Dynamic Behaviour of Materials
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Lecture - 45
Dynamic Fracture 2

Hello everyone. So, we have been discussing about dynamic fracture. So, this is the last chapter, so will be continuing this discussion today. So, what we discussed earlier is the fundamental of fracture mechanics. So, we will continue these discussions for few slides and then you know we will discuss about little bit of dynamic fracture. However, the rigorous treatment of dynamic fracture we will be avoiding.

And if you are interested, you can go through some other books or at least in the Marc Meyers book where there are some treatments, simple treatments are available and we are even avoiding those treatments as well and for complex problems, you can refer L. B. Freund's dynamic fracture mechanics book.

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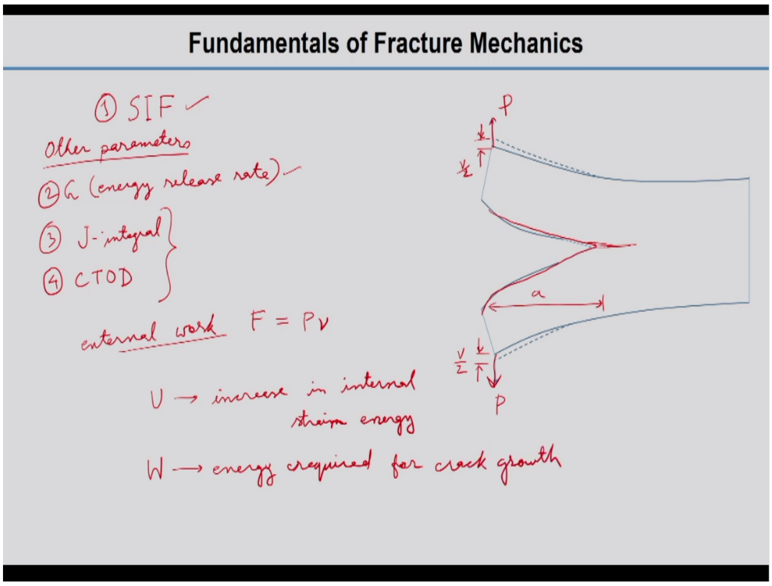

Fundamentals of Fracture Mechanics

① SIF ✓

Other parameters

② G (energy release rate) ✓

③ J-integral

④ CTOD

external work $F = Pv$

$U \rightarrow$ increase in internal strain energy

$W \rightarrow$ energy required for crack growth

So, what we learnt earlier classes, in the last class is stress intensity factor. So, stress intensity factor that is one parameter, and the other parameters are like energy release rate G which is we call energy release rate and so if this is the number 1, number 2 is G and then number 3 maybe we can have J-integral and then number 4 is crack-tip opening displacement. We are not going to discuss about these parameters.

So, we have already little bit discussed about stress intensity factor and we will discuss little bit of the energy release rate. So, if you can see that this is a crack and the crack is opening up with the help of this load P, the load is P and the crack is opening up this area of the crack sorry the length of the crack is a, small a. The displacement here we can take it as small v by 2 in this direction and small v by 2 in the other direction.

So, total displacement is small v by 2 on bottom and v by 2 on the top. So, the external work done is, external work done by the force, the PR can cause surface traction. F is equal to P multiplied by small v that is displacement and during this external work when it was done on the system, so there will be an increase in the internal strain energy that is U and then this is because an internal strain energy increase, increase in internal strain energy U.

And if the crack extend that means the crack if it propagates, so what will happen is the energy will be required. So, that energy required is W, so energy required for crack growth.

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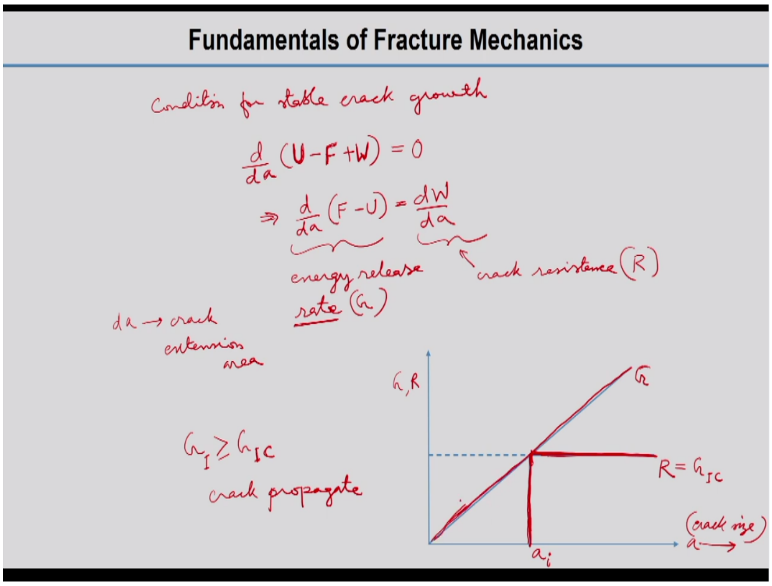

Fundamentals of Fracture Mechanics

Condition for stable crack growth

$$\frac{d}{da}(U-F+W)=0$$

$$\Rightarrow \underbrace{\frac{d}{da}(F-U)}_{\text{energy release rate } (G)} = \underbrace{\frac{dW}{da}}_{\nwarrow \text{ crack resistance } (R)}$$

$da \rightarrow$ crack extension area

$G_I \geq G_{IC}$

crack propagate

So, I am not going into details of it but you can refer to any fracture mechanics book like as I told professor Prashant Kumar's book is also already concise and you can go through other books like Anderson, professor Anderson and professor D. Broek book. So, will just summarize here, so this is condition for stable crack growth is derivative of this term U – F + W with respect to da, so with respect to it should be equal to 0.

So, this means as I told you this U is the increase in internal energy and which is the opposite of the work done by the forces that is F and plus the energy required for the crack growth. So, the external work done by the force P that means F needs to be you know that should contribute to the increase in internal energy and the energy required for the crack growth. So, ultimately this will give you; if you rearrange this will give you expression like this.

And here the left-hand side is called as energy release rate that is G that is another crack fracture mechanics parameter. So, these parameters will tell you whether the crack will grow or not and this right-hand side is known as crack resistance. So, here the crack resistance is generally denoted by R. So, here you should understand that this rate does not mean you know derivative with respect to time.

So, it is with respect to the area actually that means the crack extension area. So, in this case, yeah this a should denote that crack extension area, da is the crack extension area. However, in the earlier figure we have wrote a as the crack length, a is the crack length but you should not be confused with that. So, this da is, you know crack extension area. So, if we draw this curve for G and R, so it can be plotted like this.

This with respect to if we keep a in the horizontal axis that is the crack size, this is the crack size okay. The crack size if you plot it, so this straight line denotes G which have a linear relation with crack size and this is for R, this is mostly we are talking about a less ductile or brittle material. So, the R takes a shape like this and this R is equal to the critical energy release rate, so then the crack will propagate.

If G actually G is greater than G IC or I should write I, this is, this belongs to mode 1 crack. So, if it is greater than or equal to G IC, then the crack will propagate and R is the crack resistance as you know, so the energy release rate if it is equal to or greater than crack resistance, then the crack will grow. So, crack will grow from this point, we should write let us say ai, so that is the critical crack size. So, critical crack size above which the crack will grow.

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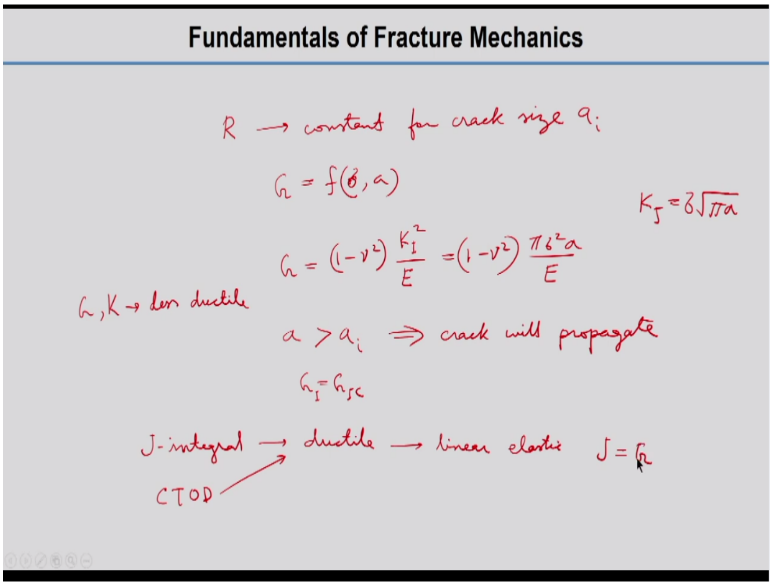

Fundamentals of Fracture Mechanics

R → constant for crack size a_i

$G = f(\sigma, a)$

$K_I = \sigma\sqrt{\pi a}$

$G = (1-\nu^2)\frac{K_I^2}{E} = (1-\nu^2)\frac{\pi\sigma^2 a}{E}$

G, K → less ductile

$a > a_i \Rightarrow$ crack will propagate

$G_I = G_{IC}$

J-integral → ductile → linear elastic $J = G$

CTOD

So, this R is generally a constant for crack size AI, constant for a particular crack size okay let us say AI in this case and however the G will be a function of sigma and a and the G can be expressed as 1 - nu square which is Poisson's ratio KI square by E and as you know KI is equal to the stress intensity factor sigma pi a. So, what we can do is we can write in terms of that and we can find the final expression is like this.

