Finite Element modeling of Welding processes

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Lecture - 30
Material models, Residual stress and distortion

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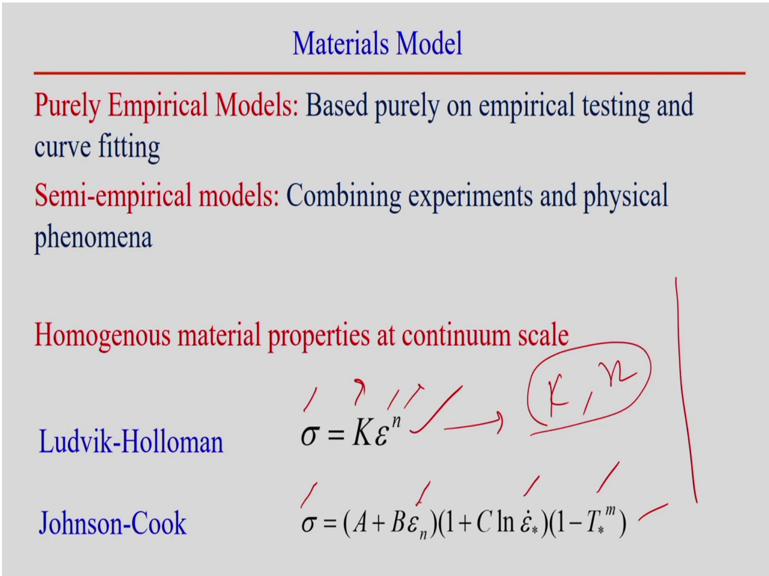

Hello everybody. Now, we will discuss the Materials model which is very important in stress analysis of welding processes as well as the stress analysis in other manufacturing processes or maybe in material forming process also. So, materials model is very important; it simply indicates that, the relation between the stress and strain and that actually always this relationship come looking into the, this actual experimental data.

We normally compare the actual experimental data with the theoretical values of the equivalent stress. If we assume that, experiments can be done in a uniaxial tensile testing or some other condition or other conditions mean, the different strain, strain rate at different temperature also.

At the same time that similar this single values of the stress which is represented by the; we have already shown the von Mises functional form, there we can represents the equivalent stress value. So, all as the equivalent stress value and all equivalent strain value, we can compare with this thing and based on that different relationship may happens with the different parameters.

For example in materials model, purely empirical models and that based on primarily purely on the empirical testing and the curve fitting; that we have say so many test data, at the different temperature value or different standard value and we feed the curve and use that data.

Then we reach, we express some formation; for example, in these cases the Holloman type of equation, Ludvik Holloman equation you can see also, this equation is a kind of empirical constant that empirical relation. The stress is related to strain with a n is the strain hardening coefficient and K is the some constant value.

So, K can vary depending upon the material also; so that means, this kind of relationship always require to input to the model also and if we want to develop some plasticity model during the deformation process. Similarly, the it is may materials model can be also semi empirical in nature; in these cases combining the experimental as well as the physical phenomenon has to be considered and based on that we can reach some kind of the expression.

For example, one of the other example is that Johnson cook model also; in this case the we relate the stress, but if stress is related to the strain and then strain rate as well as the temperature. And there may be some critical value also; then say applicability in the sense that, within certain range of the temperature, certain range of that strain rate, this relationship may be applicable.

So, this kind of the relation to find out all these relation, its needs a lots of experiments and if the data is compare or fitted purely based on the experiment, that is called the purely empirical models. Or sometimes we consider some micro mechanics available or during the deformation process also and in that cases some semi empirical models can be developed.

So, both is finally, linking the stress and strain and that is useful to develop the model. So, but in this case these materials model we need a lots of; for example, if we use the Holloman type of equation, in this case we know that K and n are the unknown parameter.

But in this case there are so many constant term involved and then maybe some limit involved and as a result parameter also; this is not only the stress strain, another temperature dependency also there as well as the strain rate dependency is also there. So, therefore, this complex formula or that relationship between the stress and strain which is required and as a function of the other parameters when you try to develop some kind of the stress analysis model; that is the importance of the materials model in the stress analysis.

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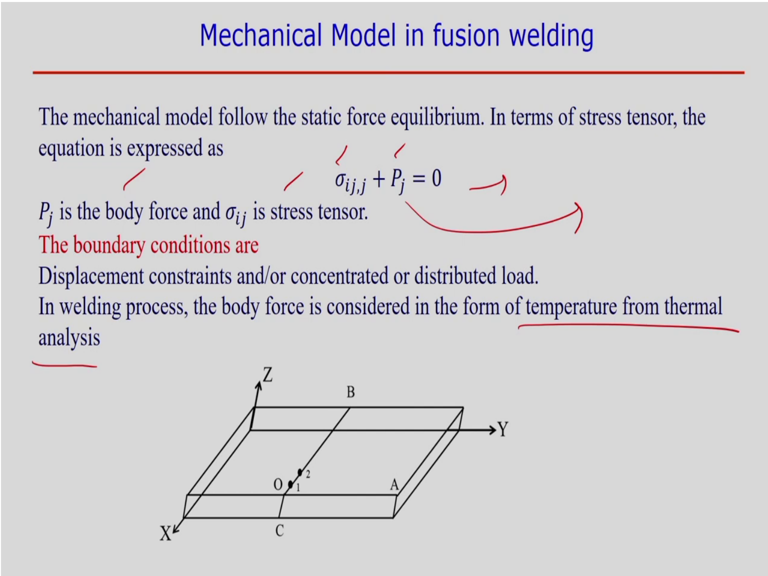

Now, in general mechanical model in fusion welding process we normally consider the static force equilibrium; in terms of the stress tensor, the equation can be expressed like that. That means, if there is a some force acting, the force can be body force or some external force, such the internal stress will be generated and its make the balance and the under static equilibrium condition, now that is the following in case of the stress analysis model.

Now, in this case P j is the body force and sigma i j is the stress tensor; so that means, sigma i j stress tensor mean in this case, the within the internal stress will be there may be some six or nine components of the internal stress within this body. Now, apart from this thing, static equation, it is also necessary to consider the boundary conditions.

So, boundary condition can be like the displacement constant or concentrated or distributed load also. In case of the, in case of welding problem, normally we considered displacement constant; in the sense that we restrict the displacement of certain part. For example, suppose this is the solution geometry and in an actual welding process, wants to do the welding process; we just clamping the other parts. So, which point the clamping is done, we can put some mechanical constant condition in terms of the displacement.

For example, in certain direction the displacement can be zero; in that sense, we put the displacement constant and that acts as a boundary interaction in the stress analysis model, along with this force equilibrium equation. But in welding process, the body force can be considered only for the due to the temperature from the thermal analysis.

So, that means the body force P i j in this case is the, in this case the it can be comes from the temperature distribution; let us say if we can consider this as a thermal load, that means because of the non uniform temperature distribution within this body. So, that can acts as a body force here and that will generate the stress value.

And then this stress we are considering that material follow the elastoplastic law; that means this stress, stress generation may cross the elast yield point and comes to the part of the plastic domain. So, therefore, once it enter the plastic domain, then we have to consider the elastoplastic analysis. So, that is way we can consider any kind of the mechanical, thermo mechanical model in fusion welding process.

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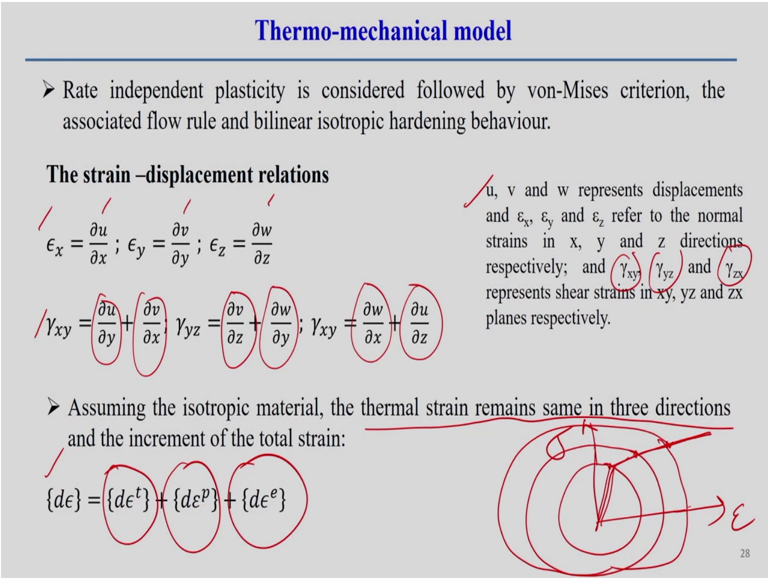

But in this case we understand that, normally we use the rate independent plasticity is the most simplified plasticity law we can we it will be useful in. For example we can use the von Mises yield condition also or else yield surface process followed by the von Mises criteria.

The associated flow rule also we have already explained and bilinear isotropic hardening behavior. Bilinear isotropic hardening behavior means that, we represent the stress strain diagram this way also, these two bilinear curve and this is the stress strain diagram and we represent this one you know this elastic part and this is the plastic part another linear curve.

So, that is called the bilinear, and hardening rule we can consider the isotropic hardening; so that means the isotropic hardening means, the yield point with the initial yield point this yield point evolves depending upon this thing. This is the second third print yield point reaching;

but this changing of the yield point; it depends on the strain hardening behavior of this particular material.

So, that is why we consider this as the isotropic hardening; that means same center point of this yield surface or yield curve that is evolved depending upon the strain hardening phenomena.

