Failure Analysis & Prevention
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Lecture – 33
General Procedure of Failure Analysis: Application of Fracture Mechanics I

Hello, I welcome you all in this presentation related with the subject failure analysis and prevention. And we are talking about the general procedure for the failure analysis and under that heading we have talked about so many aspects. In this presentation we will be taking up the application of the fracture mechanics application of the fracture mechanics in the failure analysis.

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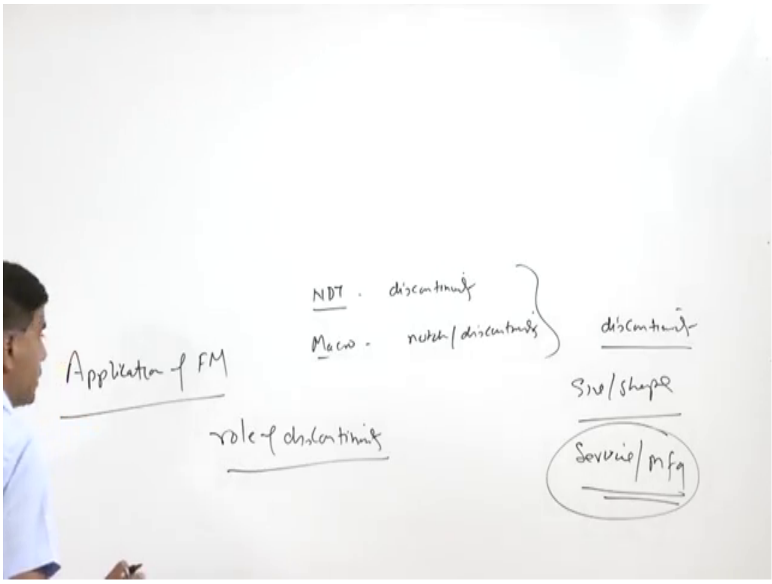

So, we know that we have done the NDT Non Destructive Testing for determining the discontinuities in the failed component, we have also done the macroscopy of the fracture surface that will also indicate the presence of the notches or the discontinuities present on the fracture surface.

So, the information from these two is used together the kind of the discontinuities, which were present in the failed component. So, their size and a shape is determined using suitable image analysis or any other technique. If we are aware of that there was a discontinuity in the component which has a failed; whether it has been created during the service or it was the result of the manufacturing improper manufacturing that can be established subsequently, but we need to find out really the role of the discontinuity; role of discontinuity on the fracture surface on the fracture.

So, for this purpose we have to carry out the analysis of the loading conditions, size of the discontinuity and the material property whether in light of the material properties, loading conditions with the given size of the discontinuity whether it should failed or not. So, that role of the discontinuity in the failure is established through the use of the fracture mechanics principles.

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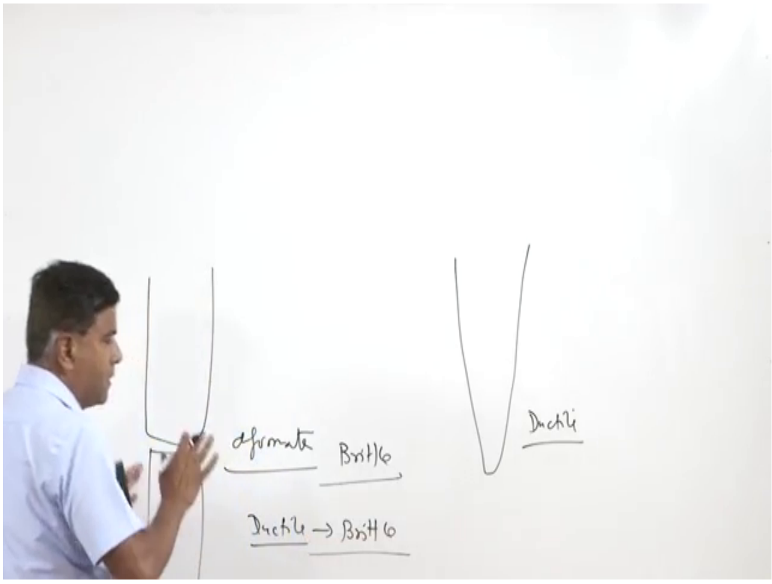

We know that a component which has failed may feel like this without measure a reduction in cross section or without showing a any sign of the deformation. So, this will simply indicate the occurrence of the brittle fracture. There can be another possibility where significant knacking is taking place prior to the fracture which will indicate that fracture was the ductile one.

But sometimes even the ductile materials tend to behave like brittle materials. So, this is what happens under the certain conditions of the service, certain conditions which are experienced by the component. So, what are those factors which make even the ductile metal to behave like brittle material, and this is the brittle materials have less tolerance to the discontinuities for the failure as compared to the ductile materials. So, we need to first see if the material is a ductile under the normal testing conditions, how why it is behaving like a brittle material or white it has behaved like a brittle material under the actual service condition.

So, there are three aspects, which leads to the discharge in behavior from the ductile to brittle aspects a brittle behavior.

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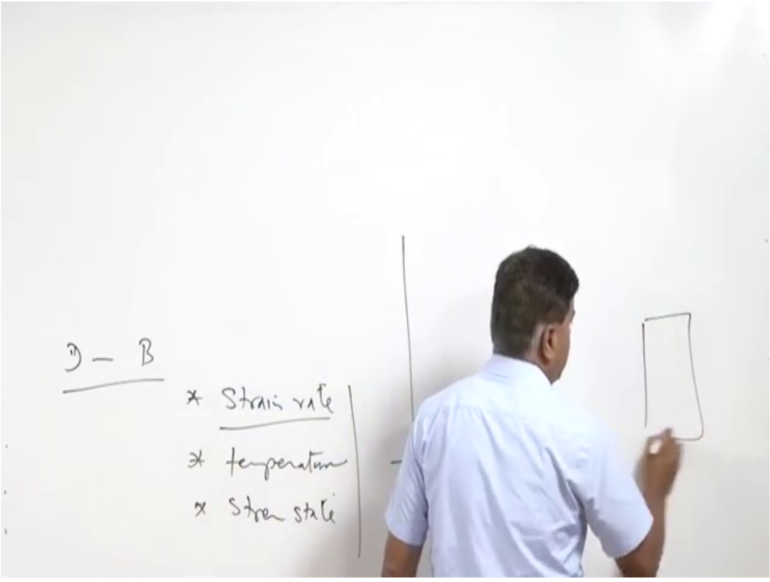

The one is the strain rate, the rate at which the component is deformed or subjected to the loading. The second is the temperature; the temperature conditions under which the component is being exposed and the third is the stress state which is being experienced by the component or given a material or given material.

