Mathematical Modeling of Manufacturing Processes
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Lecture - 06
Solid State Deformation and Residual Stress-1

Hello everybody. So far we have discussed the elastic analysis as well as the different plasticity model and normally elastic analysis I have covered the isotropic elasticity, but I have not gone through details in isotropic elasticity, but in plasticity model that means how we can develop any plastic deformation model and specifically when it is unidirectional or if it is subjected to some kind of a 3 dimensional state of the stress.

So in both the cases we can develop the plasticity model and normally I have gone through that (()) (01:08) yield conditions and we can define the yield surfaces when the system is subjected to some multiaxial loading conditions. So now once we do the elastic analysis and plastic analysis maybe next point is more significant is the residual stress generated during the manufacturing process.

Actually most of the manufacturing process it is associated with some form of the residual stress, but what way we can analyze the residual stress and what are the consequent effects and what way we can reduce in perspective of the different manufacturing process that we will try to explain in this part.

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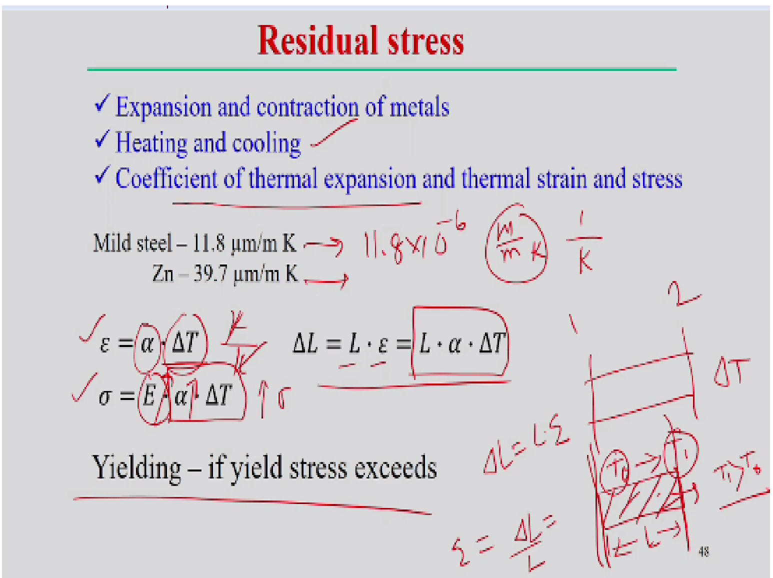

So residual stress, but before details about the residual stress we can start with this things. We know that expansion and contraction of a model of a materials or specifically metals when it is subjected to some kind of the thermal load that means if we heat a sample it will expand and once it is expand and if further cool the sample then it can contract. So this expansion and contraction actually leads to some kind of thermal strain.

And then thermal strain is associated with some kind of thermal stress and of course this thermal stress if this thermal stress exceeds the yield point of a particular material that means it enters the plastic deformation zone then some amount of the permanent residual stress or permanent stress will be generated within a component or sample. Now most of the manufacturing process it is subjected to some kind of the heating and cooling.

Because in manufacturing process normally we apply some sort of the heat source to perform a particular manufacturing process and then of course after heating desire temperature achieve then it automatically cools to ambient temperature. So therefore it is subjected to heating and cooling associated with most of the manufacturing processes and of course if we look into the thermal expansion properties.

So that we have already discussed thermal expansion coefficient and that thermal expansion coefficient we can see that in case of mild steel this is the value of thermal expansion coefficients 11.8 micrometer per meter Kelvin or we can say that 11.8 into 10 to the power -6 meter/meter and per unit degree Kelvin or we can say it is a simply per unit temperature change this is the value of the mild steel.

So in case of zinc the thermal expansion coefficient or we can say the contraction coefficient is much more as compared to the mild steel. So therefore the stress generates during this deformation and in case of mild steel and in case of zinc should be different because in both the cases the thermal expansion coefficient there was a wide variation almost 4 times zinc as compared to the mild steel.