Now, it is also necessary in stress analysis model that, that relation between the strain and displacement; because if you remember when the very first when you develop some kind of the elemental form or basic fundamentals of the finite element applicable to the stress analysis in general, we normally form the stiffness matrix.

But stiffness matrix is associated with the displacement and we solve for the displacement field. Once we get the displacement field; then from the displacement field, we further calculate what is the strain value and then after we calculate the stress value also.

So, therefore, so relationship between the stress and strain is required. So, in this case the small displacement theory if we follow; then strain can be is the u is the displacement field, del u by del x is equal to the strain; along x axis the epsilon y, the strain along y axis is the del phi by del y.

Similarly, epsilon z del w by del z. So, this way we relate the between strain and displacement and u, v, w here represent that displacement and epsilon x, y, z refers to the normal strain component in x, y and z direction. And apart from that the gamma x y, y z, z x that represents the shear strain component in the x y, y z and z x plane respectively.

So, therefore, the shear strain component can be linked with the displacement field equal to this part del u by del y plus del v by del x that is gamma x y; gamma y z, so del v by del z and del w by del y. Similarly, x y equal to del w by del x del u by del z. So, this way we relate the all the shear strain and normal strain component in terms of the displacement field.

It means that, if it is to get the solution from the stiffness forming the stiffness matrix, if we solve for the displacement field in a stress analysis model in general; then once we get the displacement field, then we can update what is the strain field or increment of the stress can be calculated.

Now, in these cases assuming the isotropic material; so material properties are same in all three direction and thermal strain remains same in all three direction and the incremental of the total strain. That means, thermal strain if isotropic material thermal strain remain in all three direction.

So, we need to calculate the thermal strain also; in this case this represents the thermal strain component. And then total strain, we can see is the simply summation of the thermal strain; plastic strain and the elastic strain, although already we have already mentioned that, we normally do the stress analysis in the incremental mode.

So, therefore, it is very important; it is particular during the deformation process, what is the increment of the strain. Now, total increment of the strain can consist of all these in case of elastoplastic analysis. So, total strain having this thing. So, the plastic component and elastic component will be there.

Because material behaves like the elastoplastic material and apart from that, there is a application of the temperature or non uniform temperature distribution that induce the thermal strain. So, therefore, this way we can say the thermo mechanical analysis, then all this strain component has to be considered.

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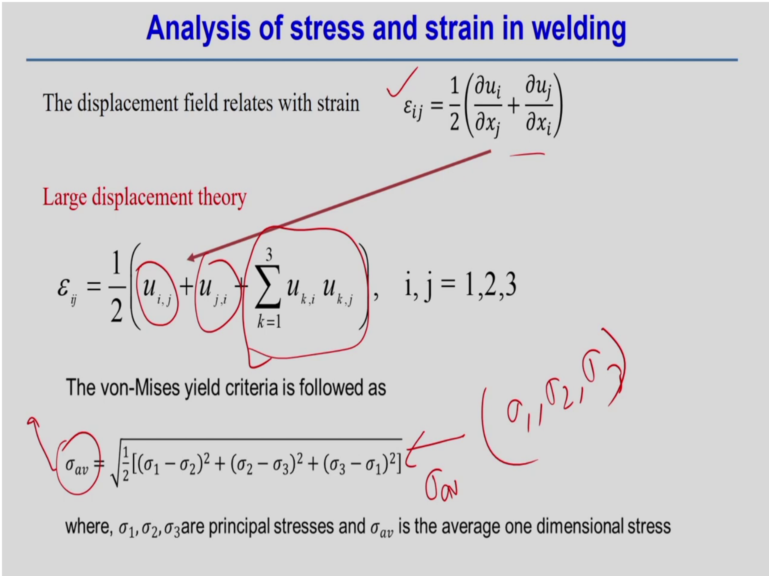

Now, based on the increment of the strain, we can put this; we can form the incremental form, what is the increment of the stress in a particular time step or in a particular load step. But before that, this displacement field relation already we have explained this epsilon i j equal to half of del u i by del x j and del u j by del x i.

So, that is we have already explained the, what are the normal strain and the shear strain component; but in these cases we assume the small displacement theory. If it is a large displacement theory, then this accounts the small displacement component; but, if variation of the or higher order differentiation of the displacement field, then we can consider the large displacement field.

And in these cases, this component, extra component accounts the large displacement or the variation of the displacement in the small zone. So, that sometimes it is possible to predict the what is the buckling happening inside the very thin plate. So, in that cases, maybe it is necessary to consider the large displacement theory.

And apart from that thing, it is also necessary to understand these stress analysis model that, average or equivalent stress; average or equivalent stress we can see that, always when we apply the von Mises yield condition, we always estimate the what is the value of the principal stress component and from the.

If we know the principal stress component sigma 1, sigma 2 and sigma 3; so, using this we say, this is the one single component, the average or equivalent stress component which consists of the all the principal stress component. So, this average value or equivalent value consisting of the all theoretical prediction of the principal strain stress components.

And this average value always we compare with respect to the experimentally measure, the stress value one particular strain component. That is why we need to know the materials model also to relate between the stress and strain. And then theoretically, once we calculate what is the equivalent value of the stress by following some kind of the plasticity.

For example, following in these cases following the von Mises yield function, then we estimate the average stress value and this stress value has always has to be compared with respect to the experimental value, but experimental value we normally obtain from the uniaxial tensile testing. So, from the uniaxial tensile that we compare and accordingly we can decide the different strategy or putting the flag and in case of the stress analysis model.

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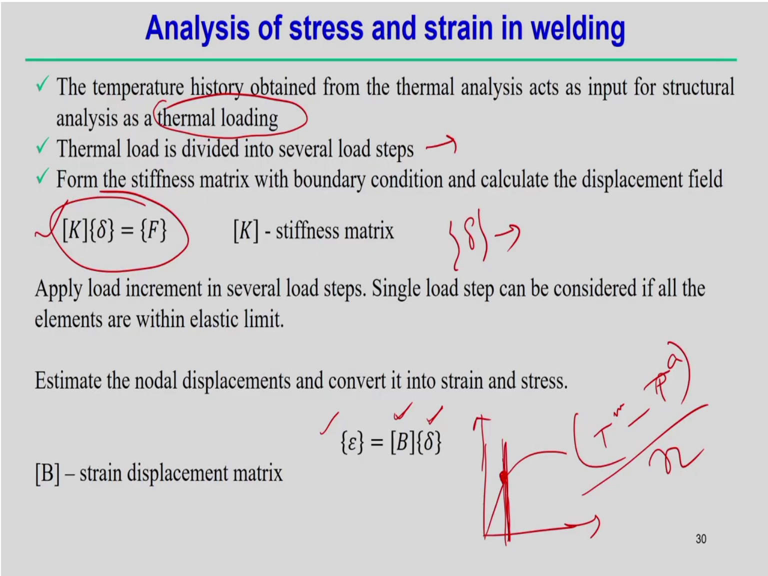

So, analysis of the stress and strain in welding in general procedure is that, first is the temperature history; definitely once we go for the stress analysis model, we need to do first the thermal analysis, that means we need to know the information of the temperature data.

So, then temperature history obtained from the thermal analysis acts basically as a input to the for the structural analysis of a thermal as a thermal loading. So, thermal loading that means this is the input as a thermal load for the structural analysis; then we do the stress analysis and we get the output as a in terms of the displacement stress and strain field also.

Now, this thermal loading, thermal loading means the completely temperature distribution; but in a in case of the transient analysis. So, it is necessary to consider each and every time step, what is the thermal data, thermal value, temperature distribution. So, therefore, if we put all this temperature history to the stress analysis model, but to do this thing, thermal load is divided into the several load step.

In this case for example, the stress can be if we assume that; there is a heating phase and the cooling phase also. So, heating phase, the temperature is increment during the welding process and during equilibrium, temperatures decreases from the maximum temperatures to the room temperature value.

So, we can divide this as a total thermal load. So, from during the heating phase and during the cooling phase also; this total thermal load once we come back to this particular temperature, ambient temperature, we divide we can this is the total thermal load, but during the analysis we have to make in the incremental way.

So, we cannot put this total load as a single time step and will we may not get the, not able to get the temperature, stress distribution as an output in a single step. Basically this total thermal load; that means the maximum temperature to ambient temperature. So, we have to make this as a n number of division that, we consider this as a consider as a thermal load.

This can be coincide with the temperature; that means the time step also within the, this is thermal load and we divide this load in terms of the total number of time steps, such that we will be able to capture after ending of the each time step what is the, what was the temperature value before and after.

So, therefore, this total thermal load can be divided into number of steps and it is possible to analyzing each and every step also. And once we getting the output as a stress, displacement stress temperature for the one increment of the strain component; then we keep on updating the what next step by simply adding all these stress value, strain component value and displacement value.

So, that is why in that way we normally progress the stress analysis model. So, therefore, thermal load is divided into several load step and though we analyze each and every load step.

And then it is obvious the from the stiffness matrix with the stiffness matrix and the along with the boundary conditions and we calculate.

So, this is the general form of the matrix, the sorry. So, we normally form the K matrix, stiffness matrix and delta is a displacement field that is defined each and every node point in a discretized domain. Then F is the load and the F is the load in this case maybe it is only, we can consider the S as a thermal load in this particular situation in welding process.

But this thermal load, but it can be added with the; if there is any concentrated load or distributed load is there in particular problem also, we can add this thing. But once we solve this equation, matrix equation; then we will be able to get the what is the displacement value.

