Dynamic Behaviour of Materials
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Lecture-32
Experimental Techniques for Dynamic Deformation 1

Hello everyone, so in the last lectures we discussed about phase transformation due to shock wave propagation. So in today we will start a new topic, so this is experimental techniques to produce dynamic deformation. We have already discussed a few techniques earlier like split Hopkinson pressure bar. So now we will discuss little details about these techniques, so we have even discussed about different strain rates.

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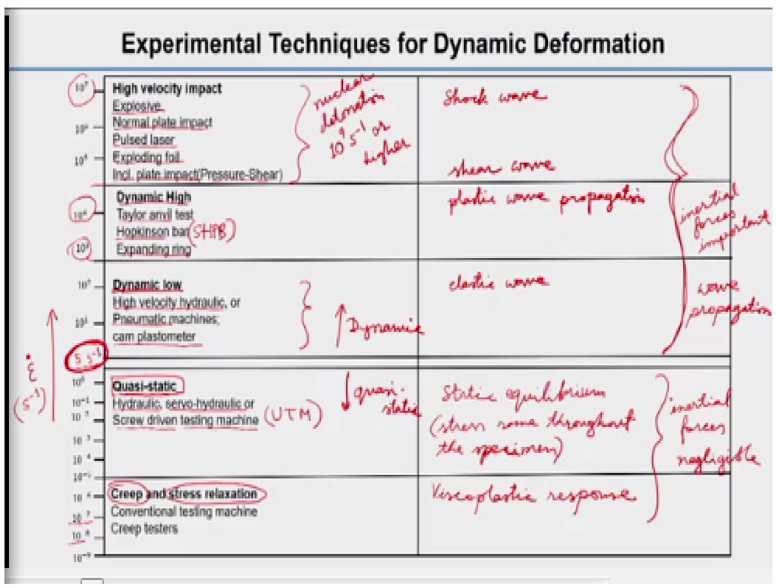

So here in this slide is increasing order of strain rate, I will write epsilon drop for strain rate. So if you see here at a very low strain rate, so 10 to the power like - 7 or – 8. So we have like we can consider about creep and stress relaxation, this is basically we call creep like viscoplastic materials response or it is right response here. And then we know that the quasi static deformation which is we can actually differentiate from quasi static and dynamic.

So the strain rate is probably 5 this is second inverse as you know the strain rate unit is second inverse reciprocal of second. So if it is less than 5 per second and then we are classifying eta as quasi static. And then if it is higher than that we are saying that dynamic. So there are different subdivisions of dynamic, so for quasi static test we know that hydraulic servo hydraulic or screwed even testing machines, we know this universal testing machines, so can be found.

And so this as you know that the quasi statics we have static equilibrium. So in these machines so test to it is constant crosshead velocity. So and we assume that the stress is same throughout the length of the specimen**.** However to in today's lecture we will be more focused on the dynamic part not these quasi static.

So we will talk about higher strain rates higher than let us say 5 per second, so as you can understand from here that the higher than 5 per second is the strain rate range the inertial forces, force of inertia or we let inertial forces are important these are important or effect of inertial forces is significant. And below that strain rate inertial forces are negligible**,** so when you increase the strain rate more and more inertia effects will be there.

So in the dynamic low, dynamic low means probably we can say that below 1000 10 cube, so below 10 cube probably we can call that dynamic low. So that includes high velocity hydraulic or pneumatic machines and another one is camp plastometer. So here as we know we will get wave propagation, so in this range for the inertial force are important this range, so as you know that will get wave propagation not in the static case in quasi static case we do not get wave propagation, we get static equilibrium.

So here we have wave propagation in this case, so in these cases the mechanical resonance in the specimen and machine is also important. So when you go a little higher in this table so let us say we have dynamic high range where we have Taylor Anvil test Hopkinson bar which is very widely used as we already have discussed several times as HPV we write split Hopkinson pressure bar.

And another one is expanding ring test, so the boundary is probably somewhere you know around in the order of 10000 to 100s of 1000. So this is dynamic high and even there are higher strain rate tests, so which includes the explosive tests and the normal plate impact then inclined plate impact that can produce pressure and shear, then exploding foil and then pulsed laser.

