Welding Engineering

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Module - 5
Heat Flow in Welding
Lecture - 5
Residual Stress – I

In this module 5th based on the Heat Flow in Welding is the 5th lecture and this lecture is based on the Residual Stresses. In this presentation mainly we will be taking about the residual stresses being developed in the weld joint and different mechanisms, that lead to the development of the weld joint. And in which way these residual stresses affect the performance of the weld joint and at the end, we will try to see that, how these residual stresses can be reduced in order to avoid the adverse effect on the performance of the weld joint.

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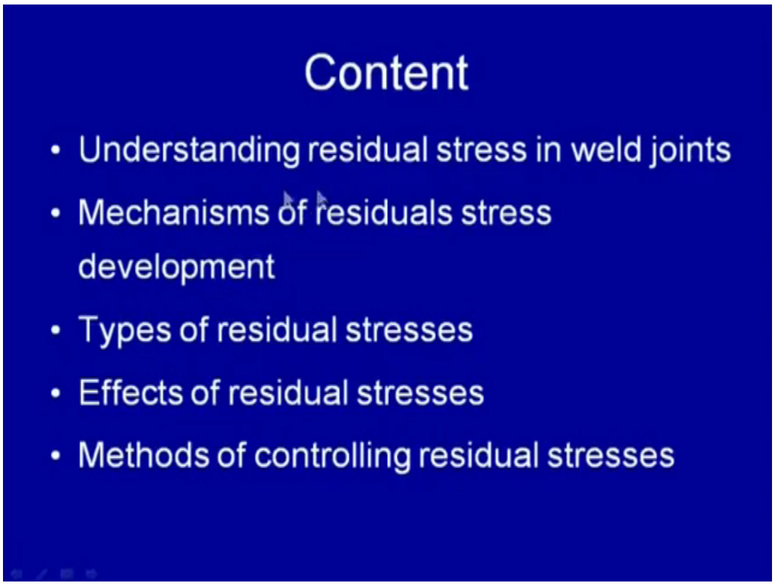

Content

- Understanding residual stress in weld joints
- Mechanisms of residuals stress development
- Types of residual stresses
- Effects of residual stresses
- Methods of controlling residual stresses

So, this as far as content is concerned, this presentation will include, first trying to understand that what are the residual stresses and how do they effect the performance of the weld joint. Then mechanism of the residual stresses, mechanisms that lead to the development of the residual stresses, then the different types of the residual stresses and effect of residual stresses on the performance of the weld joint and what methods can be used for controlling the residual stresses.

So, the residual stresses are basically those stresses, which are present in the component, which have been processed using either thermal methods or the mechanical methods without presence of the external load. So, the many components when subjected to the heat in very localized manner or the force in very localized regions to get the desired size and shape, they are subjected to the differential change in the volume. And differential change in the volume as compared to the other locations, lead to the development of those stresses which are always present, even when there is no external load and such type of stresses are called the residual stresses.

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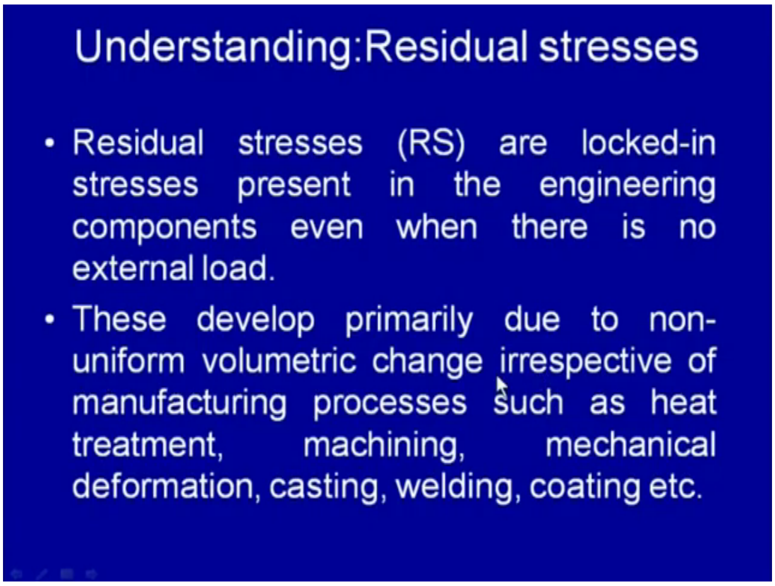

Understanding:Residual stresses

- Residual stresses (RS) are locked-in stresses present in the engineering components even when there is no external load.
- These develop primarily due to non-uniform volumetric change irrespective of manufacturing processes such as heat treatment, machining, mechanical deformation, casting, welding, coating etc.

So, starting with the residual stresses, residual stresses are basically those locked in stresses, present in the engineering components even when there is no external load. So, these can be present in the component when there is no apparent external load being applied in the component. And these mainly develop due to the non volumetric change in the material in consideration, this non uniform volumetric change can take place during the manufacturing of the component due to the application of the heat.

Like in heat treatment and the welding processes, and application of the forces in machining and the mechanical deformation based approach like contour rolling and the non uniform shrinkage in case of the castings in welding and in case of the coatings. So, in these manufacturing processes, the development of the residual stresses is mainly caused by the non uniform volumetric change occurring in the different zones. And these wherever this kind of non uniform volumetric change take place irrespective of the manufacturing process, residual stresses develop. So, the basic reason behind the development of the residual stresses is non uniform volumetric change in specific location or in very localized manner.

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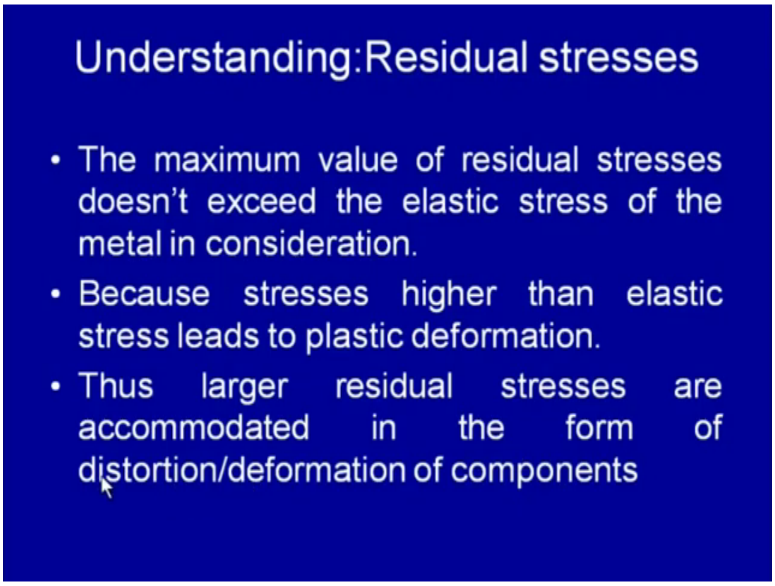

Understanding:Residual stresses

- The maximum value of residual stresses doesn't exceed the elastic stress of the metal in consideration.
- Because stresses higher than elastic stress leads to plastic deformation.
- Thus larger residual stresses are accommodated in the form of distortion/deformation of components

And the maximum value of the residual stresses or the locked in stresses that can be present in the component, because of the non volumetric change, can be of the maximum magnitude equal to the elastic stress limit of the metal in consideration. Because, as soon as the residual stress magnitude becomes greater than the elastic stress limit, the plastic deformation takes place and the yield residual stresses are released. And therefore, the maximum value of the residual stresses does not exceed the elastic stress of the metal in consideration.

Because, the higher stresses, stresses being developed greater than the elastic stress limit lead to the plastic deformation and thus, these stresses are released or eased out in the component where, non uniform volumetric change is taking place. And thus, the larger residual stresses are accommodated and when whenever residual stress magnitude is greater than the elastic stress limit then those are accommodated in form of the deformation and the distortion of the component. So, the left out stresses because of the non uniform volumetric change, are not found greater than the elastic stress limit.

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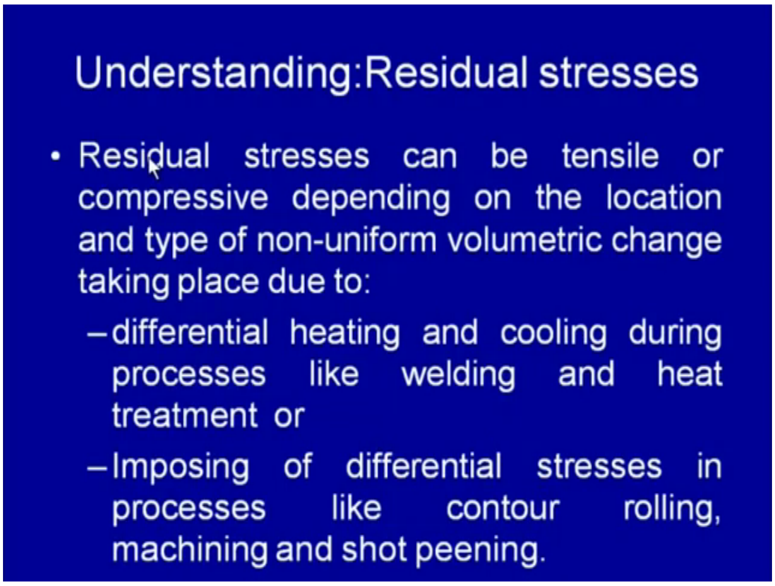

Understanding:Residual stresses

- Residual stresses can be tensile or compressive depending on the location and type of non-uniform volumetric change taking place due to:
    - differential heating and cooling during processes like welding and heat treatment or
    - Imposing of differential stresses in processes like contour rolling, machining and shot peening.