So, here the output is the displacement field; so then once the displacement field displacement value, each and every node point. So, once we get the displacement value each and every node point; then we convert to into other strain component, we further calculate and what is the increment of the stress that is also we can calculate.

So, apply load increment in the several load steps, definitely we first the division of the several load step is required and analysis of the each and every load step is required. So, single load step can be consider, if all the elements are within elastic limit; it means that it is always incremental mode, but since within the elastic limit in actual process, actual mechanical analysis.

In this case the one single load step; so that means this kind of load step can be applied, such that if we can ensure that all elements are within elastic limit. So, we can increase the this can be considered as a single load step and we can reach the analysis from directly this point, exactly the just up to the yield point.

So, there we can get the stress distribution, if it is within the elastic limit. Now, estimate the nodal displacement and convert it into the strain and stress components. So, once we getting once we getting the displacement field, then we convert into the strain components.

For example, strain can be related to the strain displacement matrix B and strain displacement matrix in the displacement field. So, displacement field is known; then if we multiply these things then displacement matrix, then we will be able to get the what is the value of the strain distribution of this point, after the particular step.

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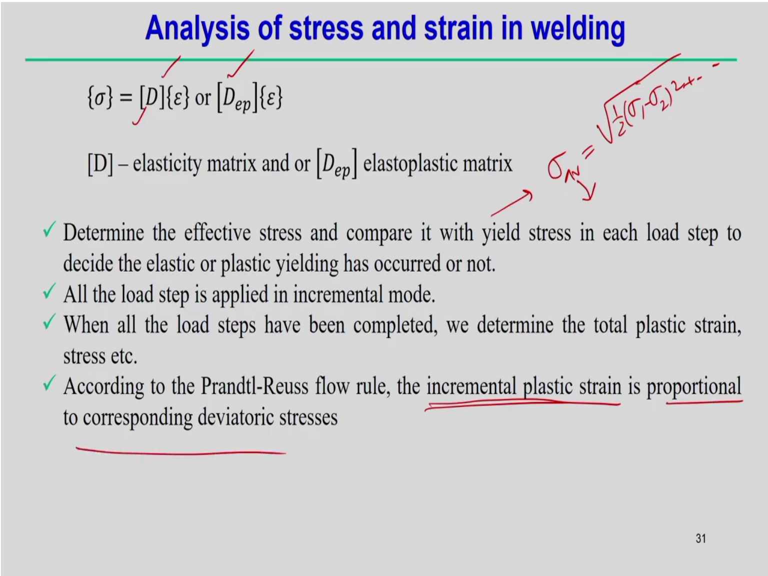

Similarly, stress can be estimated by either D into epsilon, D is the elasticity matrix; if we the analysis is within the elastic limit, then we can we can do for the elastic; we can use the value of the D the elasticity matrix. If you remember the elasticity matrix is can be consists only associated with the different material properties.

For example it is associated mostly the Young's modulus and the Poisson's ratio with that D is accounting, all the elements of the D is accounting this thing in the different form. So, therefore, D is the elasticity matrix. But if some elements are goes into the plastic domain also; that means within the plastic, then in that cases the we can estimate the stress value of this particular element by considering the elastoplastic matrix D ep.

So, therefore, depending upon the whether the element is within the elastic zone or plastic zone, we can upgrade the stress value by looking into the either D elasticity matrix or D ep elastoplastic matrix. We will show how the elasto matrix can be form also in the next slide.

So, therefore, once we focus the analysis in this during the welding process. So, it is also necessary that we have to check; because each and every load step, after the load step or the time step, we can get the effective stress value. So, we can get the effective stress value; that is the average stress or effective stress value which is can be represented by following the von Mises yield function form ok, so these in terms of the principal stress components.

So, therefore, this value always we compare with respect to the, compare it with the yield stress value; that means whether this effective value is more than the yield stress value or less than the yield stress value. Accordingly we can decide that, where the yielding has happens or not or if some elements can go before the below the yielding point and some elements go above the yield point.

So, accordingly we can use these D matrix or D ep matrix or we can do some iterative calculation to make it the converge solution whether within the whether within the elastic limit or within the plastic limit. So, therefore, all the load step is applied in incremental mode, that is already explained; because we first divide the number of load step has to be considered, then in the incremental way, we apply the each and every load step.

So, once the all the load step have been completed, then we will determine the what is the plastic, strain, stress etcetera value and we predict the what is the residual stress, the existing stress even after cooling to the room temperature; that indicates the residual stress value or residual strain value also we can get the output from the analysis.

Now, according to the Prandtl Reuss flow rule; we have already seen that the flow rule also that plastic the sustainability of this plastic deformation even after yielding, that has to be give some kind of the flow rule also. The incremental plastic strain is proportional to the deviatoric stress, if we apply the flow rule also.

In this case, we consider the incremental plastic strain is proportional to the deviatoric stress component; from that point of view, we can reach some kind of the relation between the stress strain value.

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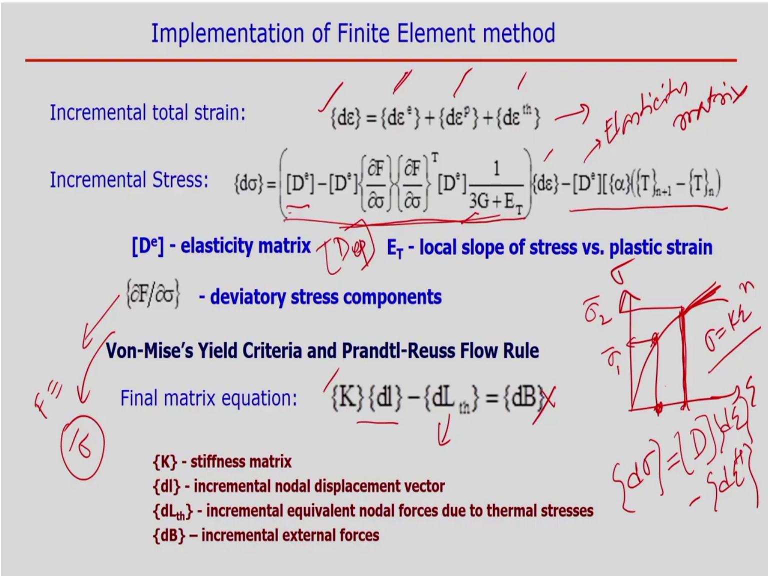

Now, at any particular load strain, this is the incremental strain value, the which consists of the both element elastic plastic and thermal strain. And now what may be the, if we know this is the incremental strain value. So, from the incremental strain value, what may be the incremental stress value? So, in the particular step.

So, incremental stress value, once we estimate the this incremental strain, from there we can estimate the incremental stress value. Like that if you see the, this is the elastic matrix and this is the plasticity matrix D P, D elastic and D plastic and then total strain; minus of this is the elasticity matrix, I think D has already explained this thing, D is the elasticity matrix if we consider. So, D e indicates the elasticity matrix

Now, from the elasticity matrix, we use the we estimate the thermal strain; but remember here we can see, we are considering the thermal strain as a elastic strain. So, in this case thermal strain we estimate minus of thermal strain; because in this case the thermal strain is the input and then from there this is the elastic and finally, we can say this can be considered as a D elastoplastic matrix, D e p thing like that.

So, therefore, D elasticity matrix and in these cases E T represent the local slope of the stress versus plastic strain. So, local slope stress versus plastic strain, suppose this is the elastoplastic matrix at this point; this is the local strain and the at this point what is the slope that indicates the E T?

So, local slope of the stress versus plastic strain or we can say the in this case the slope at particular point. And del F by del sigma it indicates the deviatoric stress component. So, in these cases it indicates the deviatoric stress components and F we can estimate the deviatoric stress component in this cases F, we assume the functional form. In these cases, we can assume the functional form follow the Von Mises yield functional form.

So, from there we can estimate the del F by del in this in terms of the deviatoric stress component and other parameters associated with this thing; for example, here we can see G is the shear modulus also. So, therefore, this way we can see that D sigma can be represented that the increment of the stress is basically equal to the D matrix and the total strain and minus the thermal strain that is the value.

And this is the increment of the stress value during this any incremental analysis. So, therefore, if we follow, this once we are considering this thing del F by delta deviatoric stress components; therefore if we follow the functional form Von Mises, then from there we are following the this expression comes from the Von Mises yield criteria and Prandtl Reuss flow rule. From the from both the point if you follow this thing, we can get the different functional form or some relation.

For example, here we assume that incremental plastic strain is proportional to the corresponding deviatoric stress component; this assumption is comes from this thing by following some Prandtl Reuss flow rule, from their point it is coming. And once we following the yield criteria and that yield criteria should, it is a functional form can be represented the Von Mises yield functional form.

So, therefore, if we estimate del F by it in terms of the deviatoric stress component as well as the this value, average value of the this is the yield point value particular point. So, this yield point value, this yield value of a particular strain value. So, then this yield value can be considered, it is depends on the strain hardening behaviour of a particular material.

So, this can be also updated of the strain hardening behavior. For example, if this particular strain value; this is strain component and this is stress. So, in this particular strain value; so you will getting, so this is the yield point. Now, this is the yield point. So, then here we getting the sigma bar.

Now, once we reach this point, we are considering the strain value at this point. So, in incremental strain reaches at this particular point; that means this is the corresponding yield value, which is more than that of the sigma 1 y. So, therefore, sigma 1 to sigma 2 and from this point to this point reaching this thing value, it is depends on the strain hardening coefficient; the n value, the slope of this logarithm slope of the, if we follow the stress is relation the K epsilon to the power n.

