Mechanical Behavior of Materials

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Module No # 12
Lecture No # 57
Fracture Mechanics – IX

Hello I am professor Sankaran in the department of metallurgical and materials engineering.

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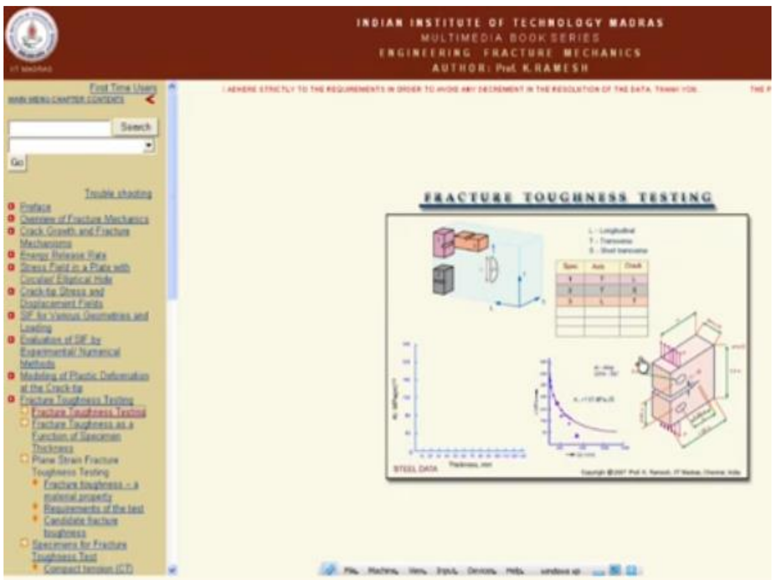

Hello everyone welcome to this lecture and in this lecture we will pay our attention to very important testing fracture toughness testing. So we will go through lot of information in this lecture about this very critical test in the fracture mechanics subject.

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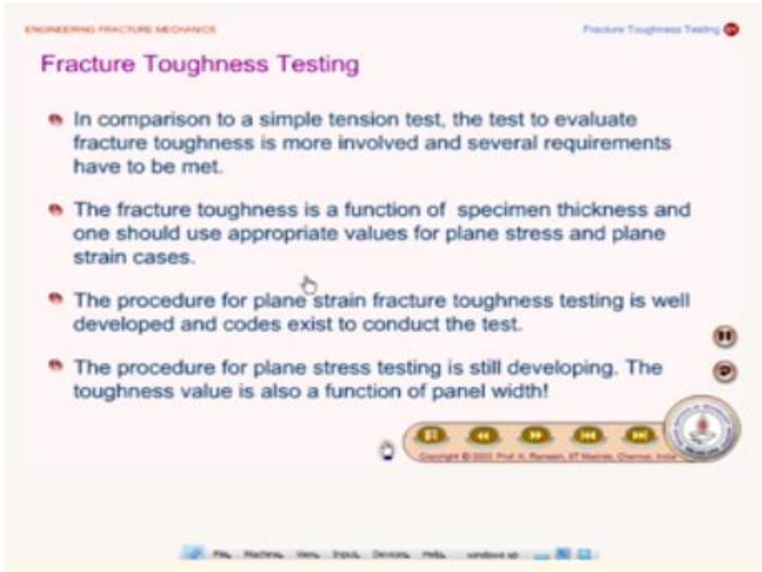

And what we will now look at is some of the salient features. In comparison to simple tension test the test to evaluate the fracture toughness is more involved and several requirements have to be met. It cannot be compared to in fact any other mechanics interest in terms of criticality and the critical analysis are concerned this is quite involved test. So, the fracture toughness is a function of specimen thickness and once should use appropriate values of plane stress and plan strain cases. This we have already see in the previous lecture about this how the fracture toughness varies with the thickness in fact I said this could be the one of the problems like how to select the thickness for a given material to attain a particular plain strain condition or a blade stress condition etc., The procedure for plain strain fracture toughness testing is well developed and codes exist to conduct this test. The procedure for plane stress testing is still developing the toughness value is also a function of panel width.

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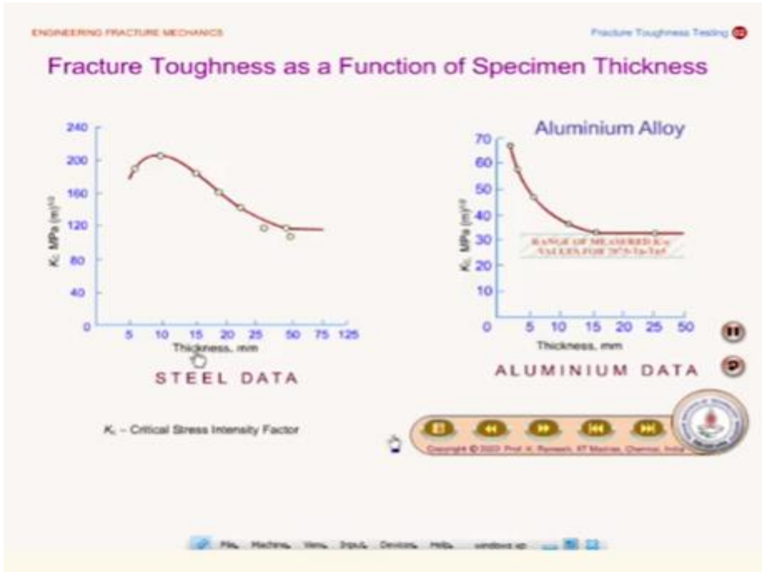

So if you look at these plots of you know k versus thickness this is typically for a steel data k_{1c} or k_c is critical stress intensity factor which varies from the small thickness to the larger thickness. That means plain stress to plain strain conditions that is what it is and for this aluminum alloy it is varying like this from plain stress to plain strain condition. And what is interested to note here is if you look at you know the steel data approximately you know 25 mm the plane strain condition is obtained in the case of steel. On the other hand, only 15 mm of thickness in aluminum alloy it reaches to plain strain condition. So, this is something very different each that is important to note that every material I will have a characteristic thickness of specimen dimension for fracture toughness testing this important point to note.

