Mathematical Modelling of Manufacturing Processes
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Lecture - 27
Hybrid Welding, Residual Stress and Distortion

Hello everybody, now I will try to discuss about hybrid welding processes. So we have discussed that friction welding processes as well as solid-state welding processes. Now how it is possible to hybridize the process to gain certain kind of advantages. So let us see that what way we can get the advantage if by hybridization of the welding processes. So we will discuss only 2 welding processes.

Once is the normally laser assisted hybrid welding process which is infusion laser and second one is that hybridization of the friction stir welding processes.

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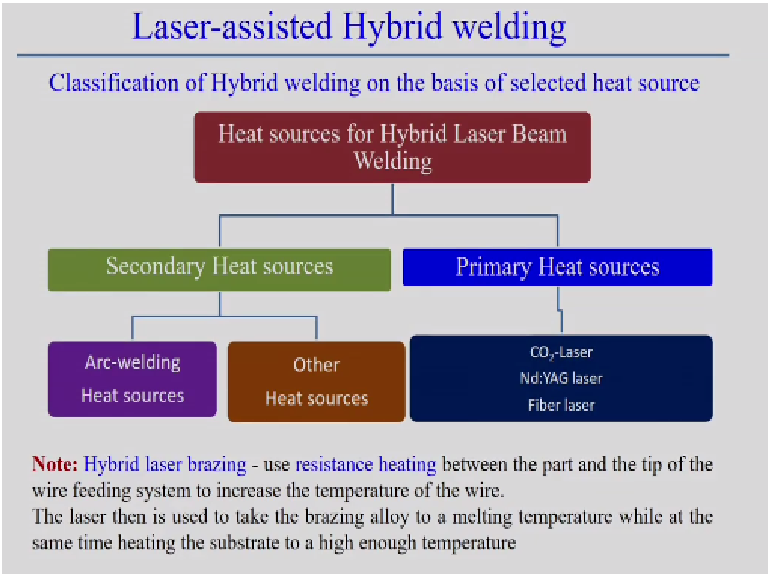

So laser-assisted hybrid welding in this case definitely it comes under the category of the friction welding process. So in general if you classify the hybrid welding process the heat sources can be used in the two. One is the primary heat source another is the secondary. Primary heat sources is the mainly the laser, CO2, Nd:YAG laser, fibre laser and then secondary heat sources can be arc welding or can be other type of the heat sources.

So laser is the primary source and laser is heated by any kind of arc, such that we can get the benefit from both the processes and overall benefit we can found out to gain certain advantages which may be difficult using only single process, single source, either laser or either arc processes. Even it is possible to create the laser hybrid, laser brazing processes also.

We know that brazing process the resistive heating normally used between the 2 components and to increase the temperature of the resistive heating basically increase the temperature of wire, but when it can be assisted, laser is used the brazing alloy to a melting temperature while at the same time heating of the substrate to a high enough temperature. So it melts the bridge alloy at the same time, the substrate material also brings relatively at high temperature. So that is why in that way laser helps to develop the hybrid laser bridging system also.

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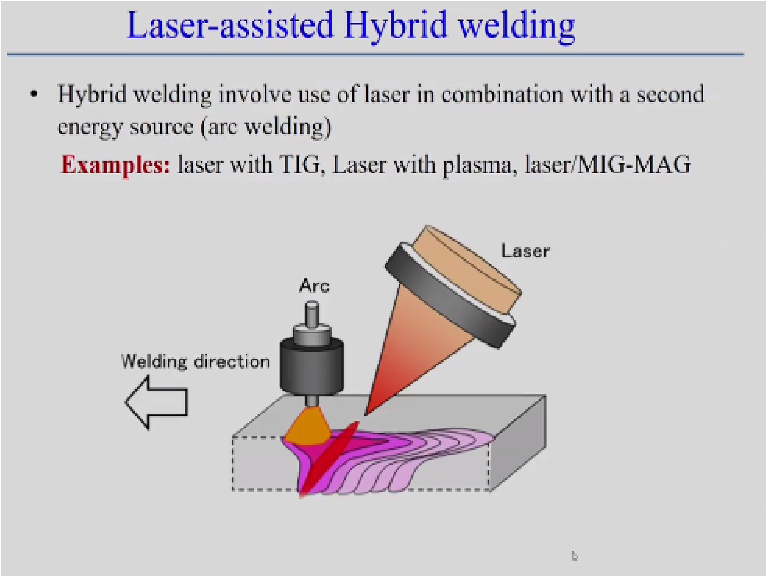

So apart from that we can see the laser assisted hybrid welding process, the hybrid welding involves laser combination with the second energy normally arc welding we involve. Arc welding for example, laser with T welding process, gas tungsten arc torch we can use in the hybrid process, laser with plasma also can also be used, laser with MIG or MAG welding processes so gas metal normally laser is assisted with the gas metal process.

So we can see that it is an application of the arc and it is an application of the laser and they march together, focus together at a particular point and we know that normally laser actually creates the high depth of penetration as compared to arc and other way arc also creates relatively wider profile, but depth of penetration is literally low, but what kind of advantage we can get by combining all this two.

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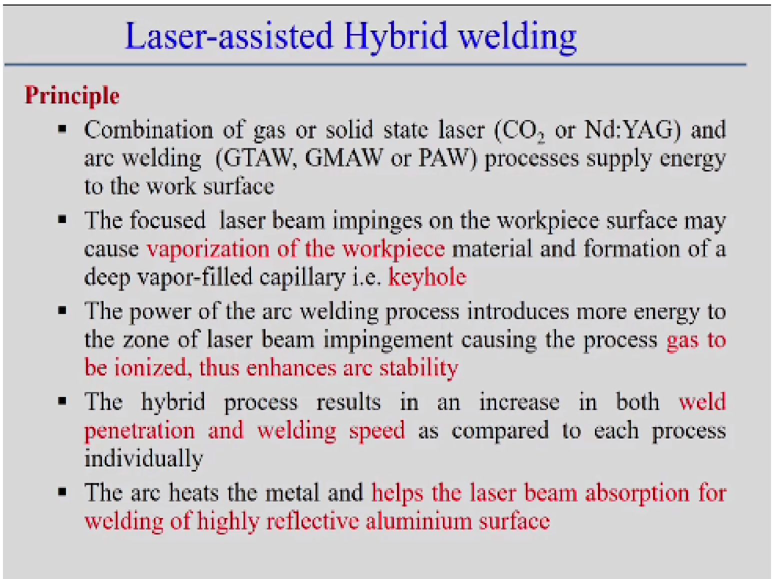

So combination of all these gases normally CO2 or Nd:YAG laser are along with arc, GTAW, GMAW, plasma arc welding process can be used here in this case that focus laser beam the advantage of focus laser beams creates the high depth of penetration and vaporization it, workpiece may cause the vaporization and definitely care some kind of keyhole formation.