Further, these residual stresses can be of either tensile type or the compressive type, depending upon the location and the type of the non uniform volumetric change, which is taking place. So, this the residual stress when it is of the tensile kind, it offers the one kind of effect than when it is of the compressive kind. Most of the time, tensile residual stresses are found to be harmful for the performance of the weld joint as compared to the compressive residual stresses, because many time compressive residual stresses are intentionally developed to enhance the performance especially, mechanical performance of the component under the normal service conditions. And these residual stresses, nature of these residual stresses can vary depending upon the situation where, how the contraction and in which sequence, contraction after the heating is taking place and how, the mechanical forces are being applied in very localized manner.

This non uniform volumetric change can take place, which can lead to the development of the residual stresses. Residual stresses due to the differential heating and cooling during the processes like welding and the heat treatment or imposition of the differential stresses in processes like contour rolling and machining and the shot peening. Basic principle in the development of these residual stresses can basically be understood from this simple diagram.

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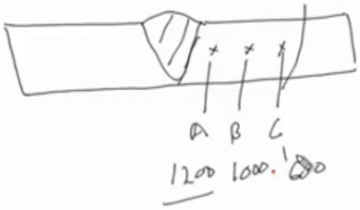

Where say, heat is being applied in very localized manner during the welding, near the faying surfaces of the base material but the region just below the fusion’s boundary is also heated to the different temperature zones. If we consider these 3 areas then they will be subjected to the different level of the high temperatures and they will different level of temperatures and for the different durations.

So, say considering that the location C, location B and location A, these three will be subjected to the different temperatures for example, of 1200 degree centigrade, say 1000 degree centigrade and 600 degree centigrade. So, for a unit for a given volume of the material the metal which is being subjected to the higher temperature, it will be experiencing greater expansion as compared to the other regions, which are at the lower temperature. So, because of this, the differential change in the volume will be taking place, because of the different weld thermal cycles being experienced by the different locations.

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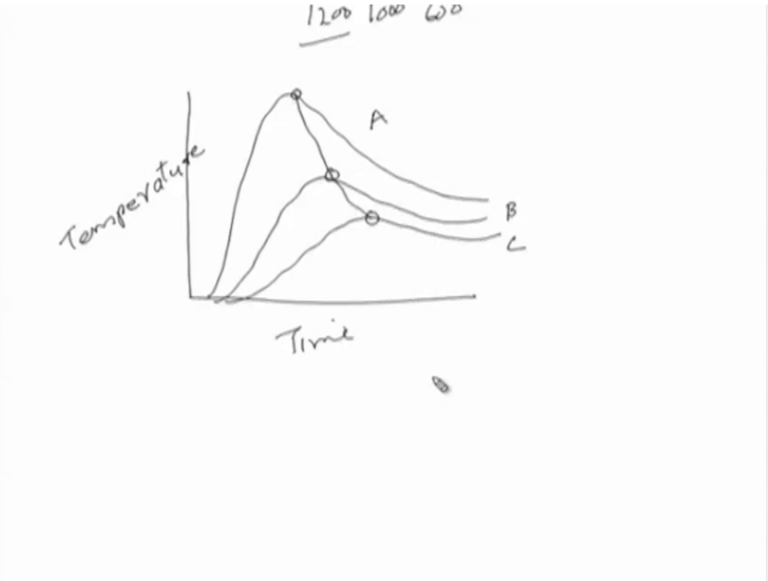

So, say this is the weld thermal cycle for location A, this is the weld thermal cycle for location B, this is the weld thermal cycle for location C. So, due to the variation in the peak temperature being experienced by these three locations, this magnitude of the residual stresses which will be developed in these three locations due to the volumetric change that is, expansion and subsequently contraction that will be different. And similarly, so, this non uniform heating in the regions close to the fusion boundary is mainly attributed to the development of the residual stresses in the weld joint. And in addition to this, when the weld metal after the solidification tries to shrink during the cooling from the melting point to the room temperature.

So, along the length shrinkage of the weld metal is restricted and this restriction to the shrinkage of the weld metal along the length also causes the development of the residual stresses. Say, this is the length of the plate over, which weld has been made so, after the development of the weld, when the weld will be cooling down to the room temperature. So, this entire length l will be shrinking from say from the melting temperature to the room temperature.

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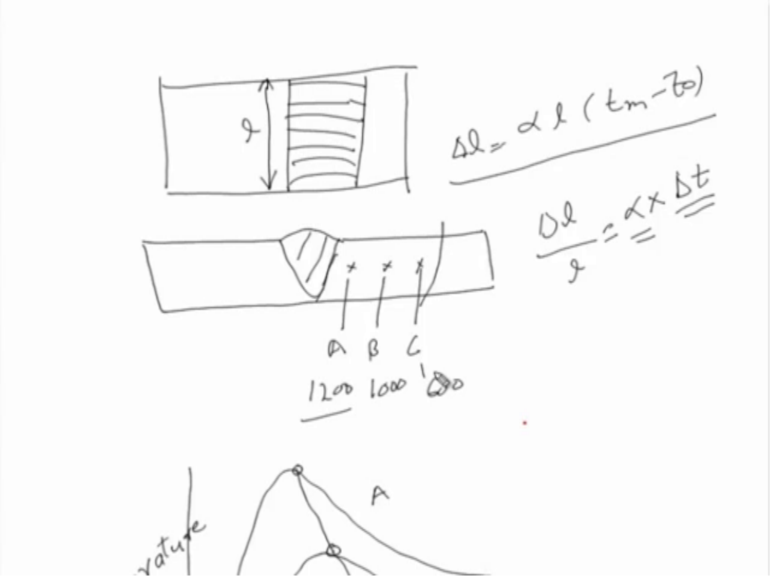

So, l alpha delta t, that is the melting point minus the room temperature so, this will be the kind of change, which should take place due to the cooling down to the room temperature from the melting point. So, for a unit length if you see the kind of change in dimension, which take place due to the reduction in temperature from the melting point to the room temperature, that should be the delta l by l. So, this will give the kind of strain multiplied by alpha into that delta t we can say, to the difference in the melting point and the room temperature.

So, for given material delta t will be fixed, alpha is the expansion coefficient so, if we consider here, case of the steel then after the welding, the weld joint should shrink by certain magnitude. As a thumb rule, weld joint is expected to shrink by length of 1 mm for per meter length of the weld but since the weld joint is firmly connected with the base material, so this kind of shrinkage is restricted. And this kind of restriction on the shrinkage of the weld metal leads to the development of the tensile residual stresses in the weld joint invariably. So, one of the main reasons, behind this development of the stresses is non uniform expansion and the contraction in the weld joint due to the differential heating and cooling.

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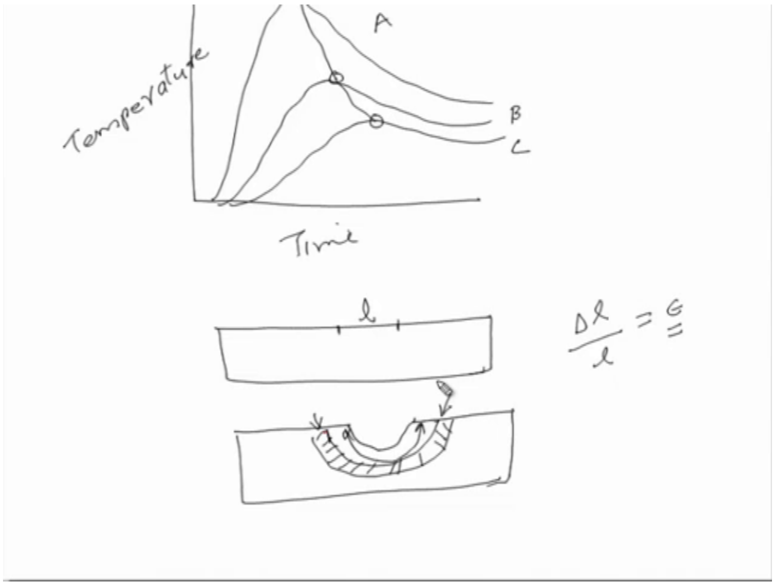

Similarly, we can consider the case of the mechanical forces where, a plain strip is subjected to the very localized deformation using the contour rolling and this kind of deformation is taking place like, this only at the surface. So, say this fiber having length l is subjected to the increase in length of this much, so this increase in length will be very localized in the near surface layers only. So, this localized increase in length of the surface layers by say, delta l that is the increase in length, which has taken place from the length.

So, this will be leading to the x, forced expansion by the delta l divided by l so, this is the kind of strain, which has been induced by the contour rolling. So, near the surface, we will have the elastic plastic deformation zone and below the surface regions, we will have the elastic deformation zone. So, elastic deformation zone will tend to come back to the original size and shape but since it is rigidly attached with the plastically deformed zone and the base material, so this coming back to the original size will be restricted.

So, this elastic deformation frequently lead to the development of the compressive residual stresses, compressive residual stresses near the surface layer. And because of this, short peening and the contour rolling are the commonly used methods for developing the compressive residual stresses at the surface. So, whenever there is a very localized heating or cooling or the localized application of the forces to cause the localized deformation near the surface layers, these things frequently cause the development of the residual stresses.

So, depending upon the case, the surface deformation can be applied intentionally in order to develop the desired type of the residual stresses in desired magnitude. Basically, this approach is used for developing the compressive residual stresses in the component so as to, enhance the tensile performance and the fatigue performance of the component.

