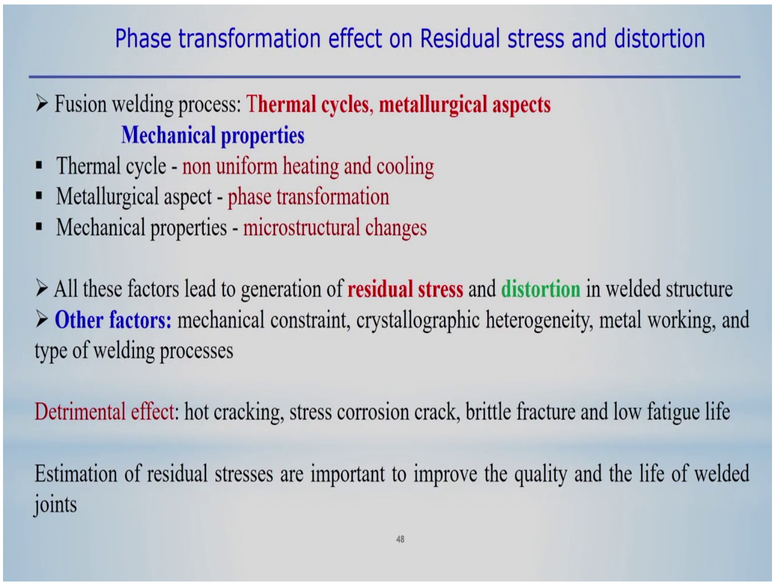
Finite Element modeling of Welding processes

Prof. Swarup Bag
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Lecture - 31
Phase transformation effect on Residual stress and distortion

(Refer Slide Time: 00:32)



Hello, everybody. We have already gone through this elasto-plastic model or maybe you can see that how residual stress variation or residual stress model can be done in a in case of thermo mechanical model. If we look into this particular aspect, but that residual stress analysis we normally perform by assuming the elasto-plastic material in that cases no influence of the micro structural changes not counted during that analysis.

Now, if we want to incorporate the effect of the phase transformation during this welding process. Definitely it is associated with some kind of phase transformation in a particular alloy system and during welding process and that normally two kind two stages we normally consider that the heating stage there is change of the then once this is the molten state.

Then gradually the solidification happens. So, there is a huge change in the micro structural and phase transforms happens during this process. But normally in this case we normally consider the solid state phase transformation that mostly accounts the generation of the residual stress in a welded structure.

With all these analysis we thermo mechanical analysis normally we neglect the effect of the phase transformation effect. But it is possible to incorporate the phase transformation effect in a residual stress analysis and that of course, it enhanced the calculation accuracy of the residual stress prediction in a even using a finite element based thermo mechanical analysis.

So, definitely fusion welding process is associated with some thermo cycle and there is a non-uniform temperature distribution or changes or we can say thermo cycles that actually influence the metallurgical aspects also and at influence the micro structural changes also. And, finally, the mechanical properties is actually decided by the microstructure of a particular material even the same material. But there is a change in the microstructure and then we can expect the mechanical properties variation must be there.

So, mechanical variation it means that mainly the residual stress associated with the fatigue loading kind of these things certain cell loading, compressive loading, torsion, behavior, hardness impact. Every all kind of mechanical properties is actually mostly influenced by the microstructures.

So, therefore, it is necessary to understand the microstructure formation during this welding process to focus on this or we can say the metallurgical aspect. And, then we can say something we can make some model that the to incorporate the effect of the phase transformation or by just investigate the different micro structural formation in case of the welding process. And we can incorporate in a finite element based thermo mechanical model.

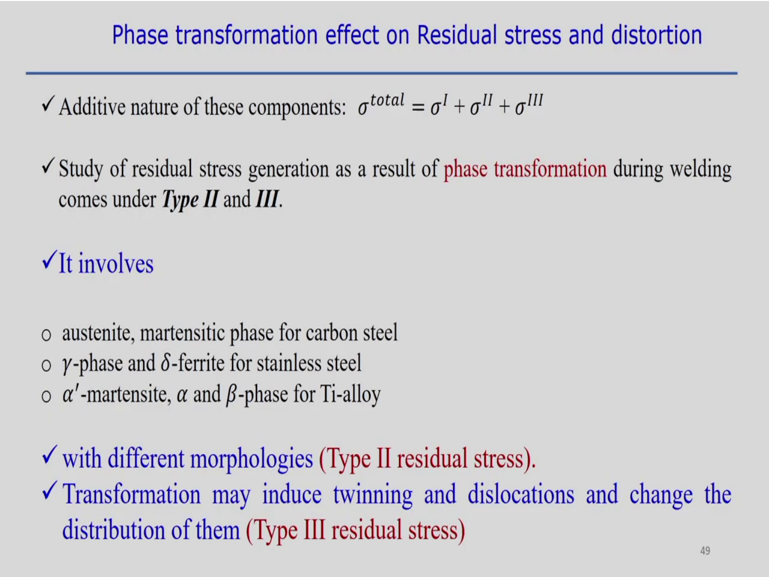
So, thermal cycle definitely it associated with the non uniform heating and cooling process. Then metallurgical aspect we can link with the associated with the phase transformation, but other metallurgy has we are not considering particular process. And, finally, mechanical properties is mainly decided by the micro structural changes. But all this affect how what way we can incorporate in a stress analysis model that we will see.

So, therefore, all these factors leads to the generation of the residual stress and distortion in a welded structure, but there are other factor. For example, this mechanical constant, crystallographic heterogeneity and there are some metal working on the surface also in particular manufacturer component or even type of the welding process all actually influence the residual stress and distortion in a welded structure, apart from the other primary factors.