So, this is the expression for energy release rate and as I told already that if the crack size a is greater than AI, then the crack will continue to grow, crack will propagate okay and that means our G = G IC or we can call GI = G IC and then another parameter as I discussed is J-integral. J-integral generally is used for ductile material. So, either G and K are used for less ductile material or brittle material and for J-integral and crack-tip opening displacement both are used for ductile material and they can be used for other less ductile as well.

So, for J-integral if it is a linear elastic case, so for a linear elastic case, J-integral can be approximated as J = G.

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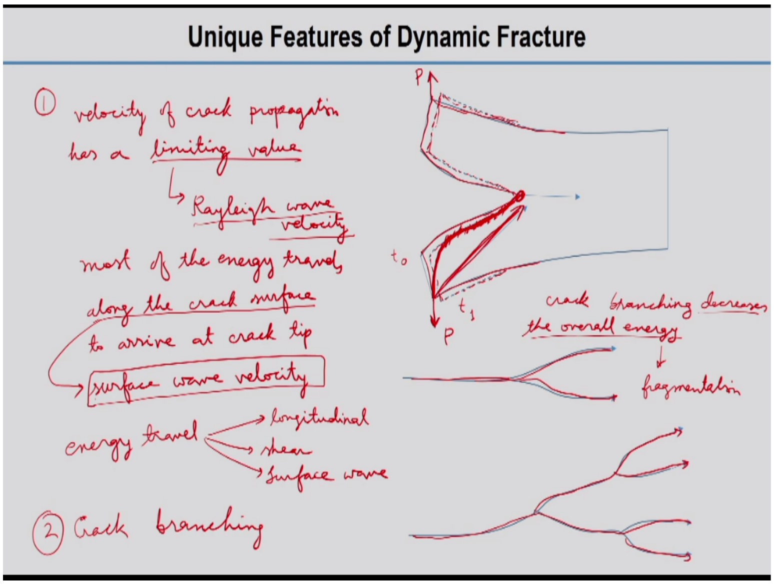

Unique Features of Dynamic Fracture

① velocity of crack propagation has a limiting value
↳ Rayleigh wave velocity

most of the energy travels along the crack surface to arrive at crack tip
→ surface wave velocity

energy travel → longitudinal
→ shear
→ surface wave

② Crack branching

crack branching decreases the overall energy
↓
fragmentation

We will now talk about some unique features of dynamic fracture. We know that some of the features of dynamic fracture is peculiar. So, it is very different in a quasi-static fracture. So, you will discuss that now. So, in this case, so we have the similar diagram what we have drawn earlier. So, we have the force P or you can call the surface traction that is trying to you know pull this track apart, open up this crack.

So, what is happening here is so this is the initial position, this is the crack surface initial position okay and this is let us say at time equal to t0. If we talk about time equal to t1, this dotted line can give you the configuration for time equal to t1. That means the crack is opening up, crack is opening up. So, now the first feature of dynamic fracture is that the velocity of crack propagation has a limiting value.

That means the velocity has a limiting value. So, that limiting value is nothing but the Rayleigh wave speed, Rayleigh wave velocity okay. So, why it is the Rayleigh wave velocity, will try to explain it. So, the most of the energy that arrive at the crack-tip, so because energy need to be transferred to the crack-tip. There are 2 ways to go let us say directly it can go this way, this is one way and there is another way it can go through this.

And then it can go travel along the surface of the crack, along the surface of the crack. So, this way is most favorable the along the surface of the crack. So, most of the energy travels you know along the crack surface to arrive at crack-tip because we know that energy is required at the crack-tip to grow. So, what happens now? So, as it is traveling along the crack surface, so that means that is it should be surface wave velocity.

It cannot cross the surface wave velocity, so as you can, again I am repeating it because if you are little confused about it, so what we need to have is that the energy should be transferred, energy should be travel to the crack-tip and this energy travel can be by stress waves and stress wave can be as you know longitudinal stress wave or let us say shear stress wave and then surface wave.

So, these are the stress waves. So, as this path is preferred, this path is preferred that is along the surface, so that means the energy will transfer through the surface, along the surface and that can have a velocity which is limited by surface wave velocity, it cannot exceed the surface wave velocity or Rayleigh wave velocity. So, that is why the crack propagation also is limited by the same velocity.

Because energy if cannot transfer faster than that and then crack also cannot transfer faster than that and the second unique feature is we can see that the second one is we have crack branching. So, branching you can see that this is the crack and it branches out like this and then finally even one crack can branches out to many cracks and then that way it will lead to fragmentation of the material.

So, what happened is the crack branching or I would write crack here decreases the overall energy and as you know if it is quasi-static fracture, there will be only probably one single crack and that will result in 2 parts of the material, the crack will divide the material into 2 parts but in this case what happened is that the crack will branch and then this crack branching will decrease the overall energy.

Probably, that will decrease the crack speed as well and this branching will lead to fragmentation that is a peculiarity or unique feature of dynamic structure that it will undergo the fragmentation due to crack bifurcation or crack branching.

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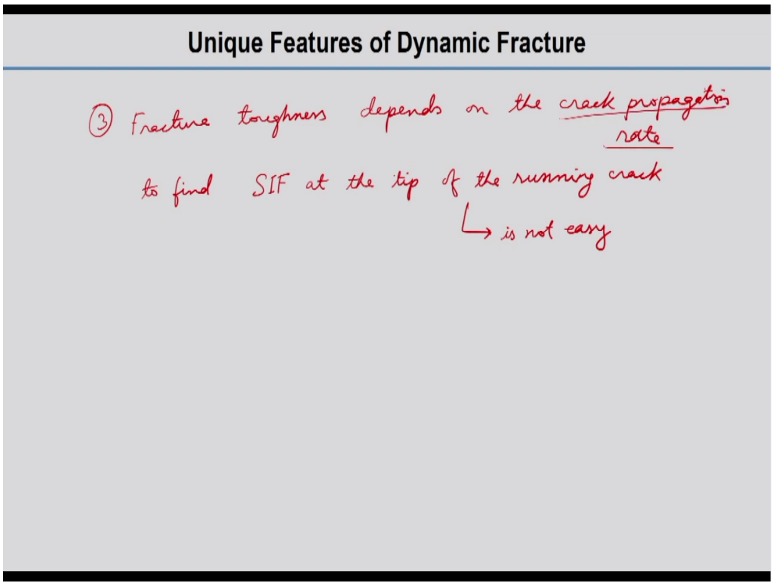

Unique Features of Dynamic Fracture

③ Fracture toughness depends on the crack propagation rate

to find SIF at the tip of the running crack

$\hookrightarrow$ is not easy

And then, so the third unique features of dynamic fracture is the fracture toughness, it usually depends on the rate of crack propagation, crack propagation rate. So, it is not very easy to you know establish or predict the stress intensity factor at the crack-tip like the quasi-static case. So, stress intensity factor at the tip of the running crack you know so is not easy to find the stress intensity factor.

It is not easy and as you know in the quasi-static condition, it is very straight forward but in this case, it is not straightforward and the fracture toughness will depend on how fast the crack propagation is happening.