Now power of the arc welding can be introduced more energy. So once the keyhole formation by the laser is there, so both it can works if we introduce the arc here. So arc actually helps to absorption of the laser energy particularly when we can use in case of high reflective material. On other laser also helps to stabilize the arc. So both the cases it is beneficial, so that it enhance the stability of the arc.

And of course both the cases if we increase the combined effect can be, we can use in the both weld penetration and welding speed. So we can use the relatively higher welding speed which may have limitation in case of individual processes and at the same time if it is possible to enhance the weld depth of penetration by using the hybrid processor. So both can be used and of course other the laser beam absorption for the welding of the high reflective surface.

So if there is high reflective surface in that cases, the absorptivity of the laser is relatively low as compared to the other process. So in that cases so absorptivity can be increased, or enhanced by the application of the arc welding processes.

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Laser-assisted Hybrid welding

Overall benefits with respect to conventional welding process

- High efficiency process (around 80%)
- Ability to bridge relatively large gaps (of more than 0.5 mm)
- Slow cooling rates due to relatively lower welding speed and higher heat input
- Welding of highly reflective materials is generally not difficult
- Metallurgy of weld can be adjusted and larger gap can be filled by adding filler material

Now what are the benefit we can see, the high process efficiency is possible by application of both the, this high process efficiency is the more amount of the heat transfer, energy transferred to the substrate material is possible which may be less as compared to the individual process. For example, if we use the laser welding process in a particular and if we assume there is a conduction of laser welding process.

So in that cases the efficiency, absorption of the energy to the substrate material is very less, immediately in case of arc welding processes also although it is relatively high as compared to the laser welding processes but combination of this laser and arc it becomes very high, maybe around 80% this is just a figure, we can say relatively high. Ability to bridge relatively large gap.

If there is a gap between these two components if specific to very complex geometric shape even for more than 0.5 millimetre then it is also possible to create the gap even if necessary by using some kind of the filler material. Cooling rate is relatively slow due to relativity lower welding speed and higher heat input. Because of the low heat input, higher heat input and if added with the some kind of the low speed of a particular welding process, then cooling rate can be slower in this cases.

So that is another characteristic of this type of process as compared to the individual processes and of course high reflective materials can be joined easily using this hybrid processes and metallurgical weld can be used even for larger gap, but using some kind of the filler material. So all this kind of advantage we can get in case of laser assisted hybrid processes.

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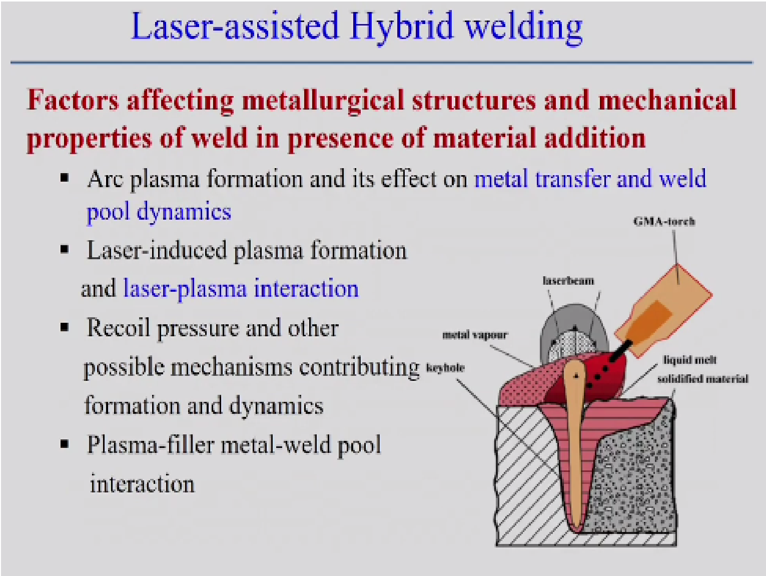

What are the factors normally affects the hybrid welding processes, the properties of the presence of the material addition even for example, we can use the hybrid process by using the gas metal, gas metal arc welding process can also be used along with laser, but in this case arc plasma formation and it effects on the metal transfer and the weld pool dynamics is also important to study in hybridization of the process using the gas metal arc welding process?

That another important aspect in the physical basis, the laser induced plasma formation and the laser plasma, how laser plasma interact during this process that is also another field of study. Recoil pressure if there is a formation of the keyhole, the recoil pressure and the other possible mechanism contribute to the formation of the dynamics, stability of the keyhole all this matters and of course this become more complex, stability of the key hole and there is interaction with the another heat energy source.

And along with that there is a transfer of the mass. So plasma filler metal, weld pool interaction that is also how plasma interact with the filler material that is also another field of study which involved in this laser assisted hybrid process and of course modelling of all this process considering all this physical phenomenon happening during the process is really a very difficult task or it becomes more complex.

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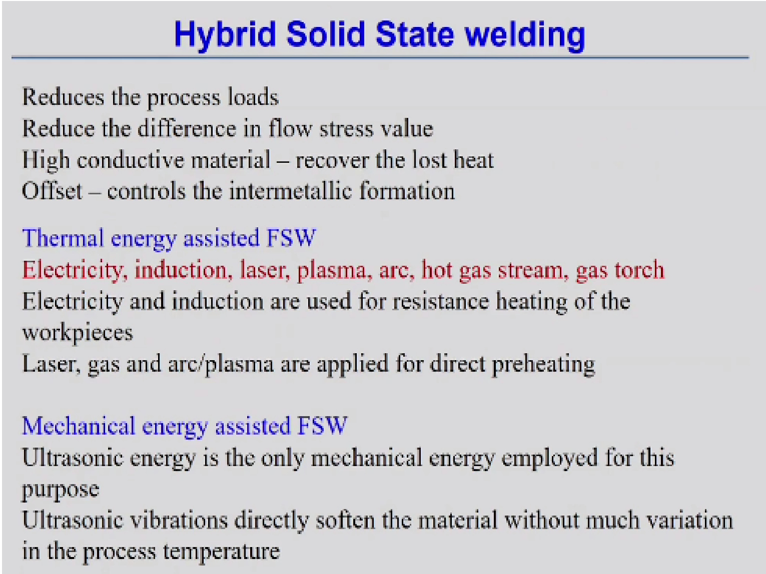

Now if you look into that solid state welding process how it can be hybridized and what are the different bases for that and of course if you hybridize the solid state welding process, normally with reference to friction stir welding processes it actually reduces the axial load first thing, reduces the difference in the flow stress value.

So definitely reducing the flow stress value specifically for joining of the similar materials and of course high conductive material can also be used because high conductive material if you use hybridize the process, so we can supply more energy to the high conductive material and that can recover the lost during the process and then solid state welding process can be successful in this cases for hybridization specifically for high conductive material.

And of course if you introduce some kind of the offset in friction stir welding process also that also beneficial to control the intermetallic formation. So let us see what way it is possible to hybridize the FSW processes on different ways. First is the thermal energy assisted FSW process. What thermal energy assisted electricity can be direct electricity can be used, induction heating can also be used.