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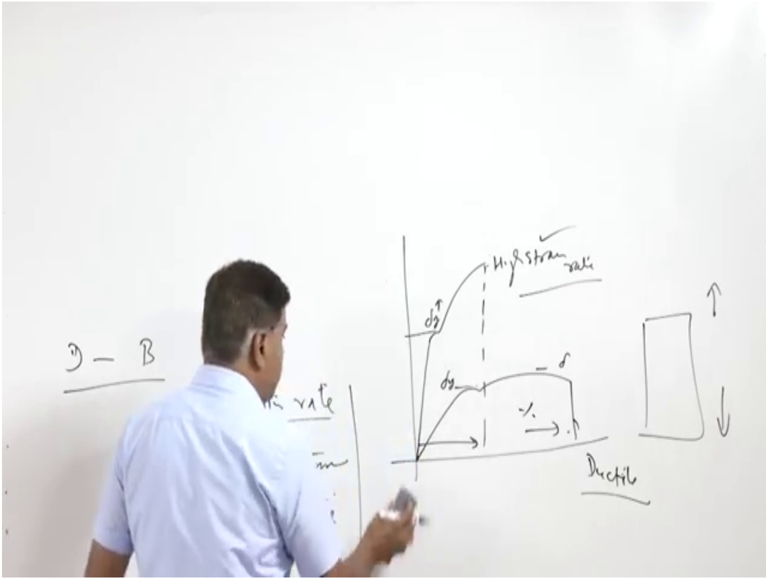

So, we know that when the stress there the we will talk about first the strain rate effect; the rate at which like say in tensile test, at what rate the cross hedges are being cross head is being moved away from each other during the tensile test that will be determining the rate at which the component is being strained. So, when the strain rate is low material can behave like this, when the strain rate is high it behaves completely in different way.

So, this is the behavior for the high strain rate. So, it shows the lower ductility although higher strength. So, sigma y is high, but the percentage elongation at fracture is low while under the low strained rate conditions it shows the it shows the lower sigma y value and the, but the greater a percentage elongation at the fracture. So, this is one effect where the material at the low rate of the loading a low strain rate it behaves like a ductile material, while at a high rate of the loading condition high strain rate conditions it behaves like a brittle material.

Similarly, when a component is subjected to a high temperature conditions like a 30 degree, 40 degree, 50 degree under those conditions it mostly shows the brittle sorry ductile behavior, but as soon as its exposure is given to the low temperature conditions like simple low carbon steels.

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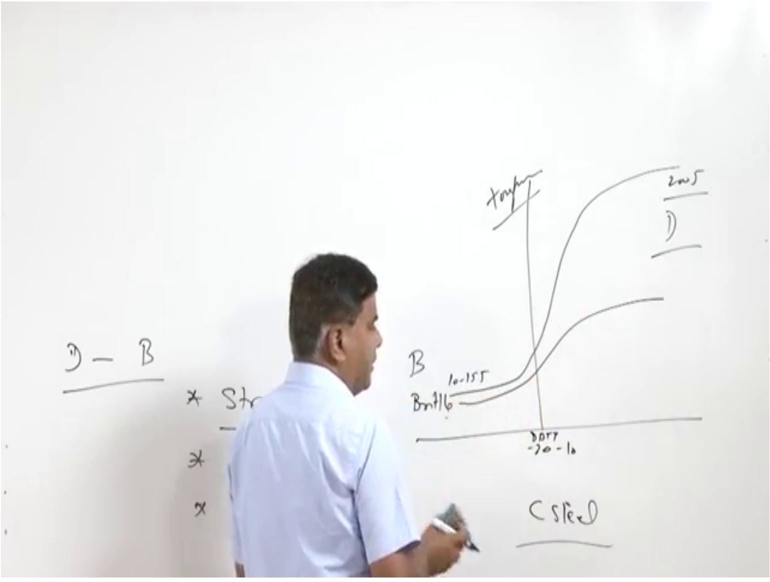

So, is very high toughness at a room temperature, but it shows the transition from the ductile to brittle behavior with the reduction in temperature. This temperature may vary like say minus 20 degree centigrade 20 minus 10 or so, and here it may have the value of like say the 200 joules, but at a room below the transition temperature, this is called ductile to brittle transition temperature. Because the transition temperature it may show very low resistance to the impact which is measured in terms of the toughness.

So, here it behaves a ductile as a ductile material and here it behaves like a brittle material. Energy requirement may be like as low as 10 or 15joule itself. So, there is a very low impact in our resistance to the impact for the different material systems this may vary significantly, this is a for low carbon steel and for high carbon steel this may go like this because a high carbon steel materials do not have much high impact resistance as compared to the low carbon steels. So, depending upon the kind of the composition of this steel, it may show the different kind of the behaviors with the reduction in temperature.

So, as there is a reduction in temperature, it tends to behave like a brittle material as compared to that what is it was behaving at a high temperature. So, the temperature is another aspect and the third aspect related with this behavior is the stress state.

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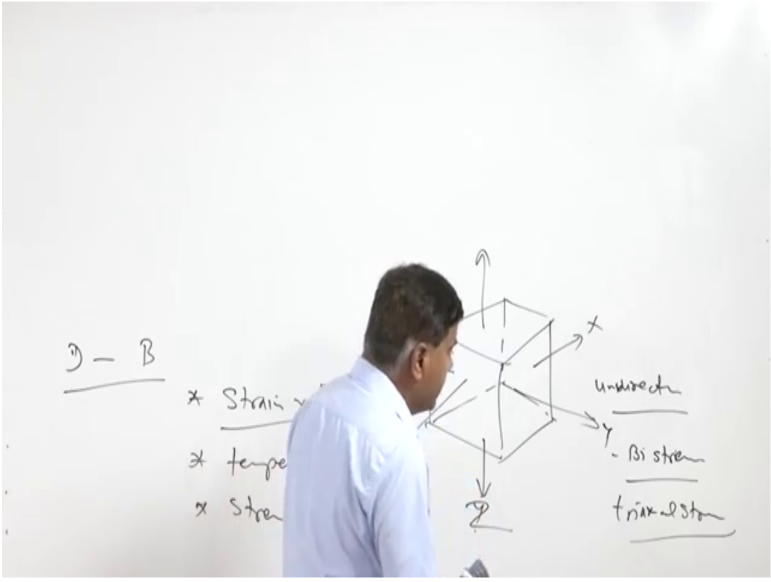

A component may be subject component like this may be subjected to the loading in one direction only like say this. So, if the component is subjected to the loading in one direction say x only, then it is called unidirectional loading. When the component is subjected to the loading in two directions, then it is like say this is y y direction this is zz direction.

So, when the component is subjected to the loading in the two directions, then it is termed as a bi stress or the or tri axial stress bi axial stress or tri axial stress loading. So, when the material is subjected to the tri axial means the loading, a loading in all three x y and z direction is tensile type and it is acting in all three directions, then it is termed as Tri axial stress state.