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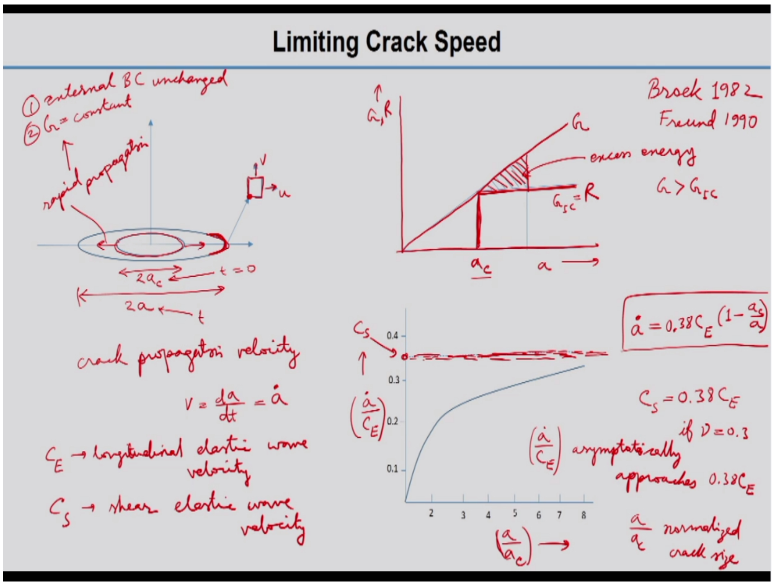

Limiting Crack Speed

① external BC unchanged

② $G = $ constant

crack propagation velocity

$V = \frac{da}{dt} = \dot{a}$

$C_E \rightarrow$ longitudinal elastic wave velocity

$C_S \rightarrow$ shear elastic wave velocity

Broek 1982

Freund 1990

excess energy

$G > G_{Ic}$

$$\boxed{\dot{a} = 0.38 C_E \left(1 - \frac{a_c}{a}\right)}$$

$C_S = 0.38 C_E$ if $\nu = 0.3$

$\left(\frac{\dot{a}}{C_E}\right)$ asymptotically approaches $0.38 C_E$

$\frac{a}{a_c}$ normalized crack size

So, now we will talk about little bit of this limiting cracks field as you have already discussed that the crack speed is limited and if we assume a crack with let us say with 2ac a crack length and then this let us say crack propagate it to a length 2a and this as we know this propagation will be a repeat propagation of crack and these repeat propagation of crack because of this repeat propagation.

So, we can have some assumptions. So, one assumption is maybe external boundary conditions. I will write BC for boundary conditions, unchanged during this process because it is a very rapid process and number 2 maybe we can assume that G the energy release rate is constant and let us say this happened at time T = 0 and this crack length, this time t, at time t.

So, also so the displacement if you see at a point close to the crack-tip, if you see the displacement let us say this is U and V, the displacement generated by the propagating crack because you know the displacement or stress field will be around this crack-tip you know or vicinity of the crack. So, these are the let us say stress field or sorry the displacement field and this crack propagation velocity, crack propagation velocity we would write as da by dt and then we write it as a dot.

So, what is happening here is as you have seen this diagram earlier also that this is we are plotting Z, R in the vertical axis and this axis is a the crack length. So, you can see a critical crack length ac here after that the crack will grow because this is where this is the R when G IC = R here because when the energy release rate will be equal to the crack resistance. So, this part will show us the excess energy as the crack propagates dynamically.

Excess energy you know after this propagation, the propagation happens at ac at a critical length and after that this is the excess energy okay. So, it happens when G is equal to greater than sorry G equal to greater than the critical value of G IC. So, this is a plot just to show you the limiting character of this wave propagation. So, in the vertical axis it is a dot, the crack propagation velocity divided by the longitudinal elastic wave velocity.

So, here we should write CE as longitudinal elastic wave velocity and we will write one more CS is shear elastic wave velocity, shear elastic wave velocity. So, here this point is corresponding to CS. So, we will so now here in the x-axis it is a by ac that you can see what is ac is the critical length of the crack that is normalized, the crack length is now normalized. So, you can check the details of the derivation.

I am not going to show you the derivation but generally the crack propagation velocity a dot has a relation like 0.38 CE 1 – ac by a. So, here we showed a by ac and this is the inverse of it. So, a by ac is normalized the crack size, you can write it this way, normalized crack size. So, what this relation shows is that crack propagation velocity has a relation with the elastic longitudinal wave velocity.

And if from your earlier discussion of wave propagation CS is actually 0.38 times of CE if the Poisson's ratio nu is 0.3. So, from this relation, you can see that this a dot by CE will asymptotically approaches as a increases, asymptotically approaches this value, I mean that shear wave velocity line. This will asymptotically approaches to 0.38 times of CE. So, that is what we discussed earlier.

So, I think the details can be you can get it at in Broek 1982 book. So, that can be you can find it there and also more rigorous statement will be available in other books like that the L. B. Freund books, Freund I think it is 1990 almost probably.

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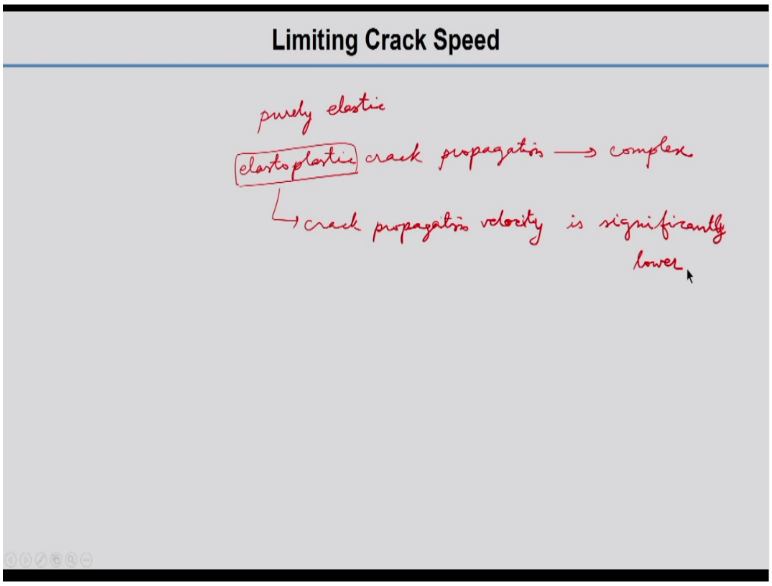

Limiting Crack Speed

purely elastic

elastoplastic crack propagation → complex

↳ crack propagation velocity is significantly lower

So, I am not going to discuss these more but what we have discussed is mostly we discussed about purely elastic cases, I mean in these derivations, it is pure elastic but if it is elasto-plastic, if we use elasto-plastic approaches of crack propagation, if we think that there is plastic deformation, then it will be more complex and then the additional energy spent for the plastic deformation also you know has to be incorporated into it.

So, even for like ceramic, we have got to know that there can be some process zones and that also process zones of micro cracks that also can complicate these calculations and so what happens is due to elasto-plastic zones that means the plastic behavior of the material around the cracks, so this crack propagation velocity is significantly lower, is lower in elasto-plastic case.

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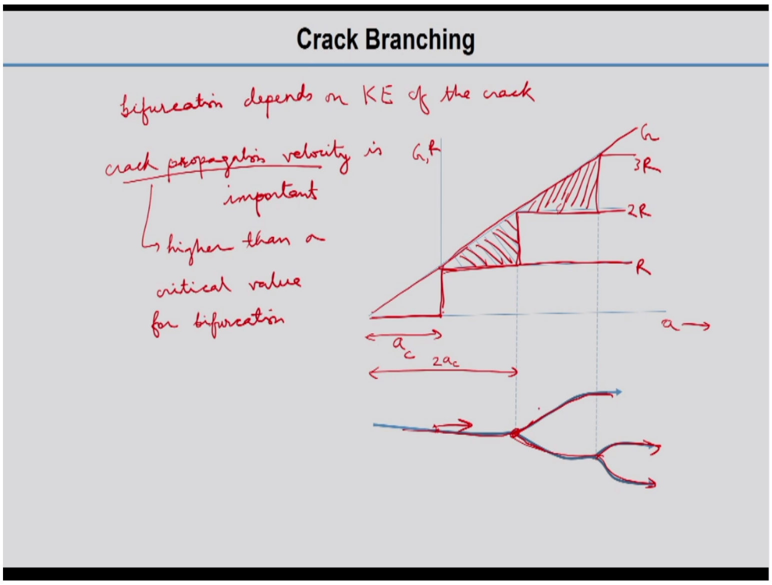

Crack Branching

bifurcation depends on KE of the crack

crack propagation velocity is important

↳ higher than a critical value for bifurcation

So, we will now talk about the crack branching. So, what happens in crack branching. The bifurcation of cracks from 1 crack to 2 cracks that is we call branching and then this bifurcation depends on the kinetic energy of the crack sorry bifurcation, so this bifurcation depends on kinetic energy of the crack okay. So, that means the crack propagation velocity is very important, velocity is important.

So, this velocity should be higher than a critical velocity. Critical value for bifurcation to happen, so what happen exactly in this case suppose if we plot G line, this will be assuming ac here and then this is a in the x-axis, G and R in the y-axis as you can see. So, this line is let us say for R. Then, we can draw some lines higher for R say 2R or 3R. So, what happens is, first let us say crack will grow.

This is the ac sorry this we should have written as a subscript c. So, this is the first crack length and then at this point let us say the crack grows at that point let say and then after that what happened, there will be another critical crack length let us say we write 2 ac. So, what happen is at that point, the excess energy is again you know sufficient for another crack growth, sorry another crack bifurcation.

And similarly again after this point, we have some more excess energy and that excess energy is sufficient enough to have another bifurcation. So, it goes like that okay.