So that what way we can estimate this thermal stress and strain during the process if we assume this thermal strain it is simply coefficient of thermal expansion into temperature difference. So basically that delta T particular there is delta T and this delta T is a difference as a particular point may be 0.1 and 0.2 in between what is the temperature difference that actually induce some amount of the thermal strain.

So if it is a thermal strain and of course we know the dimension of the thermal strain is basically dimensionless. So delta T is per unit temperature difference Kelvin and coefficient thermal expansion 1/Kelvin. So basically it becomes dimensionless. So delta L so that means suppose this is the sample size and if this room temperature is T0 and it is temperature raise of this sample T0 to for example T1 such that T1>T0 that means raise the temperature.

So therefore initial length L we assume expansion happening in this direction delta L so that delta L that means due to the temperature difference it will expand in particular direction so that delta L we can say the strain is basically delta L/L so therefore delta L=L into strain= L alpha delta T. So this is the increment of the length due to the application of the thermal load or maybe due to the application of the temperature difference between these two points.

Maybe for the whole sample it is like that we can treat initial temperature was T0 and it raise to temperature uniformly to T1 so it will expand simply so that expansion if we assume this expansion happens only one direction then we can estimate what is the increment of the length on particular direction so that when it is subjected to some amount of the temperature difference.

So here we can see this things, but this change of length or maybe this if it is free to expand so there is no restriction on constriction. So therefore if it is free to expand then it will not induce any kind of stress there also, but if it is restricted that means if we put some restriction and initial temperature is T0 and if we raise the temperature for the whole body T1 but there is some restriction.

Then it will create the thermal strain that thermal strain we can estimate in this way for T and corresponding thermal stress can be estimated the if we assume stress is proportional to the strain then stress=Young's modulus into alpha delta T this is the thermal strain so this is the amount of the stress. Now point is whether yielding will happens or not during the restricted component.

That means if you put some constant and if we increase the temperature so during cooling phase if the stress value is below the yield point of a particular material. So that means within the elastic zone so even if we remove the thermal load then after cooling it will come back to the ambient temperature so there may not be any kind of permanent stress there so it will come back to the initial position.

So therefore it may not subjected to some sort of residual stress because within this temperature difference if the phase transformation also negligible. So therefore it is may not associated any kind of the permanent stress, but if this temperature difference is too high or maybe a particular material alpha is very high value or particular material Young's modulus is more.

Then maybe if this stress sigma cross the yield point value and then even if we cool the sample then once it cross the yield point value so some amount of the permanent stress will be generated within this body and even I cool the ambient temperature so permanent deformation exist within this body and that permanent deformation will induce some amount of the stress.

So in general that is the measure of the residual stress during this process. So therefore residual stress will be there if with application of the thermal load even in absence of some kind of the mechanical loading conditions then it can induce some amount of the permanent strain or stress if the stress exceeds the yield point of a particular material.

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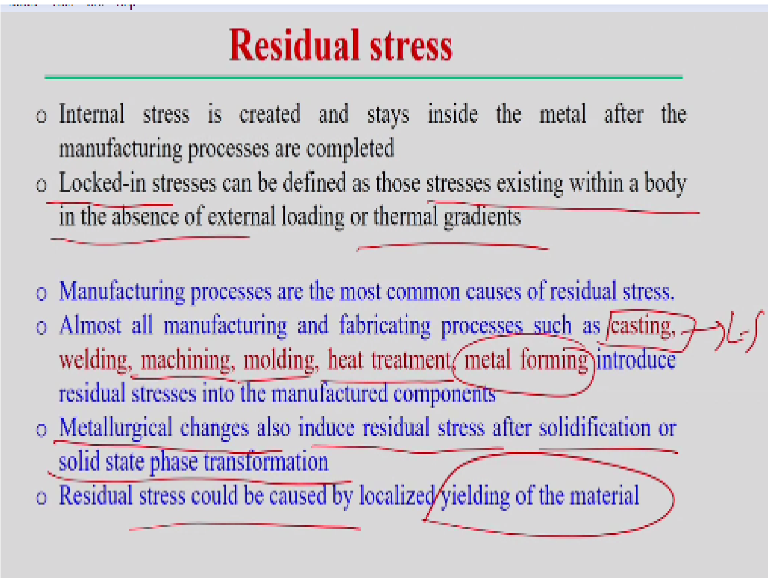