But, what is the consequence effect of the generation of the residual stress maybe or during the solidification or during the solid state phase transformation happens in a welding process. That hot cracking, stress corrosion cracking is the brittle fracture, low fatigue life these are the typical associated detrimental effect on for the formation of the residual stress in a welded structure.

So, therefore, it is very much important to very precisely estimate estimation of the residual stress in a welded restructure. And that is the objective of this particular module to understand the residual stress generation in a welded structure. And, what way we can model this we can estimate we can calculate the residual stress by using by developing some finite element based heat transfer and mechanical model.

(Refer Slide Time: 04:59)



Now, we have already discussed that residual stress, nature of this residual stress can be of three different types type I, type II, type III. Only depends all these three types are they can be active in different scale, we can see the different scale of magnification.

Now, residual stress generation as a result of the phase transformation effect that normally comes under the category type II and type III. And, type I residual stress is normally we can say that because of the some mechanical constant. Normally there is residual stress comes into the picture.

So, but therefore, type II type III may be important and for particular alloy system this type II maybe significant, but in some cases this may be insignificant. For example, in case of stainless steel probably generation of the type II residual stress may be insignificant but, in case of the titanium alloy, the generation of the residual stress type II is a very much significant. So, therefore, we can look into all this aspect.

Now, it involves the phase transform I am talking about the phase transformation, but it involves. For example, in case of low carbon steel, it is associated with the austenite mainly the austenite and martensitic phase transformation. These phases are mostly influence the residual stress generation apart from the other phases present in the particular welded structure.

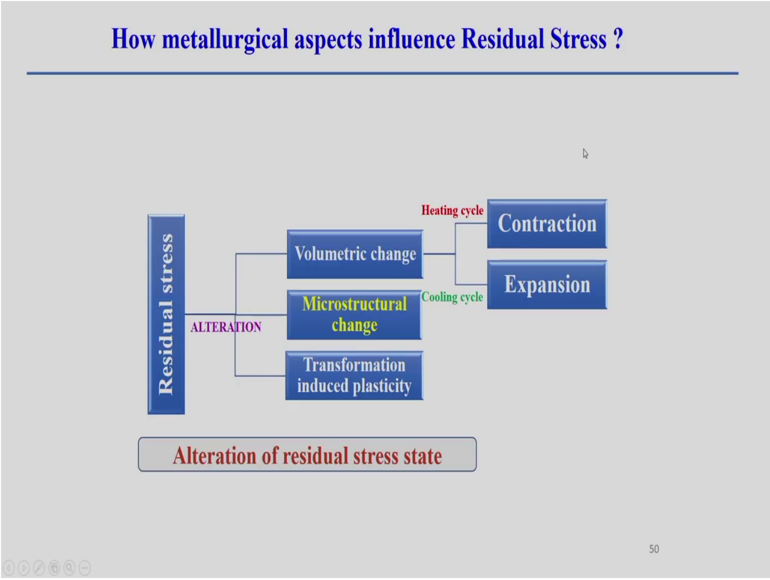
For example, stainless steel in gamma phase and the delta-ferrite. These are the accounts normally if there is a marginal change in the residual stress generation that, but these particular phases accounts that changes of the residual stress apart from the other kind of phases. Similarly, alpha dot martensite and alpha and beta phase in titanium alloy these phases are very important in case of titanium alloy.

And, normally we count we developed some model mathematical model to estimate the residual stress generation in a welded structure. So, definitely with different morphologies that not only the microstructure different kind of the microstructure where micro structural morphology also influence the residual stress. And that is mostly associated with the type II residual stress.

Even that phase transformation accounts type II residual stress, but it may induce some kind of the twining and dislocation. And therefore, their distribution also it generate some of the residual stress. But, this residual stress we consider the type II; that means, the scale we can if we understand the what is the type II residual stress and try to measure the this quantify.

Therefore, we have to lower down the scale and all these aspect you have to look into that at a lower scale the amount of the residual stress. So, definitely the magnitude or of residual stress of type II and type III maybe in some cases are less as compared to the type I. But, in type III may be insignificant in particular cases.

(Refer Slide Time: 07:35)



Now, how metallurgical aspect can be influenced the residual stress and here the focus is what way we can develop the mathematical model. Because we have already understanding what is the residual stress.

Now, what way we can incorporate, what way we can analyze the residual stress or how we can incorporate the this phase transformation effect into the residual stress calculation? Now, residual stress change of the residual stress magnitude there may be possibility of change of the residual stress in a the tensile alloy or compressive or they can vary from tensile to compressive and simply as a function of the composition of a particular welded structure.

But, this change of the residual stress or magnitude of the residual stress or distribution of the residual stress can be account in three different perspective. One is a volumetric change during the phase transformation and the micro structural changes also and of course, due to the all these changes micro structural changes that may induce some amount of the transformation induced plasticity.

So, that plasticity or plastic strain may be induce some sort of residual stress also. So, therefore, we count these three aspects volumetric change and micro structural change and transformation induced plasticity which is in general we can say the effect of the phase transformation in a welded structure.

Now, volumetric change changes can be accounting this thing or maybe we can incorporate both the effect. For example, heating cycle and cooling cycle also. It may be contraction if during the heating cycle particular in case of a alloys particular alloy system or it may be expansion during the cooling cycle or vice versa may also happen during the heating and cooling cycle in a particular welding process.