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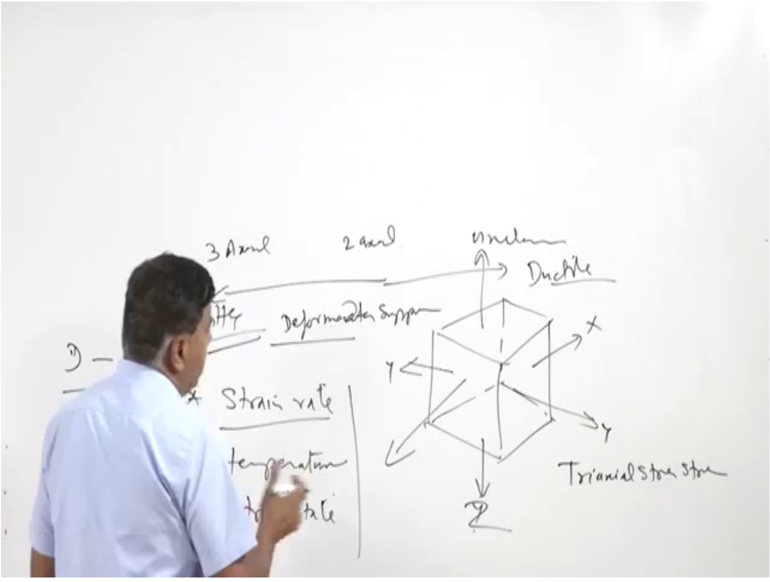

So, when material is of the tri axial stress state or a biaxial stress state or unidirectional stress states.

So, when material is of the unit subjected to the loading in one direction only it tends to behave like a ductile material and this behavior changes from in the three tri axial stress state it tends to behave like a brittle material. So, what is the reason behind this? Because whenever material is subjected to the three loading in three directions it tends to it is the ability to deform is suppressed deformation tendency is suppressed. So, it does not become brittle, but it does not tend to it does not show the deformation tendency and because of this reduction in deformation tendency it behaves like a brittle material.

So, all those conditions which are changing the behavior of the material from ductile to brittle, will be making the component more sensitive for the cracks or discontinuities.

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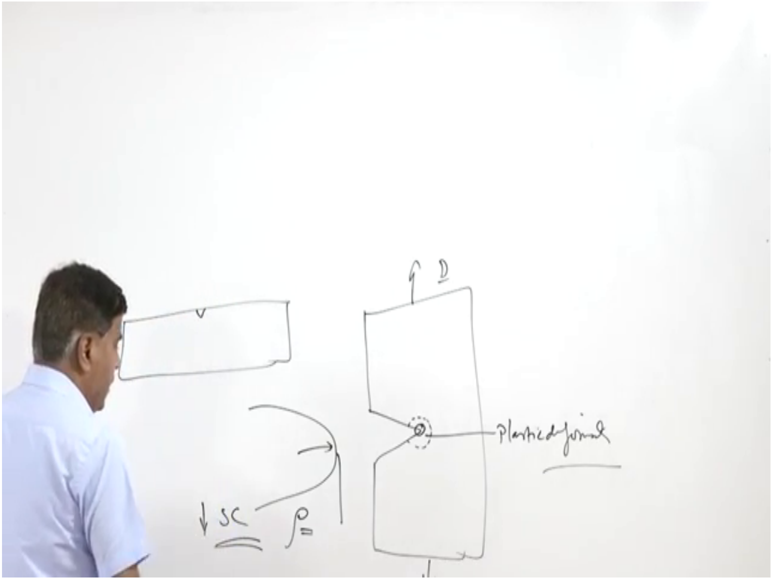

So, say a component when it was ductile, it can easily tolerate the discontinuities because the ductile metal can easily deform. So, like say this is the crack when subjected to the a ductile when material is behaving like a ductile material, all the zone all around the crack tip will be experiencing the plastic deformation and because of this deformation, the tip will actually get blunted like this.

So, the tip radius will increase from like say earlier if it was pointed; now its radius will increase. So, this increase in due to the blunting of the crack tip, which the deformation of plastic deformation taking place at the crack tip, leading to the blunting of the crack tip which is increasing the radius of the crack tip. And increase in radius of the crack tip actually reduces the stress concentration at the crack tip. So, the chances for propagation of the crack are reduced.

On the other hand when the material behaves like a brittle material.

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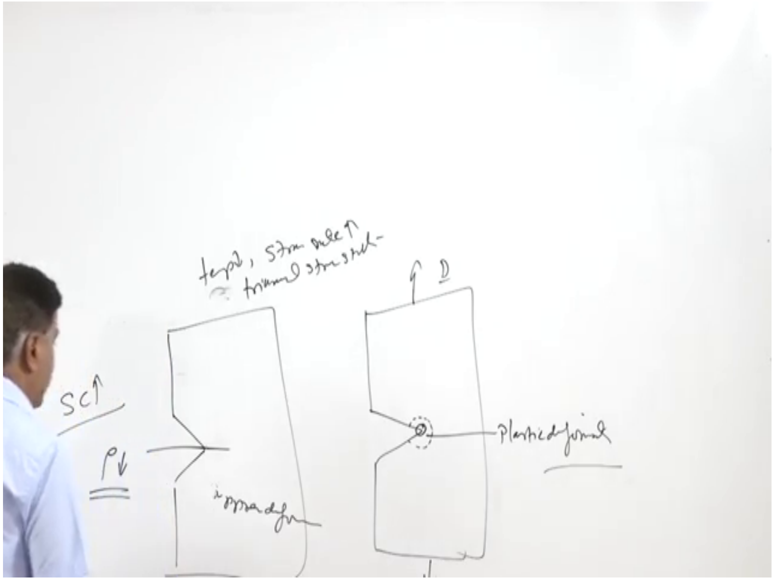

So, it has a limited ability to get deform. Deformation is suppressed either when the temperature is low or the strain rate is high or the three a tri means tri axial stress state tri axial stress state exists all these things will be suppressing the they will suppress the deformation at the crack tip. So, the crack tip blunting tendency is reduced and because of this the tip remains sharp. So, the rho remains very low and because of this our stress concentration becomes high.

So, the crack propagation tendency will be high means the rho a possibility to cause the fracture by the presence of discontinuities, in case of the in case when the material is behaving like a brittle material will be more as compared to the case when it is behaving like a ductile material. That is why what we say that the tolerance to the discontinuities is better in the ductile material systems as compared to the case when it is behaving like a brittle material. So, even the stress concentration is reduced.

So, some of the theories now have been proposed with regard to the a role of discontinuities with regard to the role of discontinuities and their possible effect on the stress concentration and subsequently to cause the fracture.

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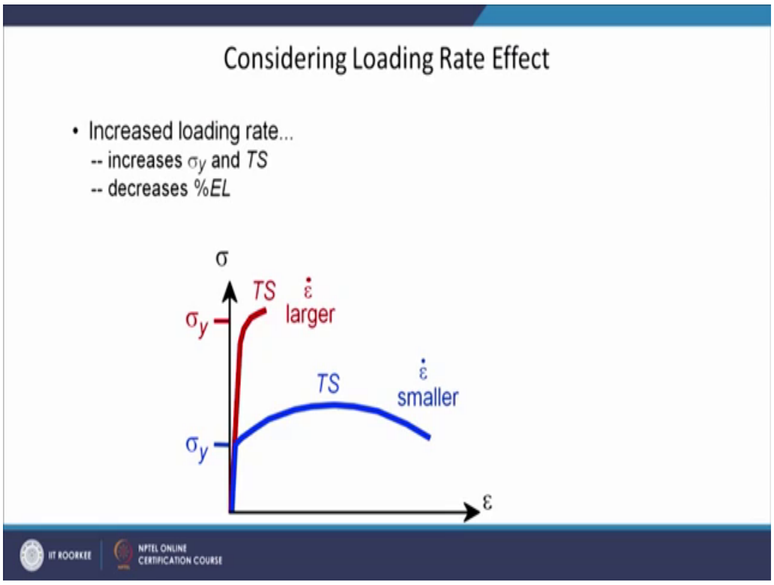

So, this is what is schematically shown in the diagram, here like as the strain rate increases the increase in yield strength, but the ductility reduces this is the case of the low a rate of the strain.