Laser can also be used but to a low intensity laser we can use, plasma can also be used but plasma should melt the surface just to heat the surface, arc can also be used, gas stream can also be used and even simple oxyacetylene gas torch can also be used to hybridize the FSW process which is normally called the thermal energy assisted hybrid FSW process. Electricity and induction are used resistive heating basically them when you use the electricity to inducing the, actually creates kind of the resistive heating in the substrate material.

And of course laser gas and arc plasma is directly applied for the preheating, to preheat the substrate material. So this we can hybridize, of course mechanical energy assisted FSW can also develop that is called we use the ultra, if we possible to use the ultrasonic energy which is the only mechanical energy employed for this purpose. So ultrasonic vibration assisted friction stir welding process.

So in this cases ultrasonic vibration normally directly soften the material without much increment of the temperature of the substrate material. So this way this is the first option, the second option is the mechanically energy assisted FSW process has been involved or has been developed to get certain advantage.

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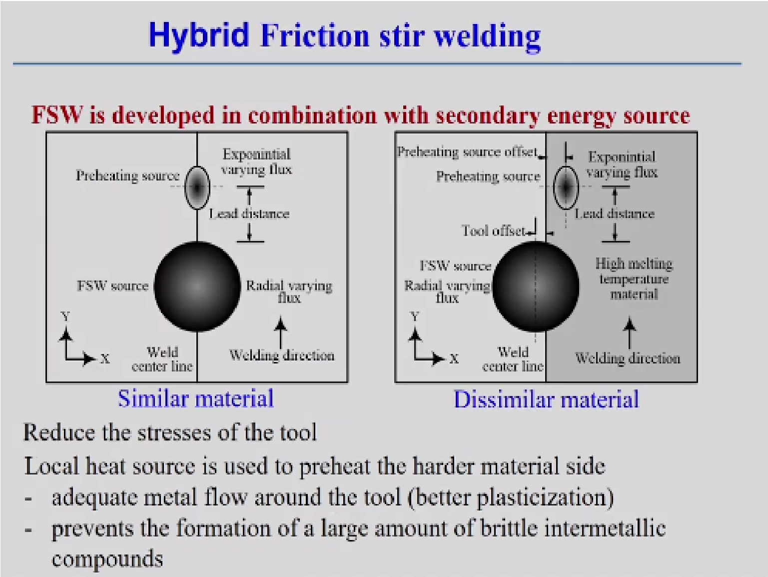

Let us look into that, so if you see first one is the similar material and in FSW, friction stir welding process and second one is the dissimilar material. So we can see the similar material also we can use if it is possible to hybridization of the FSW process for similar metal as well as the dissimilar material, but what parameters need to be controlled during the similar and dissimilar combination of the materials.

So in case of similar type of material if you want to join in using FSW process and we can introduce the arc also in the in front and in this case there is a some lead distance between this two may also happen and this one is the FSW tool source, primary source and this is the secondary source, preheating source. At that preheating source basically soft the material and it actually makes easier for the FSW tool to mixing plasticization of the materials.

So now of course it actually we can get the indirect benefit by hybridization of FSW process using some kind of the secondary heat source. First is that it actually reduces the load on the tool and of course it reduces the stress of the tool, so in that way indirectly it can enhance the life of the tool and of course flow at the same time the better plasticization is also possible using the hybridization of the FSW process.

And of course prevents the formation of the large amount of the brittle intermetallic compounds, but when you try to look into that hybridization of the FSW process by using in case of dissimilar materials in that case we can found out that this is a FSW source, the FSW tool and that FSW tool is upset towards the normaly the softer material and the secondary heat source is normal shifted towards the high melting point or you can say the harder material.

So in this case this secondary heat source for the high melting point material they actual heat the substance material and little bit more amount of heat is generated as compared to the substrate material and that more amount of when heat is generated it actually reduces the flow stress value. So in that case the difference of the flow stress between the softer and harder material can be reduced.

And second thing is that when you give the tool offset towards the softer material the primary heat source that means FSW tool, in that case, the mixing volume may not equal in this cases, there is a difference. So that mixing volume when there is a difference it can control the formation of the intermaterial, but definitely this what it is distance, position or amount of the offset, it can be optimised depending upon the particular system.

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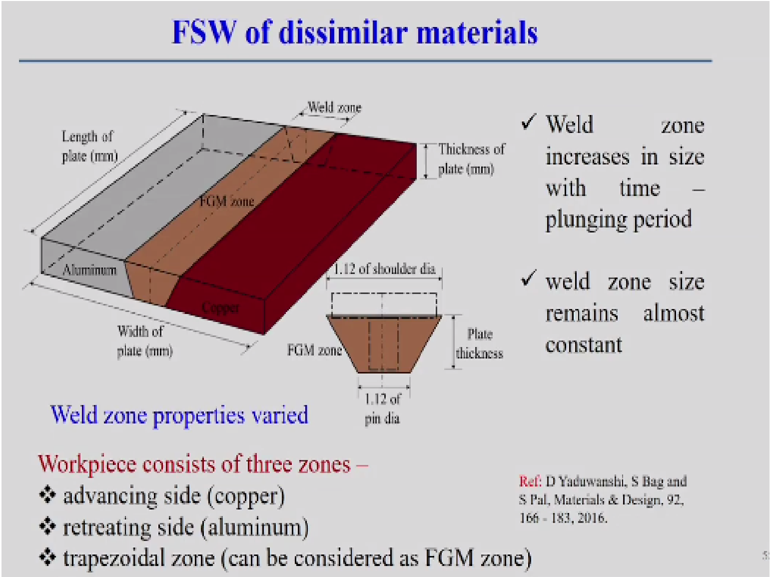

How we analyse the FSW dissimilar material, so when you try to analyse the friction stir welding of the dissimilar material of course using the hybrid process or without using the hybrid process. So what we assume for example, aluminium and copper, both are high conductive material, but heat conductivity is definitely more in case of the copper.

So in this case aluminium copper can be joined at the interface and mixing between these two that creates the we can treat as a functionally graded material. So weld zone increases in size with the plunging period definitely, weld zone remains almost constant that means when moves this direction, the size of the weld zone is more or less remains constant, that is we say it is a kind of stress situation.

But we use the material properties aluminium with this site, we use the material properties, this side but at the middle zone, when there is a mixing of the 2 materials happen that we can say, the mixing properties between the aluminium and copper. So that can be adopted in the different combination of the weightage of the properties of aluminium and copper. So but we can treat as a functionally graded material at this zone.

So normally the position of this thing advancing side copper, retreating side aluminium, and trapezoidal zone which is the mixing zone, the two components that can be considered as a functionally graded material zone. So once we define the 3 different material properties at the 3 different zone, then we can do the simulation, we can estimate what is the temperature distribution within these substrate material.

Of course heat generation model we have already discussed that how heat flux can be estimated when there is an interaction of this FSW tool with the material. So definitely if we use some kind of in hybrid process when we use the secondary heat source we need to add the heat energy from the secondary heat source. For example, if it is arc then we should know the secondary heat source can be like that efficiency volt into amp so voltage ampere we supply.

