Dynamic Behaviour of Materials
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Lecture-39
Plastic Deformation Under Shockwaves 1

Hello everyone, so we have discussed in the last lecture about plastic deformation at high strain rate, so we discussed about different deformation mechanisms. So this lecture we will start the plastic deformation under shockwaves, so we will see what happens if a shockwave propagates through a material. So we will see the what are the deformation mechanisms, so first we will talk about strengthening of due to shockwave propagation.

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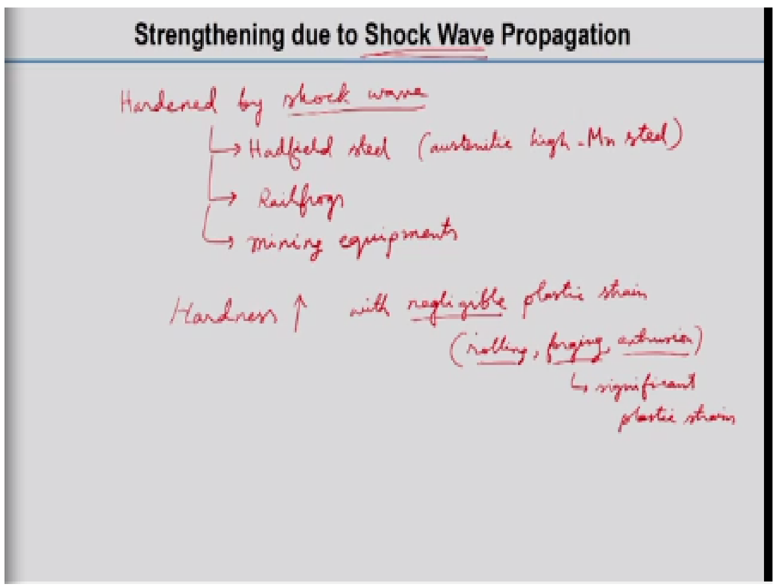

So we know that the most metals can be hardened by shockwave, and in the initial lectures we have give examples of Hadfield steel which is a austenitic high manganese steel. So these are the very popular methods for you know for a long time for hadfield steel and others are for example railfrogs or some mining equipments.

So from long ago these are the conventional materials or applications that were hardened by shockwave. And so we should understand that the hardening by shockwave we increase the hardness but with negligible plastic strain. So this is important because other methods like rolling, forcing or let us say extrusion, so these methods involved a significant plastic strain, so these involves significant plastic strain.

So why we mention these methods that we know that these are also methods for strengthening material. But if you want to strengthen with shockwaves, so what happens is hardness increases with negligible plastic strain very little plastic strain.

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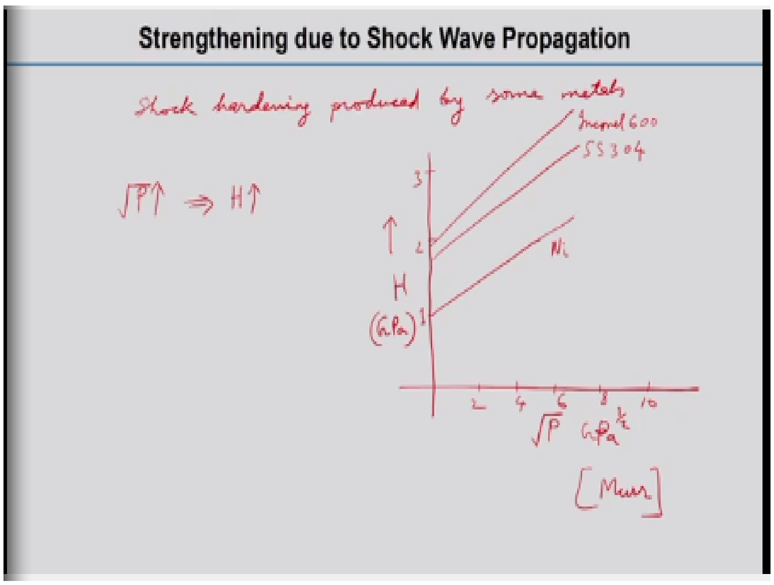

We will just see shock hardening produced by some metals, we will just get the plot those are basically from more I think this is the reference. And this is a plot a square root of pressure, this is Giga Pascal the power half and here the hardness in Giga Pascal. So for some common material let us say we have this Giga Pascal values are 1, 2, 3 and then you have the square root of pressure is let us say 2, 4, 6 you know 8, 10 something like this.