So you can see that strain rate can go up to 10 to the power 7, so high and if we talk about nuclear detonation, that is even higher. So and we if we talk about nuclear detonation that can be even 10 to the power 9 per second or even higher, so higher. So at so high strain rate how the material will behave, it will be very difficult to predict even I think at a strain 10 to the power 6 or 7 also it is very difficult for our scientists and engineers to know about the mechanical behavior of the material.

So in this case if it is dynamic low also we will have an elastic wave propagation elastic wave then. If we have higher amplitude we can see plastic wave in some of these test plastic wave propagation. And then the plastic shear wave is you can see from inclined plate impact shear wave propagation. And then at a very high strain rate shockwave propagates. So this is now the entire picture is quite clear to us this is the table from the Mark Meyer's book.

So we have the boundary 5 per second and we are differentiating that this is dynamic on the top of that strain rate and quasi static on the bottom quasi static. So where we have static equilibrium and stress same throughout the specimen. So now we will discuss few of these tests few of the commonly used tests and also we will go through how we measure this strain rate. So in the very beginning in the initial lectures we discussed about the calculation of the strain rate, we will again repeat this discussions.

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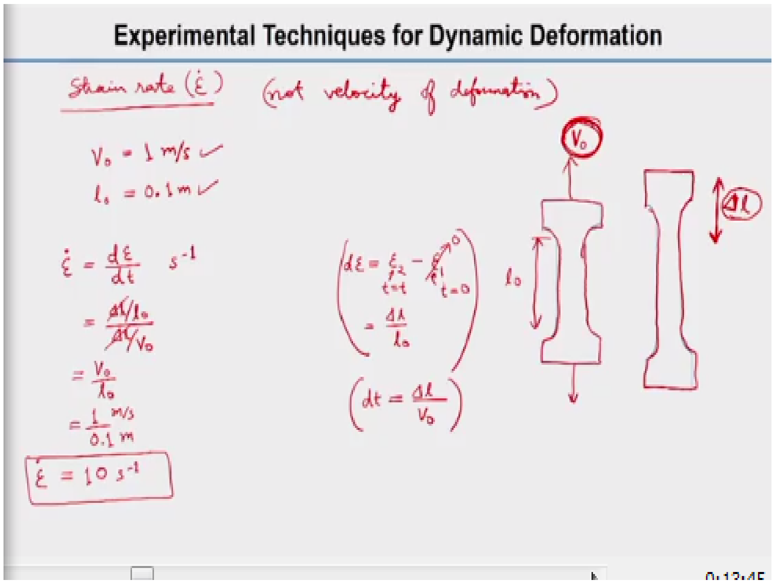

So to calculate strain rate which will represent by epsilon dot, so here you can see the tensile specimen we are using a UTM are high speed. So the velocity at which we are extending it is V0 and let us say our V0 is I would write it here. So V0 = 1 meter per second and then the length we measure from here to here that length l0, so l0 here is let us assume that 0.1 meter or let us say 100 millimeter.

Now the final shape is something like this and the change in this length let us say is delta l**.** So now we need to calculate the epsilon dot, epsilon dot is the strain rate is we use strain rate by the way not velocity of deformation, we do not use the velocity of deformation. Here in this case V0, so we do not use that we use the term strain rate and what is strain rate, strain rate is it is a rate of change of strain with respect to time.

So it is unit is second inverse, so now strain d epsilon we know that if we take it at time t = t2, so the strain is epsilon 2 and then time t = t1 let us say strain = epsilon 1. So here in this case strain = 0 at time t1 or let us say this is corresponding to t = 0 and here let us say t = t, this corresponds to this**.** And this will give us that a epsilon 2 which is delta l by l0 ok. So now the epsilon is actually delta l by l0 and what is dt we are taking as V0 by delta l.

So this is your velocity of the deformation V0 divided by this change in length. So that will give us the time required to change the length of the specimen, so that is nothing but V0 by delta l. So

V0 by delta l it look like this oh sorry so now what is dt the time required for the specimen to have these delta l change in length will be equal to delta l by V0, V0 is this velocity of deformation. So now this dt expression we will put it here so that will give us as you can understand this delta l will canceled out that will give us V0 by l0.