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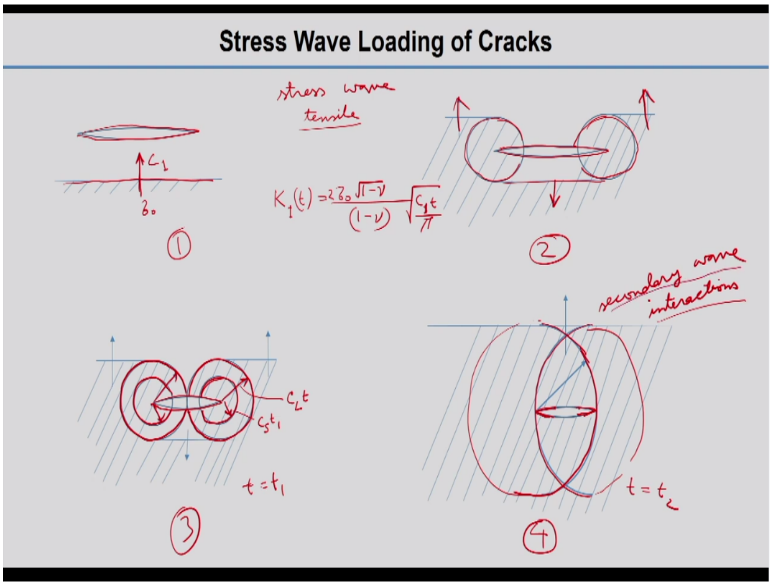

Stress Wave Loading of Cracks

We will talk about some stress wave loading now. So, whatever we have discussed in quasi-static cases or you know simple explanation of the dynamic fracture, what we used to show is we thought the loading is constant at the crack, as the crack propagation is happening loading is constant but in actual case there will be some you know wave, stress wave will propagate you know in the material and it can be you know tensile waves that help to you know open up the crack.

So, what we will see here is if you see some you know solutions, you will get that, that this sorry stress intensity factor for dynamic crack depends on these terms. So, I will just write it 1 – nu and C1 t by pi. So, I will write what these terms say. First, let me explain this. So, we have a crack here and then this is a stress wave, this is a stress wave traveling towards the crack.

So, for simplicity it is taken that the stress wave, the wave front is parallel to the crack face, this was just for you know simplicity and let us say the velocity of the stress wave is C1 and then what happened in that these crack surfaces cannot transmit the stress wave, the other portion the stress wave is moving towards this and then at this part this actually reflect back from the crack surface, so it will look like this.

But at the same time, there will be some stress wave from the crack-tip as well, so that we are showing in this other diagram. So, this is first case, this is second case, this is third case and this is the fourth step. So, what happened is we have this crack here and then there will be stresses longitudinal and shear waves radiates from this crack-tip. So, this is let us say this one is shear wave that is we can write as CS or we can write CS multiplied by the time which is let us say t = t1 here and t – t2 in this case.

And this is a longitudinal stress wave which will travel faster, which will that stress front will be away from I mean the crack-tip as compared to our shear wave front. That means this circle will be bigger, so this circle will tell you CL t that means longitudinal stress wave velocity is higher that is why the circle looks bigger than the shear wave velocity. So, similarly from the left end of the crack also you can get to you know these kind of circles just to show the stress wave front.

So, now in the last step, what will happen is from the left end of the crack, so whatever the stress wave was radiated, so that will form something like this and similarly under right end of the crack, so whatever stress wave radiated, it will form an envelope like this. So, this is actually the wave interaction from the left tip and the right tip. So, that is called secondary wave interaction, secondary wave interactions and these interactions create some fluctuations, we will see in the next slide.

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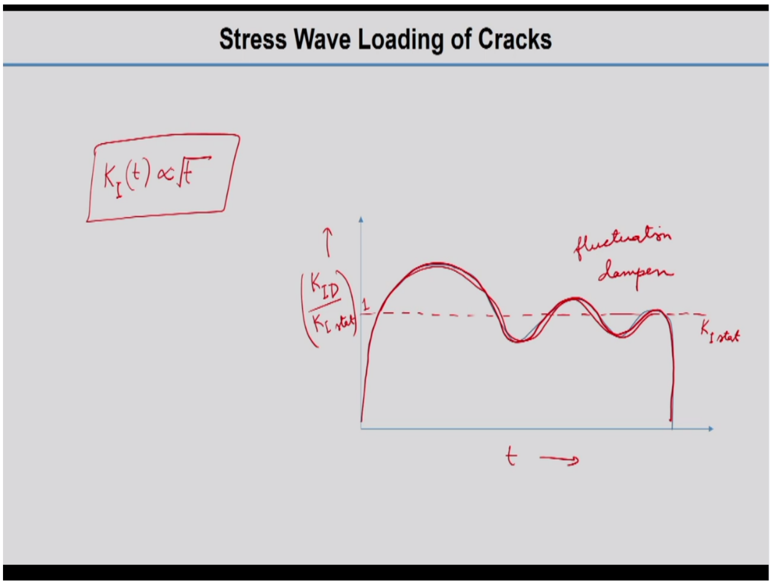

Stress Wave Loading of Cracks

So, these secondary fluctuations in the stress-strain sorry this plot K ID, fluctuations in K ID by actually KI static that means the stress intensity factor and with respect to time. So, these fluctuations, these fluctuations can be attributed to the secondary wave interaction. So, basically what happens here is due to d is expansion of in the step 3 you can see due to this expansion of the shear wave and the longitudinal wave, so the loading of the crack increases.

So, because of the stress waves generated from the crack-tip and whatever earlier expression, now you can understand here that sigma 0 is the stress wave and then these are the Poisson's ratio and C1 is the you know that wave velocity multiplied by the time and this pi and basically what happens in this relation if we write it somewhere else, so this basically that KI t. If we assume that other parameters are constant, this is a function of time and this is proportional to square root of t.

So, from the earlier expression you can tell that and there are other researchers who also got the same results and probably Freund's book or some other analysis if you check, so they also found that this intensity factor, the parameter depends on you know square root of time and also this is you can see that this is actually 1, this dashed line. So, that means this is intensity factor for the static case.

So, what you can see that these fluctuations will finally dampen, with time these fluctuations will dampen out and it will approach the static stress intensity factor. I mean assuming that we are talking about the stationery crack not a travelling crack.

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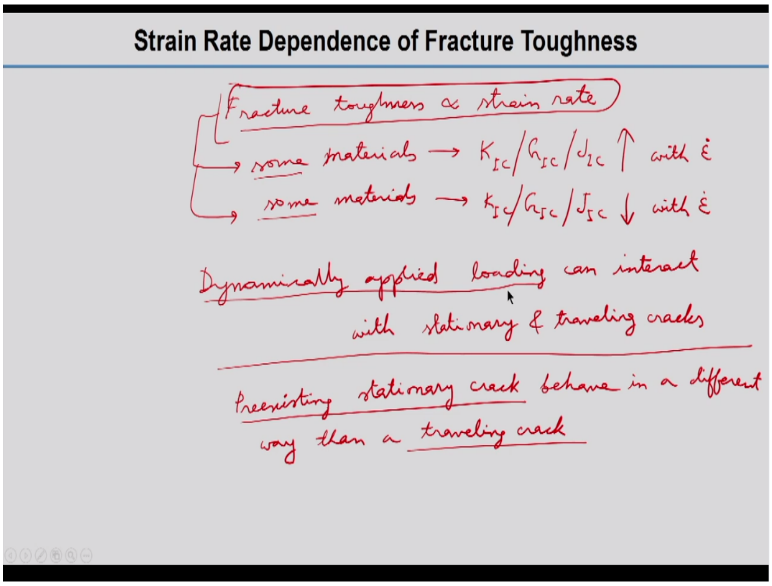

Strain Rate Dependence of Fracture Toughness

Fracture toughness ∝ strain rate

→ some materials → $K_{IC}/G_{IC}/J_{IC} \uparrow$ with $\dot{\varepsilon}$

→ some materials → $K_{IC}/G_{IC}/J_{IC} \downarrow$ with $\dot{\varepsilon}$

Dynamically applied loading can interact with stationary & traveling cracks

Preexisting stationary crack behave in a different way than a traveling crack

So, now we will talk about the fracture toughness. Fracture toughness is proportional to strain rate. So, whether this is true or not so this is complicated. That means for some materials, K

IC value or K IC or if you can call G IC or maybe you call it J IC. So, these values increases and for some materials, these values can even decrease. These parameters of that you know that measures the crack potency.

That means whether a crack can grow or not. So, these can decrease or increase with strain rate sorry I did not write it here, so with increase with strain rate. So, that means the fracture toughness is proportional to strain rate or not that we are not so sure. Some materials will show different ways, some materials will show in a different way and also this loading can you know dynamically applied loading can interact with a stationary and traveling cracks.

So, the loading will interact with cracks. If we talk about a stationary crack, that means a pre-existing stationary crack so behave in a different way than a crack that is already traveling at this maximum velocity, traveling crack. So, these things we need to keep in mind that pre-existing stationary crack and with a traveling crack with high velocity can be very different and also the dynamically applied loading.