So, in the logarithm scale, n represent the slope of the this curve. So, therefore, that is way we have we know the strain hardening coefficient and from there we can estimate the, we can define the different value of the yield point, which evolve following the isotropic hardening rule.

So, finally, this for your incremental load step, the final matrix equation can form like that; the stiffness matrix dL, the incremental nodal displacement we can say like that. And incremental equivalent nodal forces due to the thermal stress only in these cases dL thermal stresses only and dB is the incremental external force.

In these cases we normal do not consider, not associated with the welding process. So, therefore, K dl equal to the only the thermal load is there. So, if we solve this equation, then we will be able to know what is the displacement field.

And already shown that once we get the displacement field even in incremental mode; then we need to convert in terms of the strain field and from the strain field, we can estimate the what is the value of the stress field. And that is the overall analysis procedure in case of the mechanical model associated with the welding process.

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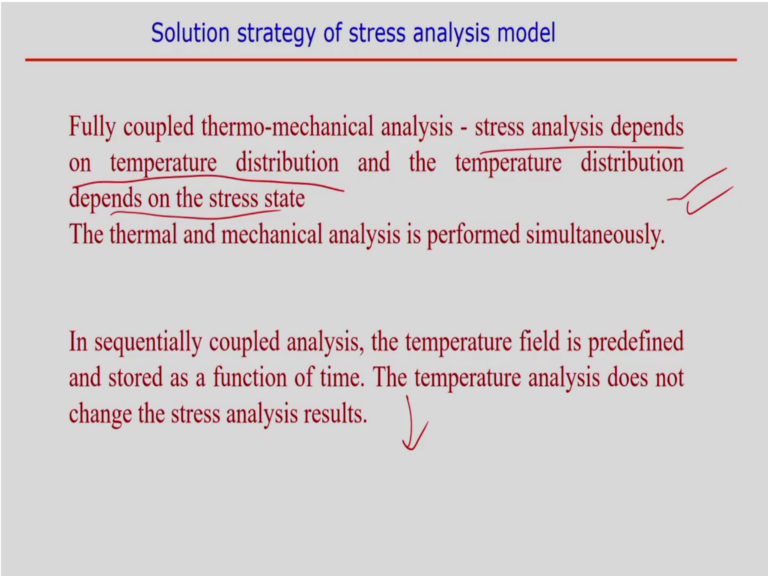

Now, solution strategy of stress analysis model. So, in these cases normally we follow even in any standard commercial software, we normally follow the fully couple thermo mechanical analysis possible. So, in these cases fully couple thermo mechanical analysis means, the stress analysis depends on the temperature distribution as well as the temperature distribution depends on the stress state.

So, it is normally happens the temperature distribution it is true that, stress analysis depends on the temperature distribution; but in some point, the temperature distribution also depends on the stress state. For example, in case of the highly deformation process; so deformation process it will generate some amount of the heat generation will also be there. So, that means stress temperature distribution also affected by the stress state.

In that cases, it is necessary to consider the couple thermo mechanical analysis; but this thermo and mechanical analysis in these cases perform simultaneously. So, computation time is very high. But in other way sequentially couple thermo mechanical analysis in these cases, the temperature field is predefined for the stress analysis; that means first we obtain the temperature analysis.

So, once we get the temperature analysis, we consider all the data; then we perform the mechanical analysis. This is called the sequentially couple, sequentially couple analysis; in that cases, this is more suitable in case of the weeding process, because the other way also temperature distribution hardly depends on the stress analysis or stress state.

So, that is why in particular to fusion welding process, we normally follow the sequentially coupled analysis; that means first we do the temperature analysis, after that we to the mechanical analysis.

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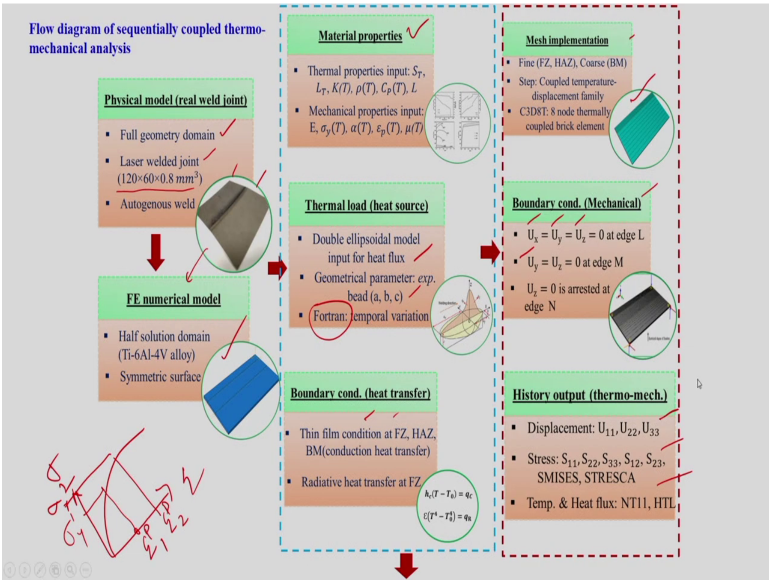

Flow diagram sequentially couple thermo mechanical energy is something like that, we follow even the standard commercial software also; we can see that how it works. So, physical model, the real world model; first is the we define the full geometrical domain, define the geometrical domain that over which we are supposed to get the solution.

Then in these cases for example, laser welded joint; we define this is the dimension of the solution domain. And autogenous welding process, there is no material deposition. So, here you can see this is the actual domain in case of the welding process. Now, we are representing this in the in the mathematical model of using the finite element method.

So, then in the FE model finite element model, we consider the half of the domain; for example, titanium alloy, half of the domain, because of the domain size of the domain depends on the symmetric nature of the problem itself. So, in these cases, we consider the symmetric problem.

So, therefore, it is not necessary to analyze the whole domain; but rather we can consider the only the symmetric part. In this case we can consider the half of the plate also and then we can do the analysis; but accordingly we have to define the symmetric boundary condition. And then in this case, we can we can reduce the computational time during this process.

So, once we convert the actual welding problem to the in the domain of the FEM numerical model if we convert it and then we consider this is the domain of the mathematical analysis. Now, in these cases, we need to define that material properties. So, first material property has to define and it is possible both constant material properties as well as temperature dependent properties; it can be we can out input can be in given in the form of a tabulated form also that, data should be available thermal properties.

For example, this thing latent heat, then density, thermal conductivity, specific heat all these values can be given. And apart from that if we do for thermo mechanical analysis; then mechanical properties should be given also that Young's modulus, yield stress value and then alpha, that means thermal expansion coefficient, then what is the plastic strain value.

All these parameters plastic strain value is required; because each and every plastic strain value what is the value of the yield stress in the plastic domain. For example, if this is the this kind of input is required also, suppose this is the plastic. So, each and every this is the strain and what is the corresponding value of the sigma y and what is the corresponding value?

So, that kind of the value is required to given, because this experimental value, because we already mention that things when we estimate the equivalent stress value from the theoretical analysis by assuming some kind of the plasticity model; from there we can convert this three principal stress in the form of a equivalent stress single value and that single value always we compare with respect to the this experimental value of the yield stress.

And then if we from this comparison, we can decide whether particular zone is in elastic domain or whether it is particular zone in plastic domain and that is why it is necessary to define all these mechanical properties.

So, now once it is defined the all the properties, then thermal load; thermal load means, the thermal analysis has to be on, in these cases we can use the some heat source model already explained this thing, the heat source model can be defined, it may surface or it may be some volumetric heat source model.

So, in this case we can consider double ellipsoidal heat source model. And then geometrical parameter, for example, parametrical bed a, b, c; that means all related to the heat source parameter has to be defined. And we can use some user sub routine also and such that we use some kind of the Fortran language to define the to user sub routine and we can define even in some commercial software also.

And we can interact with the software by using user sub routine. So, we can develop, we can define all these model in the user sub routine and then thermal load and then after application of the thermal load; then boundary condition for heat transfer is required. So, in these cases, the boundary condition for heat transfer, the film condition that fusion zone heat conduction, that means heat transfer coefficient thermal conductivity.

That means which part is basically we are considering that, that there is a heat loss from the boundary that has to be defined, which part is from the radiative heat transfer occurs on the surface boundary, the interaction on the surface has to be defined. So, once we define the all this property is the thermal load and there is boundary conditions and then we can perform the this thing analysis; but before that this is also necessary to give the mesh implementation, that means this thing we have to in the domain.

This is the input to the software and then this is they have to discretize the domain then; discretize the domain that couple temperature displacement will be depending upon the analysis type, whether you want to do only the thermal analysis or whether you want to do the thermo mechanical analysis, accordingly you have to choose the type of the element.

Then once we type of the element and also we can create the mesh for example, in near about the high temperature gradient zone; for example, near about the fusion zone, we can create the very fine mesh also to capture the high temperature. There is a drastic change in the temperature also; we capture the temperature gradient there and remaining part we can create the course mesh also to avoid the to decrease the computational time.

Then mesh generation, then mechanical boundary condition is also necessary to apply this thing; that here also we have to select the particular node point, which cases the we can assume the displacement becomes zero and then in this case for example, along a edge particular edge U x, U y and U z equal to 0. It means that one particular node, the displacement along x axis, displacement along y axis and displacement along z axis all degrees of freedom are 0 in this particular position.