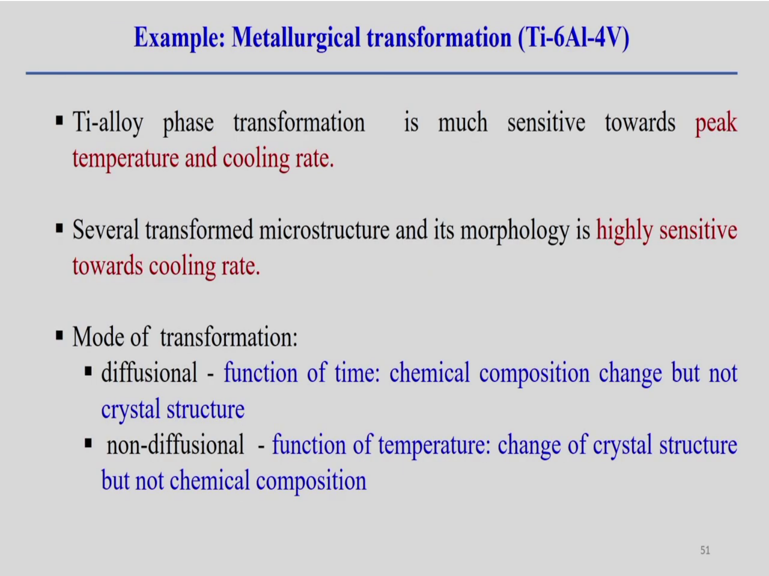
In this case, suppose, we defined in a welding process the what way the temperature varies or temperature distribution we normally represents the thermal cycle. So, that thermal cycle means simply in a sample the heating the sample, reach the maximum temperature and then gradually cooling to the ambient temperature that is normally called as thermo weld thermal cycle.

And, then that thermal cycle we say these two parts one is heating cycle, another is the cooling cycle and based on that during the heating cycle. What are the transformation of the phases one phase to another phase, then we can account maybe either contraction or expansion depending upon the type or nature of the materials. Or during the cooling cycle the it may accounts either contraction or expansion also and that actually induce some amount of the stress or.

So, therefore, but that what is the amount of the stress or strain calculation can be depends on the what kind of the phases present. Therefore, it is necessary to investigate in a welded structure what kind of the phases normally happens in a case of a in a particular alloy system.

So, that knowledge is required to develop one kind of the this residual stress model that actually incorporates only the effect of the phase transformation.

(Refer Slide Time: 10:15)



We take an example the metallurgical transformation for example, titanium alloy Ti-6Al-4V the great 5 alloy titanium alloy. And we can find out this application of this titanium in the in a medical this thing devices of and maybe we can use some medical industry.

Now, this titanium alloy phase transformation is very much sensitive to the peak temperature as well as the rate of the cooling. So, therefore, the microstructural development in case of alloy system it is very much sensitive to the what is the maximum temperature achieve or and the what is the cooling rate during the heating or during the cooling phases it follows. Depending on that the different phase transformation may happen.

So, therefore, several transform phases also several transform microstructure and at and the. So, morphological and the it is morphology then microstructural morphology both actually highly sensitive towards the cooling rate.

So, therefore, some knowledge or some a kind of information is required for a particular alloy system what are the microstructural changes as a function of the cooling rate. So, from that information we can develop some kind of the residual strain and as well as the residual stress model.

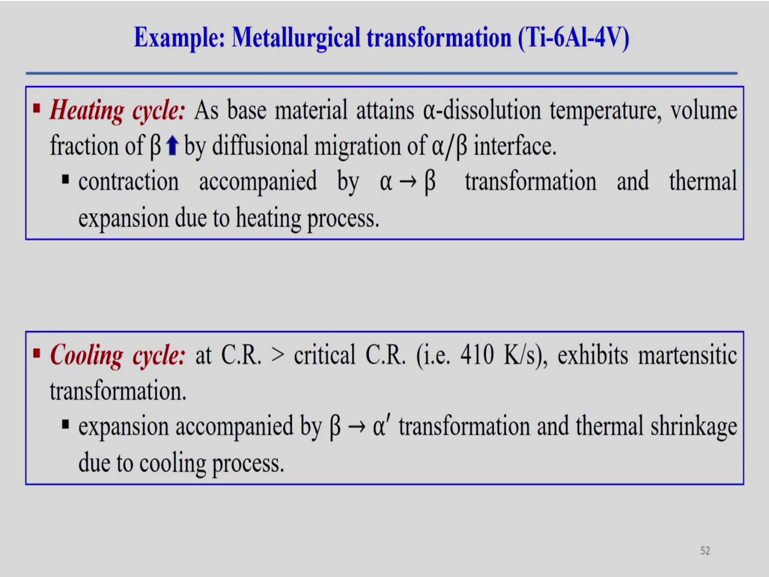
Now, mode of transformation we normally happen depending upon the rate of cooling. So, it can be diffusional, it can be non-diffusional; diffusional transformation means in this case maybe this function it is a sufficient time is there to transform from one phase to another phase. It is we can say that diffusional transform is more all towards the transformation happens towards the equilibrium conditions.

So, it means that it is a function of time. So, therefore, and in this case chemical composition change the during this transformation diffusional transformation, but not the crystal structure. Crystal structure remains the same and, but chemical composition changes in this particular diffusional transformation.

But, if it is non-diffusional means so, very quickly the transformation happens there is not sufficient time to diffusion to occur. So, in that case we can say non-diffusional transformation definitely at high cooling rate non cooling rate we can expect that some kind of the non-diffusional transformation. But it is as a function of the temperature rather than as a function of the composition.

So, therefore, change of the crystal structure is associated, but not the chemical composition. So, that is called the non-diffusional transformation. So, depending upon the welding process and different position there may be the variation of the cooling rate. So, according to the variations of the cooling rate we can adapt whether it is diffusional transformation or non-diffusional transformation and accordingly, we can develop the model.

(Refer Slide Time: 12:48)



Now, in particular alloy system titanium Ti-6Al-4V, the during the heating cycle we assume that it is a base metal consist of the this alpha plus beta phase. So, as base metal attains the alpha dissolution temperature, then volume fraction of the beta phase actually increases and then by migration of the alpha to beta interface. So, therefore, is changes from one phase to another phase during the heating cycle.