So then what happens if you have nickel, nickel will look something like this, this is nickel. And then if we talk about stainless steel 304 this will look like this, and then let us say inconel which will look like this. This may not be very accurate just please check the book for the proper diagram, this is inconel 600. So just to show you that with pressure, so with pressure when pressure increases these hardness will increase and that we can understand that there is a square root dependence, so square root of pressure increases.

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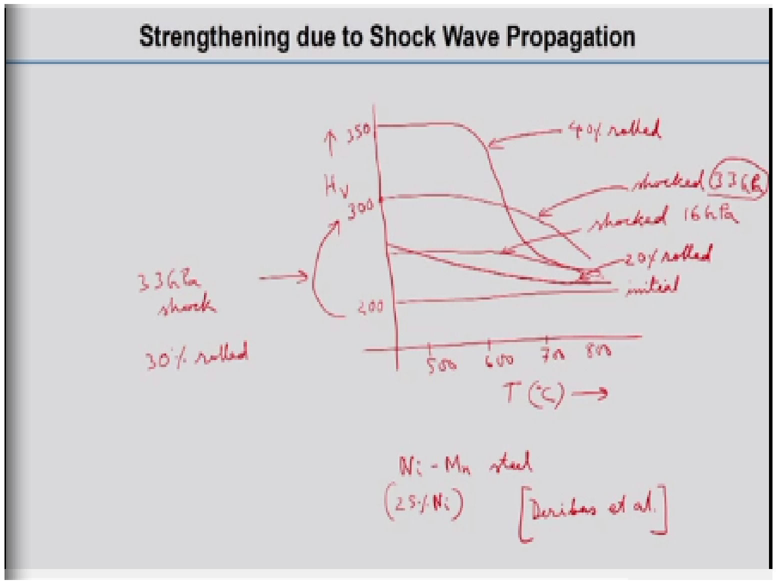

So similarly if we can see the relation or if we can see the comparison between the strengthening of the shockwave and with rolled material. Let us say what happens we can draw this, this is with illicit temperature on the horizontal axis and Vickers hardness HV this is Vickers hardness on the vertical axis. So let us say the hardness will be constant at for this is 200 this is we are having these values for nickel, manganese, steel, I think this material has 25% nickel and this is from Deribas et al, so this is the reference.

So what happen is, so if we have a 20% rolled, so if we do 20% roll, this is 20% roll the hardness will increase and then decrease with actually temperature. And then again if we do 40% rolling will look something like this, this is 40% roll and then if we apply shockwaves. So it will look like let us say for this, this will look something like this and this is shocked at 16 Giga Pascal. And then similarly if we do a shock loading at a higher pressure that will have a curve like this, so there will be let us say shocked at 33 Giga Pascal double the pressure Dalia.

So this is around almost 300 the Vickers hardness number and this is 350, so you can see that from 200 to 300 it got increased for 33 Giga Pascal shockwave, so this 33 Giga Pascal shock, so can increase the 200 to 300 Hv the Vickers hardness number. But correspondingly if we interpret probably 30% rolling will give that you know hardness increase. So this is interesting and you can see the variation with temperature as well.