And what is the efficiency for this thermal efficiency of this process multiply, this is the energy from the secondary heat source. So we just need to incorporate the position, amount of the energy, supplied to the solution domain from the secondary heat source and we can do the simple calculation of what we did in case of friction welding process.

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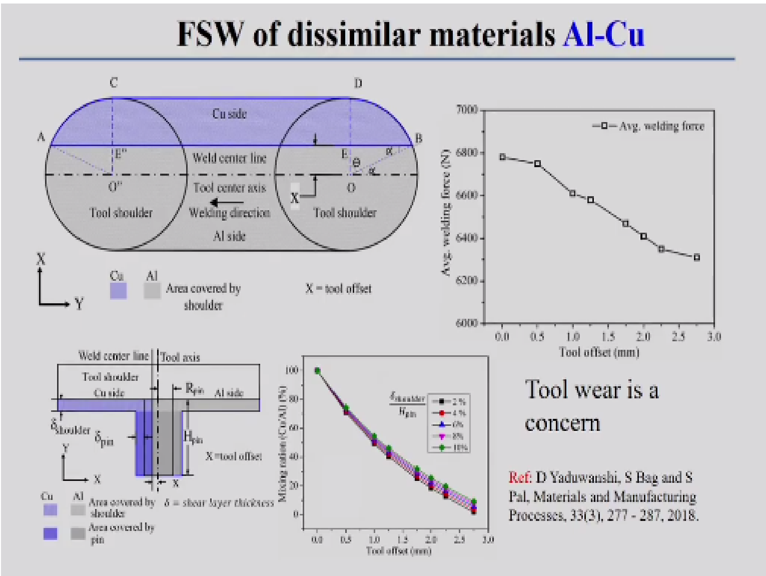

Of course the other parameter FSW of dissimilar material for example,,, aluminium, copper we can roughly estimate what is the volume mixing ratio upon the mixing ratio then percentage of the copper and aluminium are mixed with this each other just simply what is the projected area on the surface and we can estimate by this from the projected area what is the if we assume the it is uniform throughout the thickness just simply we can estimate what is the volume is mixing basically copper with the aluminium which is a function of offset.

So which is a function of tool offset and you see there is a reduction so is here, offset zero means equal volume or mixing both aluminium and copper, but if two high offset then not equal volume, the mixing these two reduces to around maybe 20%-30% is possible. So that is how we can control the mixing ratio and other way indirectly we can control the formation of the intermetallic during the FSW process.

And of course if we use the tool offset also there is a reduction of the average welding force, so it reduce from around 6800 Newton to it is possible to reduce up to 6400 Newton but of course there must be some limitation of the tool offset which is limited by the dimension of the tool that means radius of the tool can decide what is the amount of the offset can be given to a particular process.

But of course in general, in hybridization of the process, the tool wire is the major concern during the FSW process. So by hybridization of the FSW process in that cases tool wire can be reduced considerably with the application of the secondary heat source.

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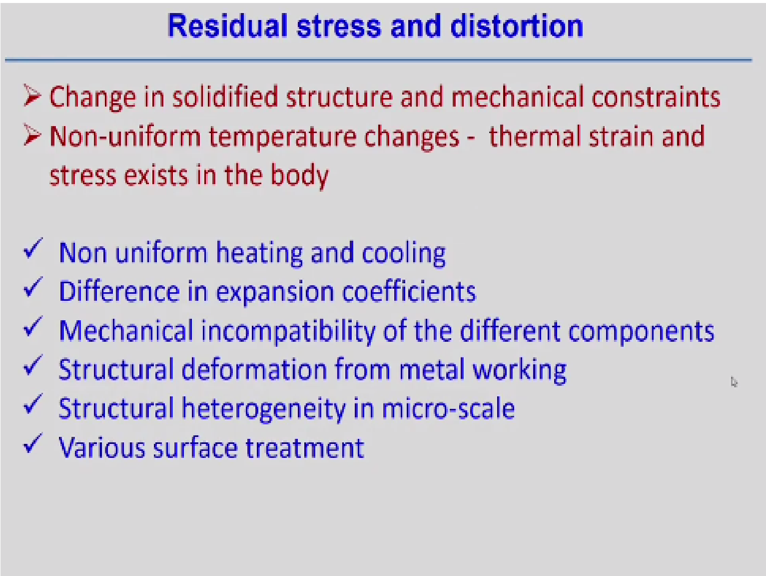

Now come to the other elements of this course that is residual stress and distortion and residual stress and distortion which is associated with the any kind of metal working process, it maybe welding process in some other processes, but specific the fusion welding process there may be the change in the solidified structure and of course the mechanical constants and that is stress generated accordingly.

And of course it depends on the non-uniform temperature distribution changes what is the thermal strain induced during the process, that actually decides what is the amount of the residual stress and distortion, of course along with the what are the metallurgical transformation normally happens during the early process. All this matters to decide the amount of the residual stress and distortion in an welding structure.

So what are the typical causes of the residual stress and distortion generation in welding structure. First is the non-uniform heating and cooling, second one is the difference in the thermal expansion coefficients. Third one mechanical incompatibility of the different components, there is an incompatibility of the different components may exist, then structural deformation of the metal work, that is also, that also create some kind of the residual stress.

Structural heterogeneity, it is not homogeneous structure in the microscopic point of view, in that case we can get some sort of residual stress generation during the processing of the material and of course various surface treatments of any kind of component that actually induces residual stress, so in general residual stress and distortion not only subjected to welding processes maybe some other metal forming process in any other manufacturing process it can induce at least some sort of the residual stress in a structure.

But our attention is focused only on the residual stress and distortion specific to the welding processes.

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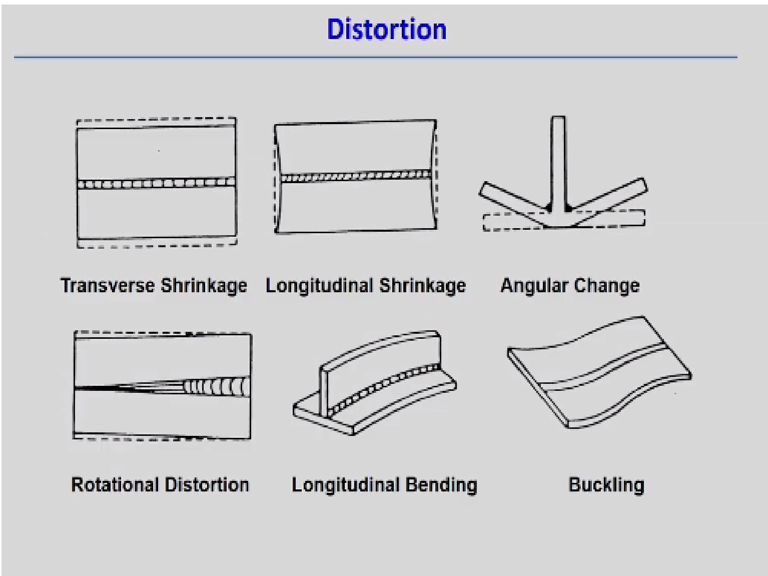

So in case of welding process we can see what are the different type, we can classify what are the different types of the distortion, first is that transverse shrinkage may also happen. So once this indicates the welding zone, so once 2 plates are joined, it can sink towards this direction and that creates kind of transfer shrinkage. Longitudinal shrinkage in longitudinal direction with dotted line indicates the original position.