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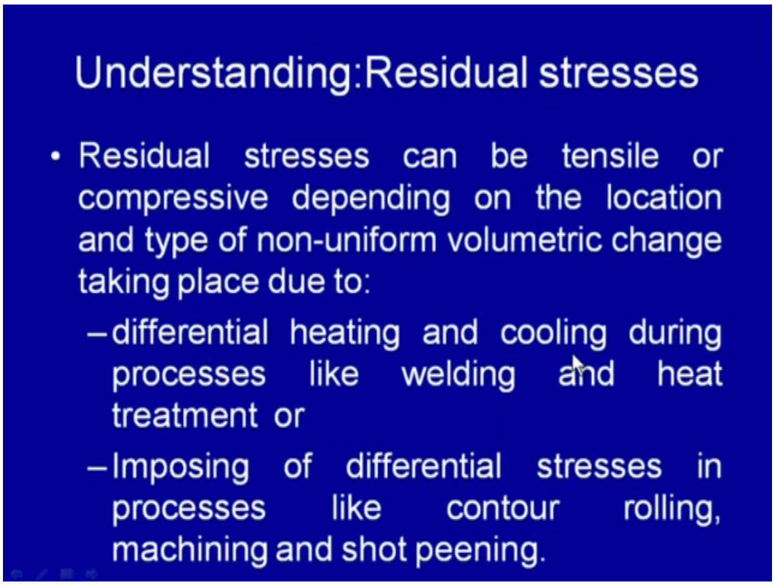

Understanding:Residual stresses

- Residual stresses can be tensile or compressive depending on the location and type of non-uniform volumetric change taking place due to:
    - –differential heating and cooling during processes like welding and heat treatment or
    - –Imposing of differential stresses in processes like contour rolling, machining and shot peening.

So, we will see some other aspects related with the residual stresses like we have said that, these residual stresses can be of the tensile or the compressive kind depending upon the location and the type of the non uniform volumetric change, which is taking place. And this change can occur due to the differential heating and cooling, which is commonly encountered during the welding or it can be due to the differential stresses experienced by the material during the localized deformation processes like contour rolling, machining and the short peening.

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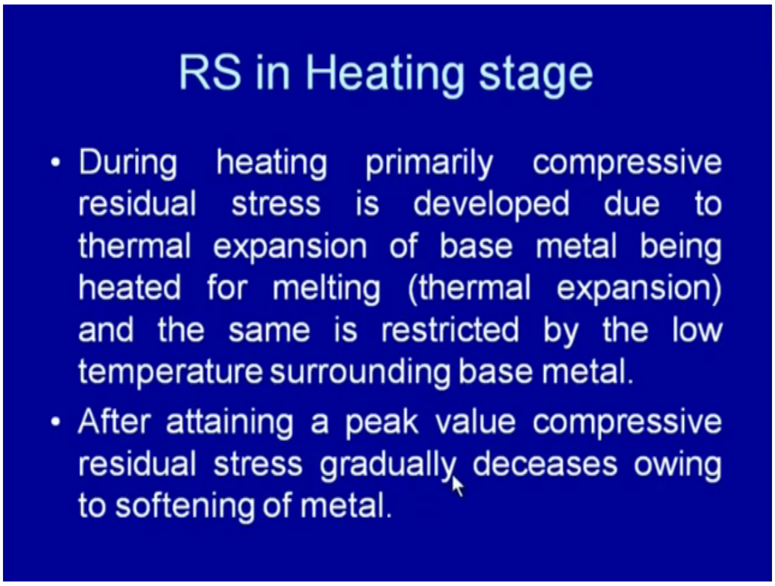

RS in Heating stage

- During heating primarily compressive residual stress is developed due to thermal expansion of base metal being heated for melting (thermal expansion) and the same is restricted by the low temperature surrounding base metal.
- After attaining a peak value compressive residual stress gradually deceases owing to softening of metal.

Residual stresses in the weld joint primarily occur due to the differential heating, differential weld thermal cycle, that is the heating peak temperature and the cooling at the moment during the welding. And this is experienced by the weld metal and the region closed to the fusion boundary we know that the residual stresses the different zones in the weld region and near the fusion boundary are subjected to the different weld thermal cycles. And because of this presence of different weld thermal cycles, the differential expansion and contraction takes place in the different zones.

And these differential expansion and contraction result in the development of the residual stresses in the weld joint. The type and the magnitude of the residual stresses can vary continuously during the different stages of the welding that is, heating and cooling. For example, when the heat is applied around material, which is subjected to the application of heat tends to, because of the heating tends to expand. But, it is expansion is restricted by the surrounding low temperature metal and because of this, compressive residual stresses are developed in the initial stage.

Once the material is brought to the molten state, any kind of resistance to the expansion is reduced to the 0 under the residual stresses in the weld region or in the molten zone becomes 0. But all the areas, which are still in the solid state has been subjected to the high temperature, they will be under the compressive residual stresses state.

Subsequently on cooling, this initially contraction is allowed in the cooling phase, but when the surrounding material tends to strengthen, this contraction is not permitted.

And that is why, at the end, some amount of the contraction which should take place is not permitted and this leads to the locking of the some strain in the welded joint. And this locked in strain in the welded joint after cooling down to the room temperature, frequently leads to the development of the tensile residual stresses. So, this is what, will be explained in the sequence, that during the welding when the heat is applied primarily compressive residual stresses are developed due to the thermal expansion of the base material being heated for the melting purpose.

And the same but this expansion is restricted by the low temperature surrounding base material, after attaining the peak temperature, compressive residual stresses decrease gradually because of the softening of the material. So, the magnitude of the compressive residual stress will increase until the material all around the zone, which is being heated is at low temperature and putting in lot of restriction to the expansion. But, once the material is softened then resistance to the expansion is reduced and this in turn, results into the reduction in compressive residual stresses. So, during the heating phase, first the magnitude of the compressive residual stress will be increasing to the maximum value and thereafter, it starts decreasing due to the softening of the material.

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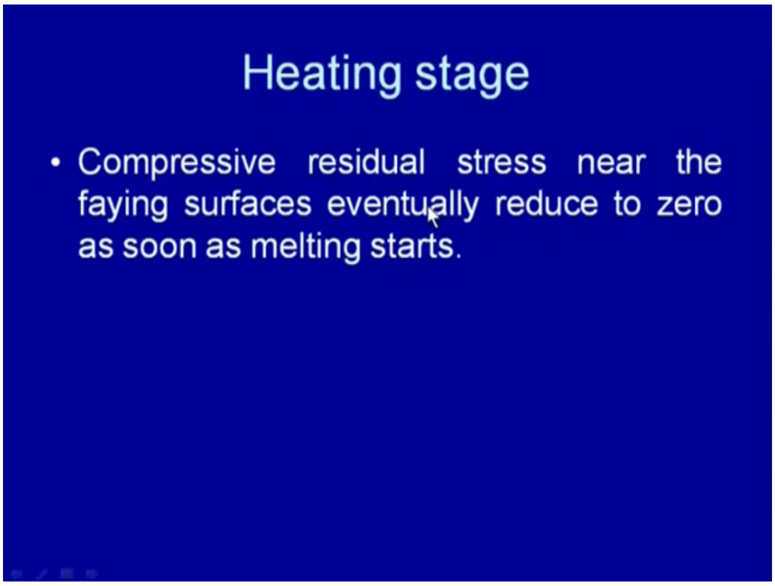

Heating stage

- Compressive residual stress near the faying surfaces eventually reduce to zero as soon as melting starts.

The compressive residual stresses near the faying surfaces eventually reduce to the 0 value as soon as melting starts.

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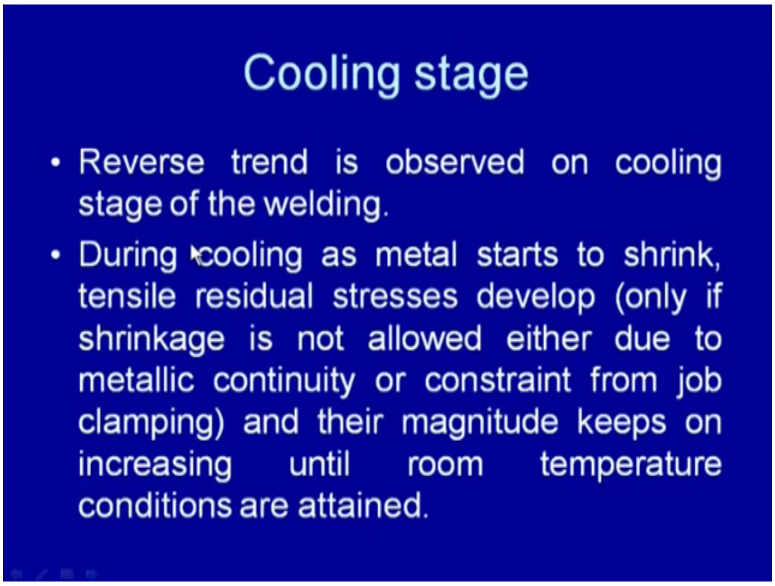

Cooling stage

- Reverse trend is observed on cooling stage of the welding.
- During cooling as metal starts to shrink, tensile residual stresses develop (only if shrinkage is not allowed either due to metallic continuity or constraint from job clamping) and their magnitude keeps on increasing until room temperature conditions are attained.

In the cooling phase, the reverse trend is observed on cooling phase, initially during the cooling the shrinkage starts and the tensile residual stresses start to develop in the cooling phase. And magnitude of these residual stresses will continue to increase until the material tend to become strong enough. So, during the cooling as the metal starts to shrink, the tensile residual stresses develop and these residual stresses will be developing only when the shrinkage is not allowed, either due to the metallic continuity or constraint from the job clamping.

And the magnitude of these residual stresses will keep on increasing, until the room temperature is attained. So, many times we find that, effect of the residual stresses is maximum when the job is cool down to the room temperature conditions.

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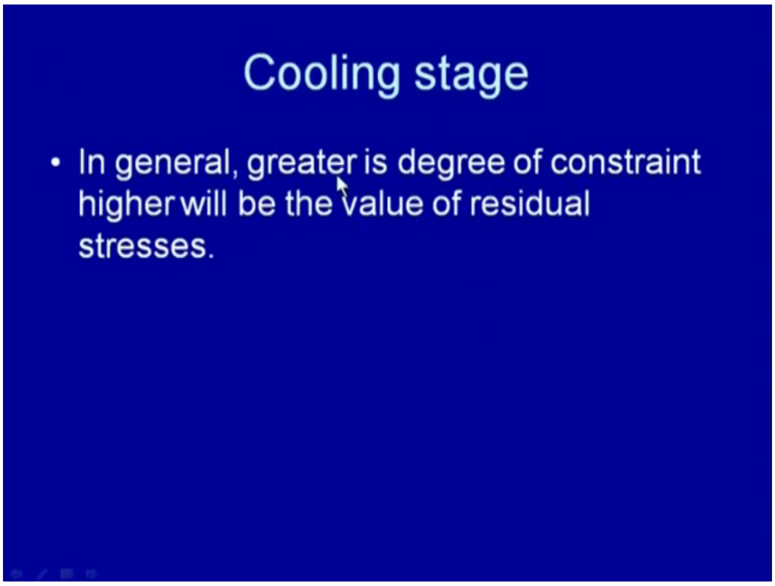

Cooling stage

- In general, greater is degree of constraint higher will be the value of residual stresses.