And that means from here V0 = 1, l 0 equal = 0.1 that will give us 1 divided by 0.1 and as you know V0 which have meter per second 0.1 is meter. So that will give us 10 per second, so our strain rate in this case for this tensile test is 10 per second, so that is the standard. But there can be some other examples where the calculation of strain rate can be little different we need to show you that calculations how we do that.

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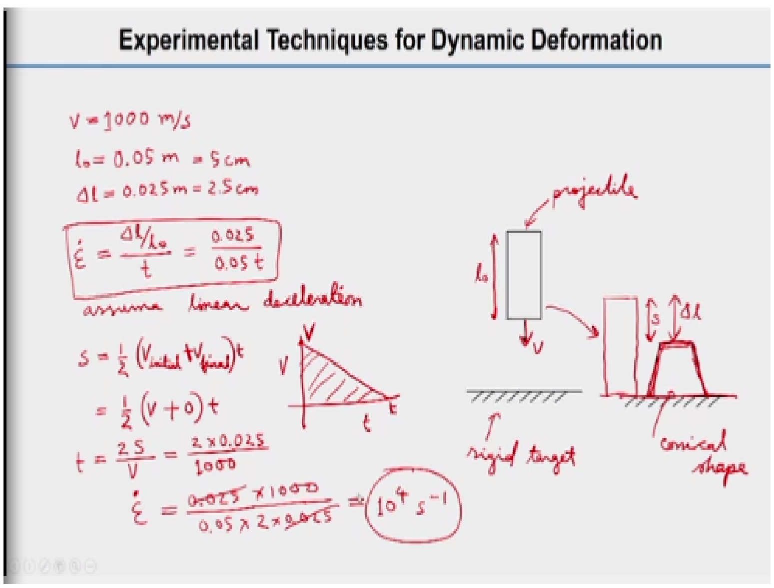

So this is the case that is a high velocity projectile, this is a project tile hit is the rigid target this is there is it target let us say rigid wall. And it has a velocity V and let us assume it is initial length of the projectile is l0 and the final length, final length means after hitting the rigid target it will take a conical shape. And the change in length suppose I am drawing the undeformed projectile close to this**,** this is the undeformed projectile length, I am drawing here.

So and this is the final shape deform shape, so this delta l is the change in length of the projectile. So let us assume that to calculate the strain rate let assume that the velocity is very high let us say the projectile is moving at 1000 meter per second. And l0 the initial length of the projectile let us assume it is 5 centimeter or that is let us say 0.05 meter and then delta l is let us assume half of it 0.025 meter or we can call the 2.5 centimeter, this is 5 centimeter.

So what we can do is to get the strain rate out, so this will be like delta l by l0 divided by time the time taken to have delta l deformation. So that will be equal to delta l by l which will be equal to 0.025, 0.05 divided by t. Now we will assume that linear de-acceleration is happening the projectile linearly de-accelerate ok. So that means let us say we have time versus velocity, so velocity is V0 and after time t is let us say time t, so velocity will be 0, here velocity will be V0.

And this area will give us the distance travel from the basic kinematic equation we have V initial + V final multiplied by t. So in this case we have the initial velocity is V which is let us say 1000 meter per second for our case. And the final velocity is 0 we have t here and then in this case also the initial velocity probably if we are writing this can be V actually it is not V0, so this will be V.

And that will give us the time now how to get the time, time = twice S divided by V, so V is 1000 meter per second and twice S, S is nothing but the 2 multiplied by 2.5 centimeter that means the reduction of the length that means these projectile move to this position. So that is equal to S, we can probably keep the time value here and then what we can do is we can go to the epsilon dot the strain formula.

And here what we will get is epsilon dot = 0.025 divided by 0.0 5, here now will put time 0 025 multiplied by 1000. So this will cancel out and that will give us 10 to the power 4 per second, so our strain rate in this case is 10 to the power of 4 per second. So this is the second example we did for strain rate calculations.