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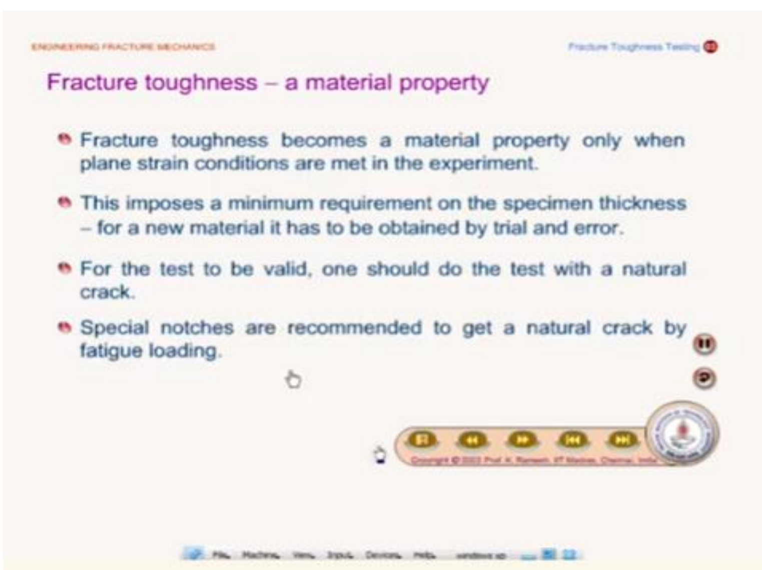

The other point to note is fracture toughness is material property fracture toughness becomes material property only when plane strain conditions are met in an experiment. This is all well-established now this imposes a minimum requirement on this specimen thickness for a new material it has to be obtained by trial and error. For the test to be valid, one should do the test with the natural crack that means you cannot make a notch or a wire cut and so on it has to be grown by typically fatigue glory and special notches are recommended to get the natural track by fatigue glory there are not designs which we will discuss how which is being done in the typical test.

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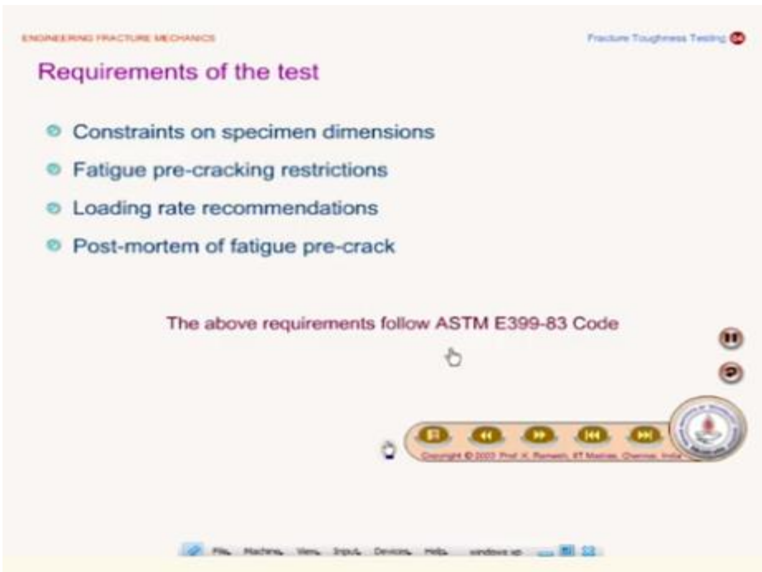

And the requirements of the tests are the following constraints on specimen dimensions fatigue pre-cracking restrictions and loading rate recommendations post-mortem of fatigue pre-crack. All these above requirements are even this ASTM code so it is quite elaborate details are given for this kind of important testing.

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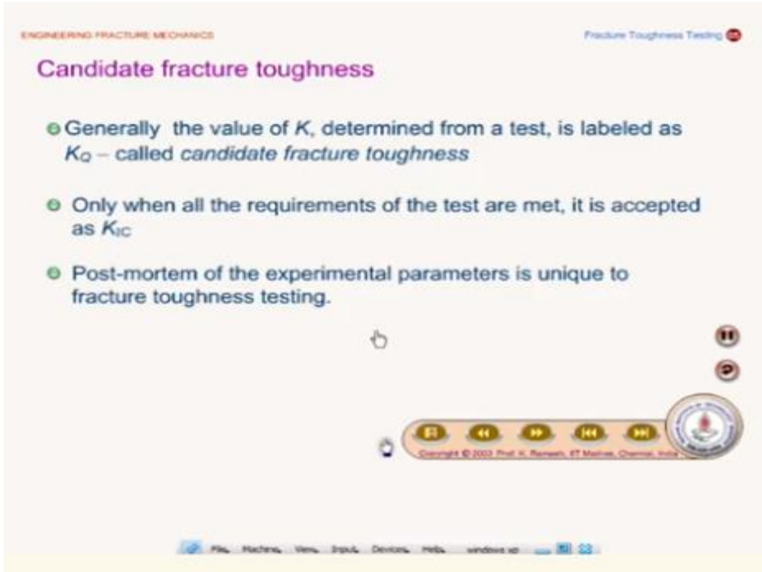

So candidate fracture toughness what is candidate fracture toughness generally the value of K $_1$ determined from the stress is labeled as K $_q$ called candidate factor toughness. So this is a test outcome and it will be recorded or declared as K_{1c} only after certain conditions only when all the requirements of the tests are met it is accepted as K_{1c}. So this is important post bottom of the experimental parameters is unique to fracture toughness testing.

It is very difficult to you know predict all these parameters before experiments once the experiment after experiments the parameters are not followed then the test has to be scrapped.

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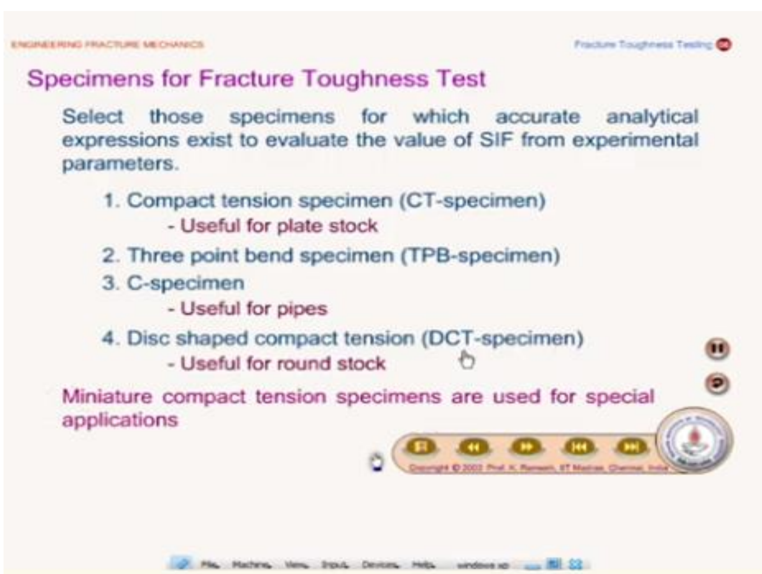

Specimen for fracture toughness test again it is need based, select those specimens for which the accurate analytical expressions exist to evaluate the value of stress intensity factor from experimental parameters. The popular ones are compact tension specimens known as CT-specimen, three point bind specimen, TPB – specimen, TPB specimen and c specimen and disk shaped compact tension specimen. So, all this also know different uses we can see that you know CT specimens are useful in the plate stock and C specimens are useful for pipes and the disc shaped compact tension specimen is useful for the round stuff. So, the miniature compact tension specimen are used in this specimen applications where the material availability is critical then this kind of specimens are prepared for conducting this fracture toughness test.