It can shrink towards these thing after welding then this type of distortion you can say the longitudinal shrinkage, angular change, so dotted line use the initial position after welding it can take this kind of shape, that indicates the angular change from this level to that level. Rotational distortion, so once initial position was the dotted line but after welding it can take this kind of safe one particular direction.

And gap is gradually decreasing and towards these thing. So that type of distortion we can say rotational kind of distortion and longitudinal bending may also happen during the welding processes and of course buckling which is normally happens in case of very thin sheet. So all this kind of distortion, types of the distortion normally involve or combination of the different types of the distortion normally observed in case of fusion welding processes. But this kind of distortion is normally very less in case of solid state welding process.

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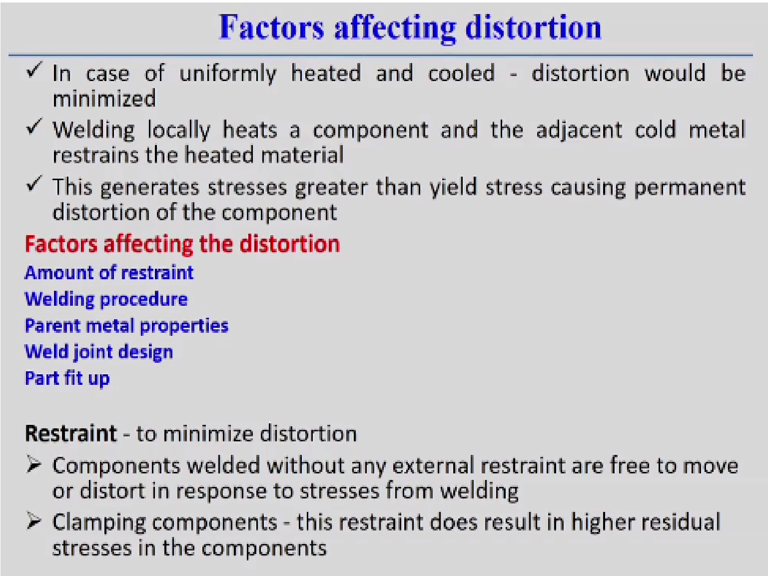

Now see what are the factors that affects the distortion. So in case of the uniformly heated and cooled structure, deformation would be minimised. So in welding process we are applying the heat flux at particular zone, the temperature gradient is very high near about that zone as compared to the base metal. So there is a difference in the temperature. So that we can say that non-uniform heating occurs and once when cooling also happens in non-uniform way.

So that is why it introduce some amount of the distortion in these things, but of course if it is possible to create the situation that uniform cooling and uniform heating is possible any kind of this process as much as possible then this actually reduces the amount of the distortion, this can be minimised. Of course welding locally heats a component and adjacent cold metal restrains the heated material.

So once we heat particular material, then adjacent cold material try to restrain that heated component, so that why it introduce some amount of the distortion and the difference. If this generates the stresses, greater than that of the yield stress causing the permanent distortion of the component, definitely if that amount of the distortion or maybe stress during the welding process.

If the thermal stress with the generates above the yield stress of a particular material then only it will create some kind of the permanent distortion in a final welding structure and of course if the stress generate during the heating of the sample, during heating or cooling of a sample less than that of the yield stress value so then there may not be any kind of permanent deformation in that structure.

So what are the factors normally happens to create some sort of distortion in earlier structure. First is the amount of the strain, basically in any welding process we need to clamp the plate before the welding process, so that create some kind of the constant to resist the deformation. So that resist deformation, so that amount of the restrain influence the amount of the distortion in the structure.

Welding procedure, what type of welding process you are using, whether arc welding, laser welding, electron beam welding, solid state welding. So different welding procedure having the different, it creates different level of the distortion that result in the structure. Parent metal properties. Definitely properties also important if thermal expansion coefficients, there is a difference in 2 different types of the materials, that actually influence the distortion residual stress generation.

Apart from that weld joint design the what way we design the weld join and then path of the weld we need to that path sequence all depends whether there is a necessary and the tack welding or not all actually influence the amount of the distortion residual in welding structure and finally part fit up. That means what we fit between these two components, the initial gap also matters to influence the distortion.

So restraint we normally put to minimise the destruction but of course once we minimize the distortion there is a chance to go to the high amount of the residual stress generation during the process. So they are the consequence happen distortion, residual stress in any kind of the welding structure.

Components if we see for example, if we do without any external restraint during the early process it is free to expand then it will not create any kind of, it will create distortion, but it may not create any kind of, or it can minimize the amount of the stress during this process, but once the clamp is pushed and we retrain the movement of the distorted structure during the welding process then only it will create some kind of the residual stress component.

So putting the restraint will create definitely high amount of the residual stress as compared to without any restrain during the welding process.

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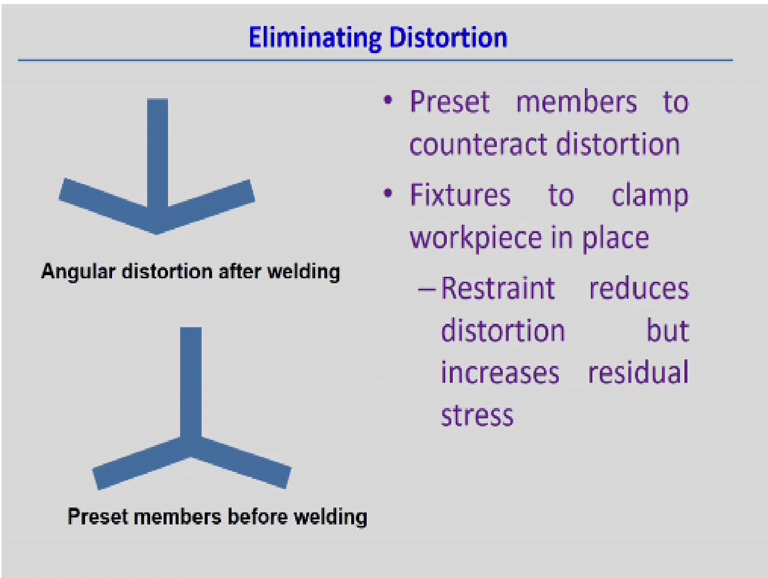

How to reduce the distortion, for example, preset members to counter act the distortion, so we know angular distortion after the welding process, if we know that what is the angular position of theta, it can create after the welding process, so we can preset the member in the opposite way and such that preset the members before welding in this way. So after welding it will create, maybe, it create can be like a flat plate.

So in that way preset members by introducing some amount of the counteract distortion then it is possible to eliminate the distortion.