Now, but during the heating cycle there is a change of the phase from alpha to beta phase. So, basically during this transformation the beta phase fraction is gradually increases and alpha phase is phase fraction is gradually decreases in this case.

Then, when this kind of the phase transformation is accounted with the contraction so, therefore, contraction and therefore, during this cases the thermal expansion happened we assume the thermal expansion during the heating process by alpha to beta transformation in case of the titanium alloy system.

Similarly, during the cooling phase also, then if the cooling rate is more than the critical cooling rate. So, that means, in this case particular if it is critical cooling it is 410 Kelvin per second. If the critical cooling rate is 410 per second, then it actually exhibits the martensitic transformation.

So, therefore, once there is a phase transformation happens from any phase to the martensitic phase transformation in this particular alloy system then it is associated with the expansion occurs during this phase transformation. So, it means that from beta to alpha dot martensitic transformation so, in when there is a transformation happens from beta to alpha dot. Then during the cooling phase then it is associated with the thermal shrinkage during this cooling process.

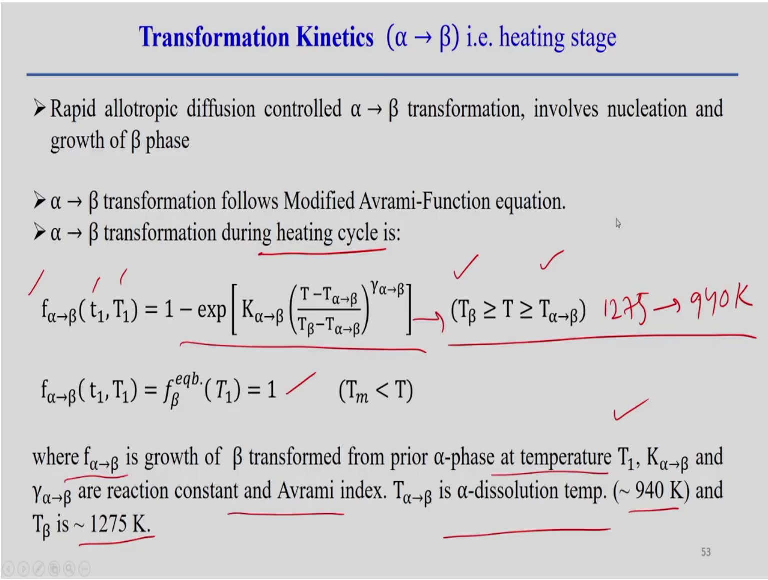
So, therefore, when there is a thermal shrinkage happens in this case it may be we can the thermal strain will be generated inside during this transformation process. And that is micro strain can generate some kind of the micro stress also in a welded structure and that may happen in a localized area. But, therefore, but this micro stress may be significant because this stress is very much sensitive to the fatigue life of welded joint.

So, therefore, it is very important to very precisely to estimate the residual stress generation during the welding process. Now, in this case we are talking about the transformation from alpha phase to beta phase or maybe beta phase to the alpha dot martensitic during the cooling cycle, but in the titanium alloy there may be some other phases. But, we are not accounting we are not talking about all these other phases then it becomes the phase transformation itself becomes very complicated.

So, in that in this case we can simplify the analysis in such a way just which phase is more influential and during this transformation which phase is accounting large amount of the strain micro strain during this transformation process. We can talk about only that a particular phases not the all phases.

So, therefore, we are neglecting the what will happening for the other phase transformation during this heating or a cooling process associated with the fusion welding of titanium alloy system.

(Refer Slide Time: 15:48)



Now, once we understand this accounting that basic understanding the what which phase is transformed to what phases and during the heating cycle as well as the during a cooling cycle. And what are the cooling rate is followed based on that we can understand we can develop some kind of the transformation kinetics or maybe it is necessary to understand the transformation kinetics during the heating phase as well as the cooling phase.

So, here as a sample I can show these things for example, a rapid allotropic diffusion controlled alpha to beta transformation. Definitely when there is a transformation from one phase to another it involves the nucleation and particularly growth; growth of the beta phase that consume the old alpha phase during this transformation.

So, that means, it takes some finite time to transform from one phase to another phase and then volume fraction increases of the one phase to another phase. And other phases the volume fraction actually decreases during this transformation. But, it depends on the what temperature that conformation happens and what cooling rate it is followed.

Now, alpha to beta transformation if it is if we assume this is a diffusion control then alpha to beta transformation follows the modified Avrami function of the equation. So, therefore, particularly equation you have to follow, but this needs investigation that what kind of equation can be better represented this transformation in the particular alloy system, for that lots of literature available for this.

But, we take in simple some understanding was basic understanding of the phase transformation we can what way we can incorporate the effect. Now, alpha to beta transformation for example, in this case during the heating cycle we are talking about. And then we can see that f the fraction alpha to beta this transformation and it happened over the particular time t 1 and particular temperature T 1 and it is more over as a particular time a time t 1.

Now, we can express this transformation like that the these fractional transformation that the fraction we can count 1 minus of exponential some expression we can see. In this particular form this is normally we call the Avrami equation or we can modify the Avrami equation, simply it is associated lots of constant terms that can be evaluated some x through the some experiments.

But, here you can see it is simply a function of temperature. So, that means, temperature were remaining parameters are constant parameter, but are ultimately it is a function of temperature. So, therefore, depending upon in this particular model if we assume this particular equation, then we represents the fraction as a function of temperature also.