And some cases also you can restrict only the 2 degrees of freedom; for example, U y and U z 0, but there is a displacement may happen along the x axis. So, similar way also we can put the all the boundary conditions. Now, in this case, once we do the all this boundary condition mechanical and history output can be getting the thermo mechanical model in terms of the displacement field; stress temperature and heat flux all parameters are the output from this model.

So, this way we can see that, first in this case the model all these things we can put that, we can do the thermal analysis once it is done and then we can start the mechanical analysis also. But before that we can choose the element in such a way that, this should support the thermo mechanical analysis.

So, therefore, once we get all the thermal analysis, then after that the mechanical analysis can be done. So, like that it is called the sequentially couple thermo mechanical analysis which is normally follow in case of the welding process

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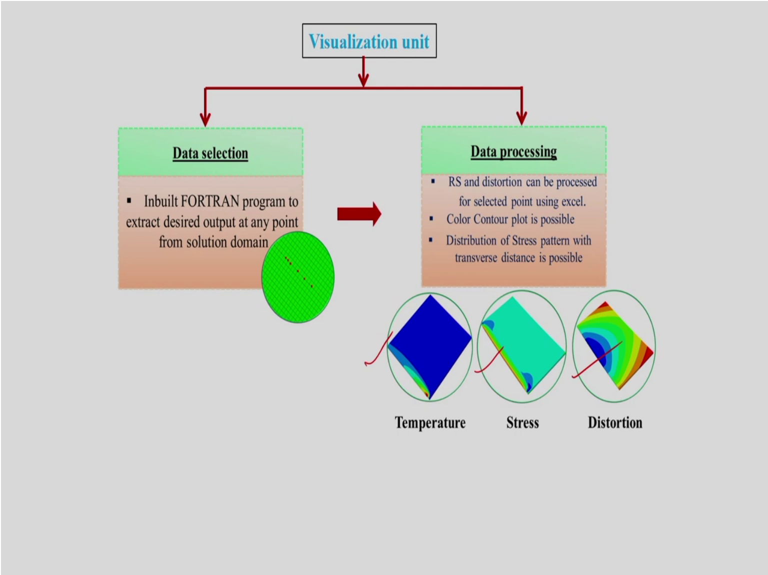

So, visualization once you the analysis over, we can see the results also that, data selection inbuilt Fortran program is also there extract the desired output; for any point may be on the one particular node point, one to get some information particular net what is the value of some temperature or some information in the sense the temperature stress value or something like that, that is possible to get particular point or finally, we can get the temperature distribution.

For example, this way temperature distribution, stress distribution and the distortion, distribution of the distortion as a output; but some sort of data processing is required. So, residual stress; distortion or stress analysis basically that represent the residual stress. And color contour plot is possible, different color we can select that contour plot both are possible to give the output and distribution of the stress pattern with the transverse direction is also possible.

That means, not only the stress distribution the whole domain; if we want the particular plane we want to see what is the stress distribution, that is also possible in this particular case or the if we want to use some kind of the commercial software in stress analysis model.

So, this way we can see generally we can see that, welding process is mostly associated with the sequentially couple thermo mechanical analysis, rather than fully couple thermo mechanical analysis; but in general fully couple thermo mechanical analysis, the computation time is huge.

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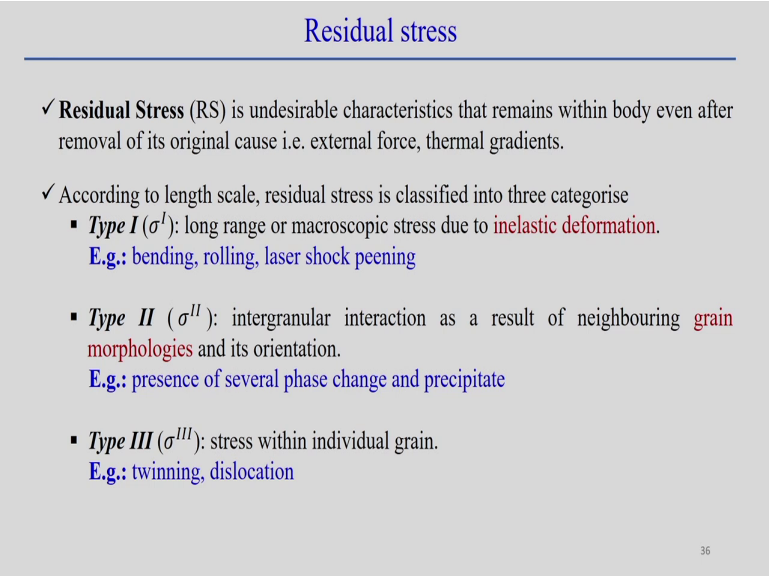

Now, I come to this point that, although we have discussing the what way we can develop the model also and what way we can analysis and from the particular commercial software, what are the output we can get in terms of the temperature distribution, stress analysis and distortion field.

Now, I come to this point what is the residual stress, which may be important associated with the welding process and one of the most important issue in a solidified weld structure; the level of the residual stress, because the life of the component depends on the what is the magnitude of the residual stress also. So, therefore, it is important to understand the residual stress generation during the fusion welding process.

So, residual stress is the undesirable characteristics that remains within the body even after removal of its original cause; that mean from the if we remove the external force thermal gradient, that means once which the comes back to the ambient temperature after solidification and then some existing stress is there and that is can be characterized as a residual stress in a particular welding process.

Now, this is residual stress distribution or residual stress according to the length scale can be of different type; for example, type I, type II and type III, in these three category ways we can categorize the residual stress. Type I basically long range or macroscopic stress due to the inelastic deformation.

For example, simply if we look into the bending rolling, laser shock peening in that particular manufacturing process, even welding process also we can see that are type I residual stress and that is macroscopic stress and definitely the due to the inelastic deformation.

But sometimes if we lower down the scale also, if we look what happens, if we in micro scale also; then we can see the inter granular interaction as a result of the neighbouring grain morphology. So, grain morphology can also be and it is orientation also induce some amount of the residual stress and this can be viewed as a lower scale.

For example, in case presence of the several phase changing precipitate. So, in general if we look into that microscopic scale, the several phase change and precipitate; that actually induce some amount of the residual stress that is considered as a type II residual stress.

And type III also even within the grain itself, even further lowering down the scale also, within the grain we it is possible to see that, within the individual grain there may be some amount of the stress generation; that is called the twinning, because of the twinning and in presence of the dislocation, they actually generate the residual stress.

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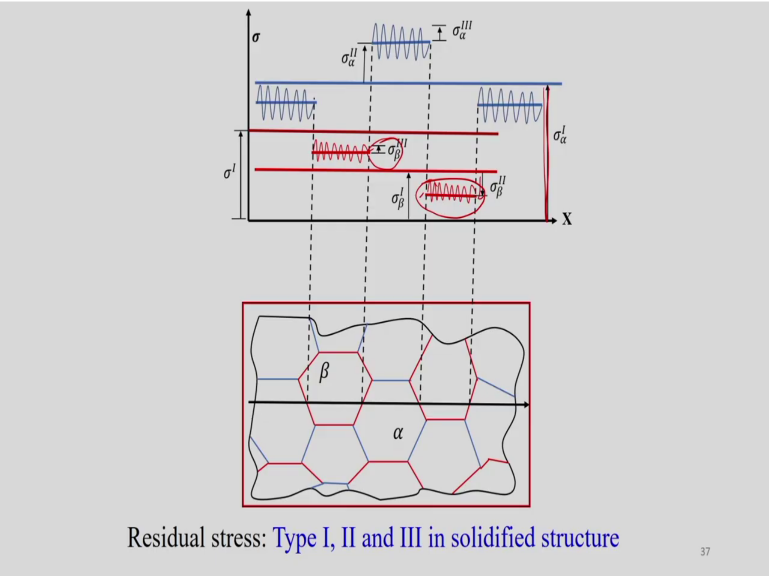

But in effect we normally look into graphically also; if we see that this type I residual stress, the magnitude is relatively higher and this case the type I. But type II also this is the very localized position; that means this within this grain or the orientation of the grain or grain morphology that induce the amount of the stress and that magnitude is in the lower scale we can see, this is the magnitude type II.

And type III further within one grain, presence of the dislocation and twinning; that induce some amount of the stress that, residual stress the magnitude is very small also. Here you can see the magnitude in this thing; but here you can see it is a very small magnitude. So, that is why it is consist of the all the three actual in actual process, in the actual if you want to look into the residual stress and in the different scale also; we can see that it is consist of the type I, type II and type III residual stress.

And we will see, because normally we analyze the, in thermo mechanical analysis, we are normally able to predict the only the type one residual stress; but if we want to look into the type II and type III, then we need to consider the microstructural morphologies or phase transformation effect and can be incorporate in the residual stress analysis.

And we will show that, what way we can incorporate the effect of the phase transformation, such that we will be able to capture; we will be able to know what is the type II and type II residual stress during the calculation of residual stress in fusion welding process.