Now residual stress can be look in that way that we can define the residual stress in that way that internal stress is created and of course that internal stress stays inside the body, inside the metal even after manufacturing process after completion of the manufacturing process. So that stress is termed as the residual stress and in other way we can say that it is a kind of locked in stress and can be defined the stress is existing within a body in absence of any kind of external load or in absence of any kind of temperature difference or any kind of thermal gradient.

So that lock in stress is normally defined as the residual stress. So most of the manufacturing process is associated with some amount of the residual stress because it may be subjected to either some amount of the plastic deformation happens or there may be some amount of the phase transformation one phase to different phase or maybe phase means from solid to liquid and then liquid to come back liquid to solid or some solid state phase transformation.

All may induce are responsible to induce at least some amount of the residual stress in a manufacture component. So therefore most of the manufacturing component such as the manufacturing process even in casting and then casting is associated with the melting of a material and then solidification happens then even welding also welding if we melt the material and then after melting when we cool it come back to the ambient temperature.

So it is subjected to some kind of the phase change then liquid phase to solid phase and vice versa also. Even for machining, machining maybe subjected to some kind of the solid state phase transformation or some kind of the high strain rate they can also induce some amount of the residual stress also, molding, heat treatment process associated to it. In heat treatment process normally we reduce the amount of the residual stress.

But it alters the residuals stress of course in metal forming also. All this basic manufacturing processes introduce or induce some amount of residual stress and of course the residual stress also comes from the metallurgical changes. So, metallurgical changes inside the body that means induce the residual stress after solidification or solid state phase transformation both are responsible to induce some amount of the residual stress in a manufacture component.

So therefore in general if residual stress could be caused or maybe caused by the local it is a very localize position if the yielding of the material happens even it is not necessary the yielding may happen as a bulk, but it is a localized area if yielding happen that also induce some amount of the residual strain in manufacturing component that is in general.

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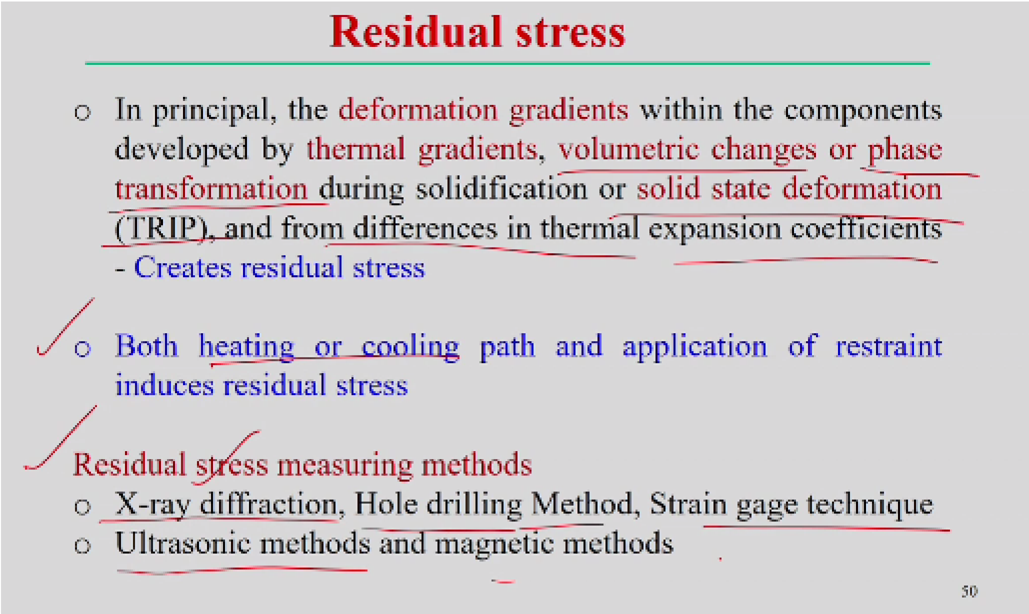