The loading can interact as we have seen in the last slide that the stress waves they can interact with the crack-tip and you know that may change the crack propagation.

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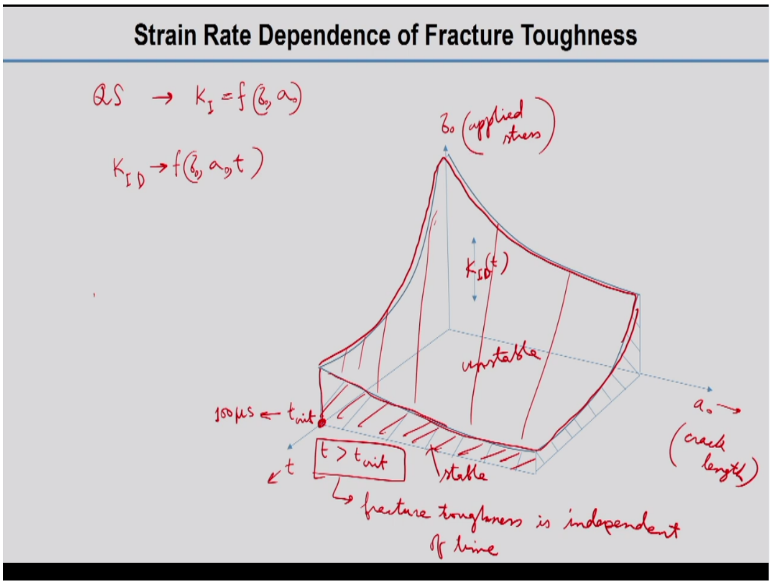

Strain Rate Dependence of Fracture Toughness

So, we will now see something, some plot on the strain rate dependence of fracture toughness. So, what this plot says is that this is a three-dimensional plot here time in this axis and this way is crack length a0 crack length and on the vertical axis it is sigma 0 which is the applied stress and this is the crack length, I would write here. So, what this surface means is this entire surface if you can see that surface means from here to here to here.

So, can give you some idea about K ID, so K ID which depends on time, so as you can see that for a static case, for a quasi-static case what happens is that we talked about that that your KI is a function of sigma and a but in this case K ID for dynamic case is you know we can see that it is a function of sigma a and time as well. So, if you see in this case, on this side that means when t is greater than t critical, let us say this point is time, critical time.

So, which is in let us say in the order of some microsecond, let us say t critical is something like you know 100 microseconds or something like that. So, if t is greater than t critical, then what happens is fracture toughness. Toughness is independent of time that means it is stable. That means this is stable if you take a higher time and the other side it will be unstable that means if the time is lower than t critical, this will be unstable.

So, that we should you know take into mind and by the way here we wrote sigma 0 we can write here sigma 0 and a0. So, because in this diagram we are showing sigma 0 as applied stress and a0 is the crack length.

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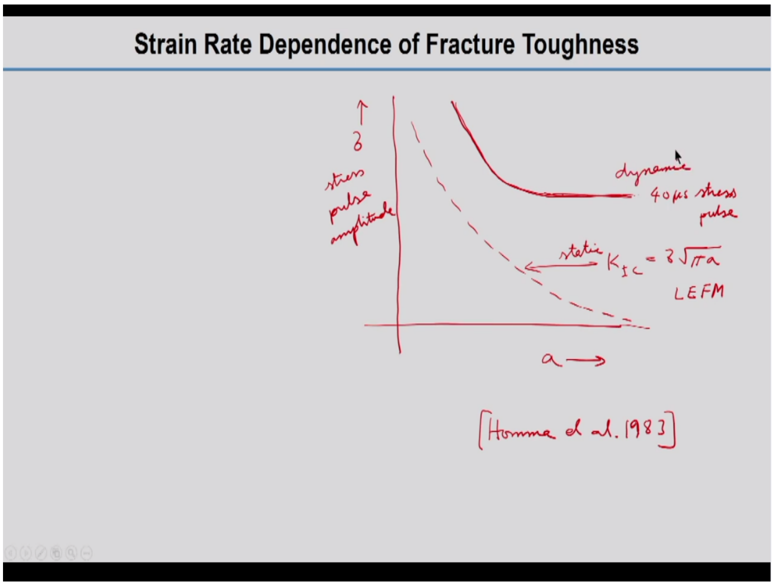

Strain Rate Dependence of Fracture Toughness

So, if you want to see some experimental results from the researchers, so if we see that area on the horizontal axis and sigma the applied stress on the y-axis, there is a stress pulse amplitude. So, whether I write stress pulse amplitude, so this is one of the research work by

Homma et al 1983. So, what it says is if you have a static, if you talk about the static crack, so this will go like this.

And then if you are talking about a dynamic crack, so if you are talking about dynamic, so it will have, so you know it trend something like this. So, this means the static crack is K IC corresponding to this curve is sigma pi a which is from the linear elastic fracture mechanics but the other experimental results plotting after the experimental results, this is the dynamic case that was with 40 microseconds stress pulse okay.

So, this is the dynamic case. So, we can see that there is significant difference between the static criteria. This is the static one and the dynamic the other one with 40 microsecond stress pulse.

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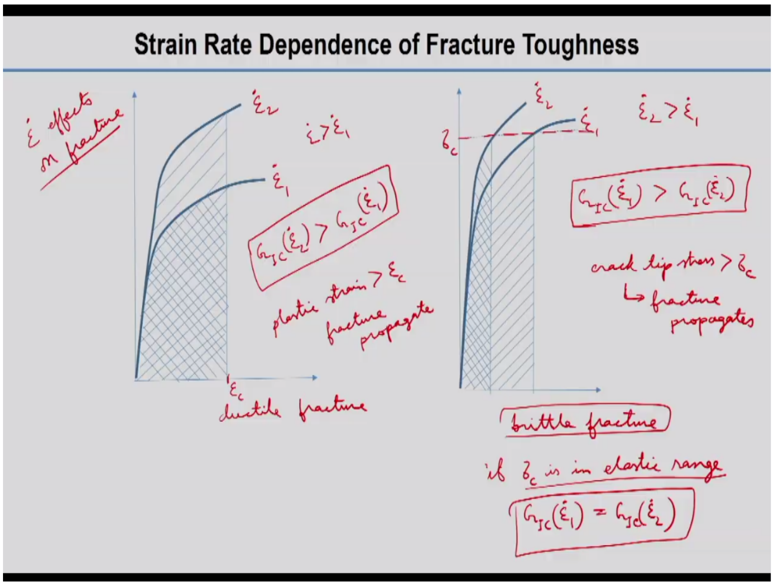

Strain Rate Dependence of Fracture Toughness

So, another aspect is if we talk about the strain rate effects, strain rate effects on fracture, if we talk about this, the first we will talk about the ductile fracture and will talk about then brittle fracture. So, if this is a strain rate epsilon dot 2 and this is epsilon dot 1 here epsilon dot 2 is greater than epsilon dot 1 that in the case of a ductile material so what happens is G IC is as you can see from the area, the area of G IC for epsilon dot 2 is higher than and the G IC of epsilon dot 1.

So, that means the energy related is higher and then higher toughness for higher strain rate but for in this case for brittle fracture, so what happened is, so this is epsilon dot 1, this is epsilon dot 2 and here is also epsilon dot 2 is greater than epsilon dot 1 but in this case, if you see G IC of epsilon dot 1 is greater, epsilon dot 2 to the opposite case of the other one.

So, also it is if you focus on these 2 curves, you can see that here for a ductile fracture what happened is the plastic strain should be more than the critical strain. So, in this case, plastic strain should be higher than the epsilon C, then fracture will you know propagate but in the case of brittle material, the criteria is different that is crack-tip stresses should be higher than sigma C.

What is sigma C here? Sigma C is the critical value of stress here. So, that is why that is the criteria for fracture propagation. So, that is why we can see that the lower strain rate has higher fracture toughness but if in the brittle fracture case if sigma C is in the elastic range only, elastic range only, that means it is a highly brittle, no plastic deformation that in this case, the areas will be almost same and that means G IC epsilon dot 1 will be equal to G IC epsilon dot 2 if the sigma C is in elastic range.

So, what we have learned here is that in a ductile fracture and brittle fracture they are very different in terms of the strain rate dependence or in terms of the strain rate effects. So, in ductile fracture higher strain rate has higher fracture toughness but for brittle fracture the opposite case or if it is highly brittle, then probably both the toughness will be probably the same.