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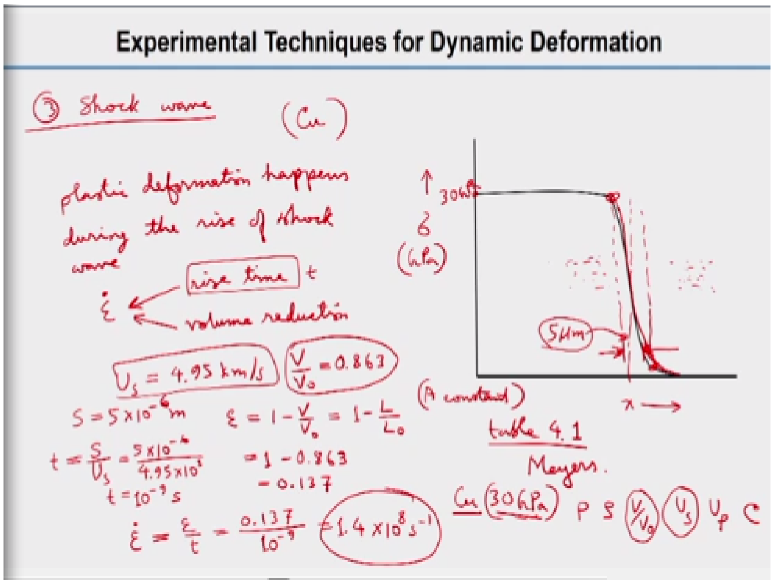

So we can do one more, so this involves shockwaves, so this is the third one I will write the third example to calculate the strain rate. So in this plot if you can see we have let us assume that the shockwave we have the sigma stress amplitude and that is in Giga Pascal and in the x axis we are showing x. And at this point it is at a very high pressure 30 Giga Pascal and as you know this is the shock front the steep shock front.

And here what is happening here is this is the material before shockwave passes through and after that the shockwave passes through the material is here. So the width if we draw a line here the width of the shock front is this one they will be very thin. That width of the shock front will be let us assume it is as 5 micrometer, so it is a very thin shock front so this is the width of the pressure rise.

Plastic deformation happens during the rise of shockwave and as you know that the width of that rise zone is very small it we can assume it to be 5 micrometer. And this rise time of the shockwave and the reduction of volume will determine the strain rate, so if you want to know the strain rate. So that rise time the time required to for the pressure rise from here to here, so the pressure rise time.

And also the volume reduction or volumetric strain will give us the strain rate or otherwise we can draw it like this. So these 2 will give us the strain rate, now you will see from our table 4.1 in our Mark Meyer's book, you can see that for let us say the material is copper and for copper 30 Giga Pascal from the table 4.1 what you can get is you can get the shock with parameters like pressure, density, specific volume.

And then shock wave velocity, particle velocity and the sound velocity, so now what we need here is we need the shockwave velocity and V by V0 the specific volume. So from there corresponding to 30 Giga Pascal and material copper, so we will get the value, so this value from the table says that it is 4.95 kilo meter per second and V by V0 is 0.863 the specific volume. And we know that shock front width is 5 micrometer which we assumed that will be very small value.

So that is we assume that S equation=5 into 10 to the power - 6 meter and then epsilon the strain is like 1 - V by V0 which will be equal to 1 - l by l0. So because assuming area is constant, so what we will get is 1 minus we have the V by V0 value here 0.863, so that will give us this strain is 0.137. And then what we need to do is we need to get the time that the rise time where we have that rise time t ok, this time will be S the distance of the width.

So you can see time required to raise the pressure, so that is the S which is 5 micrometer divided by the shockwave velocity. So that will give us 5 10 to the power - 6 divided by shockwave velocity is this one, so that is 4.95 into 10 cube meter per second. So that is give us it is 10 to the power - 9 second, so that is a very small value, so t = 1 nanosecond and then we need we can now calculate the final strain rate, so which will be equal to epsilon by t.

So this will give us 0.137 divided by 10 to the power - 9 which will give us 1.4 10 to the power 8 per second. So see this is a very high standard, if you want to go back to our earlier table, so you can see that 10 to the power 8 as we told that at a very high strain rate, the shockwave can form.