Now, this temperature flag is very important because at that different phases exist at the different temperature. And therefore, we need to always follow some kind of the temperature flag. For example, this temperature this equation is valid over the temperature of T beta and T alpha to beta. So, within that temperature range this expression is valid, but if it is T less than melting point temperature, then we can use some other expression.

So, it means that first we need to identify that what way these phase transformation effect can be represented by the simple equation as a function of temperature. And then we can once that means, this function is basically represent the transformation kinetics. So, definitely once you define the transformation kinetics and then it is easy to implement, easy to develop the model during this to incorporate the effect of the phase transformation.

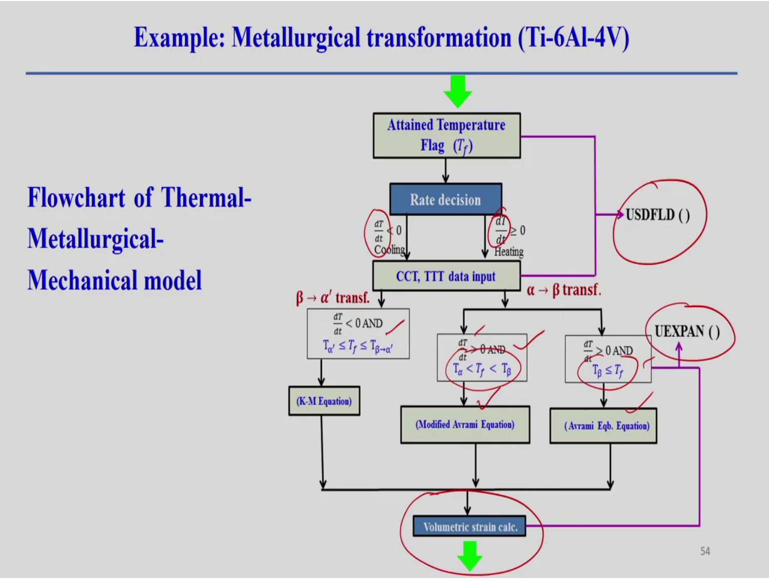
But, in this case if you see the f alpha to beta is growth of the beta transform from the prior alpha phase. That means, initially it was alpha phase and then from this alpha phase there is a growth of the beta phase happens and at a particular temperature T 1 and K alpha to beta and gamma alpha to beta that actually reaction constant and that some having some value and one reaction constant the Avrami index.

So, that it is as certain constant value we can use and for this particular kinetics and T alpha 2 beta is the alpha dissolution temperature. It is a see this temperature is 940 degree temperature and T beta is equal to 1275; that means, it is valid 1275 to in between 940 Kelvin. So, that means, this equation is valid in between these two.

So, that whatever this phase transformation we are talking about the alpha to beta phase transformation that happens within this temperature range and that we represent by using this equation. So, therefore, the similar kind of the equation can be developed in case in case of other alloy system also and in case of the other particular material.

Only maybe in that cases in if you change the alloy system the difference maybe you can use the similar kind of nature of the equation may be same but, the constant term can be different in other alloy system.

(Refer Slide Time: 20:24)



Now, example metallurgical transformation model what way we can incorporate the metallurgical model. For example, we particular position we can see because in a thermo mechanical model and definitely you are calculating the temperature distribution. So, definitely we have to take the temperature from this analysis. Now, we represent the all the metallurgical transformation as a function of temperature and time.

So, therefore, we have to put lots of temperature flag. For example, attained temperature if T f it attains this particular temperature, then we decide the rate of the cooling. So, rate of temperature change dT by dt and dT by dt whether then we decide during this rate of temperature change whether it is cooling phase or whether it is heating phase. If it is heating phase and cooling phase we take the input data different phases this thing from the CCT, TTT and diagram.

From that diagram we can get the we can get the idea of the what are the different phases exist at the what temperature and CCT continuous cooling transformation diagram. There we can get the what may be the cooling rate such that we can expect this particular structure particular phases.

So, that information is required then here we can make some taking this input then we assume that if dT by dt less than 0 and may be temperature is between this certain temperature flag is in between this thing, we assume the beta to alpha dot transformation during the during the a cooling cycle. But, in the heating cycle also we can assume the this is the transformation happens from alpha to beta transformation.

And, even if this 0 and, but there is a both are that means, both are heating cycle, but temperature flag is different. Then with a certain temperature zone range or beyond certain temperature range then we can identify using the temperature flag and then in this case we have some modified Avrami equation.

Basically, we have to incorporate the transformation kinetics if in this particular temperature range. And similarly, if with this particular temperature range we have two Avrami equation; that means, another transformation kinetics you have to define. And, similarly during this cooling phase if cooling phase if within this temperature and if cooling rate is very high in that case we can assume the non-diffusional transformation.

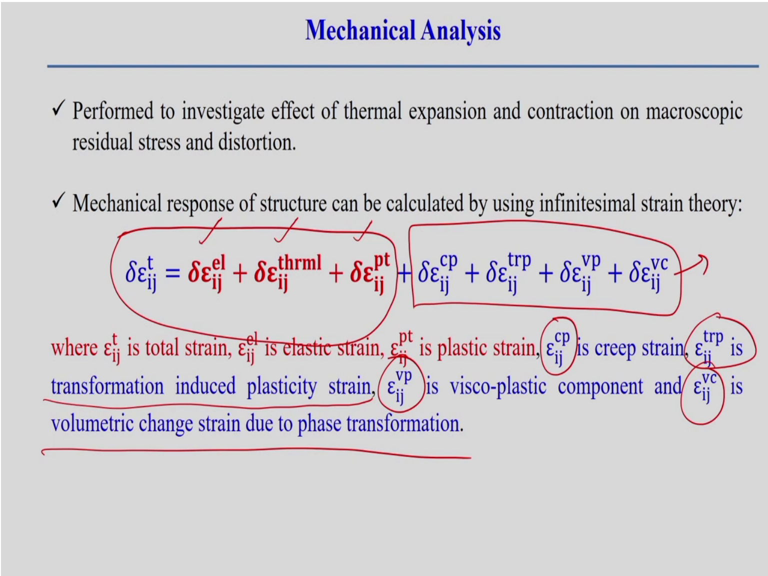
And, then we use some equation the that is normally called KM equation and then it basically represents certain kinetics also. So, that means, depending upon the cooling rate we can define and temperature range we can define the different kinetics and based on that we can estimate the volumetric strain may be in this case all these particular cases.