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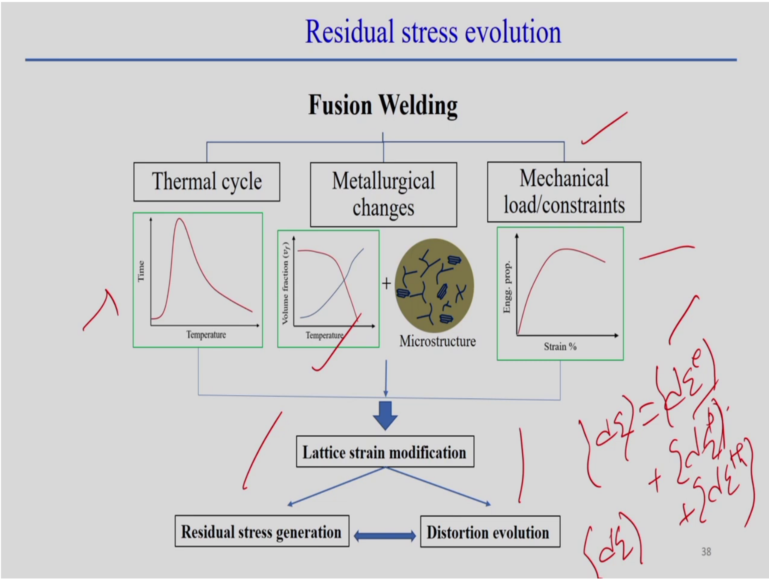

Residual stress simulation can be like that only thermal cycle; we can see the overall, this is the thermal cycle temperature non uniform temperature distribution that induce the stress value and at the same time some metallurgical changes also happen. And mechanical constraints and load; because of the mechanical constraint load and that is the, that kind of we if you know simple thermo mechanical analysis.

So, elastoplastic analysis, then we will be able to know that because of the mechanical load or mechanical constraint, what is the amount of the stress generate and that involve in the form of residual stress; that we normally predict the by simply following the thermo elastoplastic analysis.

In this case, if you remember the total strain we consider the consist of the elastic part, elastic strain, plastic strain and thermal strain these are the three. And from here elastic and plastic part and then we normally accounting this thermal cycle as well as the mechanical load constant. From that, but we if we develop apply the plasticity theory; if we do follow the thermal elastoplastic analysis, we will be able to get that the residual stress distribution on the macro scale.

But during the temperature distribution, there are some metallurgical changes may also happen and that the phase transformation may also happen, that precipitation may also happen and then within the grain also after solidification, there may be changes of the dislocation and twinning may form also.

All these actually induce some micro scale or nano in the lower scale residual stress also and that comes under the category of II and III. But if you want to capture a few that thing, then we simply added the other strain component along with these things; if we want to want to want to introduce the effect of the this phase transformation effect or the into the stress analysis.

So, therefore, all actually this merely this metallurgical model with the lattice strain modification and residual stress generation as well as the it induce the distribution evaluation. And we normally interested to know what is the amount of the residual stress and what is the residual distortion happens during the welding process.

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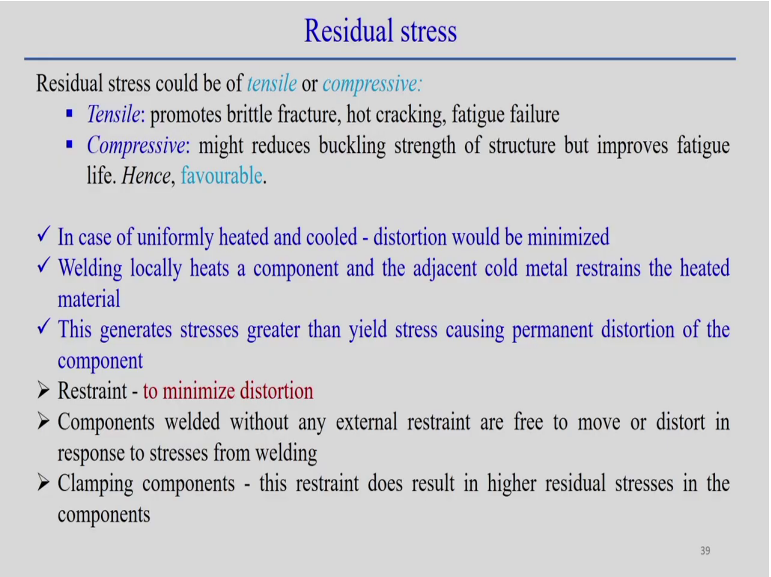

But residual stress can be of a tensile and compressing both way also; it is possible the tensile residual stress promotes the brittle fracture, hot cracking, fatigue failure. But compressive residual stress actually reduces the buckling strength of the structure, but improves the fatigue life.

So, therefore, it is beneficial if it is possible to generate some kind of the compressive residual stress in a welded structure. In case of the uniformly heated and cooled structure, distortion can be minimized by cooling or heating can be uniform; then distortion can be minimized. But if it is a no uniform, that actually induce residual stress and distortion also.

In that case welding, locally heats a component and the adjacent of the metal restrains that heated material and this amounts the greaters the greater than the yield stress value something causing the permanent deformation distortion of the component. So, therefore, this kind, then it generates some amount of the residual stress and the distortion also.

Therefore, if we put the restrain; restrain means simply clamping, if we follow the clamping also during the welding process shows the clamp can as a act as a restrain and that actually minimize the residual distortion. But components without any external restrain are free from move or distort in the response of the stress from the welding process.

Definitely if we remove the any kind of the constraint also, then it is free to move; then it is in minimize the residual stress amount in this particular process. So, that means clamping forces induce some amount of the, although it reduce the distortion; but at the same time it induce some amount of the residual stress, if we put the some mechanical constant along the in the boundary in a welded structure.

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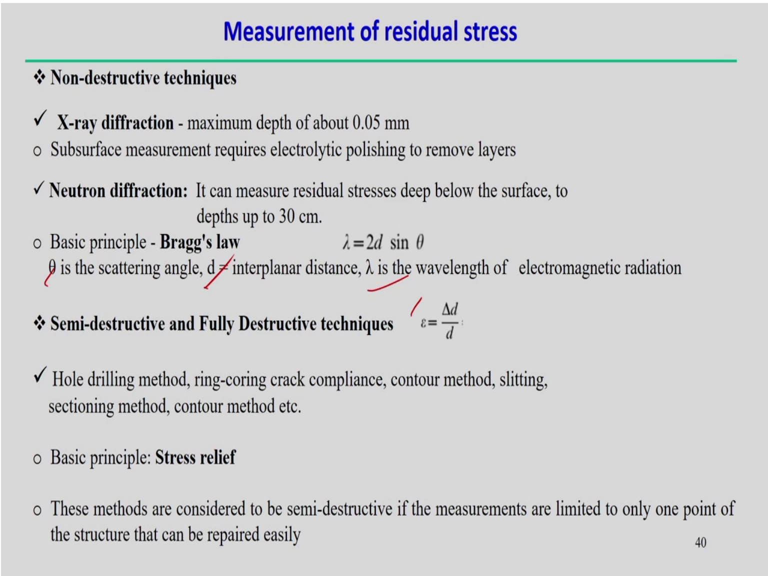

Some idea about the measurement of the residual stress is also required; because in this case we will be able to capture the different type of the residual stress also, if we know the measurement techniques. In general the non-destructive techniques normally follow the X ray diffraction method for the measurement of the residual stress; but this method is only limited to measure the residual stress only on the surface.

For example, only about the 0.05 millimeter depth we can measure the residual stress using the XRD method. And if you want to measure using the XRD method in the and along the depth direction also, in that cases it is necessary to remove layer by layer. For example, if we measure the on the surface, then we remove the particular layer; then after that next layer, we can measure the residual stress.

But in these cases the measurement may not be very accurate, if we are not careful during the removal of the particular layer. But in that other way also, if we follow the neutron diffraction technique; then it is possible to measure the residual stress along the very high depth of penetration.

So, for example, up to depth of 30 centimeter, it is possible to use the neutron diffraction technique. But all these cases, these cases this follow the simple principle that is the Bragg's law and in this case, the theta is the scattering angle, d is the inter planer spacing; lambda is the wavelength of the electromagnetic radiation.

So, since it is the inter planer spacing, all these thing inter planar spacing is basically associated with the nano scale; it means that, if we follow the XRD or neutron diffraction method or Bragg's law of diffraction to measure the residual stress, it is possible to capture what is happening within the grain scale also.

So, grain scale means, within the one grain; then we in this neutron diffraction or X ray diffraction method is more accurate to measure even in the type II residual stress also that means, at the lower scale also, but there are other techniques also. That is called the semi destructive or full destructive techniques and it use some kind of the mechanical methods and mechanical methods in the sense that.

For example, hole drilling method or contour method, slitting, sectioning method, these are the typical methods they are normally used for the mechanical measurement of the residual stress, its basic principle is the stress relief. For example, the strain is calculated in the hole drilling method also; the what is the stress it will capture and the delta d is the measure that amount and d is the along the along the depth direction what is the distance travelled.

So, delta d by d is the simply measurement of the strain. And since it is a stress relief and then once we measure the strain during in this mechanical method; then we will try to link the strain into the amount of the stress and that we normally follow the elastic limit. That means, using the Young's modulus we try to correlate this strain with the stress value.

So, therefore, these methods are semi destructive and its measurements are limited to only one point of the structure that can be repaired easily, that is true also. But the semi destructive; for example, hole drilling method, there is a need to create some small hole on the surface to measure the residual stress and this mechanical measurement techniques is not much accurate as compared to the XRD or neutron diffraction techniques.

So, therefore, but that is why the mechanical measurement is very suitable, if you want to capture only on the type I residual stress; then we can follow the any kind of the mechanical measurement technique of the residual stress.