So in principle deformation gradient that means the deformation not uniform in a particular direction if there are some gradient present there within the component and that deformation gradient if it is created by the thermal gradient or some amount of the volumetric change or phase transformation it happens during the solidification or phase transformation it happens during the solid state deformation that also induce some amount of the residual stress.

Even in solid state deformation due to the transformation so some sort of transformation induced plasticity the metallurgical changes happens so that transformation one phase to another phase that actually it is a very localized and it is very micro scale maybe lower scale that induce some amount of the plasticity. So that transformation into plasticity is also responsible to create or to contribute the formation of the residual stress within the structure.

Of course apart from that different thermal expansion or coefficients all are responsible factors to create the residual stress in a manufacturing component of course both heating and cooling, but in general if we look into the common manufacturing process most of the cases it is associated with some heating cycle and cooling cycle apart from them heating and cooling cycle if application of some constant that actually induce some amount of the residual stress.

Constant, in the sense practically for example if we clamp the components in welding process so that clamping process itself mathematically induce some amount of the constant condition and that actually influence the amount of the residual stress generation apart from the heating and cooling cycle during the manufacturing processes. So residual stress normally we measure using some x-ray diffraction technique and hole drilling method, strain gage technique, all the mechanical methods and this things.

And of course ultrasonic method and magnetic methods are also used to measure the residual stress, but in principle in x-ray diffraction we normally measure the residuals stress on the surface and of course in hole drilling method is the mechanical method we just simply create the small hole within a component and that component even if that direction we can measure the residual stress.

Normally in hole drilling method if the release of the stress during the drilling process that actually induces in the strain gauge some amount of the strain and that strain is converted to the stress value even similarly strain gauge technique can also be used simply using some strain gauges we can measure the residual stress of course in that cases some specific methodology or techniques have to be developed using this.

But in principle in using the strain gauge we measure the strain and that strain is converted to the stress amount and that stress is measure of the residual stress.

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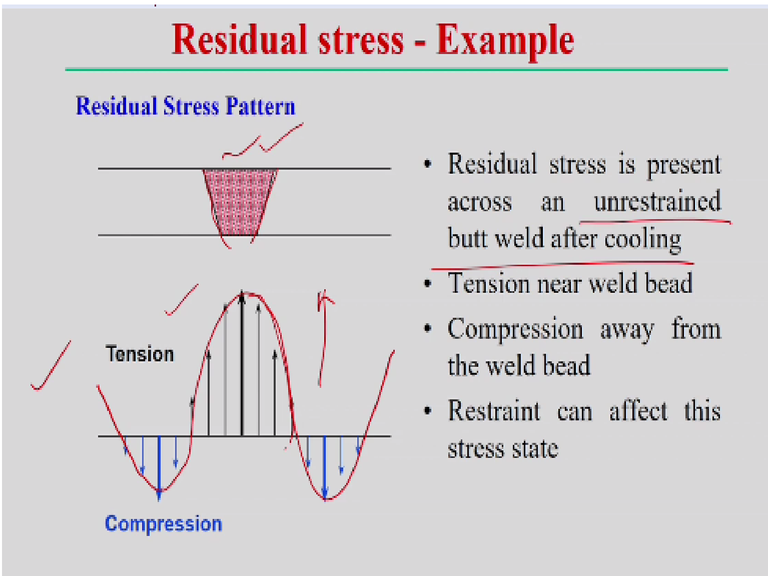

So we can give an example also residual stress example here we can see that residual stress pattern and we can keep this example in case of fusion welding process and here if you see this is a typical profile we can assume this is a typical profile of a welded zone and for a component. So therefore residual stress is present across the unrestricted butt weld so it is a butt (()) (15:16) configuration if we assume the butt (()) (15:19) configuration means 2 plates adjoined together and it creates this kind of the material volume.