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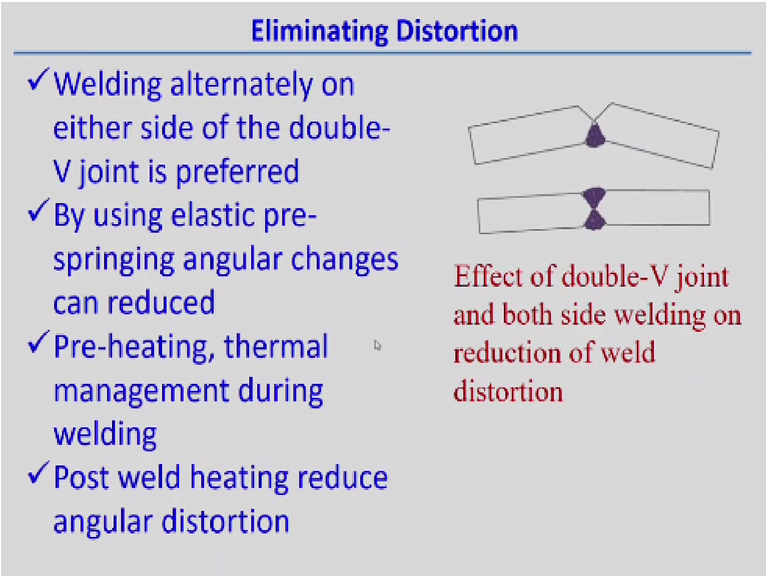

Other for example, in case of double-V joint, so one sided joint if you do it creates kind of distortion, but if you do the second joint also the distortion can be minimised and it can reduce the amount of the distortion when after during the second V weld. So basically welding alternately either side of the double V-joint is preferred, then why using the elastic pre-springing angular changes can be reduced.

Then preheating thermal management all are responsible to eliminate kind of distortion and post weld heating also reduce the angular distortion.

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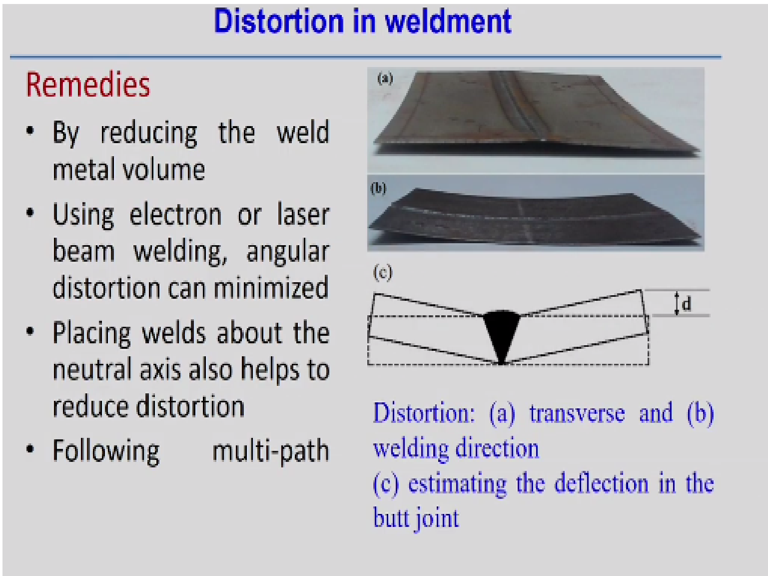

Here we can see that very thin plate, but the other way also to reduce the distortion is simply by reducing the material volume. If we melt or this thing very small amount of the volume melting, by melting a small amount of the volume and that clears kind of the weld joint which is the 2 components that will also try to reduce the weld also.

So for example, using electron beam laser beam welding process, angular distortion can be minimised as compared to gas tungsten arc welding process and of course placing welds about the neutral axis also helps to reduce the distortion. So placing, suppose this is the neutral axis, so placing the welds above the neutral axis can also be possible to reduce the distortion.

Or the same times we can placing the weld this part and after that we just rotate it and we can do the only in the other part also. This it can be reduced may be the possible of the reduction of the distortion. So these are and of course apart from that we can follow the multipath. So not only joining process, these things, the sequence and path can be different, we can create the strategy.

Such that it can neutralize the distortion effects. So this different basic simple mechanism it is possible to reduce the distortion in a welded structure.

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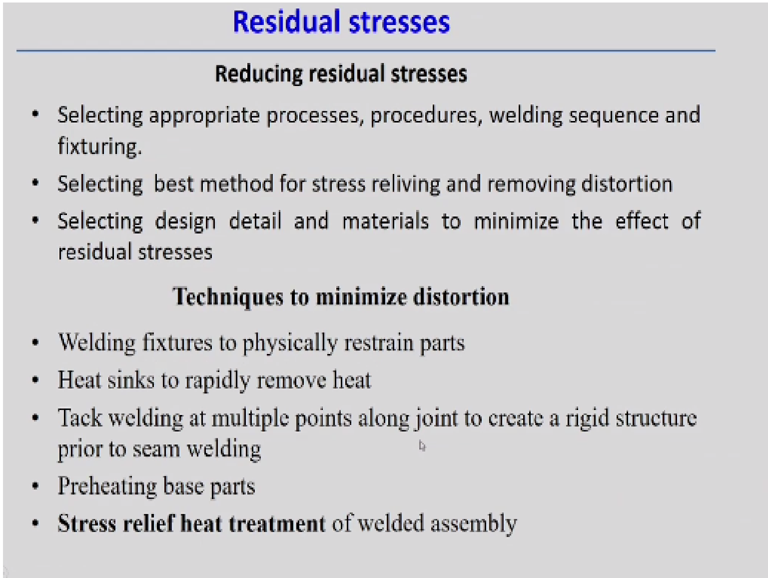

Now we try to look into the residual stresses also. So what are the reduction of the residual stress can be done appropriate processes already discussed procedures also, what procedure we are following, sequence and what we are fixturing these things then you have to put the clamp why not to clip the clamp such that it can minimize the amount of residual stress genesis.

But in general if you try to restrict the, put so many constant during in a process that actually creates large amount of the residual stress. So maybe selecting the best method for stress relieving and the removing the distortion, so many process we can produce to remove the distortion and to reduce the distortion, so we need to put the appropriate stress for a particular type of material, geometry of the weld joint, all actually influence to amount of the control of residual stress during the process.

But definitely in general after welding process we normally do the heat treatment process to reduce to some extent the distortion and residual stress and of course to bring the docility of a particular, this is the very conventional things we normally do after the welding process. So heat treatment after the welding process is an effective way to reduce the residual stress and distortion up to a certain extent.

So apart from that techniques to minimise the distortion, one is the welding fixtures to physically restrain parts, so it is a type depend what way we are putting the fixture, heat sinks to rapidly remove the rate in the back plate we can use some kind of the high conductive material that acts as a heat sink such that very rapidly we can remove this heat, that also try to minimise the amount of residual stress and distortion.