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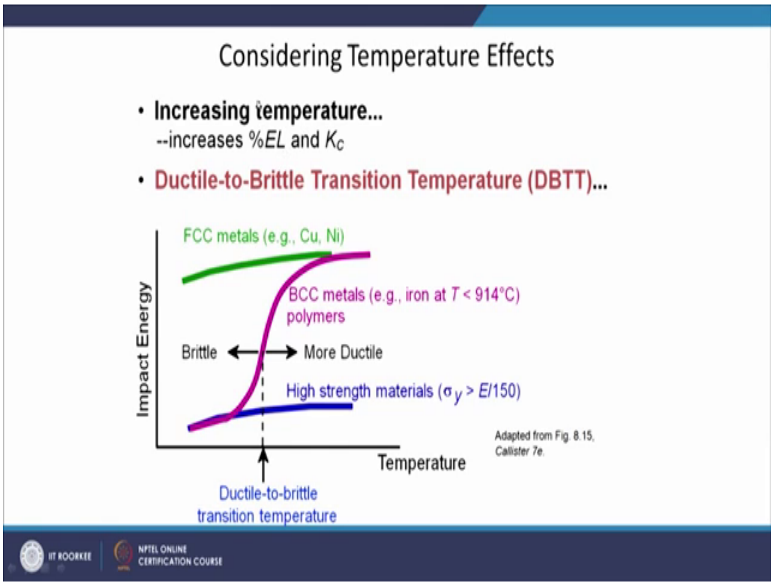

Similarly, here increasing the temperature in general increases the elongation and a reduces the increases the fracture toughness at high temperature, but on the other end the as the reduction in temperature takes place we will see that there is a change in behavior from ductile to the brittle and this is known as ductile to brittle transition.

And especially impact resistance decreases. So, FCC most of the FCC metals are immune to this there is no sharp drop in the toughness with the reduction in temperature, but most of the BCC metals tend to behave like this whereas, the sharp reduction comparatively sharp reduction in the impact resistance takes place, with the reduction in temperature. So, this is what the this behavior leads to the change in behavior from the ductile to brittle transition ductile to brittle one.

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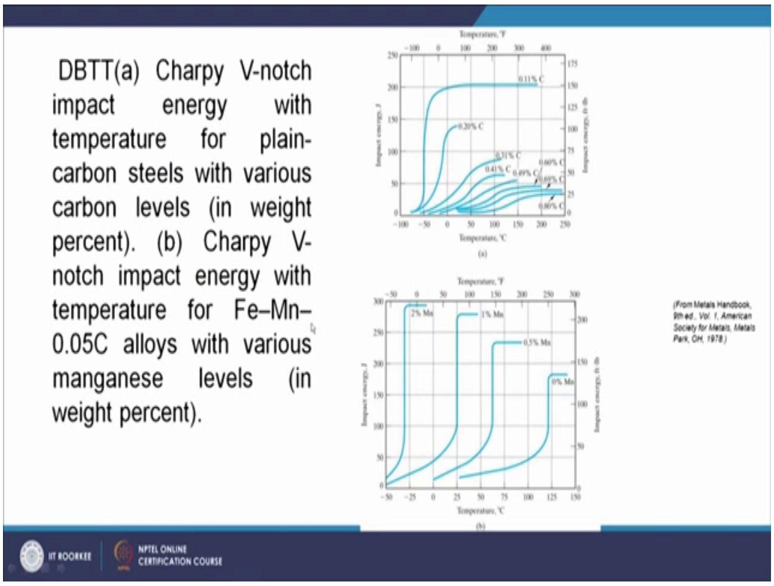

Like here we can what we can see here when the carbon content is low the impact resistance is high like say about the 200 joules and the and then it minor at minus 20 minus 50 degree centigrade such kind of sharp transition is taking place from the ductile to the brittle one.

And the impact resistance is getting reduced very low like 10, 15 or so. But as the carbon content increases impact resistance of the material even at a high temperature also reduces. So, at room temperature impact resistance is very low and that is why we do not find we do not find such a law a high at transition in behavior with the reduction in temperature, because material already behaves like a brittle material with the high carbon content. And this is what is showing the effect of the manganese addition, when we have the higher content of the manganese the transition temperature is too high.

But with the low manganese content sorry when the manganese content is low the transition temperature is high and with the increase in the manganese content, the transition temperature reduces.

So, it is always good to have the lower transition temperature as compared to the high transition temperatures, because it is a more prompt the possibility for the height high it is a it is very much possible that the component can be exposed to the high temperature conditions. So, if the transition temperature is high then it is undesirable, it is always preferred that the transition temperature is low.

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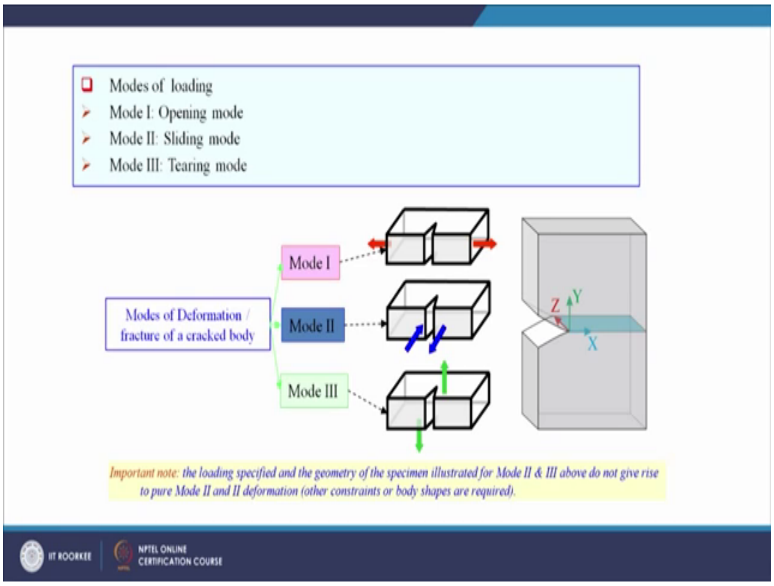

So, material behaves like a ductile material during the service conditions. Now, there can be three possibilities, we have already talked about this that there can be three possibilities of the loading under which the crack can propagate.