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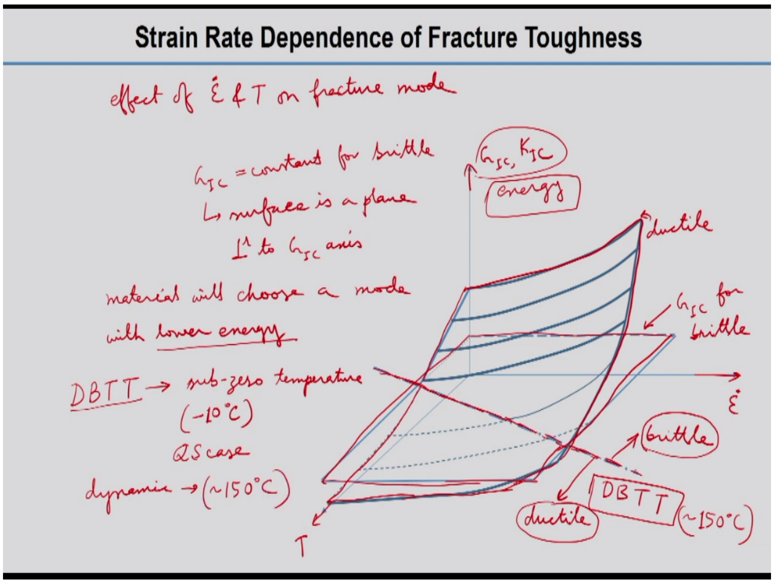

Strain Rate Dependence of Fracture Toughness

effect of $\dot{\varepsilon}$ & T on fracture mode

G_{IC} = constant for brittle

↳ surface is a plane

⊥r to G_{IC} axis

material will choose a mode with lower energy

DBTT → sub-zero temperature (−10°C)

QS case

dynamic → (~150°C)

So, we will talk about another aspect here. So, what is happening here is this plot is in this axis it is temperature and here in this axis it is strain rate and in this axis it is G IC or K IC the fracture toughness. So, here we want to know the effect of strain rate and temperature on fracture mode. What will be the fracture? Ductile or brittle? So, what is happening here is for a simplicity a plane is taken.

This plane, this is we are taking as G IC for brittle that means for simplicity we are saying that G IC value, G IC is constant for brittle material and that is why the surface is a plane you know perpendicular to G IC axis. This is basically as we can understand this is energy plot as you know the G IC and K IC, G IC is the energy release rate. So, what happens the system will, the material will choose a mode of fracture with lower energy.

So, there will be now we can draw a line that is called ductile to brittle transition temperature. So, what will happen, we can draw the other surface now which is you know the ductile one. Ductile one is little different than the brittle one. Ductile has that surface is with temperature, this will be different and if you see that these 2 surfaces will intersect at ductile to brittle transition temperature line.

And if you see that below this, this side brittle material will have less energy and if you see on the other side ductile material sorry ductile surface will have less energy. That means if the temperature let us say some material it is 150 degree Celsius also. So, if the temperature is lower than 150 degree Celsius, then brittle fracture will happen. If it is higher than 150 degree Celsius, the ductile fracture will happen.

Because that depends on the lower energy which surface will have lower energy. So, that is the case but as you know from your material basics, although we did not discuss the DBTT ductile to brittle transition temperature, for steel it can be very less let us say sub-zero I mean temperature, sub-zero means I am talking about degree Celsius. Let us say some - 10 degree or 20 degree or 40 degree even some steel can I think have even around zero degree Celsius ductile to brittle transition temperature.

That is why you can understand that at very low temperatures some fracture may happen in some steel structures like the case of ship failure, ships breaks into you know into pieces because of this ductile to brittle transition temperature but this is the case in quasi-static case, QS case but for dynamic this is the DBTT is very high and for some material it will be like 150 degree Celsius.

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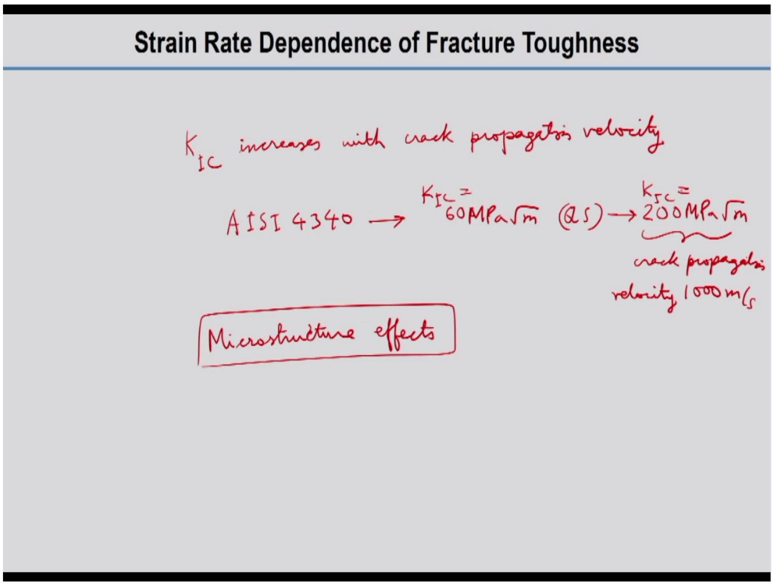

Strain Rate Dependence of Fracture Toughness

K_{IC} increases with crack propagation velocity

AISI 4340 → $K_{IC} = 60 MPa\sqrt{m}$ (QS) → $K_{IC} = \underbrace{200 MPa\sqrt{m}}_{\text{crack propagation velocity 1000 m/s}}$

Microstructure effects

And also we should understand that the K IC value increases at you know high crack propagation velocity with crack propagation velocity. For example, AISI 4340 steel, so from 60 megapascal square root meter, this is the quasi-static to increase to sorry I should write here increase to 200 megapascal square root meter. That is a dynamic case with a crack propagation velocity up 1000 meter per second.

So, if it is so high speed crack propagation, then that will be the toughness value, sorry this is K IC value, I should write here K IC equal to this, K IC equal to this. The K IC increases through a much higher value. We should understand here that the microstructure will affect. We will probably talk about that later. So, the microstructure effect, we need to take care of this but it is very difficult to incorporate these microstructural effects into some predictive models, mathematical models.

But still we should understand that the microstructural effects will be always present and I think in the book you can check how to determine these fracture toughness in the dynamic range. So, there are you can study in the Marc Meyers book itself. So, we are not discussing those into this course now. So, determination of dynamic fracture toughness that is may be important for some of you.

So, please refer to the textbook. So, we will now talk about spalling. So, we already have not talked about the spalling in earlier classes during our discussion in the shockwave.

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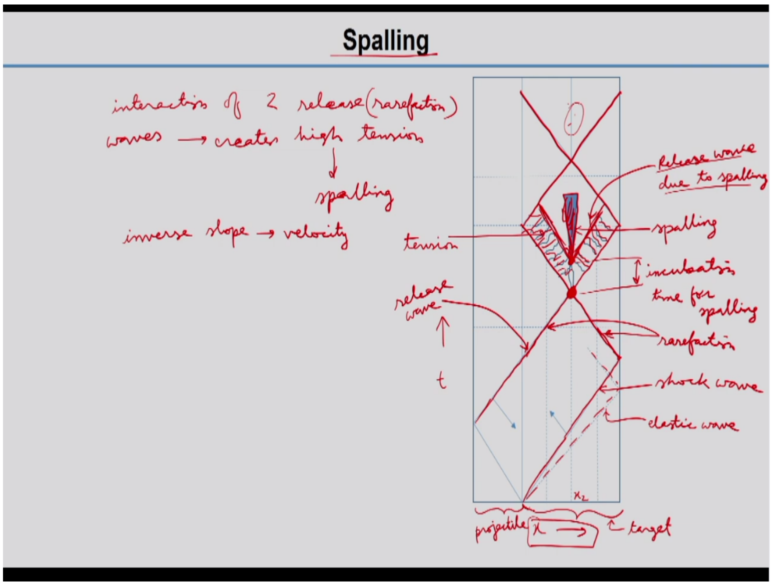

Spalling

interaction of 2 release (rarefaction) waves → creates high tension
↓
spalling

inverse slope → velocity

So, here in this case, I hope that this diagram you will understand because earlier we have discussed on that. The spalling is basically an interaction of 2 release waves or release means rarefaction waves that creates high tension; high means the tension should be sufficient enough for spalling. So, in this case, so what we are doing is this is a time displacement sorry time distance plot, x is the distance.

And here this portion shows the projectile that you can I hope you remember it from your earlier classes and this is the target. So, this portion is the target and so we will draw the elastic wave with this. This is written as elastic wave or we sometimes write as elastic precursor because this will move ahead of the shock wave probably and the shock wave looks something like this okay.

So, as you can understand, even earlier also we discussed that inverse slope here is the velocity because this is time under y-axis and x in this x horizontal axis. So, this inverse that means the elastic we will have higher velocity than the shock wave because the slope of the elastic wave is less. So, then this is the wave which is the release wave from you know rarefaction wave produced from the back surface of the projectile.