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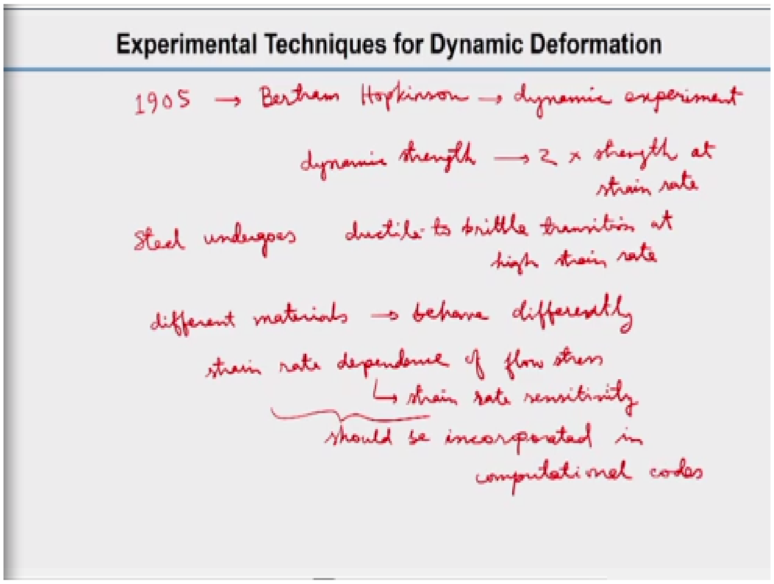

So we are discussing about the experimental techniques for dynamic deformation, the history goes back to 1905. In 1905 Bertram Hopkinson first tried dynamic experiment on material and came to the conclusion that what the conclusion is the dynamic strength of the materials at least twice of the strength at low strain rate, so that is what he found out in around 1905 A.D. Unfortunately he died in a world war 1, he was working as a pilot.

And also it was known to people that the steel undergoes ductile to brittle transition at high strain rate. Some of you already asked that questions to me that what I told you in the initial class that if we increase the strain rate then tensile ductility increases. But yes it is not for all materials sometimes the material look like more brittle or less ductility at highest strain rate. So these are the some information even known long ago but it depends on different material.

So it is very materials specific and so we will we need to know this response of different materials. So different materials behave very differently also the strain rate dependence of flow stress which we already discussed, that is a we call strain rate sensitivity in the initial lectures we discussed that sensitivity. This should be incorporated this strain rate sensitivity should be incorporated in computational calculations computational codes.

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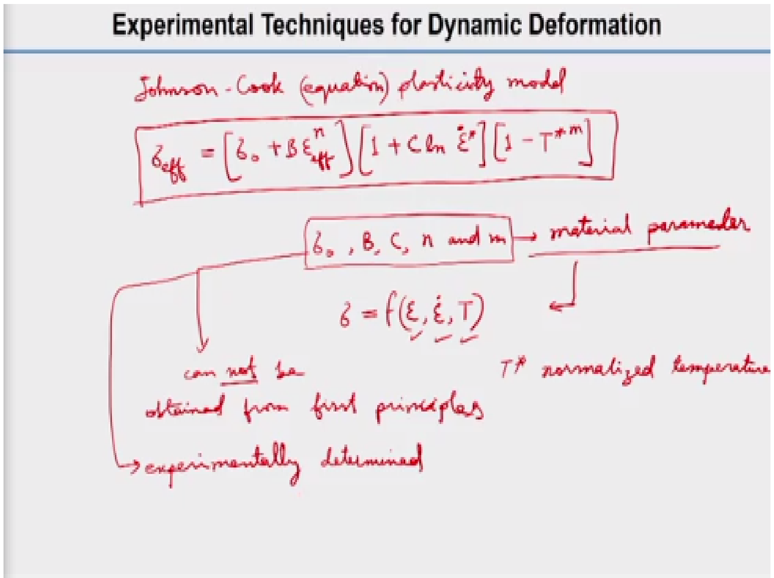

So for example very commonly used plasticity model what people use for high strain rate calculations is Johnson Cook equation or we would better call Johnson Cook plasticity model**.** That will see how the constitutive behavior looks like is sigma effective sigma 0 + B epsilon effective to the power n thus it is not ended here. So this is 1 + C natural logarithm of strain rate 1 - T star to the power m.