In general greater is the degree of the constraint, higher will be the value of the residual stresses. Say, if any region which is trying to shrink if the shrinkage is allowed then there will be no development of the residual stresses. Similarly, something which is trying to expand, if the expansion is permitted then also no residual stress development take place. So, the development of the residual stresses will be occurring only when something is trying to expand or contract but the expansion and contraction is restricted by the surrounding material or by the clamping.

So, the amount of the constraint, which has been put in for this kind of expansion and contractions, that will decide the amount of residual stresses that will be developing. In general, greater is the degree of the constraint, higher will be the magnitude of the residual stresses that will be developed. So, in case of the weld joint, residual stresses develop due to the different mechanisms, these are the 2 levels, one is the macroscopic mechanisms and another is microscopic.

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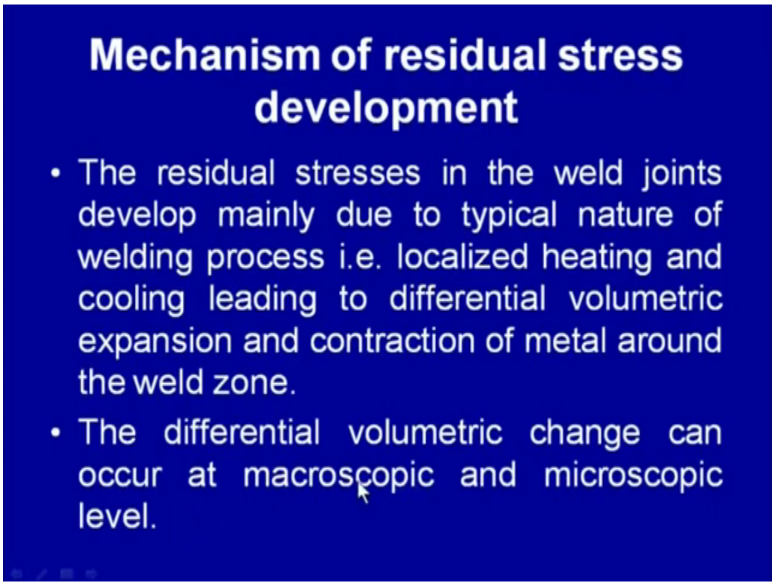

Mechanism of residual stress development

- The residual stresses in the weld joints develop mainly due to typical nature of welding process i.e. localized heating and cooling leading to differential volumetric expansion and contraction of metal around the weld zone.
- The differential volumetric change can occur at macroscopic and microscopic level.

In case of the macroscopic mechanisms, the larger scale changes in the weld region take place and which lead to the significant magnitude of the residual stress development, while microscopic changes lead to the very little amount of the residual stresses. Residual stresses in the weld joint develop may lead you to the typical nature of the welding process, which is inherently associated with these processes. That is, the localized heating and the cooling, which leads to the development means, differential volumetric expansion and contraction of the metal around the weld zone and this differential volumetric change can occur at the macro and the microscopic level.

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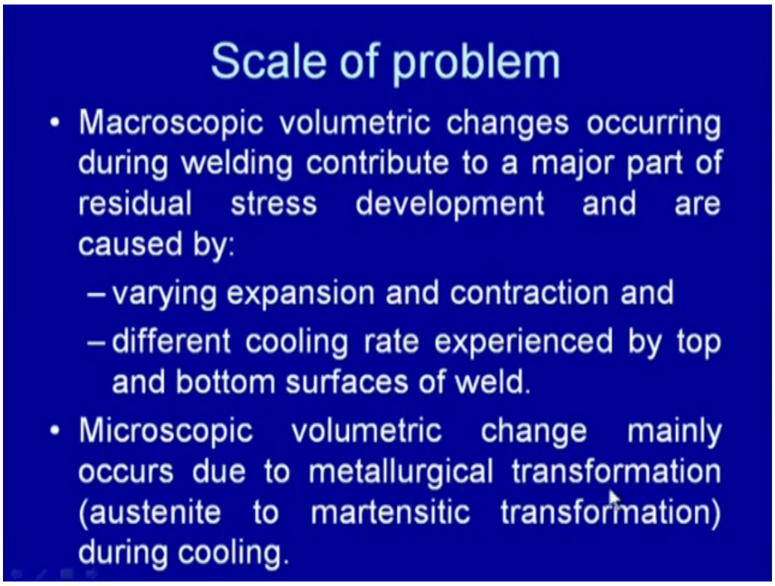

Scale of problem

- Macroscopic volumetric changes occurring during welding contribute to a major part of residual stress development and are caused by:
  - varying expansion and contraction and
  - different cooling rate experienced by top and bottom surfaces of weld.
- Microscopic volumetric change mainly occurs due to metallurgical transformation (austenite to martensitic transformation) during cooling.

Macroscopic volumetric changes occurring during the welding contribute to a major part of the residual stress development and are caused by the varying expansion and contraction due to the differential heating and cooling and the different cooling rates experienced by the top and the bottom surfaces of the weld zone. So, the first type of the stresses that is, the varying expansion and contraction, stresses being developed due to the varying expansion and contraction.

In the region closed to the fusion boundary, we call as a thermal stresses and the stresses being developed due to the varying cooling rates experienced by the top and bottom surface layers as compared to the core region, we called as quenched stresses. And the microscopic stresses developed due to the volumetric change mainly occurring due to the metallurgical transformation for example, austenite to the martensitic transformation.

In general, all types of the transformation from the austenite to the pearlite, bainite and the martensite occur with the change of a specific volume. But, since the transformation of austenite into the pearlite and bainite occur at the higher temperature that is, greater than 550 degree centigrade and because of this, the change in means the development of the residual stresses due to these transformation is limited. While the transformation of austenite into the martensite, which is occurring at very low temperature leads to the development of the means, higher magnitude of the residual stresses due to this microscopic volumetric change during the cooling.

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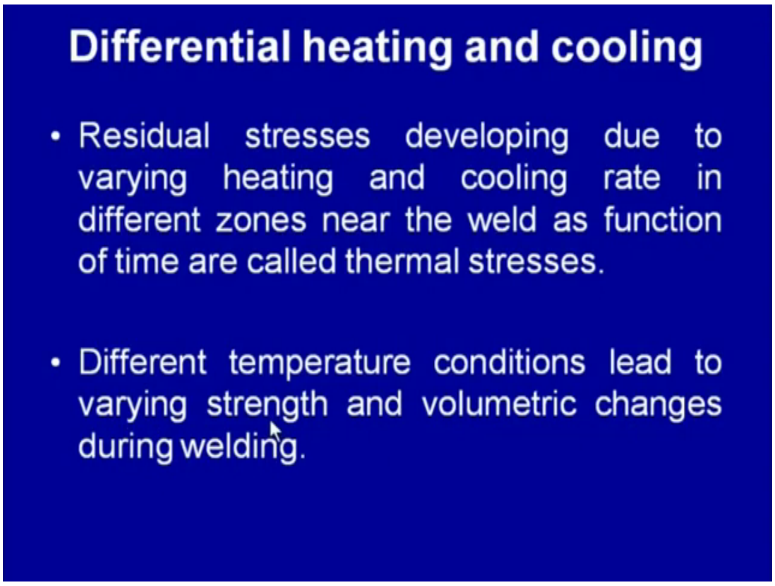

Differential heating and cooling

- Residual stresses developing due to varying heating and cooling rate in different zones near the weld as function of time are called thermal stresses.
- Different temperature conditions lead to varying strength and volumetric changes during welding.

So, the thermal stresses that being caused by the differential heating and cooling will be explained first. The residual stress developing due to the varying heating and cooling rates in the different zones near the weld, as a function of the time are called thermal stresses. And the different temperature conditions in the different zones close to the fusion boundary lead to the varying strength and the volumetric change.

So, those areas which are subjected to the higher temperature, they will be subjected to the greater, they will be experiencing greater reduction in the strength. And the greater change in the specific volume as compared to the other areas, which are subjected to the lower temperature will be considering this case, when to understand the development of the residual stresses due to the differential heating and cooling say, the 2 plates are being welded.

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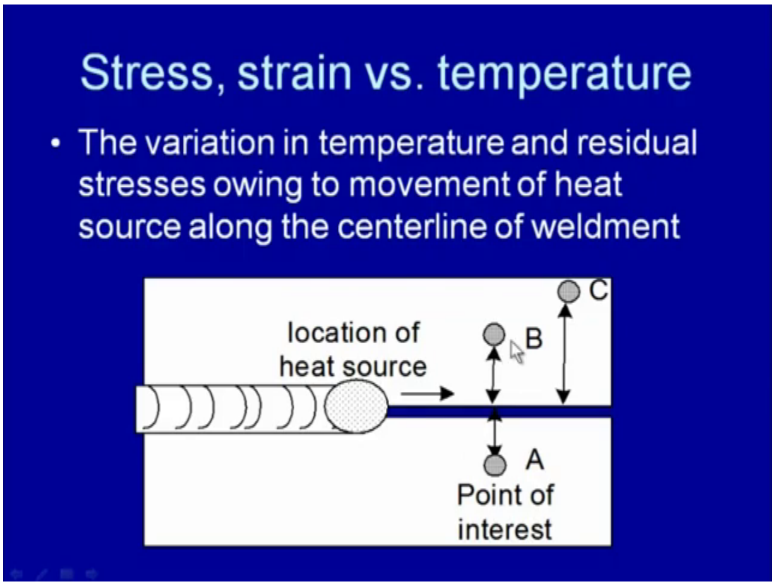

Stress, strain vs. temperature

- The variation in temperature and residual stresses owing to movement of heat source along the centerline of weldment

And this is the weld region and this is the arc position, if we consider the 2 or 3 points, the point of interest A close to the fusion boundary slightly away from the fusion boundary, that is the weld centre line and the point C further away from the weld centre line. So, since all these points are located at different distances from the weld centre line accordingly, they will be experiencing different temperatures, and so the development of the residual stresses will vary in the different points.