The loading one is the tensile loading mod and loading a mod 2 and mod 3 are the shear loading mod; in mod 2 the crack propagation takes place in the plane of the crack and the in case in the mod 3 the crack propagation takes place out of the plane of the crack surface.

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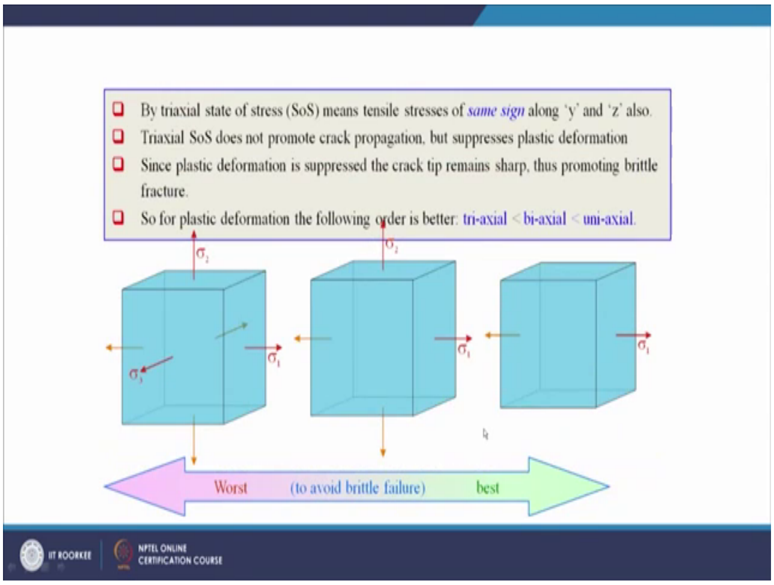

So, this is what is explained for the two dimensional was a unidirectional and a bi directional loading and bi axial uniaxial bi axial and tri axial loading. So, in this case it is uniaxial, when it is behaves like a ductile material and as that in this is the case of the tri axial loading will loading load acts in all three directions and this is the worst condition with regard to the ability to get deform. So, it tends to behave like a brittle material.

So, in case of the triaxial stress state actually the plastic deformation is suppressed and the because of the suppression of the plastic deformation, the crack tip remains sharp and that promotes the brittle fracture.

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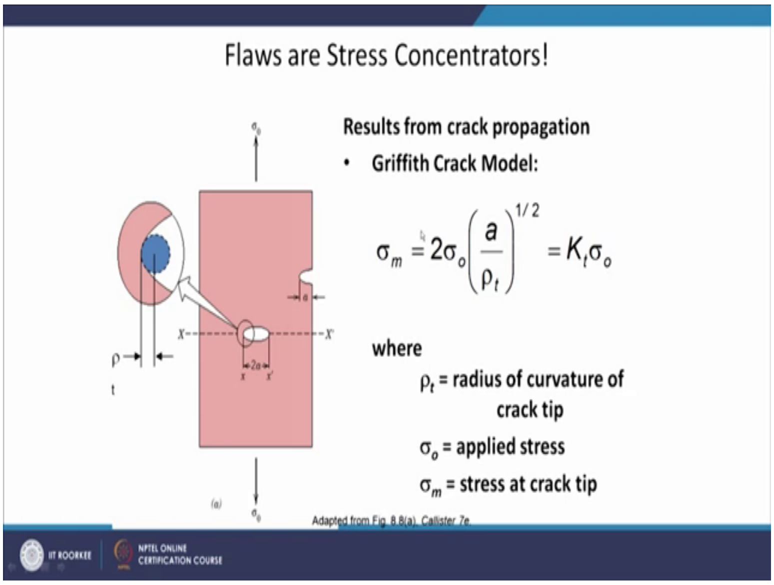

This is the kind of equation which has been shown to show that how the crack geometry affects the how does the crack geometry affects the stress concentration. So, the mac like say this is the crack which is present at the surface and a say crack can be present in the inside of the component.

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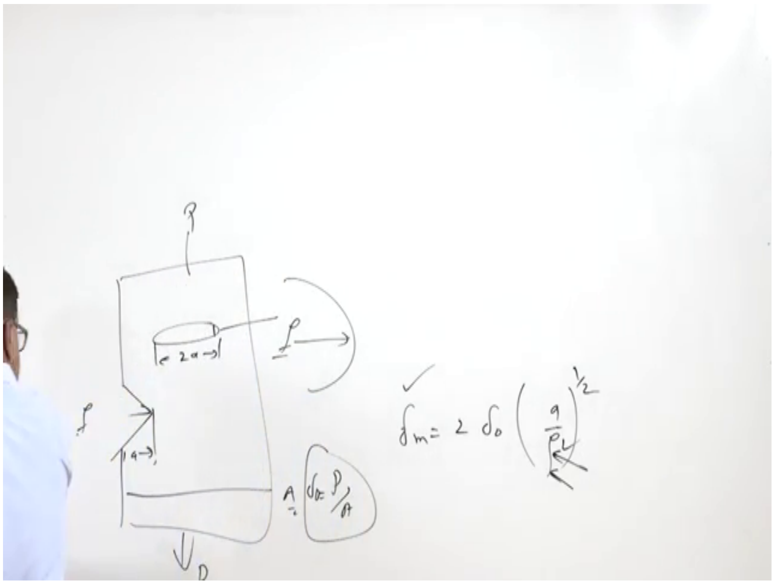

So, if like say this is the crack length to a, for the internal crack and A is the crack length for open crack. So, half crack length is taken for the internal cracks and a like say if enlarged view if you see the crack tip radius is the rho and similarly here the crack tip radius is rho. So, if the this data is available under the given load conditions and for a given cross sectional area A. P by A will be giving us the sigma naught that is the nominal stress. So, due to the presence of the these discontinuities the maximum stress which will be generated near these a stress radius that will be the tries of sigma naught a by rho.

So, a is the crack length and this is a square root. So, finer will be the crack size greater will be the maximum stress near the notch. So, it is always a good in case of the ductile material systems because of the blunting of the crack tip ray tip crack tip radius increases and which in turn reduces the maximum stresses which will be generated near the tip of a crack, but in case of the brittle materials it is not so, common to have the plastic deformation and blunting of the crack tip.