Now, this volumetric strain can be calculated using some standard software commercial software. Some subroutine can be used to write all this a kind of a equation or to solve this equation and that can be interface with the data. Basically in a particular commercial software when you use some kind of the user subroutine.

So, through the user subroutine we can interact we can take the data the what is the temperature in particular node and these things and accordingly you can decide the temperature flag. We calculate the volumetric strain and these volumetric strain can be input to the particular model during this analysis. And, then accordingly it calculates.

So, therefore, the interface is basically user subroutine in case of the commercial software. So, this way we can develop the metallurgical model and we integrate with the simple thermo mechanical model or elasto-plastic analysis of a during the welding process.

(Refer Slide Time: 23:43)



Now, what the basic analysis procedure if we want if we incorporate the effect of the phase transformation. So, that basic analysis model that we have already explained that normally we do the stress analysis is in the incremental mode. We just count what is the total incremental strain consist of the elastic component thermal and the thermal strain as well as the plastic strain.

And, based on that we if this is the component then we this is the total strain and we normally do the elasto-plastic analysis. But we can incorporate the effect of the other changes other kind of analysis for example, in these cases the microstructural analysis or other component strain component can be added with the total strain component.

But, this total other component can be added externally if we are using some kind of the user subroutine, through the user subroutine we can incorporate the effect of the all these strain component. Here you can see the total strain consist of the elastic plastic and thermal that is associated elasto-plastic analysis, but it will be the same material model, but the extra strain component can be incorporated.

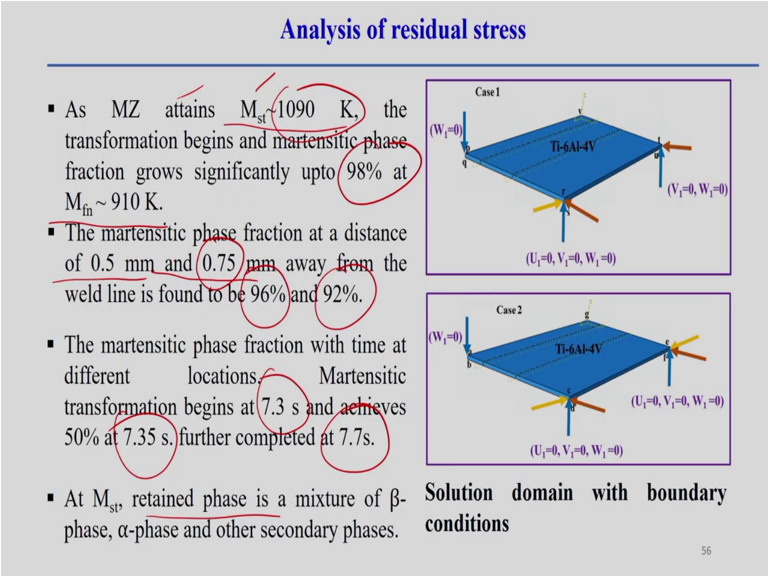
For example, this faster cp epsilon cp indicates the creep strain we can use, but we have to that model has to be developed to calculate the creep strain component. Similarly, transformation induced plasticity strain can also be incorporate during the incorporate and that is the effect of the phase transformation. Then we have to know the what are the phase transformation happens and that due to that phase transformation we have it is necessary to estimate the transform induced strain.

And, then visco plastic component can also be incorporate the effect of the material behavior this is the epsilon vp and finally, vc is the volumetric strain can be incorporated in during the phase transformation.

So, during the phase transformation what are the volumetric strain we can we have shown the last previous slide. That it is possible to estimate the volumetric strain and that volumetric strain can be incorporated with the simply adding with the total strain component.

And, after that we follow the normal procedure what way we do the simple stress analysis model or thermo mechanical model in case of a welding process. So, that is the way to incorporate the effect of the phase transformation effect or if you want to incorporate the other effect for example, creep visco plastic component, then also then we can follow the similar procedure here that we have discussed that we just discussed here.

(Refer Slide Time: 25:59)



Now, we can show some results also the analysis of the residual stress and we can see that it is possible to in a commercial software that molten zone attains the martensitic start temperature. If we assume non-diffusional transformation at 1090 Kelvin and non-diffusion transformation the transformation is a function of only temperature.

So, here it is necessary to understand what is the martensitic start temperature and what is the martensitic finish temperature, such that that at particular temperature 1090 Kelvin the transformation begins. And martensitic phase fraction grows significantly up to 98 percent at martensitic finish temperature 910 Kelvin.

So, therefore, this kind of information we can get even from the commercial software also we get the what is the martensitic fraction that will be able to predict also. But definitely all this martensitic fraction we can predict. It is must be a it is always we calculate on the basis of the what is the temperature attainment for a particular zone.

Or this particular zone what is the temperature achieved based on that we can achieve we can estimate the this fraction of the different phases during this analysis. For example martensitic phase fraction at particular distance. So, of 0.5 millimeter from the weld center and 0.75 millimeter away from the weld center is found the 96 percent and another cases it is found as 92 percent.