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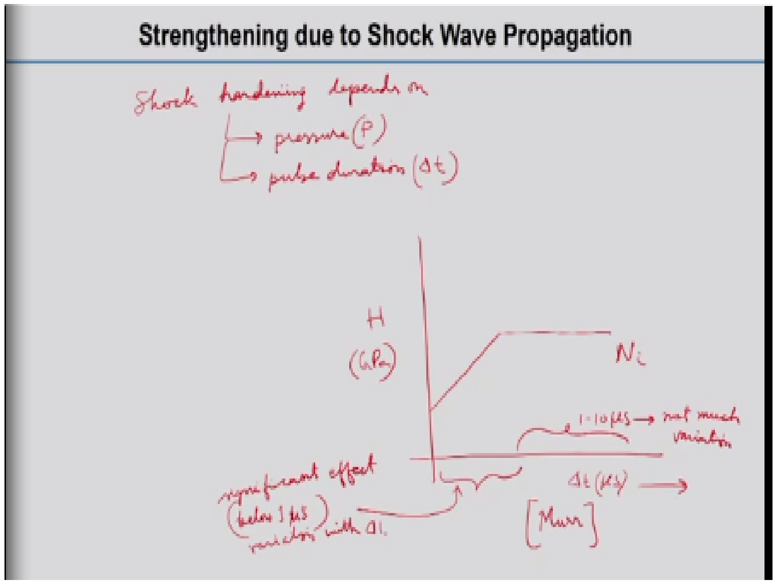

However you should understand that shock hardening, shock hardening does not depend only on pressure. So it depends on pressure and also pulse duration the shock pulse duration I would write delta t here pressure is a newer capital P. So we will see a plot again from the reference more and then that we are actually getting these from Mark Meyer’s book. So this plot has the pulse duration in microsecond in the horizontal axis and then hardness in Giga Pascal the vertical axis.

So what happens just we want to show only maybe 1 material, so the other materials also will look like this, so this will look like this for nickel this is for nickel we are not drawing for other materials there is just only one example. So what you can see is, so in this range generally this range for most of the materials let us say 1 this is below 1 microsecond. And the other range is this range that means let us say from 1 to 10 microsecond.

So in for 1 to 10 microsecond not much change or not much variation of the hardness, but in this case below 1 second, so the variation is significant, we can add significant effect of shock oh sorry the defect of actually we can say yeah effect of shock, but we can say that this is that varies with delta t. So that means what we are talking about is variation with delta t, that is the shock pulse duration.

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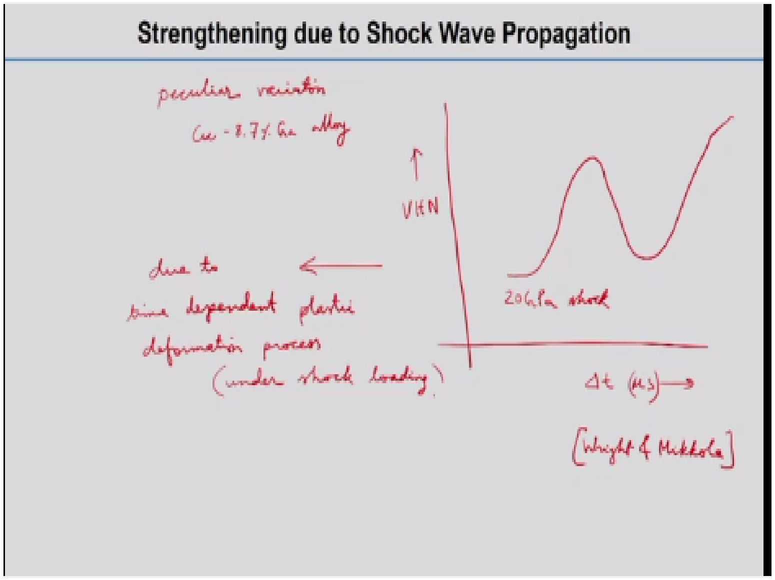

So there can be some peculiar behavior like peculiar variation of some materials like let us say copper with 8.7% of gallium alloy. So these variation this is from Wright and Mikkola, so the original plot from. So if we have delta t in microsecond in the horizontal axis and then VHN Vickers hardness number, the same age you can write. So that shows in 20 Giga Pascal shock loading, so this will vary like this, this is at 20 Giga Pascal shock.