So, this way will go and you know move like this and then this will reflect back the shock wave, the primary shock wave will reflect back and will meet the release wave at this point and then it will move like this and then again reflect back and will move like this. So, it is something like this. Now, we come to this point where these 2 waves meet okay. So, let us say this is it can be at a distance x2 these wave will meet.

But immediately when they meet, there may not be a spalling, there is some time is needed that is called incubation time for spalling. So, after that time the spalling will start from here and this can be represented as spalling, so what happened this rarefaction both these waves are rarefaction wave as you know that this is also release wave. So, I should write release also here, release from the projectile back surface.

So, both of these wave actually are rarefaction because other also is reflected back from here and these two waves will produce a high tension at this point and then that will take some time to have a spalling and in this region what will happen is there will be more wave generated from the spall surfaces because of the spoiling there will be crack generated and these cracks will again release some wave. So, these release waves are due to spalling.

And this is actually spalling in this area. I hope this diagram is understandable because most of you already have watched the video when we did these types of you know time and distance plots. So, this portion the mostly the tensile portion, so here we should write these are the tension and then when these release wave due to spalling will occur that will reduce the stresses, tensile stresses.

So, after that tensile stresses will be less and then again there can be, it can be repeated in somewhere above. So, here it can be repeated. So, this spalling can be repeated. So, I should write this is release wave here. So, I hope this is understandable, you can please refer to the textbook and then if you have not watched the earlier lectures.

Or you can even read the shockwave chapters of Mark Meyer's book to understand these kind of diagrams like time distance diagram which the slope of these curves will denote the inverse of velocity. So, now we will discuss another thing.

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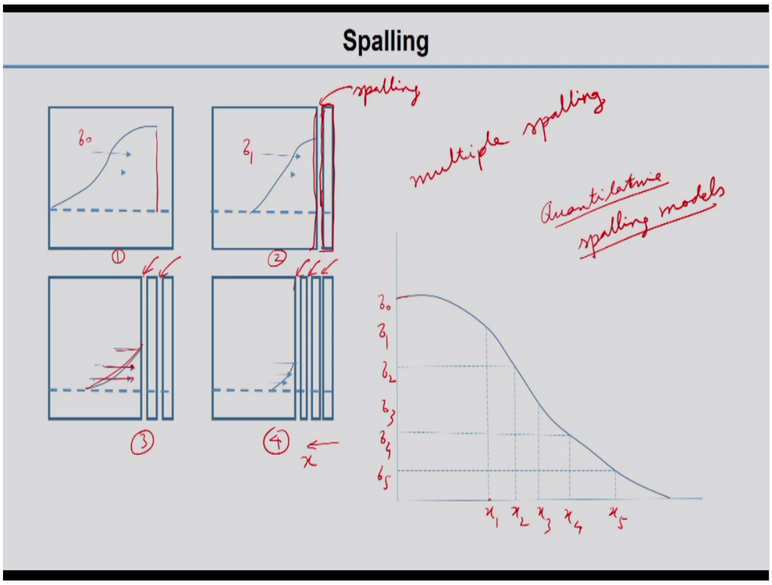

So, just to let you know that this spalling process, suppose here what is happening this is the case 1, this is case number 2, this is number 3, and this is number 4. So, the spalling happens at that point and this is at a high stress level sigma 0 and then probably stress will reduce after the spalling these areas spalling, you know this fracture happened and then this portion is come out, so this is spalling, first spalling.

And then there can be multiple spalling here. So, then stresses will be decrease or whatever the stresses and then there can be more spalling here, can happen. So, why because as you can understand that when your stresses are more I mean let us say at the distance x1, so you can have spalling and then stresses will reduce but this stresses will you know can have spalling at different distances.

So, that is we are talking about the stresses distance from the other direction. So, if you see in the previous diagram also, you can see that spalling can happen here and then it can be, even it can repeat these. The waves reflected from the surfaces can be again, you know again can meet here and then it can repeat itself you know after some time it can repeat. So, that way we can see that multiple spalling can happen, multiple spalling.

The process will repeat, so there are different models of quantitative models of spalling available, spalling models you can refer to Marc Meyers book or some other books and to know more about it. We are not going to discuss about anything else here on spalling. There are lot to discuss on microstructural effects but here we will just very briefly we will tell you what these microstructures can you know influence, how the microstructures can influence the fracture toughness or fracture behavior in dynamic fracture case.

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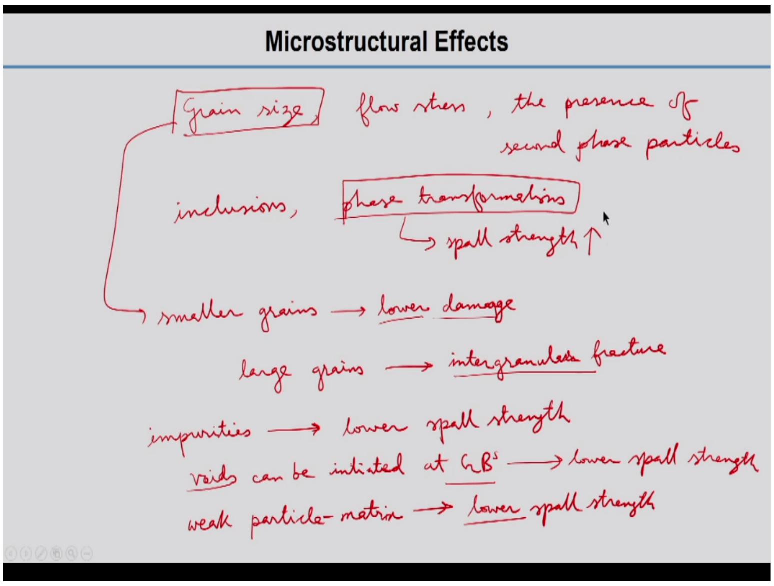

Microstructural Effects

Grain size, flow stress, the presence of second phase particles

inclusions, phase transformations

→ spall strength ↑

→ smaller grains → lower damage

large grains → intergranular fracture

impurities → lower spall strength

voids can be initiated at GB's → lower spall strength

weak particle-matrix → lower spall strength

So, microstructural is very important, the basic microstructural you know features like grain sizes, the flow stress and the presence of second phase particles, second phase particles that also their presence of kind of inclusions and then also phase transformations. So, these can influence the fracture behavior. So, if the grain size is smaller, if the grain size smaller grains are showing lower damage, lower damage than the higher bigger grains.

Large grains can lead to intergranular fracture. So, this depends on you know different materials but some of these researchers have founded that large grains have more tendency to form intergranular fracture and the small grains have you know lower damage or lower dynamic fracture and then also these some of the impurities play a role and then those impurities are responsible for lower spall strength lead to lower spall strength.

Voids can be initiated at grain boundaries GB I will write grain boundaries, weak particle matrix interface that means the second phase particle interface with the matrix can you know lead to lower spall strength. So, if the interface between the particle and the matrix is low, the strength is low that will lead to lower spall strength and also voids can be generated at the grain boundaries which will also lead to you know lower spall strength that can be you know understood.

These both are I think similar whether the grain boundary or particle matrix in interface. This will actually lead to decrease of this spall strength and also sometimes some phase transformations like martensitic phase transformations, sometimes inhibited void nucleation and then that can increase, some of these phase transformation can increase the spall strength. It can increase the spall strength because this transformation can inhibit void nucleation.

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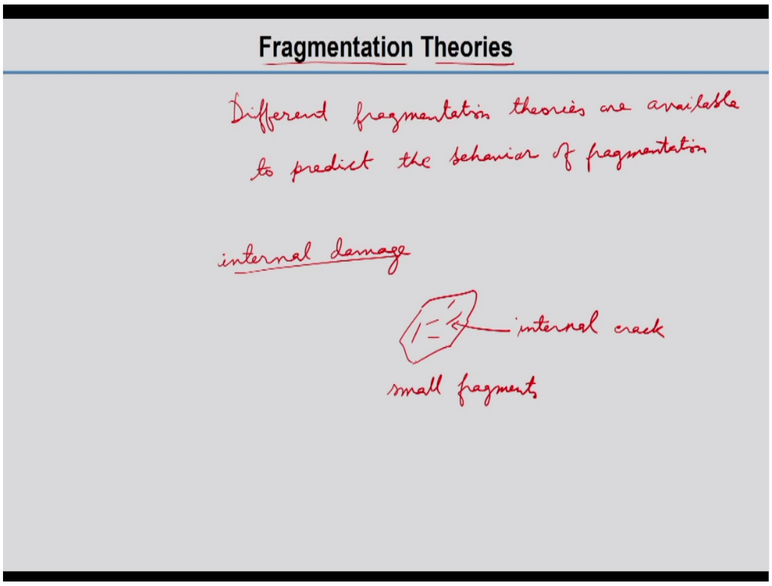

Fragmentation Theories

Different fragmentation theories are available to predict the behavior of fragmentation

internal damage

Fragmentation theories are available, some of these discussions are available in the Marc Meyers book and some can be found in, more rigorous statement can be found in other books. So, different fragmentation theories, please refer to these books are available to predict the behavior of fragmentation, how I know fragmentation can happen it is like it may be distribution of fragmentation.