And this will be due to the different weld thermal cycles, which will be experienced by them during the welding. So, the variation in the temperature and the residual stresses due to the movement of the heat source along the weld centre line, for these situations will be explained in the next slide. Here, this is a very simple diagram, which combines the effect of the temperature rise during the welding of a particular location in terms of the stresses and strain, that are developed.

Suppose, in the initial stage, when we start applying heat to a particular location, temperature starts to begin. As soon as temperature reaches to the higher level, thermal expansion of the material starts.

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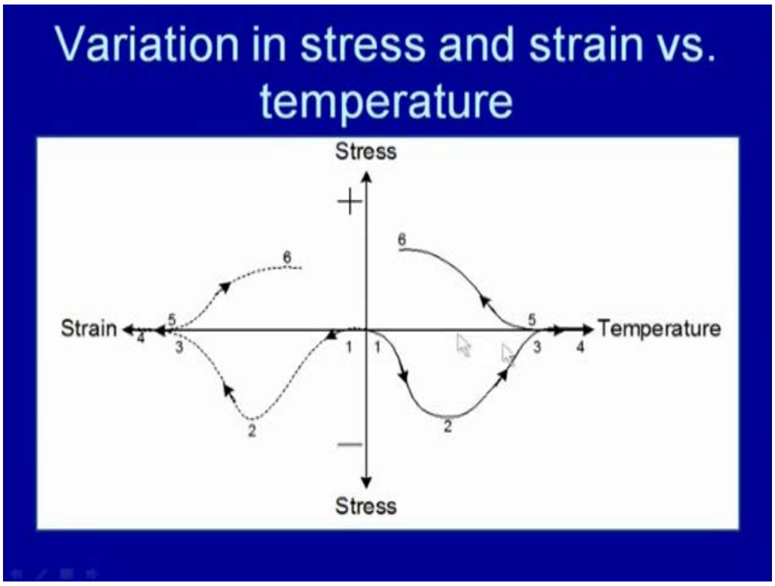

Variation in stress and strain vs. temperature

So here, we can see this axis in you can say, x axis in the right side showing the temperature variation, and this the vertical axis shows the stress variation. So above this, the x axis this horizontal line, we have the positive stresses that are tensile residual stresses and below this, it will be the compressive residual stresses. So, this particular line 1, 2, 3, 4 indicates the variation in temperature versus the stress relationships.

Since these stress line is in the compressive stress zone so, we will be showing the relationship between the temperature and the compressive stress variation especially, during the heating phase. So, this 1, 3, 4, 5 this kind of variation is indicating the stress variation, residual stress variation due to the expansion in the heating phase. And when the temperature starts means, during the cooling phase, temperature starts to decrease so, temperature will be decreasing gradually and the stresses after reducing to a certain magnitude, the stress starts become tensile in nature.

So, if see this half of means, right side half of this diagram that is means, right side of this vertical line then this shows the stress versus temperature relationship. On the other hand, the left side of this diagram or left side of this vertical line shows the relationship between the stress and the temperature, and the strain. So here, the point 1 is corresponding to the 1 temperature, point 2 is corresponding to the point 2 temperature and the strain corresponding to the 3, is the temperature corresponding to the 3.

So here, this side diagram shows the relationship between the temperature variation and the corresponding the strain values. So, if you see the stress versus strain relationship, as a function of temperature this side, so if we start, in the heating phase, the temperature will be increasing linearly but the stress will be increasing non linearly. Temperature will be increasing gradually, but the stresses will be increasing non linearly, they will be reaching maximum up to the 0.2, then they will start decreasing gradually.

To understand this variation in the stress during the heating phase, it is important to see, that the how temperature increase will be leading to the strain in the metal during the heating phase. We know that, when heat is applied, material all around the zone which is being heated will be experiencing the expansion due to the increase in the temperature and if that expansion is restricted then compressive stresses start to develop. So, in the first zone when the heating is taking place, temperature starts increasing and the compressive strain will be increasing continuously till the point 2.

And thereafter, after this, the strain magnitude starts decreasing, because of the softening of the material. So, this is the portion where, expansion takes place but the softening is not that significant and because of this, compressive strain keeps on increasing up to the point 2. And similarly, the compressive stresses keep on increasing until the point 2 is achieved and after reaching to the point 2 stage, softening in the material starts. And therefore, the compressive strain magnitude starts decreasing and it becomes 0 here, near the 3 it is very small 1 magnitude and at the 4, it becomes 0.

So, 0 is the position when the temperature becomes so high corresponding to the 4, that the melting starts and the molten metal cannot offer any resistance or any force for expansion to occur. And because of this, compressive strain magnitude becomes 0 and so, this is the heating phase and when the cooling starts, during the cooling first the temperature will be decreasing from the point 4 to 5. And during this, since the material is still in the hot molten conditions so, there will be simple reduction in the temperature without any strain.

So here, we can see 4 to 5 is a simple along the same line because no resistance will be offered by the high temperature material at high because it is of the low strength and of the high ductility so, it will not offer any major resistance for the contraction. So, because of the reduction in temperature, there will be minor contraction and as the cooling continues with the reduction in temperature, material starts gaining strength. So, as soon as material starts gaining strength, for the contraction is not permitted and because of the reduction in temperature, material tends to contract.

But, this contraction is not allowed, because of the strengthening of the material and because of this contraction. This is how, the contraction will be occurring means, the contraction will be occurring gradually and then even after reaching of the material to the room temperature, some strain is left. So, this is the amount of the strain, which is left in the material even after reaching to the room temperature and we can see here, during the cooling phase, we get the tensile strain which is locked in and here, during the heating phase, we got the compressive strain.

So, on cooling down to the room temperature, we find that, there is some locked in tensile strain left in the weld joint. And this locked in tensile strain left in the weld joint results in the presence of the locked in tensile residual stress corresponding to the point 6. So, if we see here, greater is the elastic stress limit of the material, greater will be the magnitude of the locked in strain, which will be left in the material. So, greater will be the magnitude of the residual stresses, which will be left at the end of the welding.

So, this diagram simply shows the relationship between the temperature variation and it is effect on the stress and strain variation during the welding.

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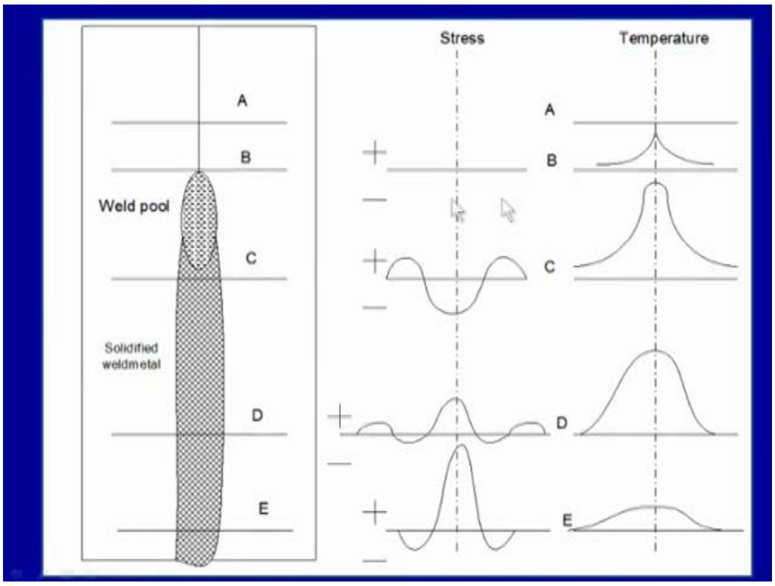

This diagram further shows that, how residual stresses vary during the welding, if we consider one you can say, there are 3 or 4, 5 different zones. The zone E say, this is zone E which has already been welded long before and it has been cool down to the room temperature and temperature is largely uniform. The D is somewhat still at higher temperature and C is close to the weld pool and this is the weld pool, and this is just ahead of the weld pool, which is going to be melted and the region A is further away from the weld pool.

So, still it is at in the room temperature so, corresponding variation in the stresses and the temperature is shown in these two diagrams. So, if we start seeing that, A having no stresses and the temperature is largely uniform but if we take up the location B, which is just close to the fusion boundary or the weld pool, we can see there is a short temperature gradient, here it is like this. And if we take up this region, here in this case, if we take up the region which has just been welded, it will have a very high temperature gradient like this.

And the residual stresses here in this case, they are on the both sides we have tensile residual stresses and in this portion means, just at the weld centre, we have the compressive residual stresses in the region, which has been just welded. If we see the region D which was welded long before, the temperature is still high but the stresses which were earlier compressive along the weld centre line, they tend to become tensile in nature.

And other areas to balance these tensile residual stresses, we have the compressive residual stresses in both the sides so, these sides basically fall in the heated affected zone. And if we talk of this region, which was welded long before and the temperature has also become largely uniform, we will be having the maximum tensile residual stresses along the weld centre line. And in the both the sides of the weld zone, will be having the compressive residual stresses to balance the stresses.

So, if we see here, the weld zone which has been welded and cool down to the room temperature, will be having the tensile residual stresses along the weld centre line and the compressive residual stresses in both the sides of the weld zone, which mainly fall in the heat affected region. So, this diagram shows that, how the variation in temperature as and during the welding takes place and how the residual stresses vary.