And if you increase the shock that will be even it will look it will go a little higher, so why this happens this behavior is due to time dependent plastic deformation process**.** So that means under shock loading or induced by shock loading.

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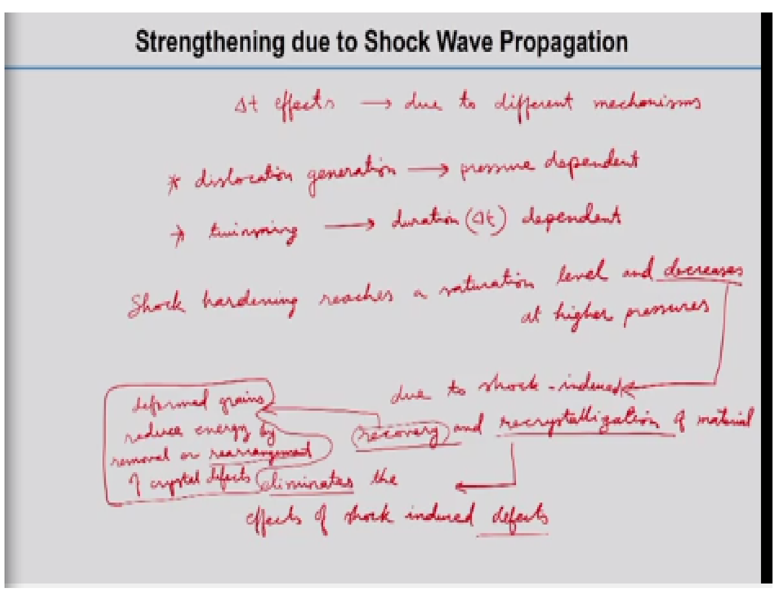

So whatever we discuss this pulse duration effect that means we will just write delta t effect whatever we discussed are due to different mechanisms. So it may not be for you know single mechanisms, we should understand that that there are many mechanisms related to this strengthening behavior. And this dislocation generation out of these is pressure dependent and the another deformation mechanism twinning that is also as we know a plastic deformation mechanism.

So this twinning is depends on the duration, duration dependent actually this delta t dependent. So we should understand this shock hardening, so we can call it as a shock hardening, hardening due to shock loading. Shock hardening will not increase indefinitely, so it will reaches a saturation level and decreases at higher pressures. So why it happens this is due to this the decrease actually this decrease is due to shock induce recovery and recrystallization of material.

This is we are talking about crystalline materials, so what happens is this will eliminate the effect of shock induced defects. So as you know I think most of you sorry this is recrystallization, so most of you know about recovery and recrystallization, I am sure that you have studied in your material science basics courses. So what happens is these are mostly related to even heat treatment, so when you are heating the material recovery and recrystallization happens.

But in this case as you know there will be temperature rise and the recovery means here is deform range will reduce energy by removal or rearrangement that is what happened in recovery rearrangement of crystal defects, different kind of defects.

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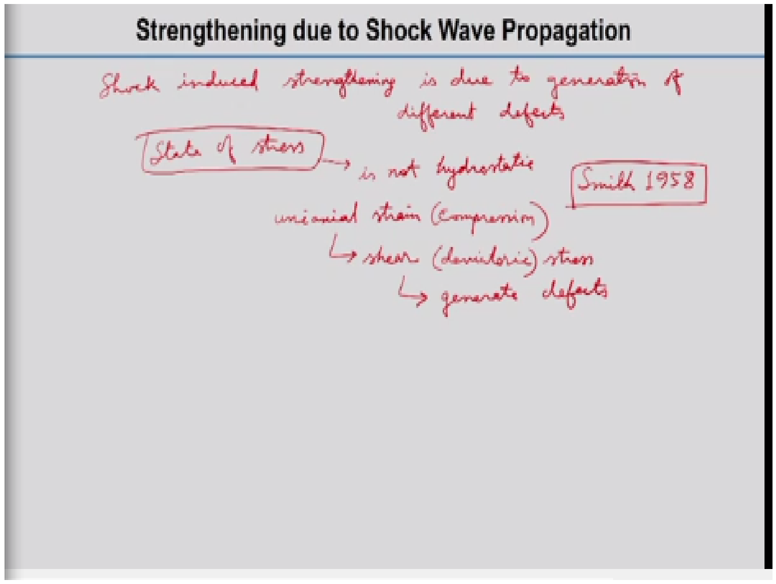