And melting volume and then if we do not put any kind of the constant if you do not put any kind of restriction then also it will changes some amount of the residual stress because some metallurgical changes happens during this process. So that it creates typical the tensile nature of the residual stress this; the direction distribution, but to equilibrate this temperature distribution then if some compressive residual stress also generated the surrounding of the weld metal pool.

So this is the typical nature of the residual stress of course this nature of the residual stress is affected by restrained condition. So if we put the displacement boundary if we restrict the displacement of this boundary of the component then it influences the amount of the residual stress generation.

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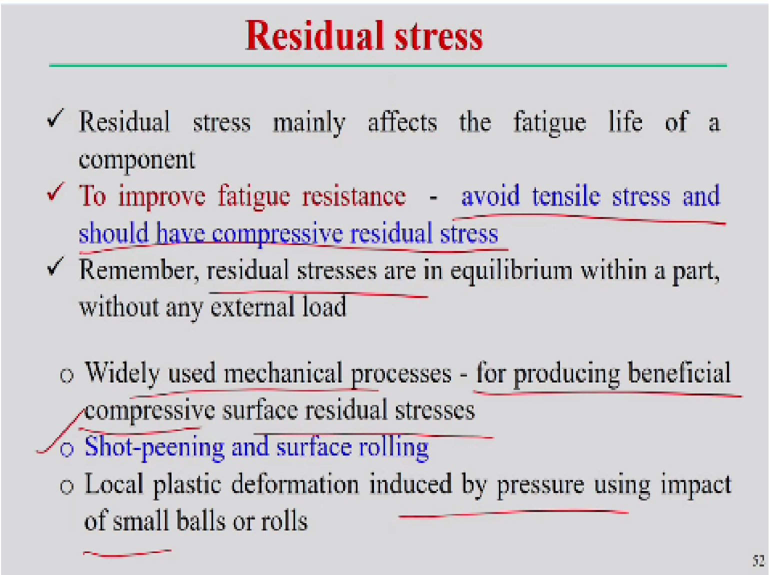

Now we can look into some overall aspect of the residual stress. So residual stress actually important when try to assess the fatigue life of a particular component. It is to estimate it is very much influence actually residual stress is measurement of the residual stress is very much significant if we try to assess the fatigue life of a particular component. Fatigue life means if the material is subjected to some kind of the cyclic loading conditions.

So in that conditions if there existence of the residual stress within the component then life of the component can be reduced or normally reduced. So therefore it is quite most of the cases it is quite objective to remove the residual stress such that we can improve the fatigue resistance of a particular component, but in general way to improve the fatigue resistance of a particular component is to promote the compressive residual stress.

And try to avoid the amount of the tensile residual stress and that is most of the cases we can find out. So even it is not possible to completely avoid the formation of the residual stress in a manufacture component, but what we can do we can do that to change the tensile residual stress to compressive residual stress it is possible to generate the compressive residual stress then it is always advantageous.

And that advantageous in the sense that it normally try to improve the fatigue life of a particular component. So therefore remember the residual stress is actually in equilibrium within the body and when it is in equilibrium exist within the body, but without application of any kind of the external load during this process. So, therefore widely used mechanical processes so when you manufacture the components if we follow some simple methodology.

Such that we can improve the; generate some kind of the compressive residual stress or maybe other way we can try to reduce the residual stress in a particular component. So therefore for producing the manufacturing processes for producing the beneficial compressive surface residual stress maybe most of the cases it is one of the objective of the manufacture component to improve the surface residual stress properties by simply converting or maybe inducing compressive residual stress on the surface.