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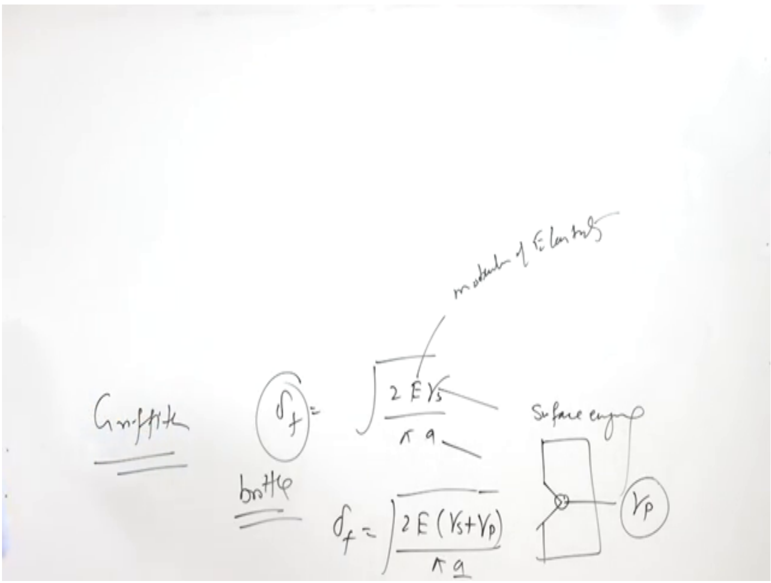

So, some of the theories have been proposed to explain and the fracture in case of the brittle materials. The Griffith is the one theory Griffith theory of the brittle failures is one of them wherein it determines the stress required to cause the brittle fracture in case of the brittle material is given with the help of this equation divided by pi c or pi a right pi a, a is the half crack length for internal cracks and a is the crack length for the open crack and this gamma is the surface energy and e is the modulus of elasticity.

So, from this what we can determine? If we have these values of the material we can determine the kind of the fracture stresses for the brittle materials. We know that most of the real crystalline materials they will be showing some kind of the plasticity at the crack tip. So, there is always possibility of the occurrence of the plastic deformation at the tip of crack. So, if some energy is required for the deformation of the for causing the plastic deformation at the crack tip and that is also considered.

So, in that case this equation is simply modified in view of the consideration of the some localized plastic deformation at the crack tip. So, in that case this equation is modified with a gamma as actually this is surface energy required for creation of the surface plus gamma p which is the like energy required for the plastic deformation divided by pi a, a is the same half crack length for internal cracks and crack length for open for surface cracks.

So, this is this is the condition for the brittle material. So, what it shows that if a material is extremely brittle then using the crack size a modulus of elasticity and the surface energy required for a creation of the crack, of tends to the gamma s or energy required for plastic deformation, we can determine the fracture stresses. So, this can be used for analysis purpose especially in case of the very brittle a material systems, this is what I have already talked when the material behaves like a brittle material then the crack tip remains sharp.

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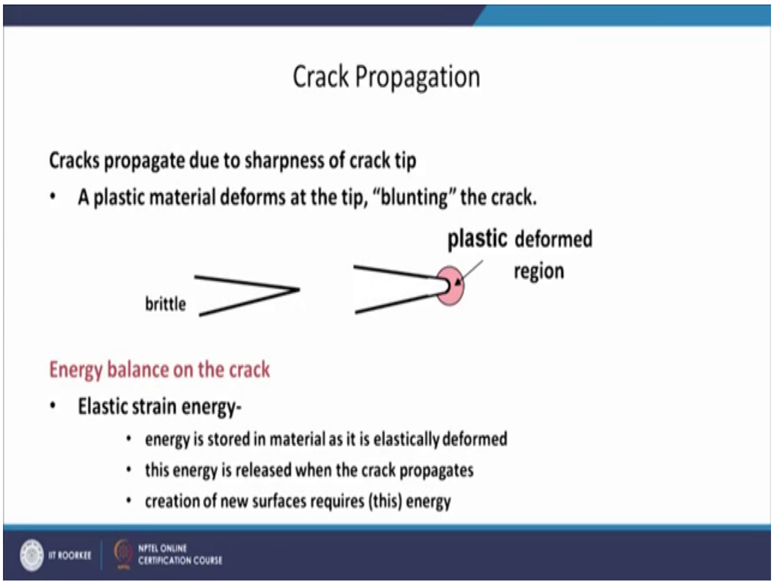

Because the blunting is a does not take place in this case due to the lack of the plastic deformation while in case of blunt crack tip blunting takes place, in case of the ductile materials where a plastic deformation is possible.

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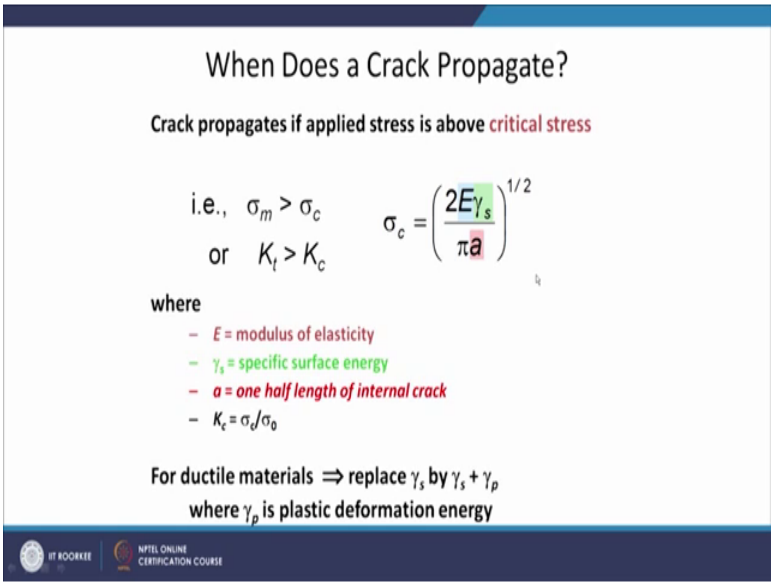

This is what I have just explained with regard to the Griffith theory on brittle fractures, the it can be used in like the sigma is the kind of fracture stresses square root of twice E gamma s divided by pi a. When it is to be applied for the ductile material where some kind of the plastic deformation at the crack tip can take place. So, the gamma s plus gamma p is to be used where gamma p is the plastic deformation energy.

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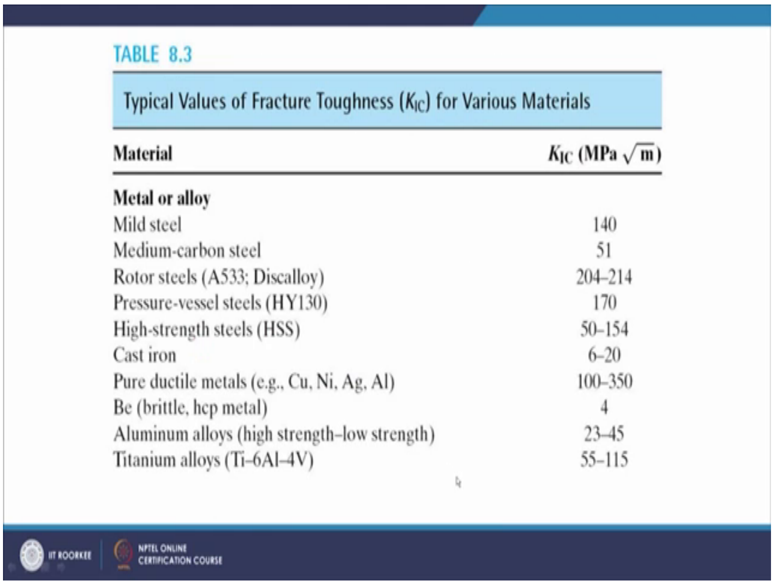

TABLE 8.3

Typical Values of Fracture Toughness (K_{IC}) for Various Materials

Material	K_{IC} (MPa $\sqrt{m}$)
Metal or alloy	
Mild steel	140
Medium-carbon steel	51
Rotor steels (A533; Discalloy)	204–214
Pressure-vessel steels (HY130)	170
High-strength steels (HSS)	50–154
Cast iron	6–20
Pure ductile metals (e.g., Cu, Ni, Ag, Al)	100–350
Be (brittle, hcp metal)	4
Aluminum alloys (high strength–low strength)	23–45
Titanium alloys (Ti–6Al–4V)	55–115

This table shows the value of the fracture toughness of the different materials.