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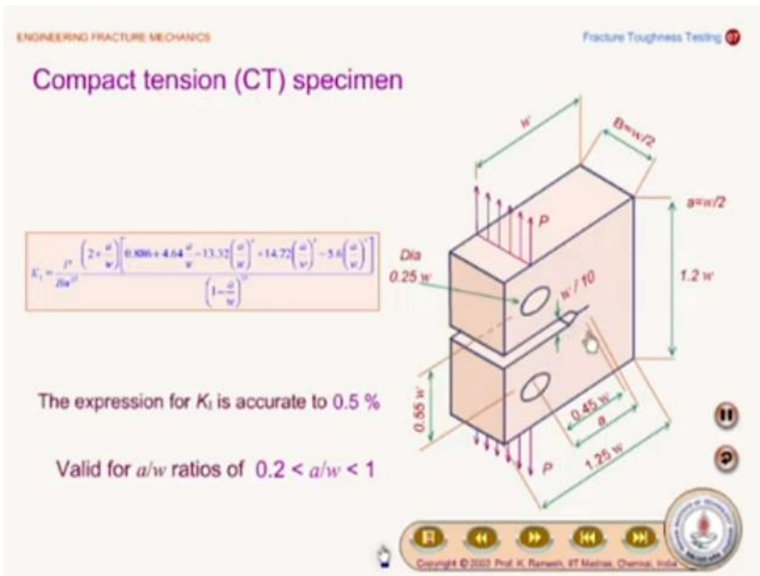

So what you are seeing here is a compact tension specimen dimensions and you can see that the values or A by W values are given here with respect to this thing. And this is the typical expression to obtain the stress intensity factor as the function of a/W for this particular geometry. And this expression for K_1 is accurate to 0.5% and valid for a/W ratio of 0.2< a/W<1, I mean a by W value should be within 0.2 to 1. So, this is very important to note and this is not we talked about we will separately discuss how to understand this kind of notch.

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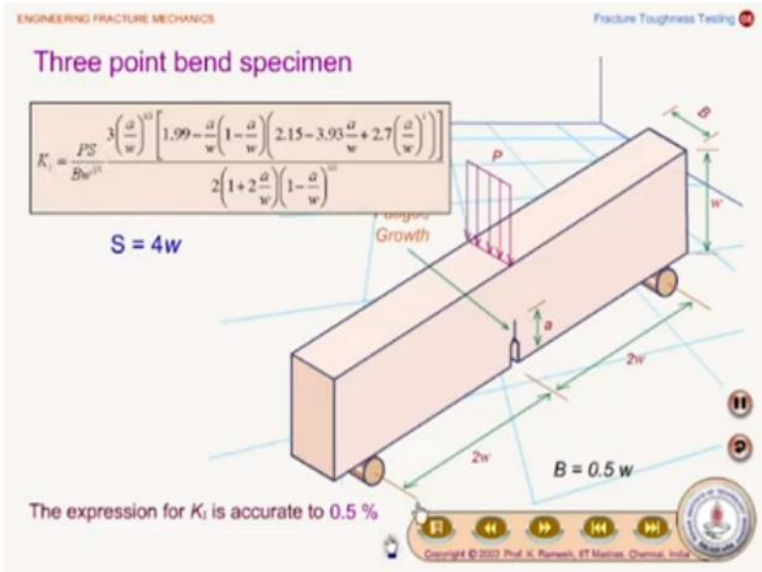

Next one is the three point bent specimen and we will have separate empirical relation for K_1 as a function of a/W. And what is shown here is you know the dimensions are all shown here then we can just understand this expression for K_1 is accurate to 0.5% in the range.

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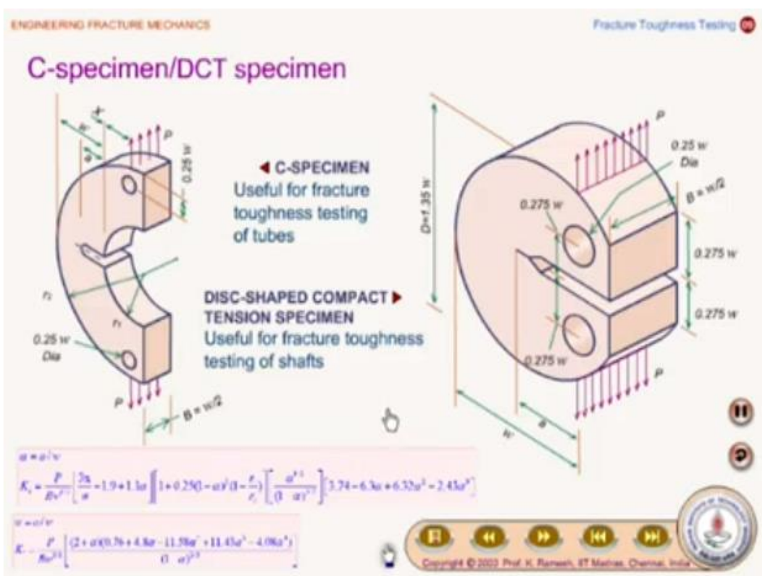

And what is given is S = 4 w, use that in the formula C-specimen or DCT specimen useful for the fracture toughness testing of tubes. So, this nicely configured in that manner and you can look at this kind of expression for a / w relation and the disc shaped compact tension specimen are also useful for the shafts testing of shafts. So, the expression is different for this dimension you can see that.

So but all of them are already they are also given in the ASTM codes so just for a reference you should know what are all the types of specimens available and why it is different. So, for that reason only.

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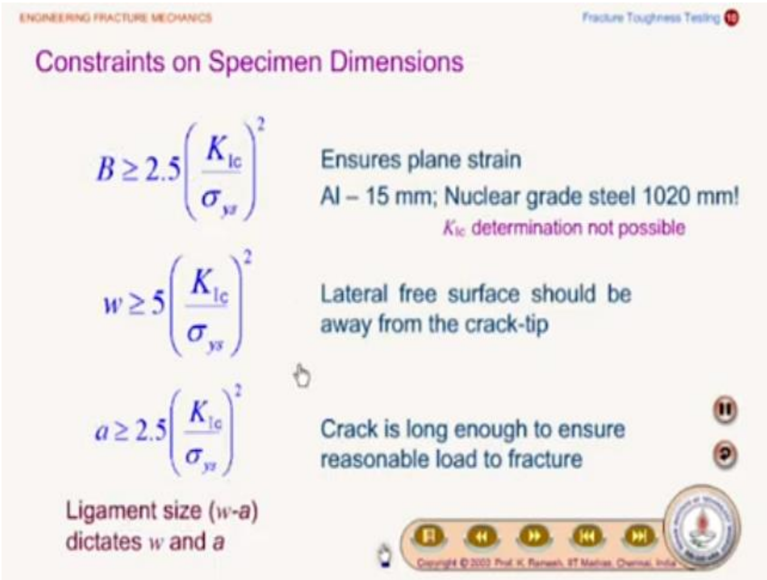

So now let us look at what are the constraints on the specimen dimensions, this expression we have already seen that minimum thickness of the sample should be B which should be equal to or greater than $2.5(K_{1c}/\sigma_{ys})^2$, ensures the plane strain condition. For aluminum alloy 15 mm nuclear grade steel it is a 1020 mm. So, this is very interesting to note you know so finding out the K_{1c} for such kind of thickness is not possible because of the conditions.