So there is a point defects, line defects, so these will happen during recovery, so due to that, so what I wrote it here that eliminates the effects of the shock induced defects. Because shock will induce some defects and this will be during recovery and recrystallization that means recrystallization means the nucleation of new range and you know those range will grow.

So during these processes rearrangement of these defects and then nucleating new grains, so what will happen that whatever defects were generated during the shock loading will be now reduced or eliminated and that is why the strengthening will decrease after the reaching the saturation pressure during shock loading. So that means if you go beyond a limit then it will stop increasing that means the hardness will stop increasing, a strength will stop increasing.

And it will decrease because of these recovery and recrystallization process. By now we understood that this shock induced strengthening is due to generation of different defects. So and then I just want to mention that the first of the researchers who actually have a the first probably one of the first publications who actually presented these shockwave effects on plastic deformation is Smith. He published in 1958, so fundamental deformation modes induced by the passage of shockwaves.

So in those discussions, so our state of stress is important, so we should understand that the shock loading is not hydrostatic. So it is because it is mostly uniaxial strain or we can call that is in compression the shock we discussed about that earlier this is in uniaxial strain. And this actually produce shear, so shear is the not hydrostatic is the deviatoric stress, shear stress and these shear stresses as we earlier also discussed they generate defects.

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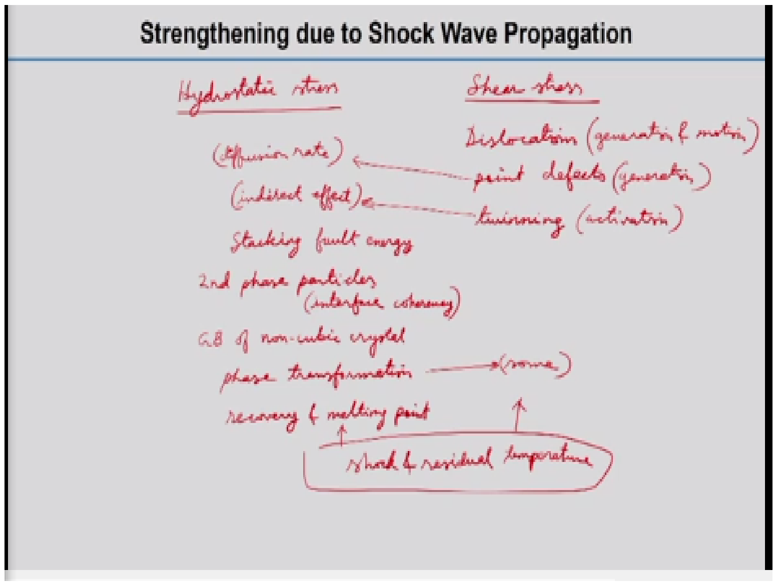

So if we discuss different defects, so we will just see the difference between the hydrostatic stress and deviatoric stress or rather we would write shear stress. We will not give any definition here all of you know that but we just want to discuss it in terms of these defects. So the shear stress can generate dislocations and point defects and the twinning. So shear stress is responsible for most of these defects and then hydrostatic stress can be related to you know stacking fault energy.

That means taking fault energy is influenced by the hydrostatic stress and then second phase particles, so basically the interface of the second phase particles. And what happens that because this depends on the coherency, so I will just write interface coherency, we can discuss that later. So for second phase particle like precipitates or some particles, so and the grain boundary I will add GB for grain boundary specifically for non cubic crystals.

So hydrostatic stress will affect that and also phase transformation like our martensitic phase transformation are mostly affected by hydrostatic stress. And then recovery and melting, recovery as I told you recovery and melting or you can write melting point is affected by hydrostatic stress. And then shock and residual temperature related to shock they are affected by actually both of them, so both shear stress and the hydrostatic stress.