So here sigma 0 B, C, n and m are material parameters that means they are specific to materials, so different materials have different material parameters. So these parameters allow us to get the relationship that is the constitutive relation that means the stress dependence on strain, strain rate and temperature. So what you can see here in this plasticity model or Johnson Cook model it has all strain, strain rate and temperature terms.

And sigma effective and epsilon effective are the effective or equivalent values and T star is a are actually normalized temperature that is why we have use superscript star temperature. Important to note that, so these parameters cannot be obtain from first principles. So we cannot calculate those without doing any experiment, so these are experimentally found out experimentally determined**.**

So these parameters they cannot be obtained from first principles, so that we should take care of that. So for different materials will behave differently that we need to do a some experiments let us say split Hopkinson pressure bar then we see the response of the material how it deforms a different strain rates. So from that we can get these material parameters out and then we can do any use those parameters into computational codes.

And then get the correct or we can approximate the predictions of the material behavior from the computational code. So now we will see some materials behavior here let us say if we talk about different materials.

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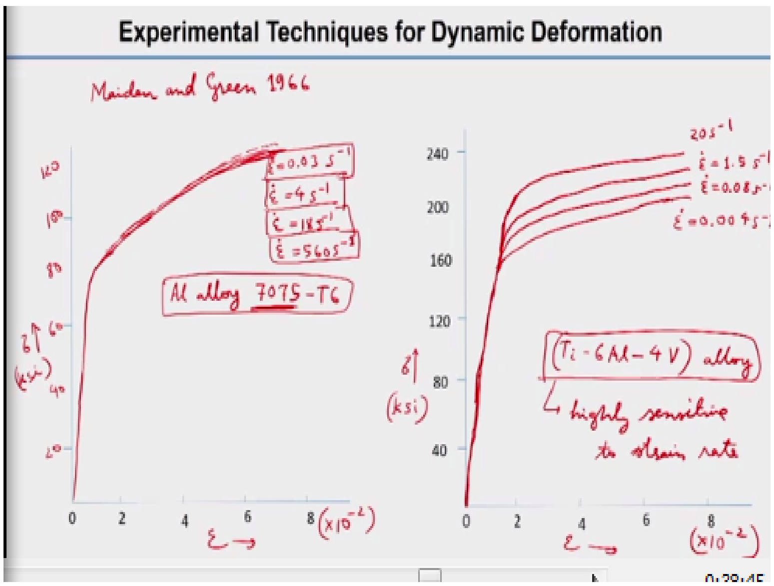

So in these 2 plots I will show you different material these are stress strain curves, let us say stress and strain here is also stress and strain. So this is stress is in this has it in ksi is the unit here, so ksi is a unit and here a strain is you know this is without any unit but we have 10 to the power - 2 here multiplied with all the scale. So now if we talk about the this first plot, so we have let us say 2,0 40, 60, 80, 100, 120.

So for aluminum 7075 material and aluminum I will write that about the material but let us see the plot. So it will look like something like this, so this is the material is aluminum alloy and it is 7075 T6, T6 shows the heat treatment condition but 7075 is the basic material nomenclature designation for this particular aluminum alloy. So it looks the stress strain curves looks like this but when you have a so this is a particular strain rate.

Let us say it is at strain rate 0.03 per second**,** epsilon dot is 0.03 per second and if you increase the strain rate let us say 4 per second epsilon dot is it let us say 18 per second and then epsilon dot is 560 per second. So these are the experiment done by in the reference made and Green it is the very old experiment in 1966. So what they found is the all the curves for all different strain rates they found not much difference**.**

There is no significant difference and all the curves very close to each other, so that means the material this material is standard sensitivity is not high and it is almost negligible. But in the other case this material is titanium 6%, aluminum 4% vanadium, so this alloy is specially a titanium alloy is very popular for suppose biomedical applications and specially nowadays it is very popular in 3D printing metal 3D printing, so they use this material.