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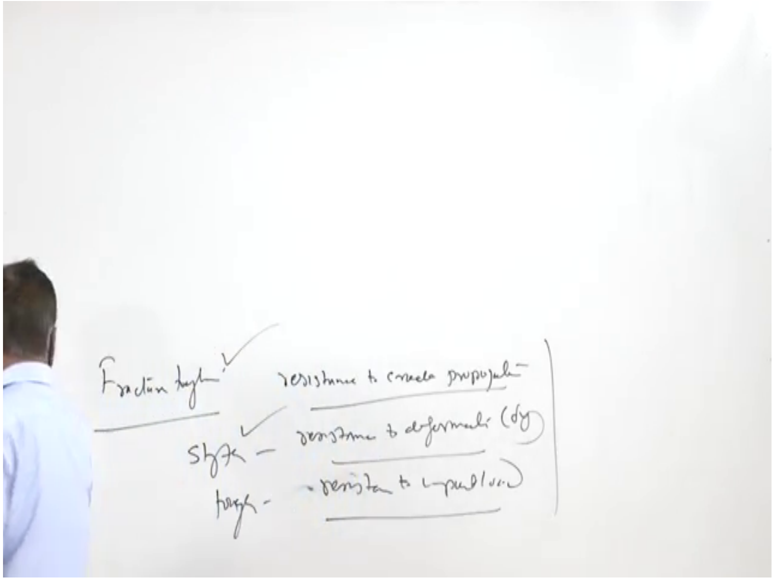

So, before talking about this let me talk about what the fracture toughness is fracture toughness. Fracture toughness is a it is a different from the in impact toughness which is obtained from the sharpie and io test, it shows the resistance to the crack propagation. While the common strength of the material what it shows the resistance to the deformation or the plastic deformation, which is basically sigma y. If we talk of the toughness, toughness shows the energy you can say the resistance to the impact loading.

So, these are the three different things strength indicates the resistance to deformation fracture toughness shows the resistance to the crack propagation and a toughness shows the resistance to the impact loading.

Now, to since in presence of the discontinuities if you want to study the behavior of the material under the given service conditions, it is important to see the fracture toughness of the material. So, depending upon the kind of the material, the different fracture toughness parameters have been established one is the k, which shows the stress intensity factor is one of the most commonly used parameter.

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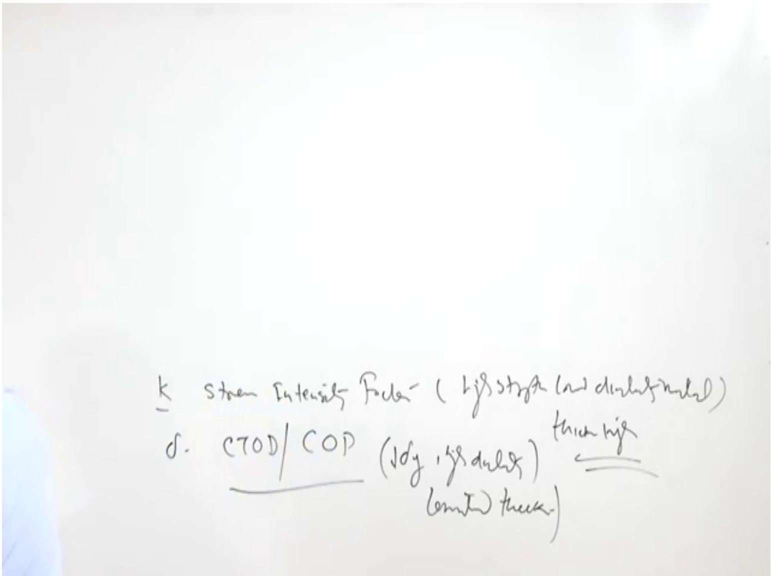

The second is the delta which is known as CT OD or the Crack Tip Opening Displacement or crack opening displacement. This is mostly used for a high strength and low ductility metals especially, when the thickness is high thickness is high and this is a used for the like low strength and high ductility metals and limited thickness conditions exist. So, here basically the a lot of deformation in the material takes place material tends to behave like a ductile material.

So, even in that case if you have to see the resistance to the crack propagation, then the crack tip opening displacement is obtained and otherwise the crack the stress intensity factor which shows the distribution of the stresses ahead of the crack tip is obtained say this is the crack tip.

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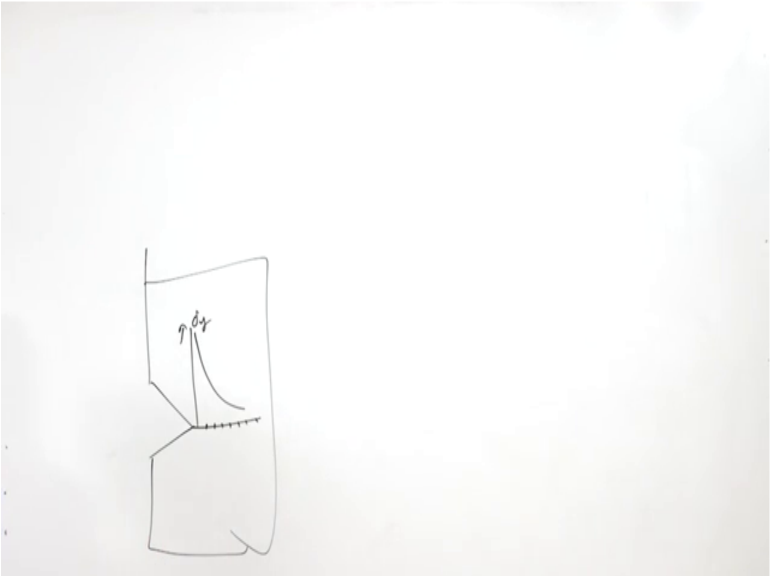

And if we have to determine the stress intensity factor then the distribution of the stresses ahead of the crack tip is obtained which normally becomes a like this just at the crack tip it is too high and as we move away from the crack tip especially ahead of in the direction ahead of the crack tip this distribution comes out to be like this which is the sigma y value.

So, stress intensity factor is the factor, which shows the distribution of the stresses at near the crack tip zone. Now, crack the fracture toughness basically fracture toughness is a material property.