The residual stresses in the weld region, they will largely be absent because material is in molten state, the weld region which was just welded will have compressive residual stresses. And just after the welding, it will have the tensile residual stresses and long after the welding, it will have means, on cooling down to the room temperature, it will have the tensile residual stresses.

So here, there will be shift in from the compressive residual stresses in the weld region just after the welding to the significant tensile residual stresses, after the welding when the weld joint cools down to the room temperature.

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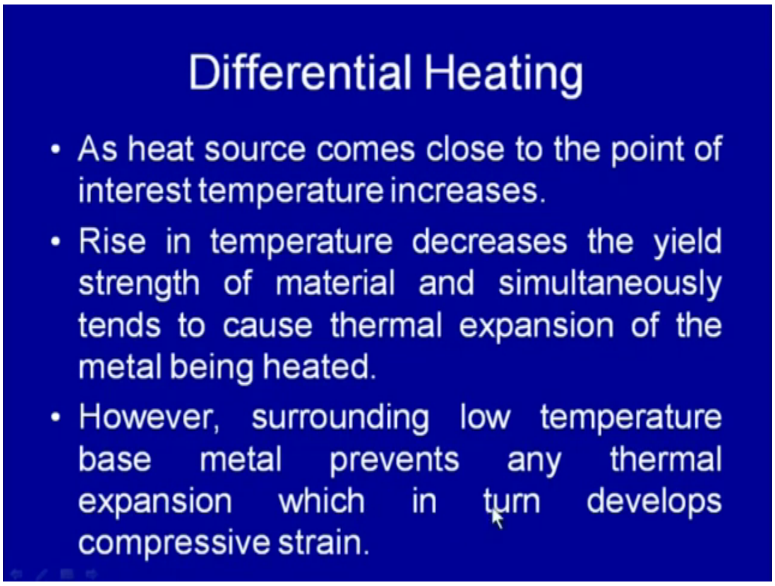

Differential Heating

- As heat source comes close to the point of interest temperature increases.
- Rise in temperature decreases the yield strength of material and simultaneously tends to cause thermal expansion of the metal being heated.
- However, surrounding low temperature base metal prevents any thermal expansion which in turn develops compressive strain.

So, this is how, since the different zones during the welding are heated and cooled in different times and because of this differential heating and cooling, the differential expansion and contraction takes place, and which leads to the development of these residual stresses. As the heat source comes close to a point of the interest, temperature increases as we know and the rise in temperature decreases the yield strength of the metal.

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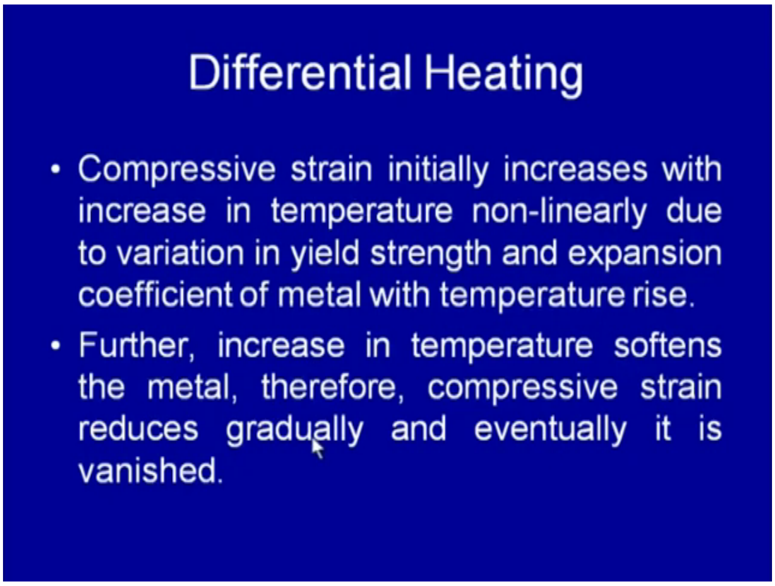

Differential Heating

- Compressive strain initially increases with increase in temperature non-linearly due to variation in yield strength and expansion coefficient of metal with temperature rise.
- Further, increase in temperature softens the metal, therefore, compressive strain reduces gradually and eventually it is vanished.

And simultaneously, it tends to cause the thermal expansion of the material being heated however, the surrounding low temperature base metal prevents the any thermal expansion, and which in turn develops the compressive strain. This is what, happens in case of the heating phase during the welding.

And the compressive strain initially increases with the increase in temperature non linearly due to the variation in the yield strength and the expansion coefficient of the metal with the temperature rise. So, we know that, with the increase in the temperature the yield strength will be decreasing and the expansion coefficient will also be varying. And because of this, we find the non linear change in the compressive strain with the change of or with the increase of the temperature.

Further increase in temperature, softens the metal therefore, compressive strain reduces gradually and they eventually are vanished, as heat source crosses the point of interest.

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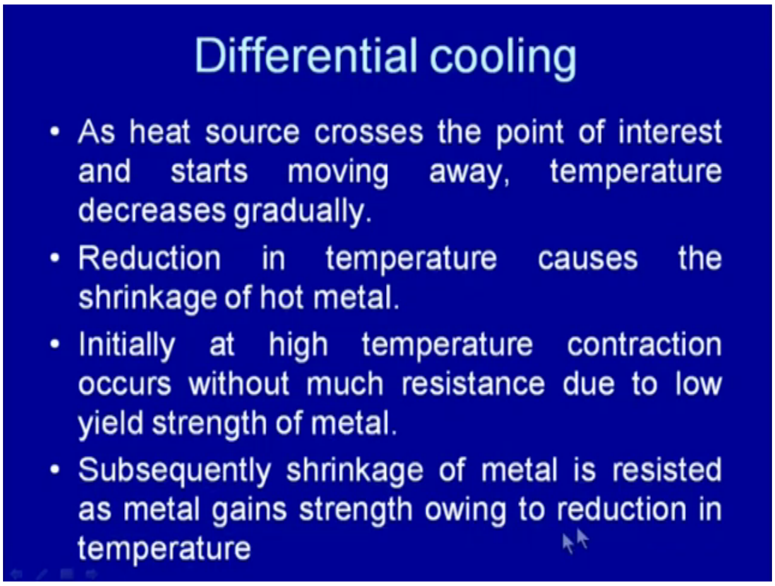

Differential cooling

- As heat source crosses the point of interest and starts moving away, temperature decreases gradually.
- Reduction in temperature causes the shrinkage of hot metal.
- Initially at high temperature contraction occurs without much resistance due to low yield strength of metal.
- Subsequently shrinkage of metal is resisted as metal gains strength owing to reduction in temperature

And cooling starts moving away from the point of interest, the temperature starts decreasing gradually. This reduction in temperature causes the shrinkage of the hot metal, initially at high temperature contraction occurs without much resistance due to the low temperature, low yield strength of the metal. So, during the contraction phase, initially when the temperature starts decreasing after the solidification, some contraction is allowed without much resistance.

Because, material at high temperature has the lower strength and the higher ductility subsequently, shrinkage of the metal is resisted, because of the metal starts gaining strength and as the reduction in temperature takes place. So, as this cooling continues, the material starts gaining strength ductility decreases and this in turn, results in the reduction in shrinkage of the metal, which is taking place. So, this resistance to the shrinkage comes as soon as cooling starts to greater degree because metal starts to gain strength and ductility starts decreasing.

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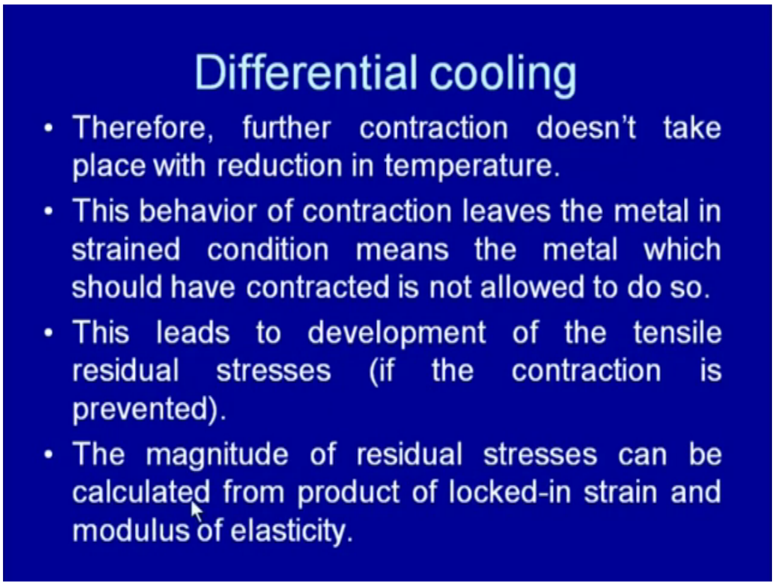

Differential cooling

- Therefore, further contraction doesn't take place with reduction in temperature.
- This behavior of contraction leaves the metal in strained condition means the metal which should have contracted is not allowed to do so.
- This leads to development of the tensile residual stresses (if the contraction is prevented).
- The magnitude of residual stresses can be calculated from product of locked-in strain and modulus of elasticity.

Therefore, further contraction does not take place with the reduction in temperature and this behavior of the contraction leads the metal in the strained condition. Means, the metal which should have contracted is not allowed to do so and this leads to the development of the tensile residual stresses, if the contraction is prevented. The magnitude of the residual stresses can be calculated from the product of this locked in strain, which is left after cooling down to the room temperature.

So, this is strain multiplied by the modulus of elasticity, product of these two gives the magnitude of the residual stresses present in the weld joint after the welding. The quenched stress is another mechanism, through which residual stresses are developed during the welding.