And ligament size, I mean the lateral so the width is, should be greater than or equal to $5 (K_{1c}/\sigma_{ys})^2$. Lateral free surface should be away from the active that is another condition for this. And a should be greater than or equal to $2.5 (K_{1c}/\sigma_{ys})^2$ and crack is long enough to ensure to ensure reasonable load to fracture. So, these are all the very strict specimen constraints for fracture toughness testing.

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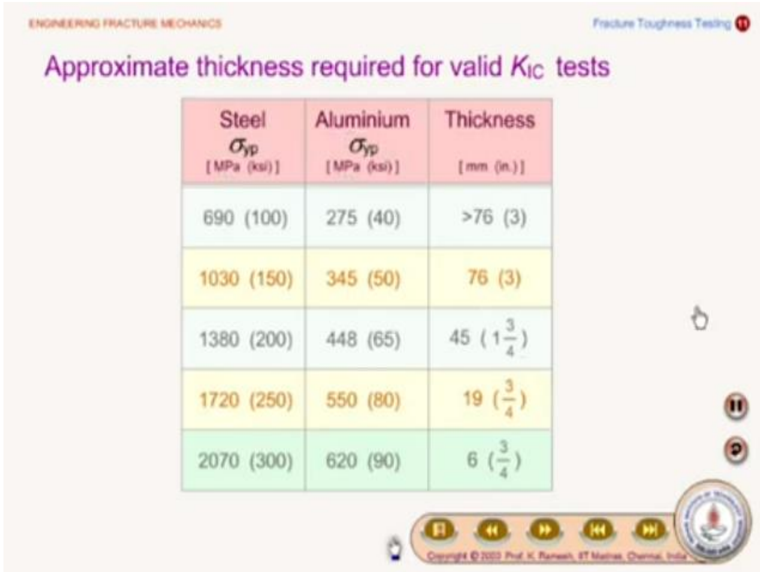

Steel σ_{yp} [MPa (ksi)]	Aluminium σ_{yp} [MPa (ksi)]	Thickness [mm (in.)]
690 (100)	275 (40)	>76 (3)
1030 (150)	345 (50)	76 (3)
1380 (200)	448 (65)	45 ($1\frac{3}{4}$)
1720 (250)	550 (80)	19 ($\frac{3}{4}$)
2070 (300)	620 (90)	6 ($\frac{3}{4}$)

And we will just see the approximate thickness required for a valid K 1 c test this is for generally steel it is 690 it is given in MPa and K 1 c depending upon this and if it is of this range then the thickness is should be 76 mm or greater. Depending upon the σ_{yp} that is the yield point this values then this is also very that is that is constrained at least. For test common material like steel and material system here.

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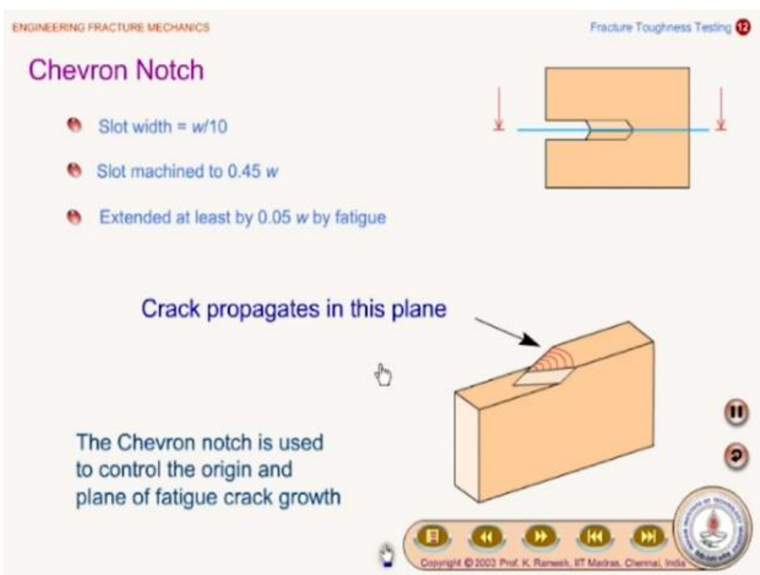

And this is just for a reference now I was just mentioning about this notch now we will look at what is the importance of this Chevron Notch the side view is like this and then slot with this w/10. And slot machine to 0.45 w and extended at least by 0.5 w by fatigue. So, this is why so to understand this geometry, let us, you should cut this specimen in the plane this perpendicular to the screen that plane and this Chevron Notch is used to control the origin and plane of the fatigue crack growth.

So this plane are the fatigue crack will grow and then we will just try to cut this plane like this and then we can see how it is looking like this. So after cutting this plane the notch I mean look like so the point is the when the specimen is subjected to the tensile loading and this point will be the weakest. So, the crack will be initial from here and then will grow the crack will grow like this. So, this is how and crack propagation in the plane same plane so that is the advantage of having Chevron notch and in fact most of the CT specimens will have these kind of Chevron notch made.

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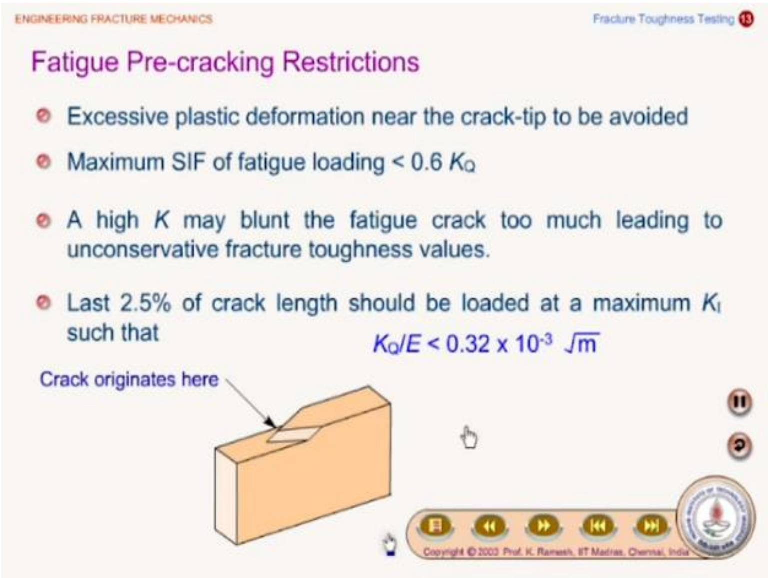

And what are the fatigue pre-cracking kind of restrictions excessive plastic deformation near the crack tip to be avoided and that is precondition. And maximum stress intensity factor of fatigue loading should be less than 0.6 K_Q. That is a candidate fracture toughness value a high K may blunt the fatigue crack too much leading to unconservative fracture toughness values. Last 2.5% of the crack length should be loaded at a maximum K_1 such that K_Q / E should be less than 0.32 X 10^{-3} √meter. So, that is the kind of crack growth condition at the final stage so this is again how the crack grows and then propagate and originate and propagate further shown here.