So and also some phase transformation can be influenced by shear stress not all the transformations of the hydrostatic stress but mostly it is hydrostatic. And then twinning has some indirect effect from hydrostatic stress and also the point defects diffusion rate can be controlled by hydrostatic stress. So but the generation is due to this is generation, so we are talking about the generation here even dislocation this is generation and the motion are due to shear stress.

And then point defect generation is due to shear stress but diffusion rate is controlled by hydrostatic stress. And the twinning is as you can understand that activation it depends on the mostly shear stress. So we should understand these differences, so that will help us to you know to help us to know that what will happen when a shock loading act on a material. So we can now from this discussion hydrostatic stress and shear stress differences we can find out that which defects or which phenomena will prevail. So we will discuss about this now precipitates strengthening.

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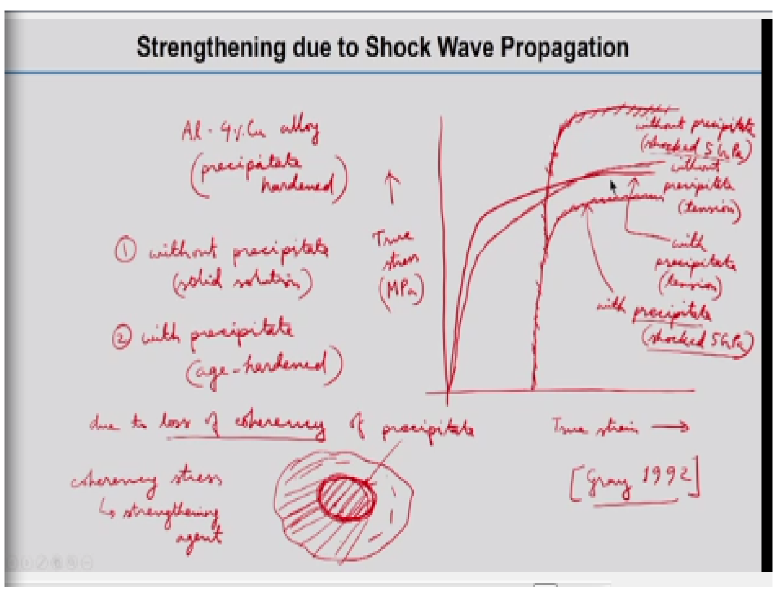

Their strengthening related to the precipitate and we will discuss under what happens in the shock loading. So this is from gray 1992, so what these says is, this is a little bit interesting that , so what happens is this is a true stress versus true strain. True strain in a horizontal axis and true stress in the vertical axis, so this is in Mega Pascal and let us say we have this is a strain. So we do not need to have the values but you need to understand that that shockwave can produce high strengthening this is more than that whatever tension test we do.

So any axial tension we do, suppose if we do uniaxial tension for this material, so what this publication says is aluminum 4% copper alloy, it is an aluminum alloy with 4% copper and this is precipitate hardened. But we can just take the solid solution without the precipitate harden, so what we can do is there are 2 cases, case number 1 without precipitate just the that means the solid solution.

And other one is which precipitate or that means precipitate hardened or is hardened that you check how we do age hardening how to produce the precipitate that we are not going to discuss there. But the first we will take the solid solution one ok, so what we will draw first is first case is without any precipitate let us say this is without precipitate case, without precipitate in tension ok, that means uniaxial tension test.

And then we will take the another one which is with precipitate that means age hardened, that is also in tension. Here in this case that you know the precipitation does not have much effect on the strengthening, so although without precipitate it has a quite high strength. So now what we will do I mean what the publication it shows that there are some shock loading.

The shock loading if we do 2 cases first case is this one, that is with precipitate and that is in shock loading, shocked at 5 Giga Pascal. And if we increase the shock pressure, so this will look something like this, so this is without precipitate and that is again as shocked at 5 Giga Pascal. So what you can understand this figure is what we understand this plot is that for tensile test, we can see that there is even for with precipitate and without precipitate case.

