we have temperature value. So, the GP zones these are the coherent precipitates with the lattice and of thickness 4 to 6 Angstrom and 80 to 100 angstrom in the diameter. These zones are richer in copper because the copper is finer in size than the aluminium. So GP zones whatever are formed, so these are basically the solid solutions of copper and aluminium having the more percentage of copper because it is finer in size.

And since the crystal structure, since the GP zones are coherent with the lattice in the solid solution and therefore the lattice is strained around the locations wherever GP zones are present. We can see here these are the various precipitates in form of and their thicknesses and the diameters is as I have said for GP zones it is 4 to 6 angstrom or like 80 to 100 angstrom in the diameter. Then theta double dash phase is also coherent its size ranges from in terms of thickness 10 to 40 angstrom. diameter ranges from 100 to 1000 angstrom and on the other hand the theta dash phase is semi coherent with the lattice and its size ranges from the 100 to 150 angstrom in thickness and 100 to 6000 angstrom in the diameter. And the sizes will depend upon the temperature and the time for the exposure which has been given during their formation stage.

And finally the theta phase which is incoherent with the lattice which is formed in the solid solution. So the maximum strength is offered by the coherent phases. and somewhat less strength is offered by the semi coherent and the minimum contribution towards the strength is offered by the incoherent phases. Since these phases and these precipitates are not stable at a high temperature, so whenever the heat is applied during the welding. these precipitates will get dissolved and will be leading to the reduction in hardness.

So, the maximum dissolution will be occurring next to the fusion boundary wherever the peak temperature is high. So, it will be leading to the maximum softening then somewhat reducing softening away from the fusion boundary. So, the low stacking fault energy metals when they are subjected to the welding by the solid state joining process. The behaviour of the weld joints with regard to the structure and properties is completely different as compared to what we normally observed in case of the fusion welding.

So, the such kind of the metals are like the steels, copper alloys. In steels basically austenitic stainless steel and the head field steel, high manganese steel these are the metals which show the lowest stacking fault energy and very good the work hardening capability. Similarly among the aluminium alloys like the aluminium magnesium alloys of 5000 series like 5086 or 5052 such kind of the alloys also show the good work hardening tendency. So when such kind of the metals when subjected to the joining. joining by the plastic deformation based welding processes where whether the plastic deformation is occurring at a micro level at the mating interface like in ultrasonic welding or explosive or the macro scale deformation is taking place macro scale deformation occurring like in the friction stir welding or friction welding. So, in all these cases wherever the plastic deformation is involved that causes the strain hardening.

in the region which experiences the plastic deformation and because of this strain hardening basically increase in the hardness of the metal and the yield strength takes place. So, if we take any example where this kind of the joining is applied where either the large scale plastic deformation like in friction stir welding. where along with the plastic deformation some frictional heat causes the rise in temperature of the nearby metal system. And so in this case also like where the heat is generated due to the plastic deformation as well as friction that causes the rise in temperature of the metal next to the weld zone.

And this also leads to the development of the heat affected zone. So as per the metal system type of metal system the properties of the heat affected zone due to the weld thermal cycle will be different and that may vary significantly that may change significantly. While in case of the weld metal the plastic deformation will be causing the work hardening strain hardening and so in any case the hardness and the strength of the weld metal produced by the plastic deformation based joining processes will be higher. So there can be very extreme cases like. These are two components of the work hardenable metal when subjected to the joining through the plastic deformation based processes which is involving macro scale deformation. So, such kind of the system like 5000 series aluminium alloy when subjected to the deformation.

So, weld zone experiences the rise in deformation. hardness like this and this increase in hardness is attributed to the work hardening behaviour. But the heat generated in the weld zone due to the deformation in the friction will be leading to the development of the heat affected zone. So, the heat affected zone in this case will be experiencing the recovery. and the recrystallization and therefore this zone or the heat affected zone being formed in the work hardenable metal systems of 5000 series aluminium alloys basically experiences the softening due to the recovery and the recrystallization. And because of this whatever the work hardening effect was present in the base metal that will be neutralized.

While the weld metal zone which has been severely plastically deformed will have the effect of the work hardening or the strain hardening. So, in that case the hardness of the heat affected zone hardness trend of the heat affected zone will be different as compared to what I have shown more precisely it will be like this. like say if we start this is the weld zone and this is the heat affected zone HAZ both the sides and the weld zone HAZ zone. So the base metal will have the higher hardness Then the softening will be observed in the heat affected zone, then weld metal again will have the higher hardness due to the severe work hardening. And then again the heat affected zone will have the lower hardness and then again the base metal will have the higher hardness.

So this soft zone formation in both the sides of the weld metal region is attributed to the recovery and recrystallization. But this kind of trend may not be the universal for all other metal systems. So, wherever recrystallization and recovery is dominating that will be leading to the softening. And if in some of the metal systems like carbon steel if the heat affected zone is experiencing the transformation hardening then that zone will also have the higher hardness as compared to the base metal. So, for example say in case of the carbon steel subjected to the plastic deformation based processes then the trend of the hardness variation or the hardness distribution across the weld will be completely different.

So, the maximum hardness will be experienced by the weld metal then somewhat higher hardness will be experienced by the heat affected zone and the further lower hardness will be there for the base metal. So, the heat affected zone will also have the higher hardness as compared to the base metal. So, this higher hardness in case of the hardenable steels wherever the transformation hardening is involved that can be attributed to the transformation hardening while in the weld nugget It may be the combination of the work hardening as well as transformation hardening because lot of heat is generated coupled with the plastic deformation. So, that causes the transformation hardening as well as the work hardening. So, you may have the maximum hardness in the weld metal and somewhat lower hardness in affected zone and further lower hardness in the base metal.

And this kind of trend can be there both the sides in case of the transformation hardenable systems like the steels when they are subjected to the solid state joining involving the plastic deformation. Now I will summarize this presentation, in this presentation initially basically I have way by which the heat associated with the fusion welding will be affecting the heat affected zone of the work hardenable metals. And what is the underlying principle of the precipitation hardening metals and the way by which probably the heat of the welding can affect to the properties of the HAZ properties of the precipitation hardenable metal system. Thank you for your attention.