This can be known from different theories available in different books especially on dynamic fracture mechanics L. B. Freund's books you can refer to that. There is another aspect; there are internal damage in the fragments. Suppose, if we have small fragments out of this dynamic you know fracture fragmentation, there can be small fragments which may have some internal cracks.

So, these are internal cracks or we can call internal damage that will also be taken into account sometimes. The fragments itself has some cracks inside and those internal damage demise can also influence the overall behavior of the fragmentation.

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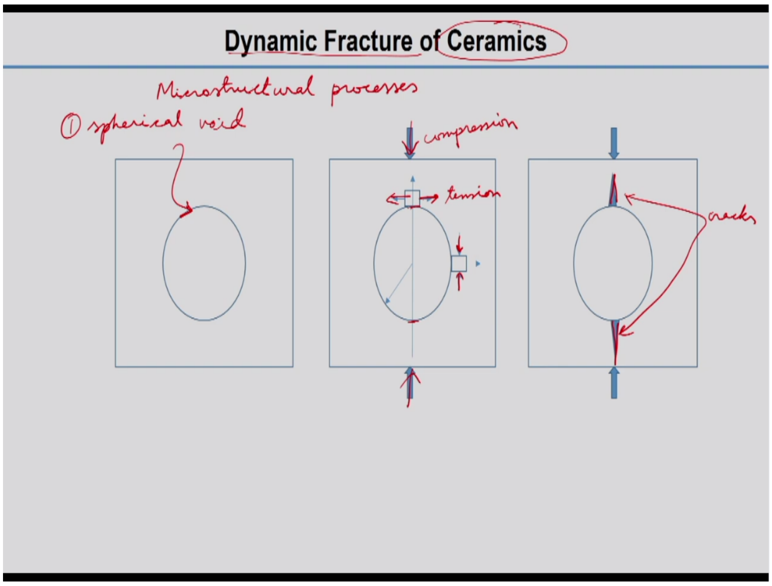

Dynamic Fracture of Ceramics

At last, we will discuss little bit about the dynamic fracture of ceramics. So, ceramics is very widely I mean explode for dynamic fracture because this is very brittle material and it has probably very different behavior from the ductile materials. Some of the microstructural processes will be discussed very briefly here. So, number 1 is if we have a spherical void, spherical void like this is a small void.

So, what will happen if it is under compression, so here it will develop some tension, tensile load, here it will be compression by the way but because of these tension and probably here as well, so there will be some cracks can be generated. These cracks can be generated due to compression, the cracks can be generated. So, these 2 are cracks. So, if you can see that the compression can generate you know tension on those voids you know surfaces then that can lead to some cracks.

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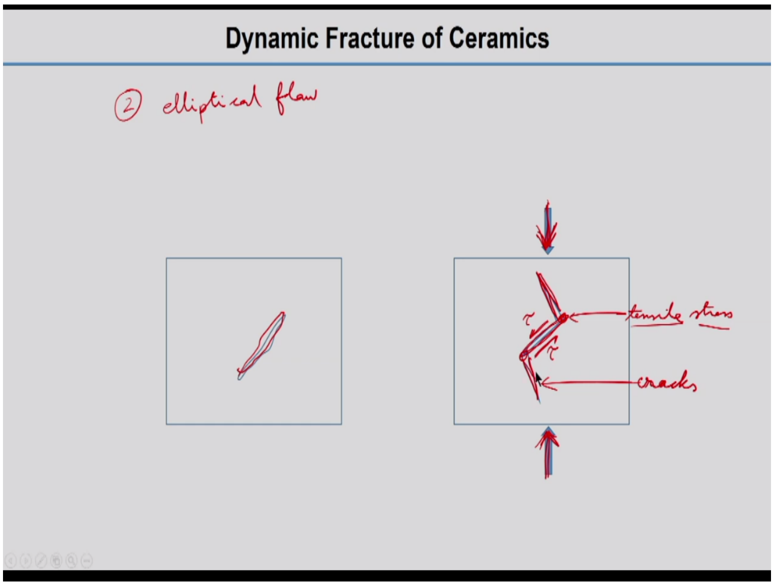

Dynamic Fracture of Ceramics

Similarly, on the second case this is an elliptical flaw by the way the spherical case is a kind of a special case of an elliptical flaw but anyways this elliptical flaw if we have you know apply compression here, this is the original flaw but then what will happen is that shear stresses will be applied here. Due to these compressions, there will be shear stresses here tau. So, these shear stresses due to the applied compression will generate some tensile stresses at the extremity.

So, here you know tensile stresses will be in the extremity, so that tensile stresses can lead to some cracks. These are the cracks because of the tensile stresses. So, what again to summarize it, so what is happening here, this compression and the material for field compression can give us some shear stresses and these shear stresses will lead to tensile stresses and the end of the crack okay.

And that will lead to sorry at the end of the yeah at the end of the elliptical flaw but that will lead to some cracks on the extremity of that elliptical flaw.

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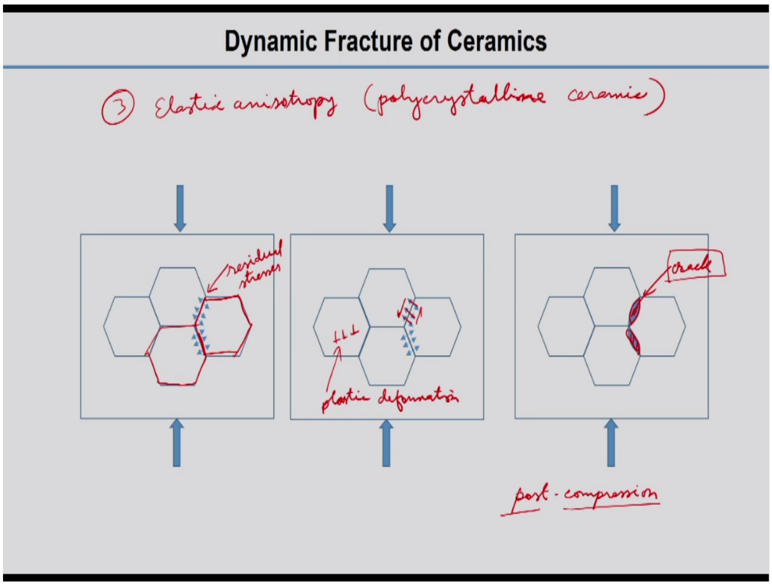

Dynamic Fracture of Ceramics

And the third case is elastic anisotropy that is in case of a polycrystalline ceramic, there are different grains here, polycrystalline sorry polycrystalline ceramic. So, these grains if you can see that these grains have different orientation and then this is in compression and this is this will have residual stresses. So, because of the anisotropy of this you know polycrystalline structure, so what will happen is because of you know plastic deformation so some dislocations.

Because of the plastic deformation, some plastic deformation is happening due to the stresses applied, plastic deformation and these plastic deformation will have you know because of that it will shear and then in these you know grain boundaries, there will be you know elastic anisotropy or because of the orientation mismatch and due to that there will be some crack will form. This crack will form at the grain boundary.

So, this is mostly because of the orientation mismatch between the grains. So, that will lead to these cracks and basically what happens this is not exactly at the compression but after the compression, after the compression. So, this is actually after post you know after compression or post compression that residual stresses due to the plastic deformation that developed in the grain boundary due to the mismatch of the orientation.

So, that will create the cracks and that will open up. So, that is mostly the post compression. So, with that so we have actually finished this chapter, the last chapter of this course dynamic behavior of materials. So, I understand that these few lectures the last lectures are we were in a little hurry because we have already completed the 30 hours and because of some constraint I should stop it today itself.

So, that is why I think the last lectures, it was they were not very you know at a slow pace like the earlier lectures. So, I am sorry about that but I think this is what we you know learnt in this course that we started from the elastic wave, plastic wave or shockwave and we introduced what is dynamic deformation or how it is different and quasi-static deformation.

So, this wave especially we worked on you know extensively on elastic wave, plastic wave and also in the shockwave and then how the shockwaves induce some phase transformation, how these waves are connected to dislocation dynamics, so we have discussed that and finally we have discussed about the failure mechanisms like shear bond which is called as precursor to dynamic failure and also in the last chapter the dynamic fracture.

So, we have discussed very briefly on different aspects of dynamic behavior, dynamic fracture, so different unique features of dynamic fracture and very briefly on these features we discussed and at last we discussed a little bit of microstructural effects and the microstructural effects on ceramics, dynamic fracture of ceramics. So, with that we are concluding this you know course dynamic behavior of materials.

Hope whoever are watching this video in a consistent manner in all the videos, so hope you enjoyed it and please write to me for your feedback.

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Thank you !

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