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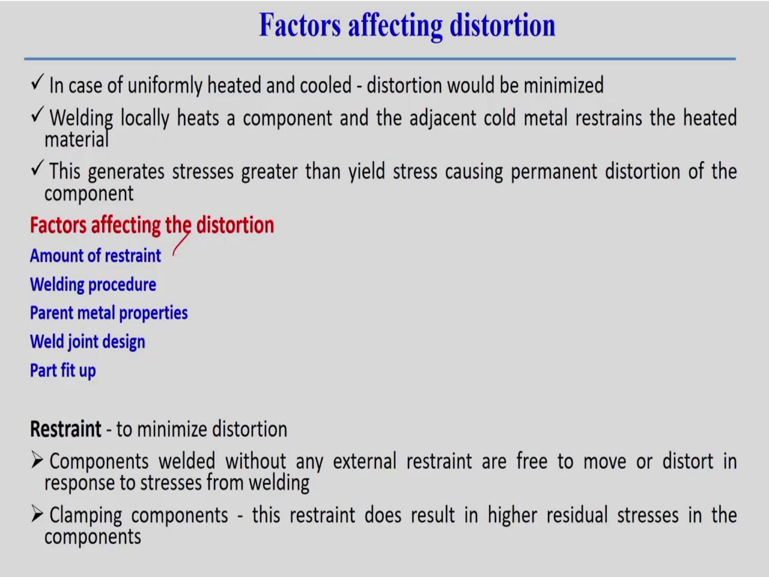

But factors affecting the distortion also; so anyway once we looking into the residual stress, distortion is also associated. In case of the uniformly heated and cool material uniform, it is in principle the distortion can be minimized.

But welding locally heats the component and the adjacent material try to restrain that particular material, heated material and these generates the residual stress and that called the yielding of the material and causing the permanent deformation of the component.

What are the different factors affect this distortion also that, the same thing what is responsible for the residual stress the amount of the restrain. For example, if we clamping the different constant, the different position if we increase the clamping force also or clamping points also during the welding process.

So, therefore, amount of the restrain this distortion depends; what are the welding procedure? For example, if we follow the arc welding process or laser welding process; definitely the distortion pattern and residual stress generation will be different. Then parent material properties; that means parent material properties for example, in one cases we are doing the welding process in the high conductive material or other cases is the low conducting material.

So, therefore, properties and at the same time thermal expansion coefficients, there is a difference in the thermal expansion coefficient among the different materials also. All these differences in the properties actually generates the different pattern or different value of the residual stress and distortion in the welded structure. And weld joint design for example, whether it is bar joint left joint or t joint or any other the gap between these two joints is very high.

So, all these factors influence the amount of the distortion residual stress also and what fit up; that means what way we can fit up the, we can join preparation before the weld process also that actually influence the amount of the distortion. Restrain to minimize distortion that we have already seen these things and of course, if we remove the components welded without any external restrains also are free to move distortion; that means if we put the if we remove this distortion that is free to move that, actually minimize the residual stress.

And therefore, clamping components, definitely it is very important in the residual stress also the clamping part to correctly analyze the residual stress and distortion analysis, because this is this acts as a boundary condition during the welding process.

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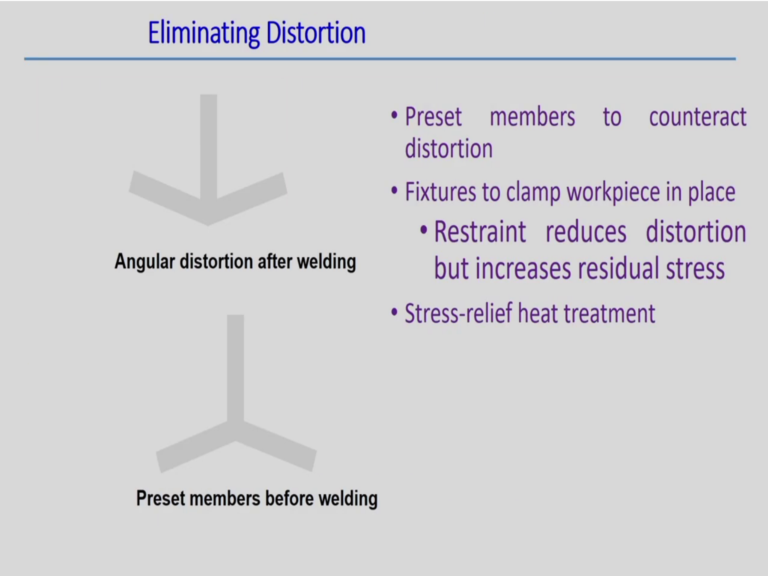

Eliminating distortion simply the two methods, the preset members to counteract the distortion. So, if we know the angular distortion after welding process what will happen; though if we pre stress also before welding, that will help to reduce the element distortion in the simple way.

The fixtures to the clamp workpiece in place, fixturing fixture can be made to clamp the workpiece in place; the restrain reduces the distortion, but in cases residual stress that is true also. If we put too much of restrains, then that also reduce the distortion, where at the same time it increases the residual stress; therefore, we needs to optimize in the real situation in the practical cases.

And in finally, if we want to reduce the residual stress and distortion that, some sort of heat treatment we normally follow after doing the, after the welding process; that is the one of the most convenient way to relieve some amount of the residual stress, stress relief through the heat treatment techniques.

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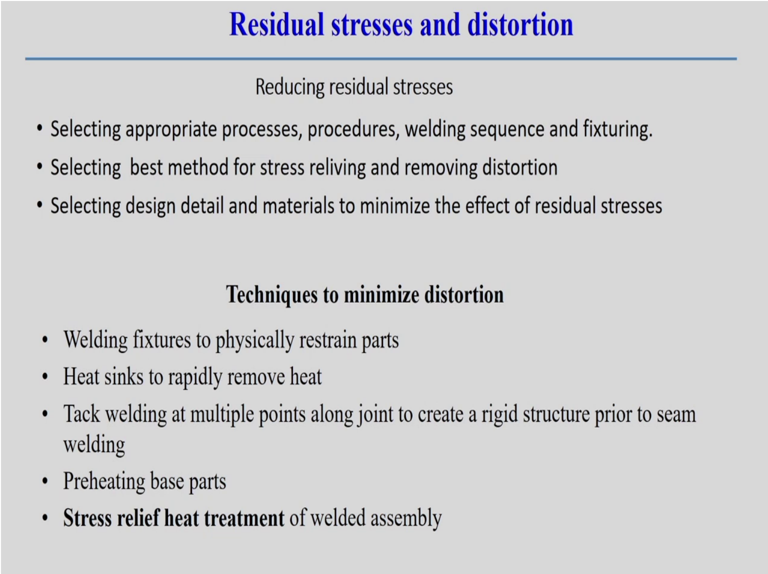

Other part also reducing the residual stress can also be done; the selecting appropriate procedures, the welding sequence that is also important and what way we can design the fixture also all this important to reduce the residual stress.

And selecting the best method for stress reliving and the removing the distortion; we will have to optimize the different process also, different techniques, different methods for the reducing the residual stress.

Selecting the design detail and the materials to minimize the effect of the residual stress; so selecting the design of the particular weld joint as well as the choice of the material also influence or the choice of the fixturing material also that also influence the residual stress generation in case of the welding process.

So, therefore, techniques to minimize distortion that welding fixtures to physically restrain parts that is the one point. Heat sinks can be used to rapidly remove the heat that also possible; that means we can use the high conductive material also and the at the base plate on the fixture material, so that quickly conducted the heat.

Tack welding, for a long welding we can put the tack before actual welding process; also create the rigid structure prior to the welding process and this is the one most convenient way to simply pre heating the material. So, if we preheat the material; that means before welding if we pre heat the material, then in that case the temperature difference, temperature gradient can be reduced.

So, therefore, generation of the residual strain distortion can be minimized. And of course, stress relief heat treatment can also be used in case of the welding process.

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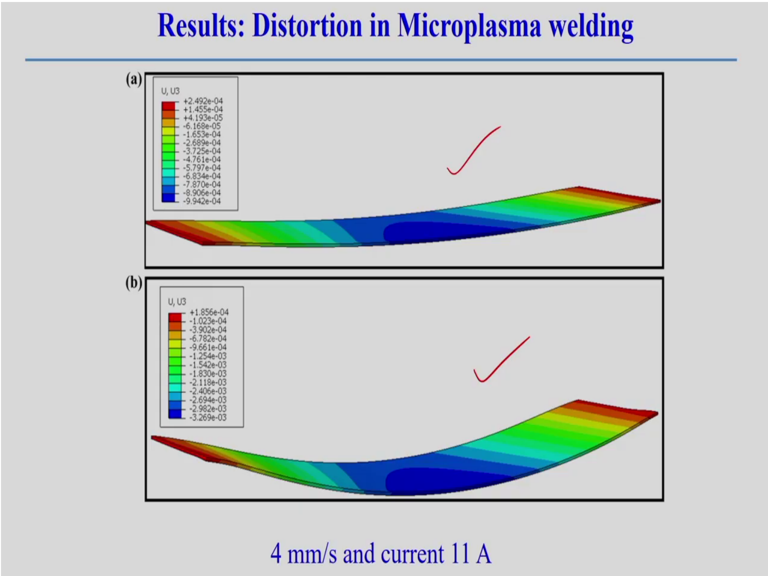

So, here we can see some results also, the distortion in the micro plasma welding process; if you see that in the micro plasma arc welding process, we have used the, I think in this case we use the titanium alloy and the 4 millimeter per second the welding speed and the current is the 11 ampere and the thickness of the material is I think point 7 millimeter sorry, point 5 millimeter thickness sheet.