Tack welding at multiple points to create the rigid structure before the welding, due to the actual welding process that also helps to minimise the distortion. Preheating the base part, so if we preheat the before welding if we preheat the base material that actually reduces the temperature difference, after application of any kind of the heat source during the welding process.

So preheats also helps to reduce the amount of the minimise the residual stress and distortion. Of course stress relief most significant point is that simply performing the heat treatment of the welded structure to reduce significantly the amount of the distortion and residual stress.
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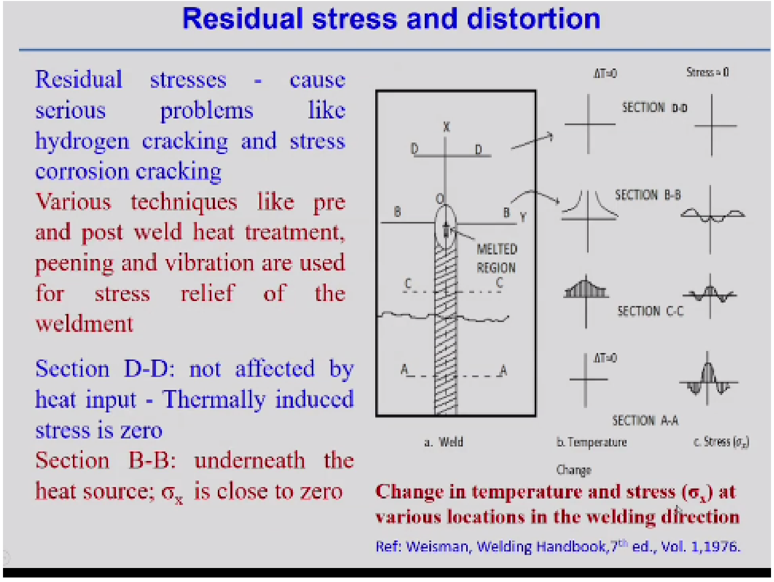

Now in welding process what we can explain the nature of the residual stress normally generate in any kind of fusion welding process. So here if you look into this figure that different sections suppose the welding has been done in particular directions and here we can see this is at any particular time this is the position of the heat source. Now if you look into the section A, already solidified, that means the temperature gradient is already 0.

So in that case we can find out that as the centre it is a kind of tensile type of, if you see the upper side is the tensile stress and that will try to equilibrate the surrounding material so exactly at the centre point certain zone, it creates kind of the tensile stress and surrounding it will try to clear the compressive stress and because at the centre that temperature, it is the maximum temperature gradient normally at this process.

And that around this direction, transverse direction the temperature gradually equilibrate to the room temperature or maybe this thing. So when you try to equilibrate to the room temperature, it will try to make the valence creating the tensile stress in the centre and gradually creating the compressive strength. For example, what happens to the near about zone of the this thing exist some sort of temperature gradient.

For example, temperature distribution is like or you can say the temperature gradient is something like this. So in this case it will also create the tensile strength on less magnitude, but just adjacent is the compressive to just equilibrate the amount of the strength and remaining certain stress is the small amount of the tensile. So in that way you try to equilibrate these things.

But exactly at the centre point just to hitting this thing which point escalating at this point the temperature distribution is something like that in this cases, you can create some kind of the compressive load and which maybe symmetric with respect to each other and then tensile load try to equilibrate, but once it goes after solidification it creates to this kind of structure in general in a specific welding process.

And of course we can see that nature of the residual stress generation during the welding process it depends entirely the what way the temperature distribution that means temperature distribution or what way we can say that temperature gradient exist at the particular point. So of course at point DD we can see that it is a room temperature, temperature gradient 0, it will create the stress = 0.

Now look into this comments various types like P and post weld heat treatment definitely peening action, some mechanical action and vibration are used for the stress relief. So if you do the heat treatment apart from that some mechanical action simply peening and creating the vibration and the zone that actually relief certain amount of the stress. Now section DD the heat input thermal induced stress equal to 0.

Because heat input not affected by the heat input that part. Section BB, that means already discussed the near about the heat source sigma x close to 0, at the centre point.

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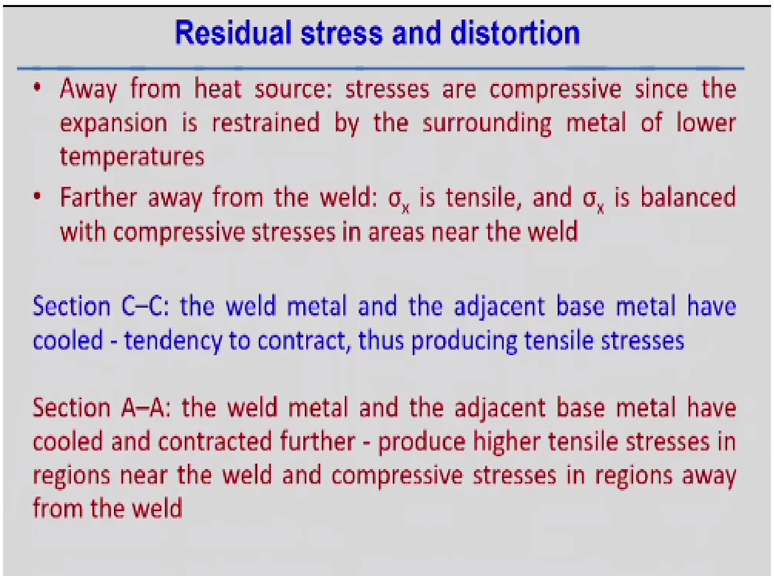

But it is gradually away from the heat source, stresses are compressive and then since the expansion is restricted by the cold wind surrounding metal of the relatively lower temperature that is why it is compressive and farther away it becomes again tensile. So that means it is a tensile compressive in that it make the balance stress near about the weld joint. So it entirely depends on the nature of the temperature distribution at this path near about the centre.

Section CC, this metal have cool tendency to contract thus producing the overall tensile stress, so it is a near about zone, it is near about the weld zone, it is very cool, it will try to contract, tendency to contract thus producing the tensile stress at this zone. Section AA adjacent base metal have cool and contacted father produce the higher tensile stress in the regions near about the weld and compressive stress in the regions away from the weld.

So this kind of stress generation actually depends because during the welding process what is the temperature, what is the profile of the temperature and up to what extent the weld heat is formed and this weld it tries to bring and temperature try to come back to the, try to equilibrate with the surrounding temperature. So in that at any particular instant it will create the nature of the stresses, is kind of wavy, certain point it is compressive and just adjacent to part it can be the tensile or vice versa as well.

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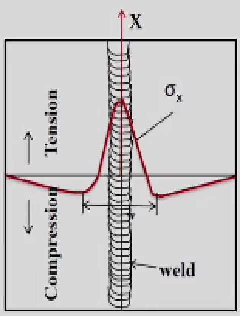
Residual stress and distortion

Analysis of Residual Stresses

According to Masubuchi and Martin, the distribution of the longitudinal residual stress σ_x can be written as

$$\sigma_x(y) = \sigma_m\left[1 - \left(\frac{y}{w}\right)^2\right] e^{-\frac{1}{2}(y/w)^2}$$

where σ_m is the maximum residual stress and w is the width of the tension zone σ_x.