The martensitic phase fraction with time at different location martensitic transposition begins at 7.3 second different location and achieves 50 percent at 7.35 second and further completed at 7.7 second. So, therefore, at the different time we can estimate the what are the different fraction martensitic fraction achieve particular position.

Now, at martensitic start temperature retained phase may also be there is a mixture of beta phase, alpha phase and the other secondary phases also let us call the retained phase is there also.

For example, once the particular position the martensitic transformation the temperature cycle is such that at a particular position for example, at away from the center 0.75 millimeter temperatures is that the if you look into the temperature history at this particular point such that in this case the only 92 percent will transform the martensitic, remaining 8 percent maybe other phase transformation may happen.

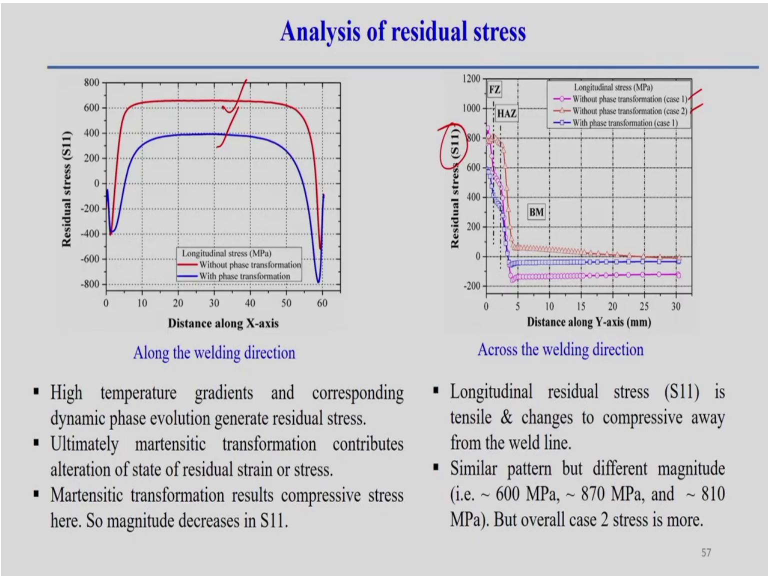
So, that kind of the information is possible to get even if we look into the simple do that stressed analysis model, but incorporating the effect of the phase transformation. Now, we can see that two cases also the titanium alloy case 1 and case 2 maybe solution domain with the boundary condition.

So, in this case we can see the different boundary condition we have put the which degrees of freedom is 0, one particular node. For example, at this point we have we have use the W 1 equal to 0; that means, U Z the displacement along Z direction equal to 0, but displacement may happen along the X and Y direction.

Similarly, two direction arrested here and that V 1 W 1; that means, Y and Z component are 0 and in this at this point may be X, Y and Z all the displacement components are 0 in the particular node point. So, that is way. So, this way we can incorporate the effect of the boundary condition in a particular a model.

So, therefore, this boundary condition is very much sensitive to the amount of the residual stress generation. So, boundary condition should reflect the what are the actual clamping condition we follow during the actual welding process.

(Refer Slide Time: 29:27)



Now, we can see that residual stress also that high temperature that this is the one cases the longitudinal stress with phase transformation, another is the without phase transformation. We can see there is a difference in the prediction of the residual stress with phase transformation and without phase transformation.

So, it means that even if we incorporate the effect of the phase transformation in particularly in titanium alloy we can make some difference and the prediction of the residual stress generation. Therefore, it is necessary to incorporate the effect of the phase transformation if you want to very precisely calculate the residual stress generation.

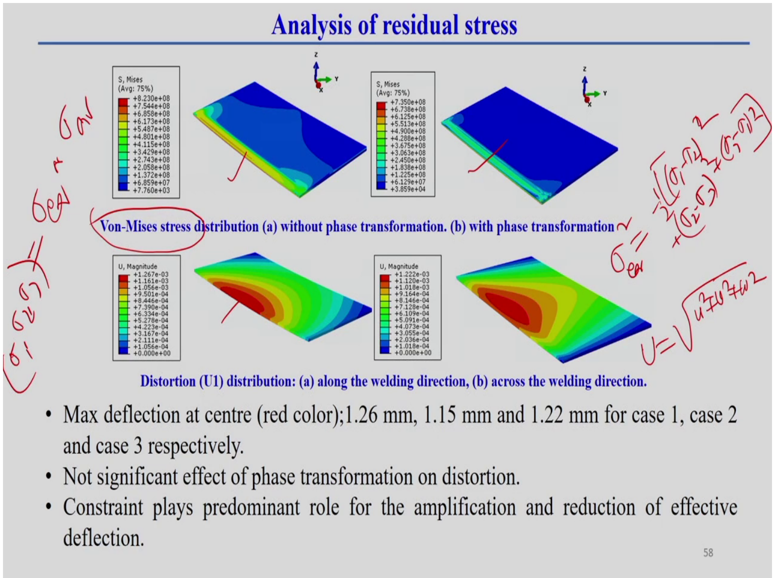
But of course, it may be significant in titanium alloy, but if we look into the other alloy system for example, very low carbon alloy or in case of the stainless steel; in stainless steel the carbon percentage is very low. So, in that cases you may not get that much of difference even if we consider the phase transformation effect. So, it depends on the particular alloy system and that how volumetric change happens from transformation of the phase from one phase to another phase.

Similarly, distance longitudinal residual stress if we see that with the with and without phase transformation the prediction are different and even if we change the boundary condition also without phase transformation case 1 and case 2 means the O 2 boundary condition we have shown two different boundary condition there may be some variation of the residual stress generation.

But, in this case residual stress s one means we are talking about only one particular residual stress component of the residual stress. And, normally the S 11 is the first one sigma XX you can say that this is the residual stress component. So, the residual stress component is basically there is a variation.