So the methods can be used simply that shot-peening surface rolling process can be used to improve the compressive residual stress on the surface. So shot-peening is a local plastic deformation induced by pressure using the kind of small impact simply impact load by a small ball or by a roll if we try to impart some amount of the load on the surface and that actually try to induce some amount of the compressive residual stress.

And most of the cases we follow this shot-peening and surface rolling method to improve the fatigue resistance properties of a particular manufacturing component.

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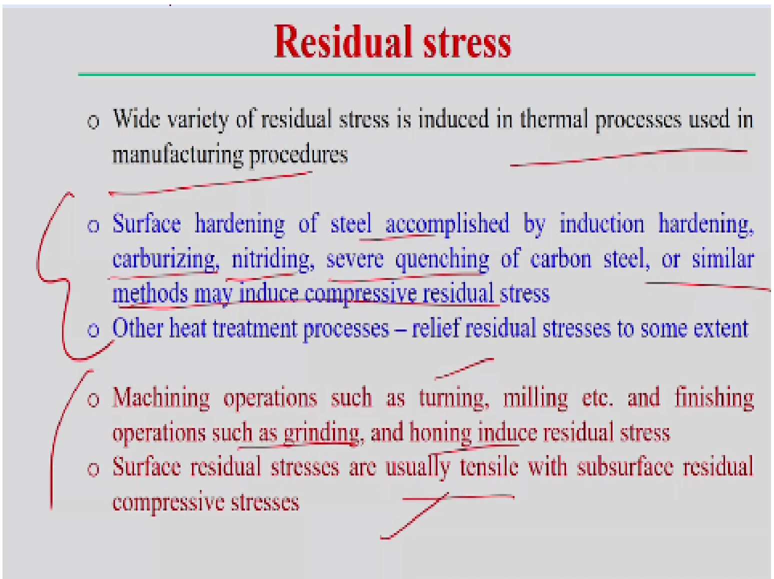

Now wide variety of residual stress actually nature of the residual stress there is a wide variation and maybe sometimes it becomes very random and that depending upon the thermal processing used in the manufacturing procedure. So maybe thermal processing, the application of the heat and the cooling process are completely different type of manufacturing processes.

So in that cases we can find out that there is a wide variation of the residual stress generation. For example, the surface hardening of the steel sometimes in a steel product there is necessary for the surface hardening, but if we do the surface hardening of the steel by using some induction hardening. So on the application of the heat induction hardening such as carburizing, nitriding, induced carbides nitrides.

And the quenching process also carbon steel or similar methods or kind of other similar methods they can induce some kind of the compressive stresses. So therefore sometimes to improve the surface properties we can induce the surface hardening we follow some kind of surface hardening methodology. For example, carburizing, nitriding and if we do this kind of methodology by this process we can improve the residuals stress on the surfaces.

Of course apart from that if we follow the other heat treatment process also. So for example after welding processes there must be some amount of residual stress in the component and most of the cases after welding we normally follow the heat treatment process for particular component. Once you follow the heat treatment process it actually try to reduce the residual stress up to certain extent not completely.

So that residuals stress magnitude can be reduced by following the heat treatment process after welding or it redistribute the amount of stress also. So that is why most of the cases after manufacturing component we can do some kind of the heat treatment process. So of course other processes for example machining (()) (21:39) process, milling process and some kind of the finishing processes they also such as grinding and honing that type of machining processes also or finishing process also induce some amount of the residual stress.

So therefore surface residual stress normally in this cases, in this machining processes the surface residual stress is normally tensile in nature, but in the subsurface residual stresses normally compressive in nature this is the typical observation of the residual stress. So this is all about the residual stress just I am trying to give some overview of the residual stress which is very much relevant to the different types of the manufacturing process.

And of course it is a design or practicing engineer it is always objectives to reduce some amount of the residual stress or at least to induce some amount of the compressive residual stress to improve the fatigue life properties of a particular component. So thank you very much for your kind attention.