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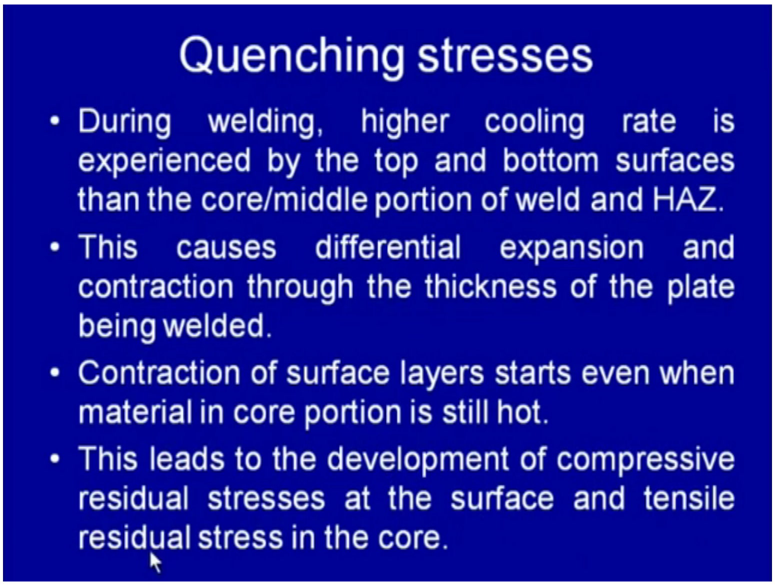

Quenching stresses

- During welding, higher cooling rate is experienced by the top and bottom surfaces than the core/middle portion of weld and HAZ.
- This causes differential expansion and contraction through the thickness of the plate being welded.
- Contraction of surface layers starts even when material in core portion is still hot.
- This leads to the development of compressive residual stresses at the surface and tensile residual stress in the core.

During the welding, higher cooling rate is experienced by the top and the bottom surfaces as compared to the middle portion of the weld zone and in the heated affected zone. Means, the surface and the bottom layers will be extracting the heat rapidly and they will be cooled rapidly, as compared to the metal in the core region of the weld zone and the heat affected zone.

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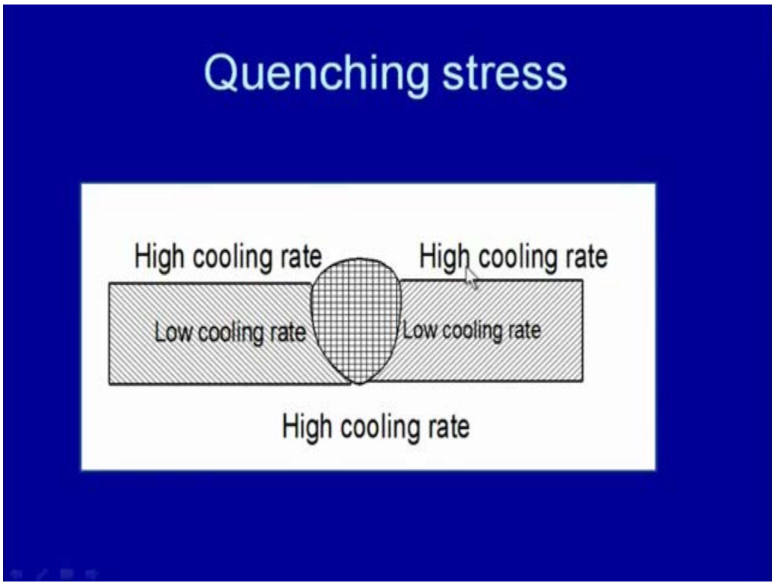

Quenching stress

And because of this differential cooling at the surface in the core region, the differential expansion and contraction is observed through the thickness of the plate, which is being welded. And the contraction of the surface layers starts, because of the rapid cooling of the surface layers, even when the material in the core portion is still hot. This leads to the development of the compressive residual stresses at the surface and the tensile residual stresses in the core.

This is what, we can see the surface layers being cooled at a higher rate and similarly, surface layers means the top and bottom surfaces layers are cooled rapidly and while the core region is subjected to the lower cooling rate. So, this differential cooling results in the significant lower temperature of the surface layers as compared to the core region. And subsequently, on cooling down the entire system to the room temperature leaves the compressive residual stresses at the surface and tensile residual stresses in the core portion.

Probably, this is a favorable situation where, we have the compressive residual stresses present at the surface near the surface layers, while in the inner portion of the component means, in the sub surface zone or below the surface, we have the tensile residual stresses. Presence of the tensile residual stresses below the surface is not considered to be that harmful as compared to the case, when they are present at the surface.

Because, tensile residual stresses frequently promote easy nucleation of the crack and crack nucleation and the crack growth and so as to, cause the premature failure of the component. So, the presence of the tensile residual stresses, frequently promote the premature failure of the component under the tensile and the fatigue load conditions. So, it is always favorable to have the compressive residual stresses, which are developed under the quench, because of the quenching. That is the differential cooling and cooling being experienced in the surface and in the middle zone.

The third mechanism is the metallurgical transformation we know that, the hardenable steels during the welding are subjected to the transformation from the austenite to the various phases like peralite, bainite and the martensite. So, depending upon the temperature, at which these transformation take place, the different kind of residual stresses can develop.

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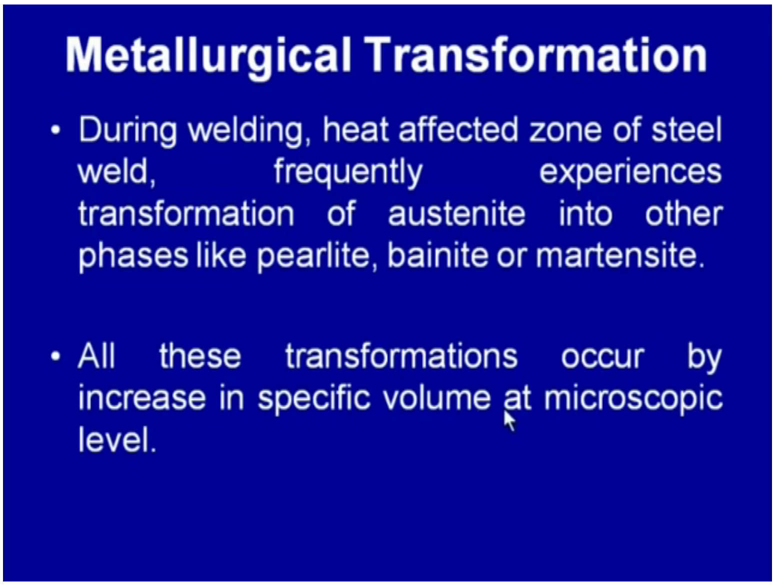

Metallurgical Transformation

- During welding, heat affected zone of steel weld, frequently experiences transformation of austenite into other phases like pearlite, bainite or martensite.
- All these transformations occur by increase in specific volume at microscopic level.

During the welding heat affected zone of the steel, weld frequently experiences transformation of the austenite into the other phases like pearlite, bainite and the martensite and all these transformations occur with the increase in specific volume at the microscopic level. So, those transformations which occur at the higher temperature with the increase in the specific volume, these transformations can be easily accommodated, because of the low yield strength of the material and the high ductility at high temperature.

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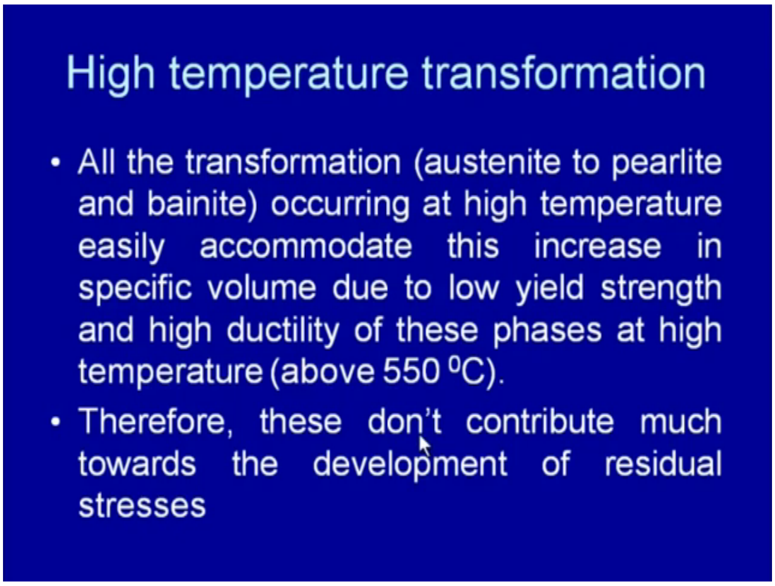

High temperature transformation

- All the transformation (austenite to pearlite and bainite) occurring at high temperature easily accommodate this increase in specific volume due to low yield strength and high ductility of these phases at high temperature (above 550 ^{0}C).
- Therefore, these don't contribute much towards the development of residual stresses

So, all those transformations like austenite to pearlite and bainite, which occur at the higher temperature. These can be easily accommodated with the increase of specific volume due to the low yield strength and the high ductility of these phases at the high temperature that is, mostly above 550 degree centigrade. And therefore, these kinds of phase transformations, these do not contribute much towards the development of residual stresses.