So now let us assume we are drawing the stress strain curve for let us say a strain rate 0.004 per second it is a very slow strain rate quasi static range. And then let us say if we increase the strain rate little bit it will show a different behavior let this is strain rate 0.08 per second we have it is increase to let us say maybe 20 times. And then if we have higher strain rate like epsilon dot = 1.5 per second and then even higher it is 20 per second.

Then what will happen is this stress strain curve will be different, so this portion the elastic portion will look almost the same. And but if you go when after the yield, so it will be different. So that means it is a highly sensitive this material is highly sensitive to strain rate variation or simply I will write strain rate.

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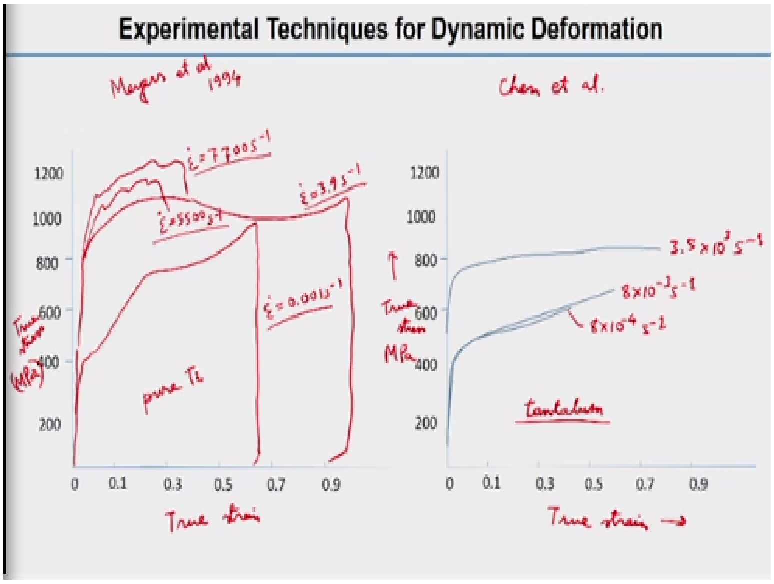

So similarly there are more materials we want to discuss, so let us say this is true stress, this is mega Pascal true strain. Similarly here also the same true strain and true stress better to write it full true stress on and true strain here in mega Pascal. There are 2 material we wanted to show the first one is pure titanium commercially pure titanium alloy and here is we have another alloy this titanium metal not an alloy.

And here we want to show then another one is tantalum, so for pure titanium which is the reference is both for Meyer's and co-workers, so Meyer's et al 1994 and the other one is Chen et al, I think a co-worker of Mark Meyer's. So if you see in this case in tantalum it is already the curves are drawn and the strain rates I just wanted to tell you this one has a strain rate of 8 into 10 to the power - 4 per second very low strain rate quasi static range.

And then if you increase the strain rate 10 times which will be also quite similar these are quasi static range**.** And then if you increase it to a dynamic range and actually it is a high strain rate range not we cannot say it is a very high strain rate because these are all relative this terms are. So if you say that split Hopkinson pressure bar has high strain rate then what will happen to explosive test or what will happen to even nuclear detonation.

So in this case then 3500 per second is a high strain rate, so you can see that this tantalum has shown this strain rate sensitivity. And in this case for pure titanium what we can get is this is the curve here the Taylor. So this curve is strain rate 0.001 per second and then another curve is and another curve we want to show you this is has epsilon dot 3.9 per second.

Then 2 more curves 5500 strain rate, this will show some fluctuation 5500, this has epsilon dot is 5500 per second. And then another one is even higher strain rate, so this has epsilon dot is 7700 per second. So these are it is very difficult to get a trend like if you can see that the quasi static grains you are getting more ductility. But if you compare the high standard case you can see that if you increase the strain rate you are getting more ductility, so which is kind of contradictory.