There are not much difference and in this case it is not very you know normal but still it is the with precipitate case, we are getting actually not very high strength but some other materials you can get much higher strength with precipitate. But in this case when we do shock loading at 5 Giga Pascal you can see that without precipitate shows much increase in strength.

So why that is happening it was explained as due to loss of coherency or precipitate, so and then that induced by shock loading. So what happens is this loss of coherency, first we need to understand what is coherency. So coherency please study about that but I just want to tell that so the you have a precipitate and you have these atomic planes, this is the precipitate. Let us say this is the precipitate and you have a matrix surrounding it, so this matrix rounding it.

So there are these atomic planes will be different, so now whether these atomic planes of the matrix is matching I mean matching does not means exactly matching but I just please check it what is incoherent and what is coherent and what is semi coherent with dislocations. So this due to this coherency there are some coherence is stressed generated, so that is called coherency stress ok. So this coherency stress are the strengthening is not and that means they act as an obstacle.

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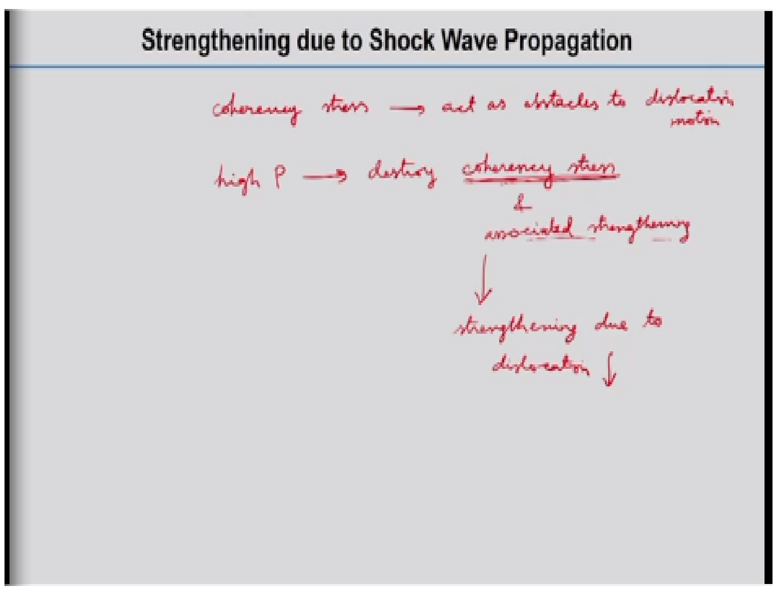

So write in this next slide coherency stress act as obstacles to dislocation motion ok. So what happens when you have high pressure due to shock loading, high pressure that can destroy that coherency stress. We are not going to discuss much about it please if you are interested please study and what is coherent incoherent and semi coherent interfaces.

So that what I meant by interfaces if you go back to the previous slide this interface between the precipitate and the matrix, so coherency is referring to that precipitate matrix interface. So this high pressure destroyed a coherency stress and also the associated strengthening that is strengthening due to coherency stress. So that is why these lead to strengthening due to dislocations decreases.

So why we are discussing this because we can see from here, so this curve does not have precipitates it is only the solid solution. And on the other hand, so you have this curve which have the precipitate, so what happens when the precipitates are there. So the due to shock loading because these 2 curves are shock loaded at 5 Giga Pascal due to shock loading, due to high pressure what happens the coherency stress is destroyed.

That is the coherency that means in between the precipitate and a matrix that interface. So that decreases the associated strengthening that means the dislocation motion obstacle are reduced and then strengthening is decreases. So that is why we see the differences so that difference is not can be seen in case of uniaxial tensile test. The shock loading is very different it is done at very high pressure and the mechanisms of deformation is different.

So with that, so we are closing for today. So what we discussed today is mostly strengthening mechanism related to shock loading. And so we will continue these discussions in the next lecture, thank you.