Distributions of longitudinal (σ_x) residual stresses

In general, you see the two longitudinal and transverse residual stress we can measure. Longitudinal means which direction the we can perform the welding process and suppose this is the longitudinal direction and we can say that this is the transverse direction. So this longitudinal direction, transverse direction, residual stress can also be measured experimentally.

Now what are the typical nature of this residual stress in the longitudinal direction. So here we can see the longitudinal residual stress can be written this in way as a function of y. Suppose this is x axis and this is y axis. So at the centre the longitudinal residual stress has become tensile, but up to certain tension a compression equilibrium tends to try to equilibrate and tends to 0 away from the weld central line.

So this is the width of the this thing W, so over this the tensile zone actually exist. So this expression is sigma x can be expressed, the amplitude of the sigma x it is sigma M is the maximum residual stress at the centre point, 1 – y/w square and indicate the exponents into the minus of Y – w square. This way it actually vary. So in general the typical nature of the longitudinal residual stress at the exactly centre point is a very high magnitude, normally in tensile and then it becomes gradually becomes 0 and transport to the compressive.

And then compressive stress is gradually away from this, try to equilibrate become 0 towards the y-axis.

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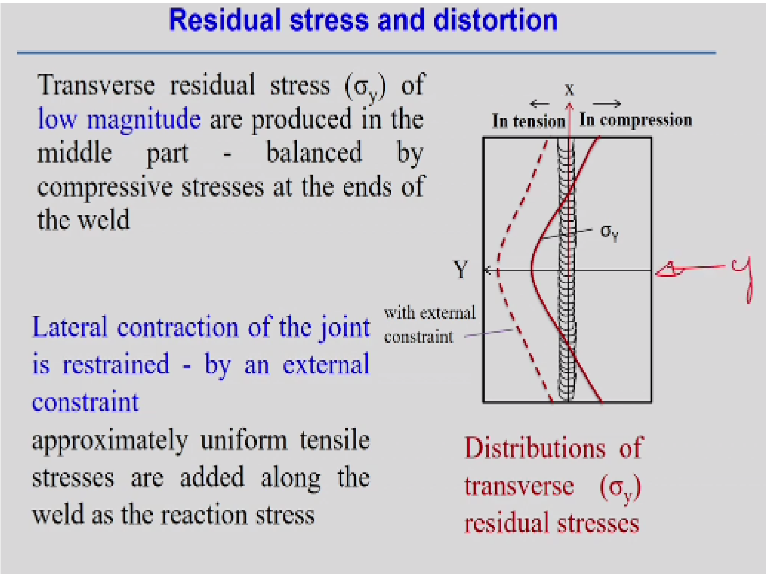

Similarly, in case of transverse residual stress if you measure the sigma y. So this is the y direction. In this case the transfer residual stress typical nature is the see at the middle point, there is tensile residual stress and gradually becomes 0 and it becomes compressive away from the middle point. So in this case if you see that this magnitude actually this magnitude the maximum magnitude of the residual stress tensile is relatively less as compared to the longitudinal residual stress.

But of course if it is, it can be extended if it is possible with some put the external constraint then this level of the stress can be shifted to this. So we can get the high level of the tensile stress and throughout the structure we can say the transfer residual stress maybe tensile in nature by introducing some kind of the external constant. So lateral conduction of the joint is restraint by then external constant approximately uniform tensile stress are added along the weld.

So this uniform residual stress is added these things and it can be represented completely in the tensile residual stress is possible to generate in case of welding stress, but accordingly we need to put the constant. So these are the typical nature of the longitudinal and transverse residual stress in a particular fusion welded structure.

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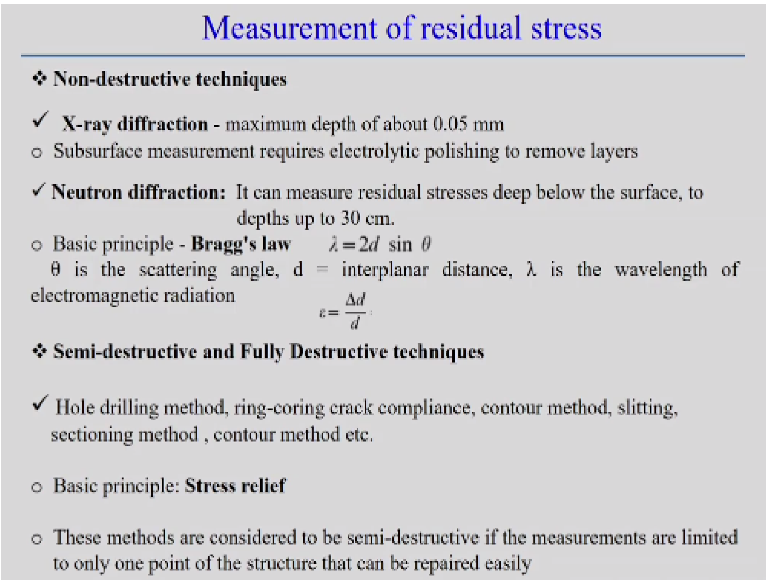

Now how we measure the residual stress, normally specific to the welding process. So non-destructive technique use the x-ray diffraction and Neutron diffraction and of course that follow the Bragg's law of diffraction. Lambda = 2d sin theta. So that theta is the scattering angle, d is the interplanar spacing and lambda is the wavelength of the electromagnetic radiation.

So these are well defined, but what way we can correlate with the residual stress. So actually the strain can be measured by changing the delta d with respect to d. So once we estimate this delta d by d that basically strain measure during the experiment either x-ray or neutron diffraction in that case that strain maybe converted to amount of the strain normally following some kind of the Hooks law.

Basically we assume the elastic stress and we relate between the stress and strain. So basically in this cases we measure this changes in terms of the strain and strain is converted to the stress and that stress represent the residual stress, it is the basic principle of the non-destructive techniques normally follow x-ray diffraction technique or neutron diffraction technique.

But there is a difference between these two techniques because x-ray diffraction technique we can measure the stress only on the surface, normally surface. So I think maximum depth can be 0.05 millimetre, but other way neutron diffraction we can get in the depth direction so the different layer also different point in the depth direction can also be measured by using the neutron diffraction, that is the difference between the x-ray and neutron diffraction techniques.

Semi-destructive or fully destructive techniques, so normally some kind of mechanical method which is hole drilling method, contour method, slitting, sectioning method, these are the methods that can be used to measure the residual stress but this is kind of the destructive techniques. So basic principle is the stress relief happening basically during the drilling of a sample.

So at that time what is amount of the stress relieved that can be relate to the what is the amount stress can be generated during the process. So of course by using the putting the different simple strength also at particular position and from that strain we can measure the strain during the deformation and that strain can be converted to the stress. So this at the principle of the mechanical means through which we can measure the residual stress. So thank you very much for your kind attention.