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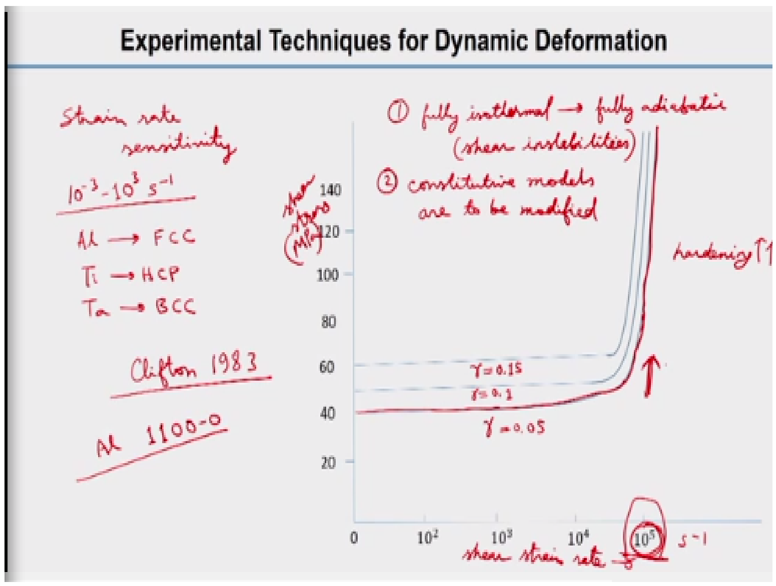

So whatever we have shown in the earlier couple of slides we are showing strain rate sensitivity. So we took different strain rate range in the earlier we have shown different strain rate range, so 10 to the power - 3 to 10 to the power 3 per second whatever we have shown in the earlier cases. But we should understand these materials are very different in structure, if you see specially the crystal structures as you can understand we have shown about aluminum alloy.

But basic aluminum has an abscess structures then we talked about titanium, titanium has a hexagonal close pack crystal structure and then tantalum T a is has a BCC structure. So the plastic deformation as we will discuss in the later part also it depends on the crystal structures that you probably studied in your B. Tech material science course. So different materials basically will behave differently, we need to get the material parameters out from the experiments.

Let us say from split Hopkinson pressure bar and you now understood that those material parameters cannot be calculated from the first principles. And so this curve what we want to show you in this slide is from a reference Clifton's this is the reference from 1983. What this reports says is if you increase the strain rate at a very high strain rate value, so this is strain rate by the way sorry this is shear strain rate**.**

And in the y axis we have shear stress that is in mega Pascal, so what happens here is this is a material this is aluminum we write it as aluminum 1100. So this is so this material, so what happened there are 3 curves here associated with a different plastic strains. Let us say the first curve the first one corresponds to a plastic strain gamma that is 0.05 and the second one is gamma = 0.1 and the third one is gamma =0.15.

So this says that the shear stress is very high when it reaches a 10 to the power 5 strain rate, so that is quite interesting. So that means that the profound effect on the computational predictions of very high velocity projectiles or shaped charges and other high standard events. So the hardening is very high, hardening increases to a very high value, we need to understand here the first thing is the plastic deformation mechanism, how the deformation process happening it changes.

Let us say it changes from fully isothermal to fully adiabatic, so we will discuss more about these in later chapters. So this can give us the shear instabilities or shear band, so we will discuss these in the later chapters. So and also second thing is the constitutive models that constitutive relations need to be modified to models like we have shown the Johnson Cook model, constitutive models are to be modified for this extraordinary or sorry for it is unusual behavior at high strain rate range.

That has a limiting strain rate if you see that this has a limiting strain rate for the strength of the material becomes infinity. So at that 10 to the power 5, so strength becomes infinity, so we need to know that whether a limiting strain rate is available and then how the plastic deformation mechanisms decide that limiting strain rate. What we discussed in today's lecture is that we discussed the basics of the experimental techniques.

The range of different strain rates of the experimental techniques for to produce plastic sorry dynamic deformation. So we also discussed how to calculate the strain rates for different cases for let us say uniaxial tensile test specimen. And or for the projectile impacting a rigid plate or for a shockwave, so we have seen how the calculations can be done. And also we have seen that the material strain rate sensitivity is different for different materials.

We discussed about some of the very well known materials and we have seen that the constitutive relations like Johnson Cook plasticity models have some materials parameters that can be determined from the experiments. For example split Hopkinson pressure bar experiment. And these parameters cannot be find out from these first principles. So we will continue these discussions in the next lecture, so we will see some we will discuss some of the commonly used experimental techniques, thank you.