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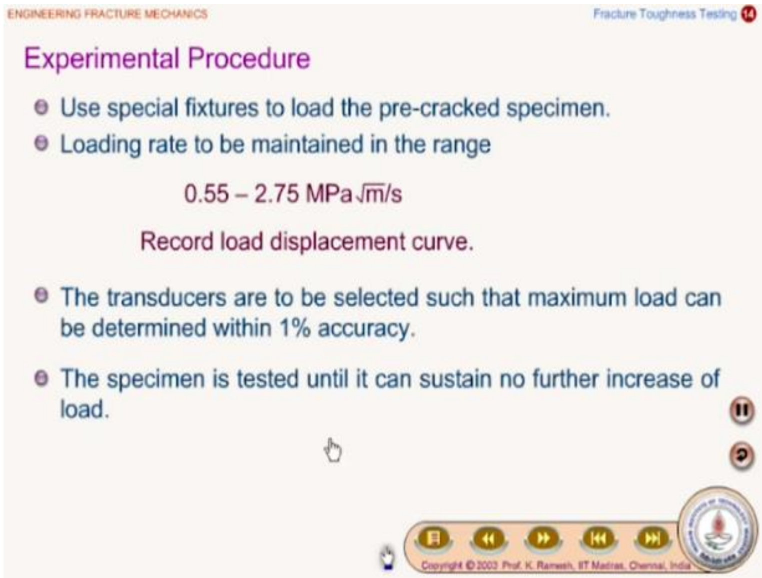

and saw the experimental procedures use special fixtures to load and the pre-cracked specimen loading rate should be maintained in the range of 0.55 to 2.75 mega pascal square root meter per second. Record load displacement curve that transducers are to be selected such that maximum load can be determined within 1% accuracy, the specimen is tested until it can sustain no increase of load it is like some simple pulling but with all the pre-conditions.

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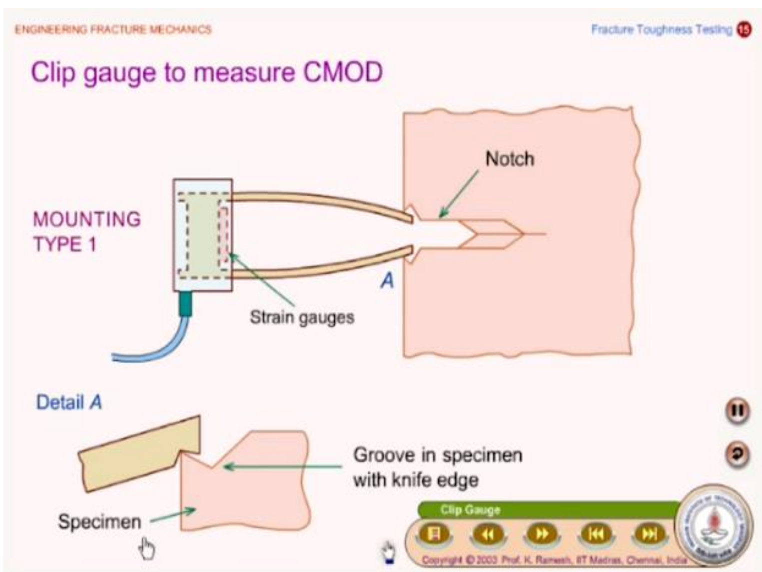

And what is to do noted now is how the clip gauges are fixed to measure the CMOD crack mouth opening displacement this is called a CMOD and typical gauge length, I mean the gauge is fixed here and this is a mounting type and this is chevron notch and this is a close up view how this gauges are fixed. And what we are trying to so now we will how the data is collected and.

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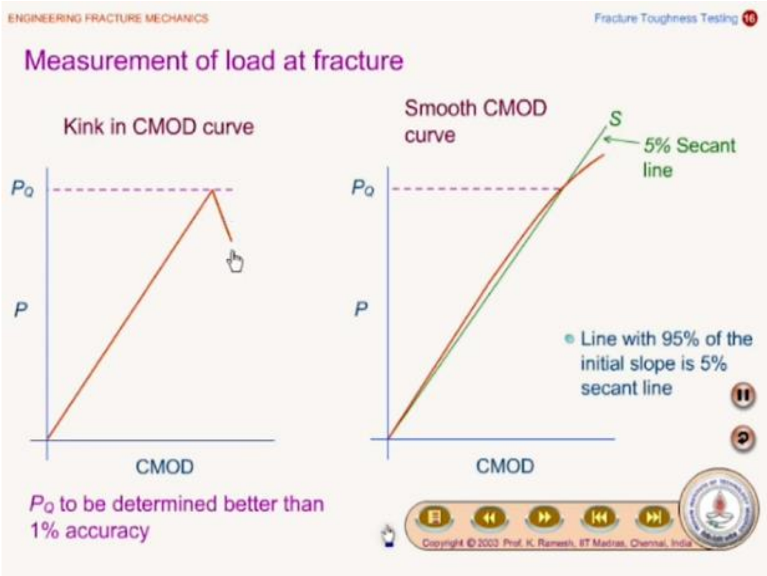

So load versus displacement, we will have the PQ value this is the load maximum PQ to be determined better than 1% accuracy and a smooth COD that is a kink in COD and the smooth COD curve will see that then the point of P Q is at 5% tangent line and line with 95% of the initial slope is 5 secant line not tangent, secant line. So, this is 95% of the initial slope is 5% secant line so we will see that (()) (17:10) the load versus displacement curve will also have some in between step or a kink you can call it.