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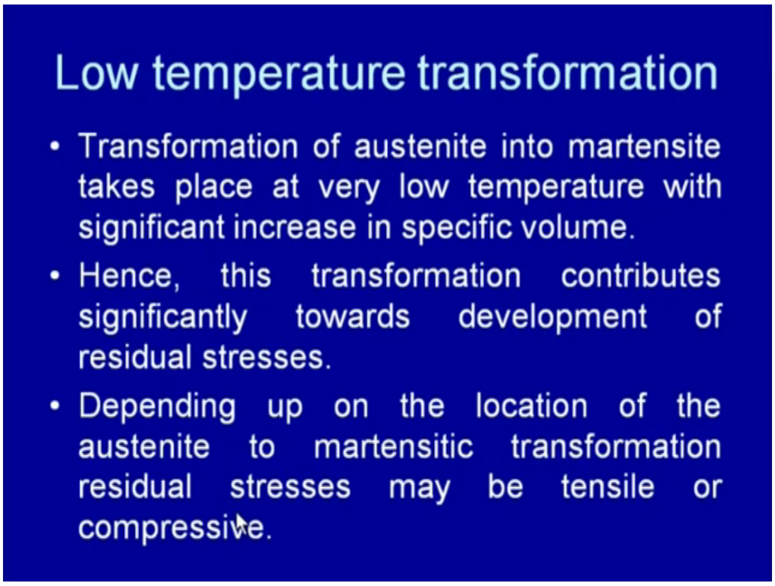

Low temperature transformation

- Transformation of austenite into martensite takes place at very low temperature with significant increase in specific volume.
- Hence, this transformation contributes significantly towards development of residual stresses.
- Depending up on the location of the austenite to martensitic transformation residual stresses may be tensile or compressive.

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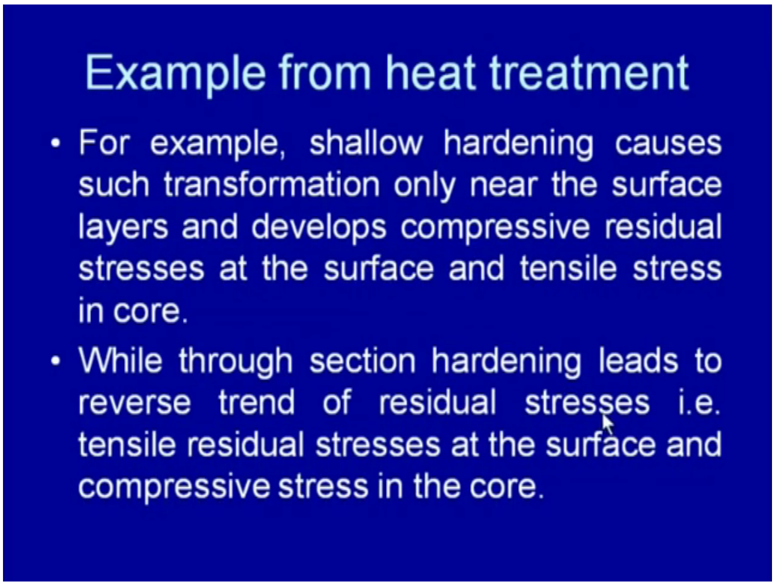

Example from heat treatment

- For example, shallow hardening causes such transformation only near the surface layers and develops compressive residual stresses at the surface and tensile stress in core.
- While through section hardening leads to reverse trend of residual stresses i.e. tensile residual stresses at the surface and compressive stress in the core.

But the low temperature transformations mainly, austenite to the martensite, which are at very low temperature and that too, with the significant increase in specific volume. So, this transformation contributes significantly towards the development of the residual stresses. Depending upon the location of the austenite to the martensitic transformation, residual stresses may lead to the transformation stresses, may be the tensile or the compressive in nature.

For example, during the shallow hardening means, we commonly use the 2 types of the heat treatment for the hardening purpose, one is called shallow hardening, another is through section hardening. In shallow hardening, only the subsurface means near surface layers are hardened to the desired degree of the hardness and in case of through section hardening, entire section is hardened.

In shallow hardening, the transformation of the austenite to the martensitic, martensite occurs only near the surface layers and develops the tensile compressive residual stresses at the surface and the tensile residual stresses in core region. While in case of through section hardening, the reverse trend is observed as far as the development of the residual stresses is concerned because we get the tensile residual stresses at the surface and the compressive residual stresses in the core.

So, if it is required to develop the favorable compressive residual stresses in the component then shallow hardening is found suitable in developing the compressive residual stresses, so as to have the these stresses, which are commonly used for enhancing the tensile performance and the fatigue performance of the component during the service. While the presence of the tensile residual stresses adversely affect the tensile and the fatigue load carrying capacity.

Now, we will be talking about the effect of the residual stresses, residual stresses affect the performance of the weld joint in 3 ways. One is the mechanical load carrying capacity of the weld joint and the second is the kind of, the performance of the weld joint in the coarse ((Refer Time: 44:29)) environment and third is the way, by which the dimensional stability of the component is affected. So, because of this localized presence of these residual stresses, various favorable and unfavorable effects are observed in the performance of the weld joint.

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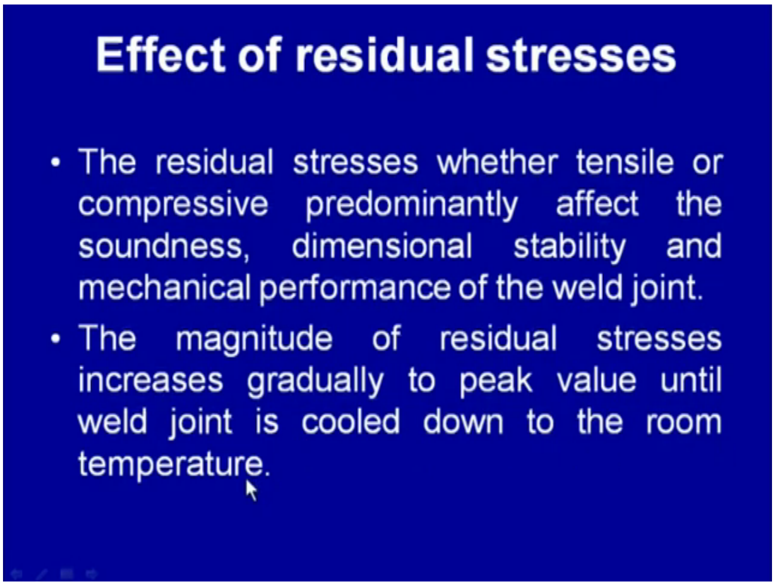

Effect of residual stresses

- The residual stresses whether tensile or compressive predominantly affect the soundness, dimensional stability and mechanical performance of the weld joint.
- The magnitude of residual stresses increases gradually to peak value until weld joint is cooled down to the room temperature.

Residual stresses whether they are of tensile or the compressive, predominantly affect the soundness of the weld joint, dimensional stability and the mechanical performance. Soundness because if the tensile residual stresses are very tensile in nature then these can promote to the cracking of the weld joint especially, in the heat affected zone and in the weld region. While the dimensional stability during the welding, excessive development of these residual stresses lead to the change in the shape of the components being welded.

And when these go out of the shape we say that, the distortion in the weld joint has taken place or there will be change in the size and the geometry of the component due to the presence of these residual stresses. Further, the mechanical performance in terms of the tensile load carrying capacity, compressive load carrying capacity and the fatigue load carrying capacity is observed. The magnitude of the residual stresses increases gradually to the peak value, until the weld joint is cooled down to the room temperature.

So, we have seen that, magnitude of these residual stresses grow gradually and it will be at the peak value, when the weld joint comes down to the room temperature.

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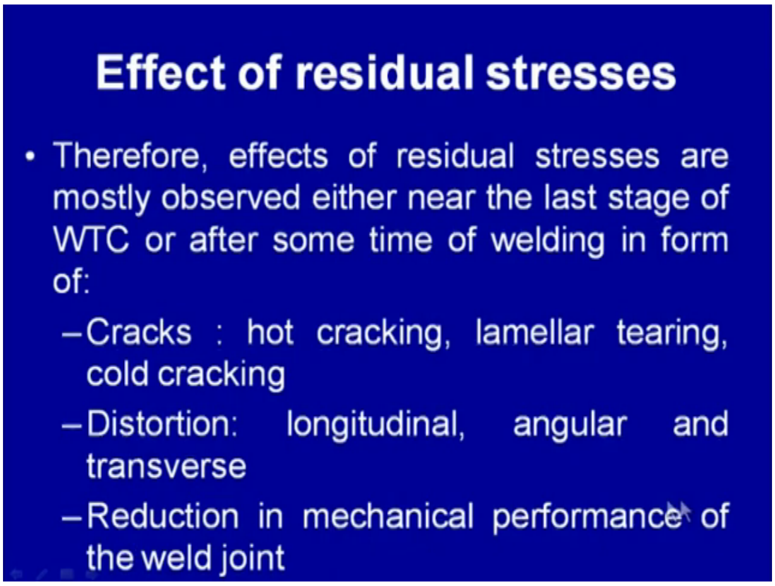

Effect of residual stresses

- Therefore, effects of residual stresses are mostly observed either near the last stage of WTC or after some time of welding in form of:
  - Cracks : hot cracking, lamellar tearing, cold cracking
  - Distortion: longitudinal, angular and transverse
  - Reduction in mechanical performance of the weld joint

And therefore, effects of the residual stresses are mostly observed near the last stage of the weld thermal cycle or after some time of the welding, in the form of cracks means, since we get the maximum magnitude of the residual stresses only on after cooling down to the room temperature or at the last stage of the weld thermal cycles. So, these adverse effects of the residual stresses can be observed in form of the cracks, these cracks can occur at the high temperature.

Accordingly they are called hot crack or they can occur near the heat affected zone, in the heat affected zone just below the weld fusion boundary. And due to the decohesion of the inclusion, these are termed as lamellar tearing and the development of the cracks after some time of the welding due to the presence of the tensile residual stresses and the hard and very brittle microstructure in the weld joint, which have been made under very restrained conditions and the distortion.

The weld joints can go out of the shape, when there is significant magnitude of the residual stresses developed during the welding and this out of shape weld joints can be in form of the longitudinal distortion, angular distortion and the transverse distortion. And there can be reduction in the mechanical performance of the weld joint, this reduction in performance of the weld joint can be in form of the reduced tensile load carrying capacity and other reduced fatigue load carrying capacity.

So, effect of these residual stresses in detail will be discussed in the next presentation now, I would like to summarize this presentation. In this presentation, mainly we have tried to understand the residual stresses, the mechanisms that lead to the development of the residual stresses and what are the important effects of these residual stresses on the performance of the weld joint.

Thank you for your attention.