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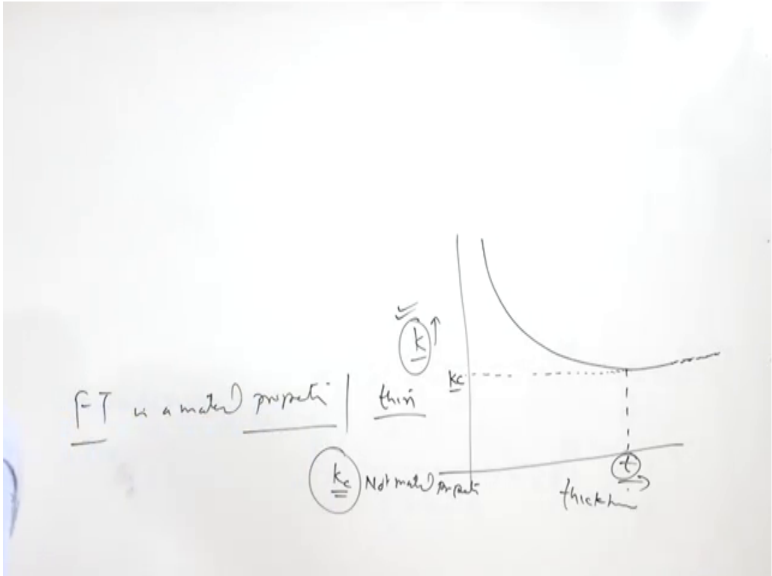

Initially it if we initially if we see if we take very thin sections, then we will find the resistance the fracture toughness of the material is high, but thereafter it becomes constant; So, the K that is the stress intensity factor of the fracture toughness of the material as a function of the thickness.

If we try to see this then what we will notice that a for low thickness fracture toughness is right then it tends to become constant. So, what it will suggest that, when the thickness is low the toughness is high. So, this portion of the fracture toughness indicating by the k or the k c this will not be the this is not of material property because it is a function of the thickness. But of course, when for larger thicknesses when its value becomes constant and then it can be used for the design purpose.

So, this value is obtained. So, this value is normally obtained. So, this value of the thickness becomes the critical parameter to find out whether the material being tested using given thickness sample, will be giving the a critical stress intensity factor or it will be giving just the a stress intensity factor or the fracture, but it will not be the fracture toughness of the of that particular material. So, the k c if you see the for the given thickness parameter becomes important to be determined for obtaining the value of the k c.

So, this value becomes the critical value and it will be acting as a it will be used as a fracture toughness of the material. So, how to measure the fracture toughness of the material that is altogether extensive procedure is there, for determining the value of the fracture toughness of the material in terms of the k c or the CTOD value or Crack Tip Opening Displacement, but how to how to use it different materials offer the different fracture toughness values.

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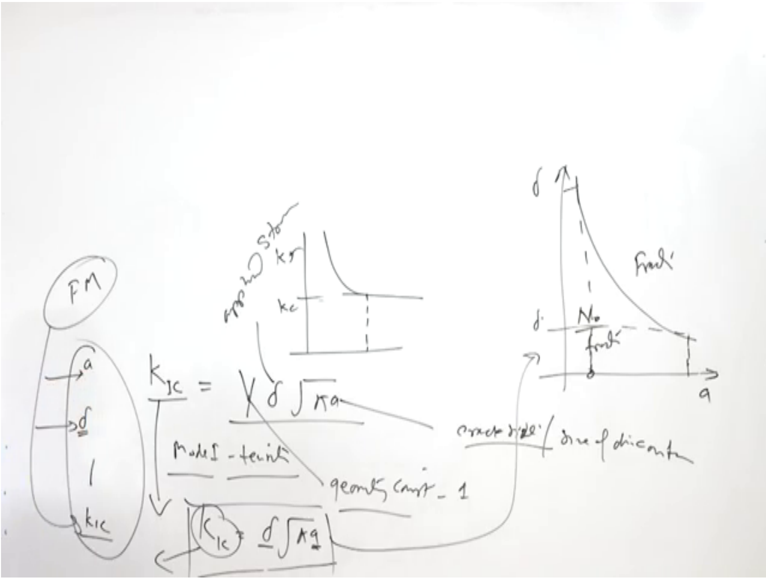

So, stress intensity factor like say this is the material property, one indicates that the fracture toughness has been measured under the mod 1 loading that is the tensile mod and this is now independent of the thickness.

So, this value is the k c else it is k. And this is means the test has been conducted using the thickness parameters test has been conducted using the thickness which is satisfying the requirement for the fracture toughness test. So, this if we know this is the material property and if we know that then it can be related with the particular equation which is a is this one this y into sigma root pi a.

Now, y is the geometry constant which is basically for very a wide and thick plates it is taken as one sigma is the applied stress it is the normal applied stress or it can be designed stress also and a is the crack size or the size of the or size of discontinuity.

So, under the simplified conditions K 1 c which is a material property becomes equal to the sigma pi a. So, now, these are this is the equation which is of our use and using this what we find? Since this is the material K 1 c is the material property. So, if we put the a in the y axis and sigma in the a in the x axis and sigma in the y axis and you find a plot of this kind, which shows that in this band there would not be any fracture and here this is the fracture zone. So, for different combinations we will see that when the sigma is high, the crack size tolerable crack size is this much beyond that fracture will occur and when the crack size is more or discontinuity size is more this is the maximum sigma it can handle.

So, because this K 1 c is the combination of the sigma and the pi a and so, any combination of the sigma and pi a can be used to see that its value is equal to the material property. So, if a higher is the applied stress then low crack size it can tolerate a low size of discontinuity it can tolerate.

Since, we have the fracture toughness or K 1 c which is specific to the material then using this value we can definitely find out that under the given applied load conditions whether in presence of the crack or discontinuity of the given size a can lead to the crack can lead to the fracture or not.

Once the combination of the sigma and a reaches to the particular value which is equal to the equal to or greater than the fracture toughness of the material in terms of K 1 c, then it will be leading to this certain fracture; So, what this table shows in like the different metals have the different fracture toughness values like mild steel has got 140 megapascals under root m while for other metals this value will be changing for beryllium, it is very low and this these values are also sensitive to the environmental conditions this value is given for the normal ambient condition.

But if we expose the metal in the as particular kind of environment for which the metal is sensitive, then there can be significant reduction in the K 1 c values and this reduction can be like 10 to 20 times of the normal fracture toughness of the materials. So, if we know the fracture toughness of the material then using this kind of analysis it will be possible to using this kind of analysis, it will be it will be possible to see whether under given applied stress conditions whether for a given crack size fracture can occur or not.

Definitely if the material is fixed; So, the K 1 c value will be knowing, we know the design stresses or the stresses which were for which component was subjected and from NDT and macroscopy we know the size of this is a discontinuity. So, use using these three basically we can we can establish if the if the if the discontinuity has a really led to the failure of the component or not. So, basically this is the fracture mechanics which relates in the material properties, applied stress and the discontinuities present in the component.

Now, I shall summarize this presentation here. In this presentation basically I have talked about that how the material behavior changes from ductile to brittle and a in which way the material property like fracture toughness can be used to find out whether the discontinuities have played any role in fracture of the component under the given stress conditions or not.

Thank you for your attention.