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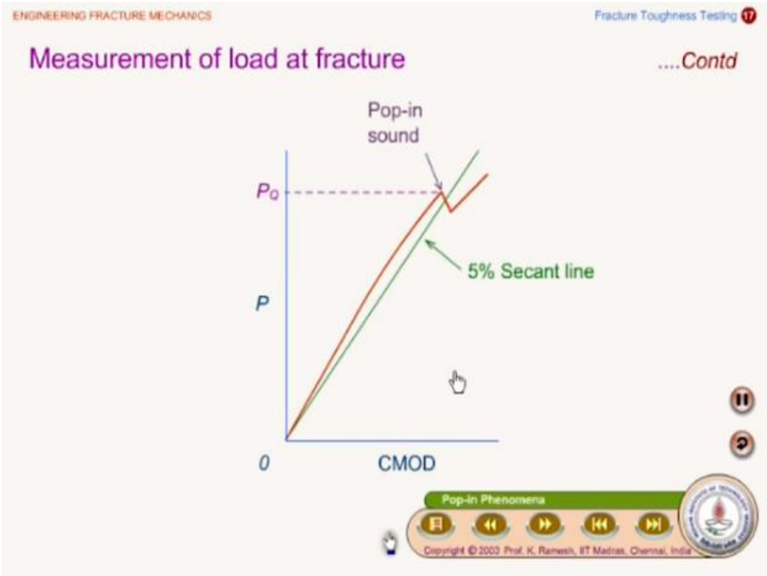

Then also there is a pop in sound phenomenon so in this case also you have the take the 5% secant line to take the P Q value this kind of load displacement data are normally obtained in the medium thickness specimens.

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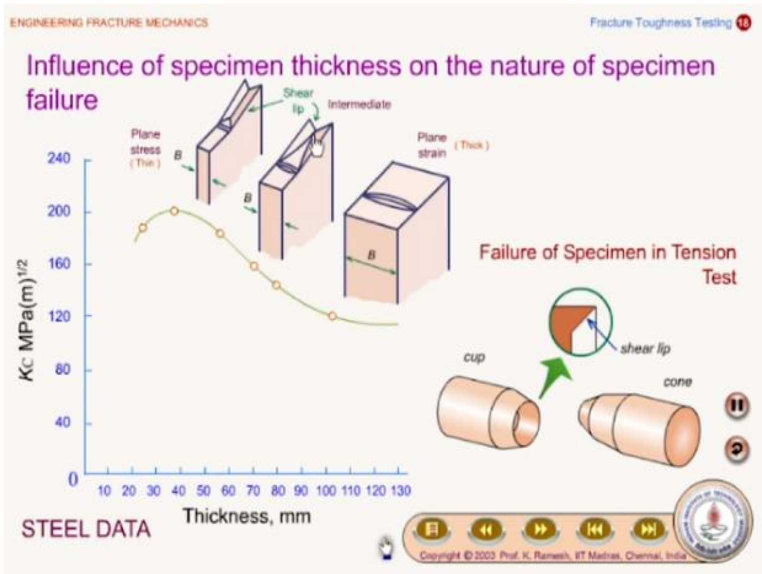

One is you know extreme thin specimen and thick specimen and in between specimen also you will get the pop-in phenomenon. So once again this is the K_C versus thickness data which you have seen in the previous lecture so you can see that you know the plane stress to plane strain as a specimen thickness increase so this is an intermediate thickness where a pop-in phenomenon many occur. But this is a plane strain condition this is plain stress condition maybe. Failure of specimen in tension test is you know this is normally accompanied by this you know cup and cone fracture with the shear lip. So, similarly here also you see that shear lips are possible because as a crack growth and then sudden failure also will involve this shear failure in fracture toughness test.

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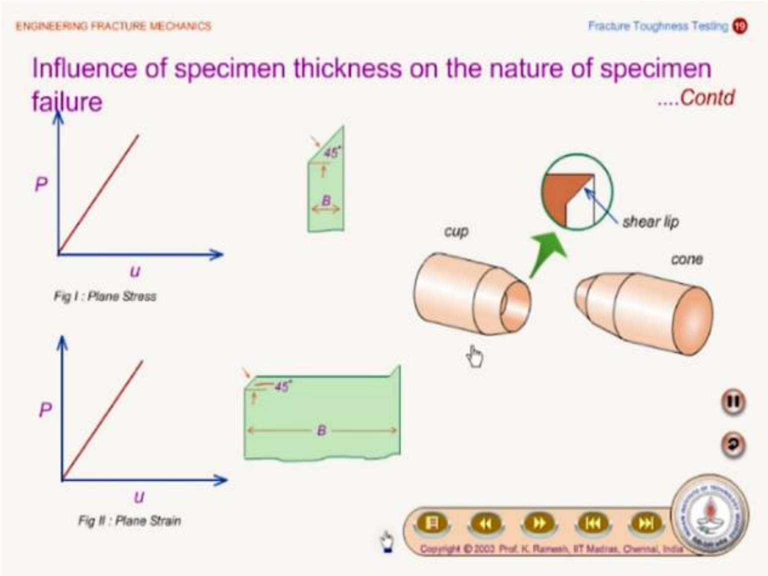

and the influence of specimen thickness on the nature of specimen again nature of specimen failure on this shear lip formation. So, this is for the plane stress condition and then this is a plane strain condition, you can see that this is a long and then finally shear lift formation takes place at this kind of setup.

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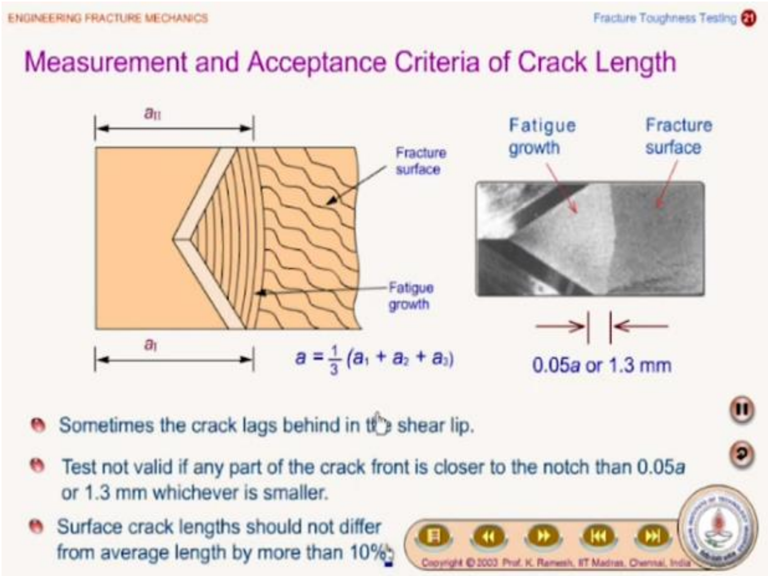

So now what we will do is? we will look at very important aspect, measurement and acceptance of criteria for a crack length. S,o, the pre-crack we have generated and then how to make sure that is really valid. So what you are seeing in this sketch is this is a crack growth region and this is done by fatigue free cracking and then this is a fractured surface this is you can see that actual specimen where you can see the fatigue crack growth region appears bright as compared to the actual surface here. So, the crack length measurements are made at the 3 locations and then some kind of an average is taken here. So, $a = 1/3(a_1 + a_2 + a_3)$, a_1 or a_2 or a_3, should not differ more than 5 of a, So, that is our condition this is a postmortem analysis. So, it as to make you know K_Q as K_{1C} then these are all the one of the conditions pre-crack tensions. So now sometimes the crack lags behind the shear lip test not valid if any part of the crack front is closed to the notch than 0.05 a or 1.3 mm whichever is smaller. Surface crack length should not be smaller from average length by more than 10% so this is again another condition which is strict for this test. So now we understand that you know these are all very critical and you know difficult experiment to perform.