If we change the boundary condition also there is a prediction of the variation of the residual stress as well as if you incorporate the with and without the phase transformation there are also some variation of the residual stress may occur.

(Refer Slide Time: 31:10)



Similarly, you can see the Von Mises stress distribution this thing without phase transformation with phase transformation. So, Von Mises stress distribution means when you are talking about the Von Mises stress distribution it is basically we equivalent or sigma average value. We are calculating which consists of the all the components of the residual stress.

This equal to as a function of sigma 1, sigma 2 and sigma 3 the principal stress definitely the principal stresses having is a itself function of the normal stress component as well as the shear stress component. Now, these components can be represent one of the single component that we are representing the Von Mises distribution.

Simply when you are talking about the Von Mises stress distribution. It follows certain functional form; that means, in this case it may follow that half of sigma 1 minus sigma 2 square plus sigma 2 minus sigma 3 square plus sigma 3 minus sigma 1 square. So, this functional form it will follow and this is the Von Mises yield function.

So, maybe if we plot the other kind of the stress condition if the yield function are different then the stress distribution can be different also. But, in these cases we are following the Von Mises yield distribution; that means, it follow this kind of functional form then we are plotting this a single component of the stress over the space also.

So, here we can see that this without phase transformation effect and with phase transformation there is a difference definitely there is a difference if we look in the color scheme also. So, there are some difference in the prediction of the residual stress with and without phase transformation.

Similarly, this residual stress can be distributed in other way also; that means, distribution along the welding direction. So, here the distortion U magnitude this cases U magnitude means in these cases we are calculating the say small u's or the component the magnitude of the three component of the displacement.

And, here you can see there is not much difference in the displacement. It is not necessary that we are not always able to correlate the residual stress and distortion also. Because it is not necessary there is a change of the residual stress that does not mean the distortion may will change, not like that. It is a completely a independent of the residual stress and distortion analysis.

Therefore, in this particular cases even if we consider the phase transformation effect then there is a change in the residual stress distribution. But there is not much change in the distribution in the distortion pattern in case of the welding process. So, these are the typical results I have shown you when we consider phase transformation effect and other cases we consider the without any phase transformation. But, analysis we follow simple elasto plastic analysis.

(Refer Slide Time: 33:58)

Summary

- Different heat source models – depending on type of welding
- Estimation of temperature distribution in the weld zone and heat affected zone by solving heat conduction equation
- Mechanical analysis predicts distortion and residual stress
- Fully coupled thermo-mechanical analysis is also computationally expensive
- Cooling rate is linked with the microstructure in a welded structure
- Experimental measurement of all phenomena in welding is difficult and costly

So, therefore, in summary you can say that looking into all the stress analysis part. The different heat source model depending upon type of the welding process and it is very important to use the heat source model. Because the stress analysis calculation or results of the stress analysis model entirely depends on the heat transfer analysis.

And, heat transfer analysis we can get correctly depends on the interaction of the heat source with the material which is represented by the heat source model. So, therefore, heat choice of the heat source model is very much important to improve the or to predict correctly the temperature distribution.

So, once the temperature distribution is very correct, then we can very preciously predict the residual stress. And even residual stress prediction become more accurate even if you incorporate the effect of the phase transformation also.

So, therefore, the estimation of the temperature distribution in the weld zone and the heat effected zone by solving the heat conduction equation that we have already shown that heat conduction equation. Normally stress analysis is performed link with the by solving the heat conduction equation.

We do not normally do not use the temperature distribution by following the thermo mechanical model, thermo mechanical analysis; that means, fluid flow phenomena we normally consider during this when you try to analyze the stress. So, in that cases normally we use the conduction mode welding process. And from there we estimate the temperature distribution and temperature distribution can be used as for the calculation of the residual stress in a welded structure.

And, that is normally followed in case of the sequentially coupled thermo mechanical model. But, mechanical analysis definitely predicts the distortion and residual stress as compared to the temperature distribution, where the heat condition equation predicts the only the temperature distribution.

Fully coupled thermo mechanical analysis that is also possible, but in this cases fully coupled thermo mechanical analysis it is always necessary to each and every time step. each and every load step in the calculation stress as well as the then calculation of the temperature profile. So, each and every step the stress analysis as well as the thermal analysis both has to be conducted.

So, that is a fully coupled thermo mechanical analysis or in this fully coupled thermo mechanical analysis is useful when the stress analysis is dependent on the thermal analysis as well as the thermal analysis temperature distribution dependent on the stress analysis or influence the stress analysis results.

So, they are internally dependent with respect to each other then when in this cases fully coupled thermo mechanical analysis is required. Otherwise if the temperature not dependent on the stress analysis or definitely stress analysis depend on the thermal analysis, but thermal analysis may not depend on the stress analysis result. In that cases we can follow sequentially coupled thermo mechanical analysis.

So, it is very important the cooling rate always we try to link with the microstructure in a welded structure that is necessary So, therefore, once we perform the mechanical thermal analysis it is always necessary to estimate the cooling rate and that cooling rate can be a parameter and we take the phase all the information from the time temperature transformation TTD diagram and CCT diagram or equilibrium phase diagram.

From that information taking that information of the different phases, their existence with respect to the different cooling rate then we can develop some of the phase transformation effect or the; that means, the residual stress model including the effect of the phase transformation.

But, therefore, once we go for model all these analysis everything is important because in certain cases the all the experimental, measurement of all the phenomena which happens during the welding process is very difficult and may be costly also. See in that cases it is very much useful to develop model and of course, once we developed some model the validation of model is also required.

So, that is all today and thank you very much for your kind attention. So, next part of this particular module I will try to discuss the what way we can develop a model using some kind of the commercial software.

So, thank you very much.