So, here we can see the distortion pattern that U 3, distortion pattern are different in these two cases. So, why it is different? Because first cases it is done, the stress analysis; stress and distortion analysis both, here we are showing only the distortion pattern also. But in these cases, we can use the small displacement theory and the second case we can consider the large displacement theory.

So, once we consider the large displacement theory; then it considers the very localized variation of the displacement. So, that is why it is able to predict if there is any bulk, any buckling is there or not that, kind of the phenomena is possible to consider if we consider the large displacement theory.

So, that is why although we have done the same process parameter, the distortion analysis; but the two cases the distortion pattern are different, but because one cases we have used the small displacement theory and large displacement theory, definitely large displacement theory more intricate localized variation of the displacement changes. So, that is why we are getting the different pattern.

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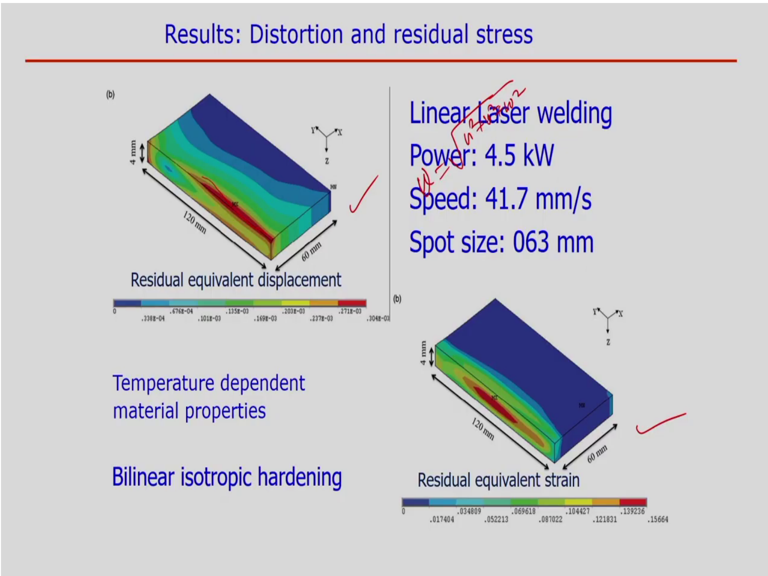

Here some results of distortion and residual stress we can see, the residual equivalent displacement; so that means residual equivalent displacement means that, in this case the displacement field is there each and every node point. But we consider the magnitude of the displacement field equal to root over of u square plus p square by w square; that means the sink component value magnitude of the each and every node point.

There are three displacement field U x, y and z component, we just making the magnitude of this thing, then residual equivalent displacement. We can see the displacement becomes very high at the particular zone and low in the other point also that, kind of the prediction is possible if we do the stress analysis; that means thermo mechanical model, if thermo mechanical analysis. Here the residual equivalent strain.

So, displacement will can be predicted, at the same time the equivalent residual displacement strain component can also be predicted from the analysis. So, here in the strain component we can see at the middle; the strain component is very high, so around 0.15, the single value of this thing.

So, temperature dependent material properties has been used; bilinear isotropic hardening model is used in this particular analysis. And the linear laser welding process the power equal to 4 was 4.5 kilo Watt, speed 41.7 millimeter per second and spot size was 63 millimeter 0 063 0.63 millimeter.

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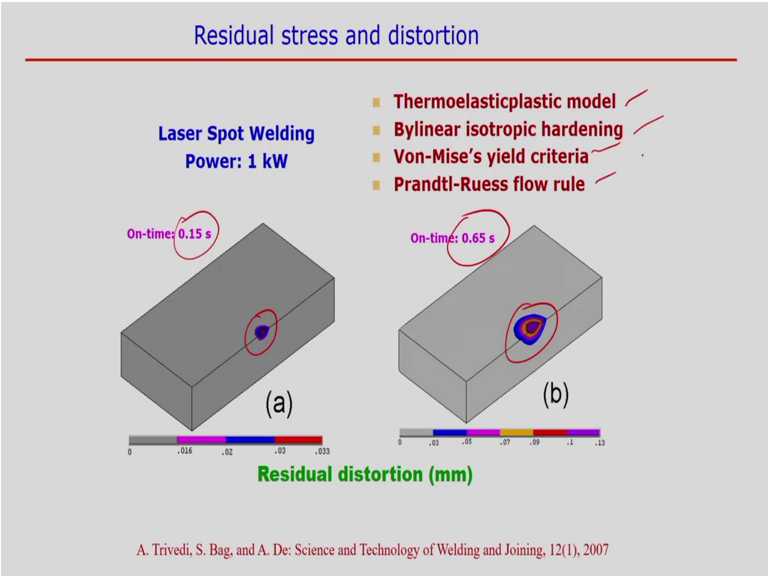

Similarly, some sort of analysis can also be explain this laser spot welding process, the power 1 kilo Watt and on time 0.15 second. So, once on time 0.15 second laser is was on for 15 second, then after the switch of the laser; then we can get, this is the residual distortion, this is the equivalent distortion is confined in the very small zone also.

Similarly, on time 0.65 second. So, laser was on up to 0.65 second and then after the switch of the laser and then we can get, this is the distribution, residual distortion at particular point. So, this kind of the output; so in terms of the individual component also as well as the equivalent value, we will be able to get the as output from the analysis thermo mechanical analysis.

In this case thermo elastoplastic model, that means material behavior has been considered the elastoplastic material; bylinear isotropic hardening, Von Mise's yield condition has been used and followed the Prandtl Ruess flow rule, from that point we are getting this kind of the residual distortion we can get.

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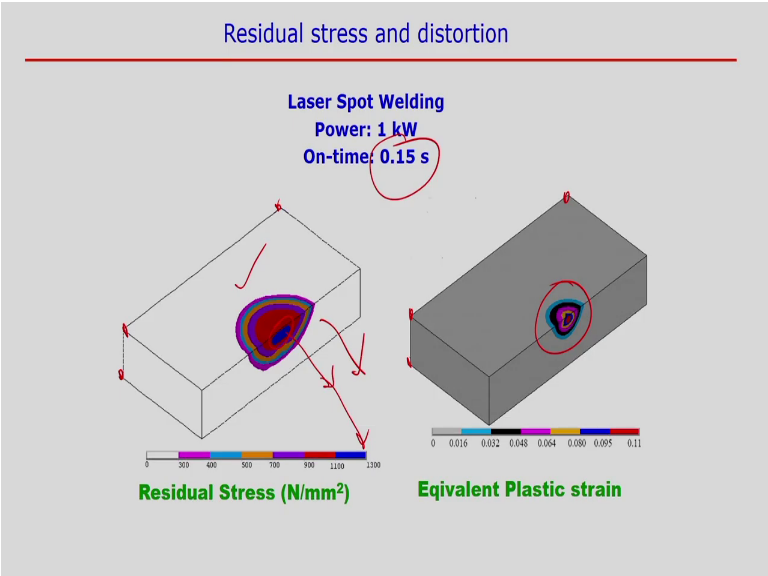

Similarly, for the these two cases we can use the sorry; in this case the 0.15 second on time power laser spot welding process, we can see the residual stress generation. Residual stress is confined with very small zone and we can see the residual stress is maximum at this point and this point is the maximum residual stress.

We can see the this maximum residual stress and this is the equivalent plastic strain also we can estimate, this thing; equivalent plastic strain is the very small value, which is confined in the small zone in case of the spot welding process. So, it is very important to know that, in this case the boundary condition is very important; because it influence the level of the residual stress as well as the distortion.

So, therefore, in actual welding process, what boundary condition we have follow the clamping condition; the similar can be represented by like in this particular analysis for example, here also we can put some constant value, here also we can put some constant value depending upon the and at this side was the symmetric surface. So, putting the proper appropriate boundary condition we will be able to get this predict the accurately this residual stress and distortion field.

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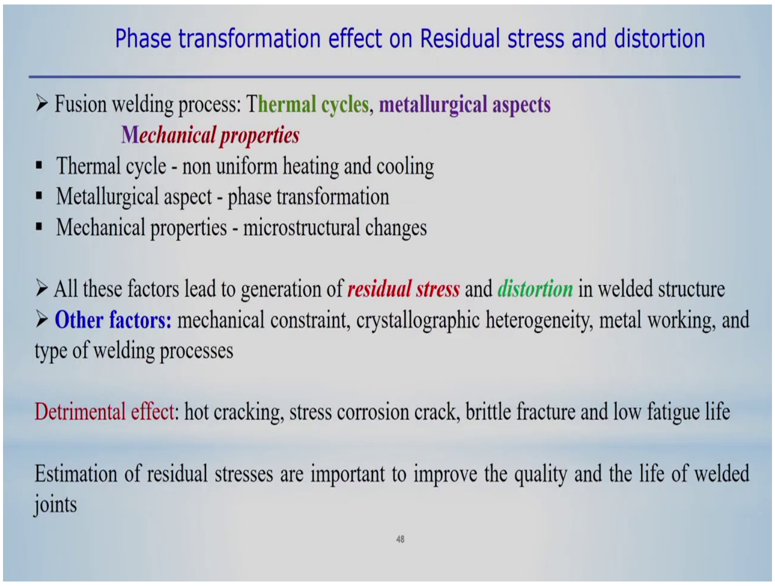

So, that is all today. Thank you very much for your kind attention. And next part, the effect of the phase transformation effect; what way we can on residual stress analysis that we will discuss in the next part.

Thank you.