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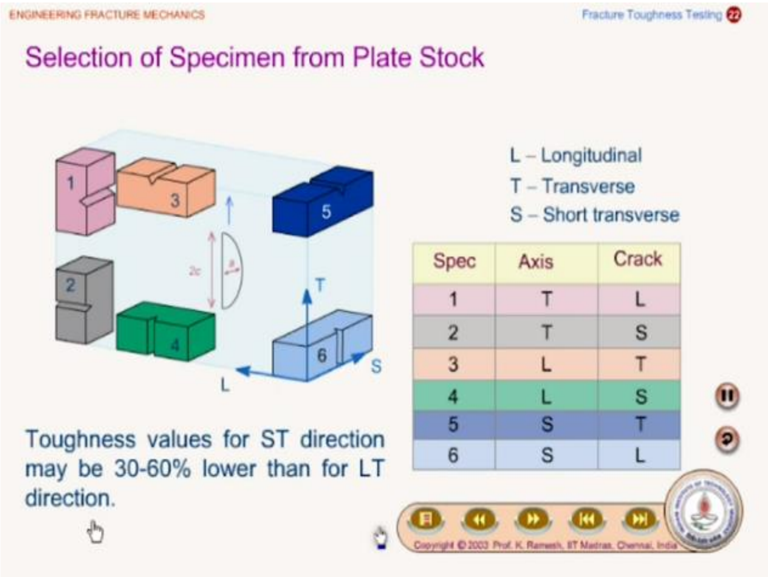

And how do we select the specimen from the stock there are some recommendations where there is suppose if you have the material stock of this nature then how do we take the samples and this is a table specification where we have an axis and they crack orientations are given that L is longitudinal, T is transverse and S stand for short transverse. So, toughness values for ST directions may be 30 to 60% lower than the LT direction.

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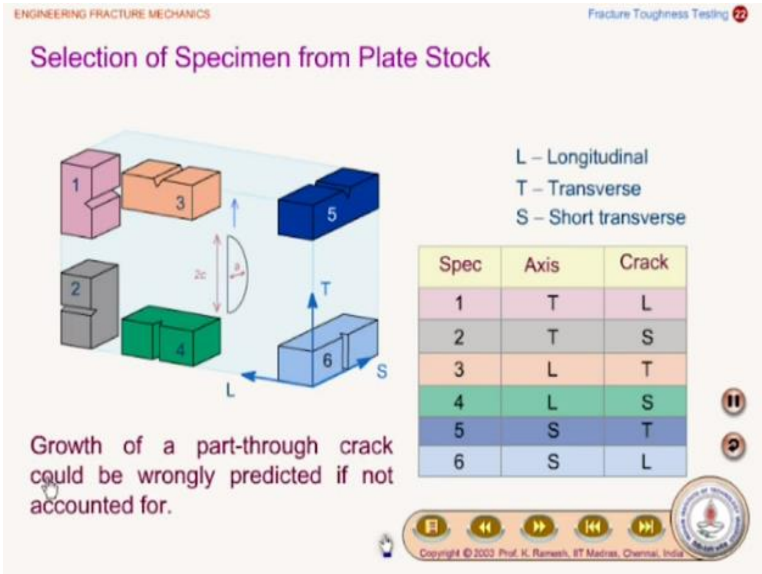

So, this is some recommendations about how to prepare this samples or how to take this samples from the material stock, to before we perform the test. So that is very important and this is also given in some of the codes but just to give an idea in a bulk material how to take the samples.

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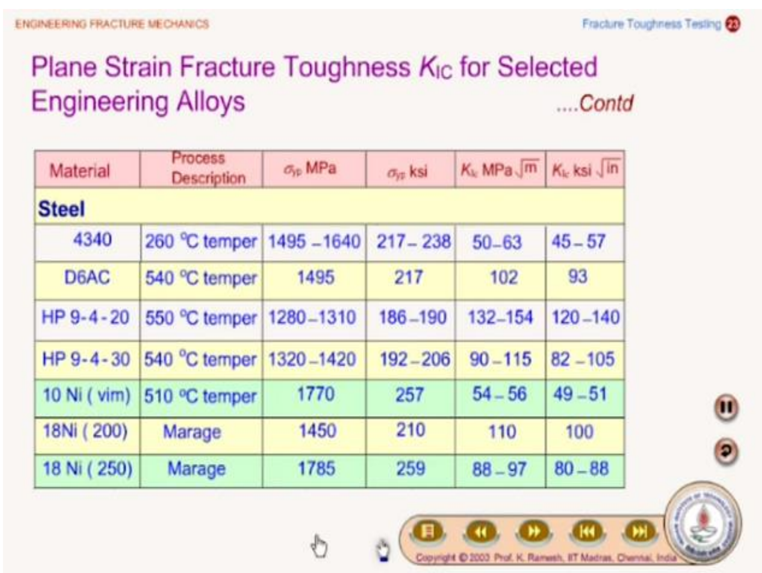

Material	Process Description	σ_{yp} MPa	σ_{yp} ksi	K_{Ic} MPa $\sqrt{m}$	K_{Ic} ksi $\sqrt{in}$
Steel					
4340	260 °C temper	1495 – 1640	217 – 238	50 – 63	45 – 57
D6AC	540 °C temper	1495	217	102	93
HP 9-4-20	550 °C temper	1280 – 1310	186 – 190	132 – 154	120 – 140
HP 9-4-30	540 °C temper	1320 – 1420	192 – 206	90 – 115	82 – 105
10 Ni (vim)	510 °C temper	1770	257	54 – 56	49 – 51
18Ni (200)	Marage	1450	210	110	100
18 Ni (250)	Marage	1785	259	88 – 97	80 – 88

So, this is just to give you a knowledge about the testing as well. So, some of the plain strain fracture toughness values for the selected engineering alloys. What you are going to shown here just to give an idea about what kind of material we are dealing with 4340 very important steel which is after tempering at 260°C, that is quenched and tempered condition. This is a yield stress value and then you have 50 to 63 MP√meter and you can see that you know other type of grades not very heavily alloyed steels. You can see that they all have very high fracture terms and then you also have the meraging steel very important steels you can see that strength values are extremely high. And then still they are able to have very high fracture toughness because of the alloy design and heat treatment and so on.

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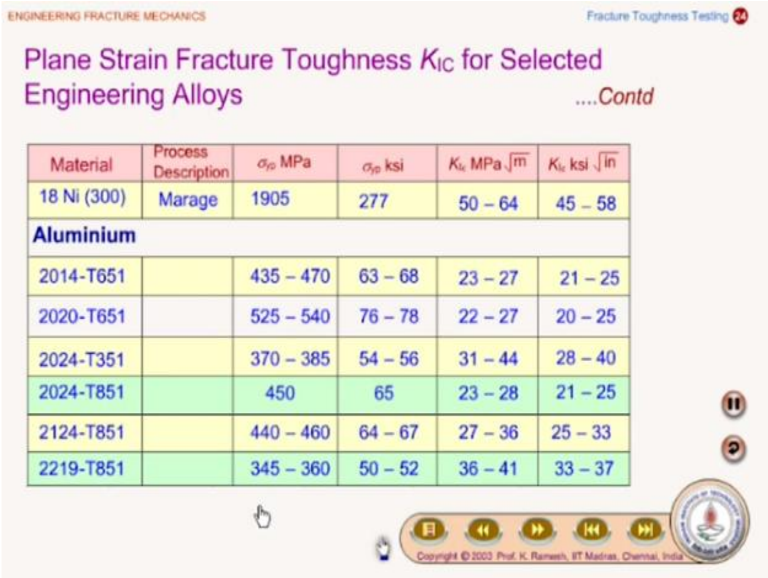

Material	Process Description	σ_{yp} MPa	σ_{yp} ksi	K_{Ic} MPa $\sqrt{m}$	K_{Ic} ksi $\sqrt{in}$
18 Ni (300)	Marage	1905	277	50 – 64	45 – 58
Aluminium					
2014-T651		435 – 470	63 – 68	23 – 27	21 – 25
2020-T651		525 – 540	76 – 78	22 – 27	20 – 25
2024-T351		370 – 385	54 – 56	31 – 44	28 – 40
2024-T851		450	65	23 – 28	21 – 25
2124-T851		440 – 460	64 – 67	27 – 36	25 – 33
2219-T851		345 – 360	50 – 52	36 – 41	33 – 37

This is for non-ferrous alloys aluminum and you can see that strength levels are very different from the steel and then the K $_{1C}$ value is also accordingly very different as compared to steel structures. Just give you a perspective about what kind of values one would expect in an engineering alloys.

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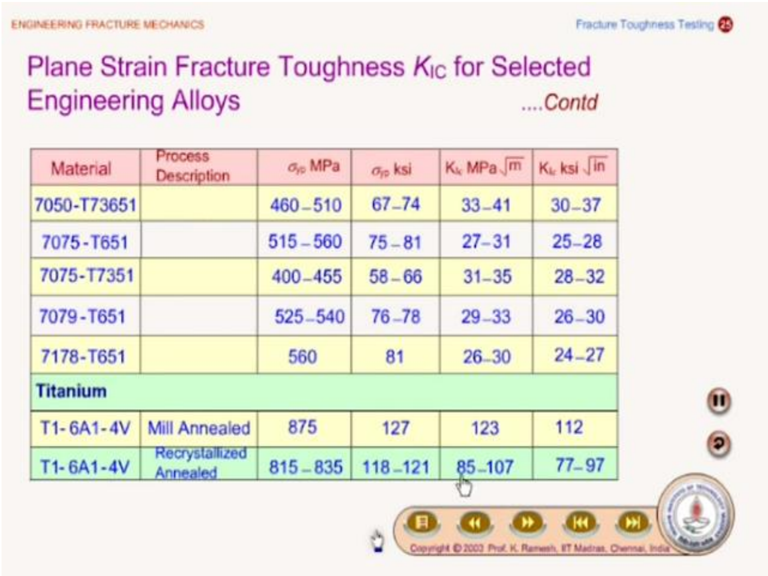

Material	Process Description	σ_{yp} MPa	σ_{yp} ksi	K_{Ic} MPa $\sqrt{m}$	K_{Ic} ksi $\sqrt{in}$
7050-T73651		460 – 510	67 – 74	33 – 41	30 – 37
7075-T651		515 – 560	75 – 81	27 – 31	25 – 28
7075-T7351		400 – 455	58 – 66	31 – 35	28 – 32
7079-T651		525 – 540	76 – 78	29 – 33	26 – 30
7178-T651		560	81	26 – 30	24 – 27
Titanium					
T1-6A1-4V	Mill Annealed	875	127	123	112
T1-6A1-4V	Recrystallized Annealed	815 – 835	118 – 121	85 – 107	77 – 97

So this is for same material with different grades and then all this aluminum alloys are typically again subjected to different heat treatments. And which is not given because we quite elaborate treatment so the T when you say T this kind of coding will also indicate the type of heat treatment the materials subjected to. For titanium alloy this is a type 6 for Ti-6Al-4V, very popular alloy. Then you can see that the K_{1C}, values are very high that means they are all you know arrow space alloys. So titanium alloy generally will have very high fracture toughness.

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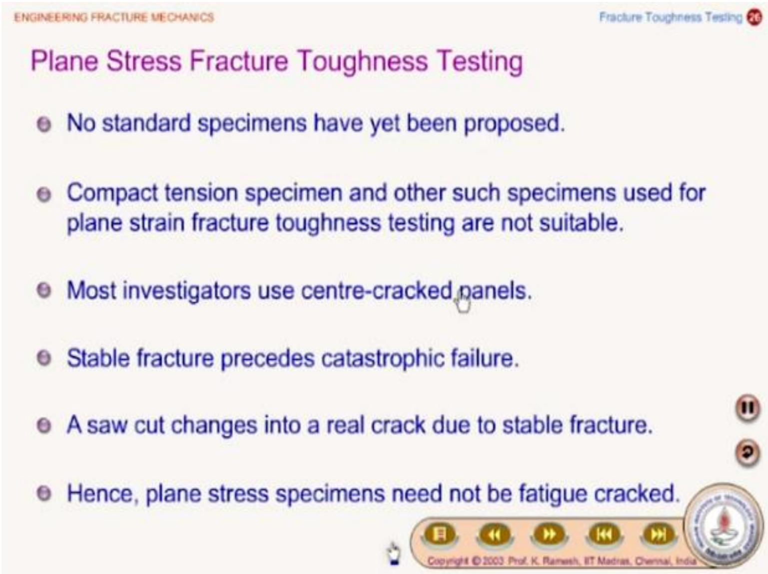

And what about plane stress fracture toughness testing, so no standard specimen have been proposed and compact tension specimen and other such specimens used for obtaining strain structure toughness testing are not suitable and most investigators use center-cracked panels and the stable fracture precedes catastrophic failure, a saw cut changes into a real crack due to stable fracture. Hence the plane suspicions need not be fatigue crack. Since, it is still under the development and we are not primarily practicing any engineering setup, I just leave it here and then I will move on to our next topic