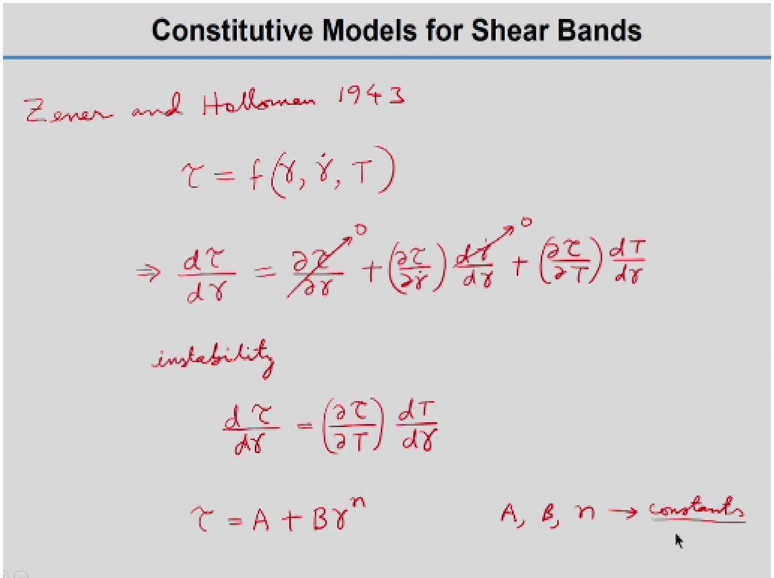
**Dynamic Behaviour of Materials**
**Prof. Prasenjit Khanikar**
**Department of Mechanical Engineering**
**Indian Institute of Technology - Guwahati**

**Lecture - 43**
**Shear Band 2**

Hello everyone, so we have been discussing about shear bands that is shear instabilities under high standard loading. So we already discussed about the basics of shear bands. So today we will discuss very simple constitutive modelling for shear band, we will just very briefly describe and then we will discuss about the methodological aspects of shear band.

**(Refer Slide Time: 01:00)**

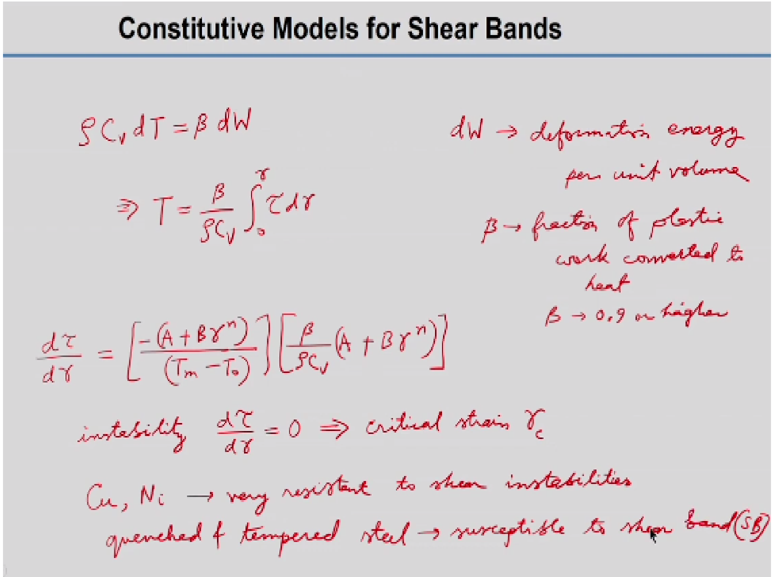



So whatever we will be discussing here it is mostly based on the work of Zener and Holloman, that is a very old work of 1943. So for the calculation of shear band, so what we need to assume is that the shear stress tau is a function of gamma dot T, temperature, shear strain rate and temperature. So from here so what we can do is so this work hardening rate, so the derivative of tau with respect to gamma, which we can write in terms of partial of tau with respect to gamma and then partial of tau with respect to gamma dot.

So it should be d gamma dot, d gamma plus partial of T, partial of tau with respect to T, here, it is multiplied by dT d gamma. So if we want the instability condition, instability that means where the stress-strain curve will you know start to decrease. So this will be 0 and then d gamma dot that means the constant strain rate we can have this as 0. So ultimately it will you know boils down to only partial of tau with respect to T and dT d gamma.

So if we can use the work hardening power rule that is isothermal work hardening which is equal to tau equal to A + B gamma to the power n, so these A, B and gamma n are constants and they should be actually dependent on temperatures, but we are assuming them as a constants. Then we can calculate the increase in temperature with the help of this relation.

**(Refer Slide Time: 03:43)**




Density into heat capacity, dT the temperature rise is equal to beta dW, which is the deformation energy per unit volume. The plastic work per unit volume and the beta is the fraction of plastic work converted to heat. So as you have discussed earlier also beta can be 0.9 or it can be or higher than that. Generally it is assumed as 0.9. So with that what we can do is we can get even temperature.

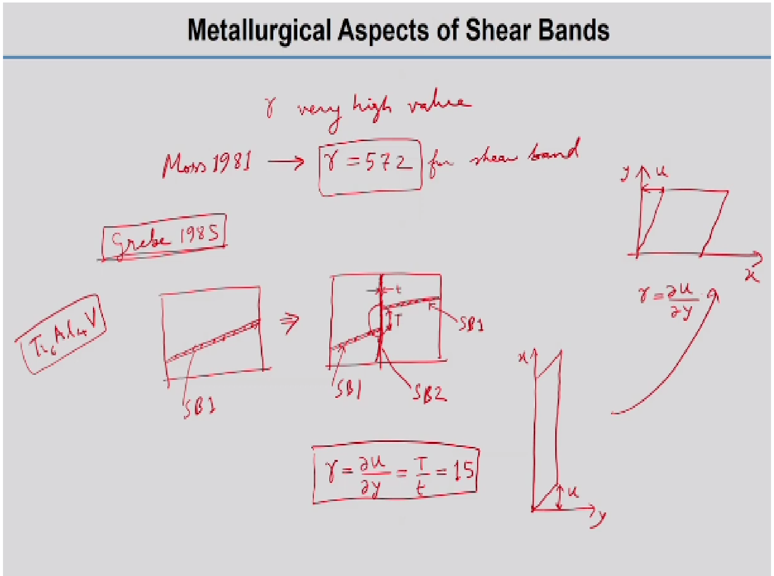
I am not going to write the intermediate steps, so this is just a brief introduction to the constitutive models, we are not going to write each and every step. Please check in the textbook for details. So this will be 0 to gamma tau d gamma. So where after all these calculations you can derive a final expression which is something like this. This is - A + B gamma to the power n and TM – T0.

T0 is the initial temperature and Tm is the melting point and then beta Rho CV A + B gamma to the power n. So this is the final expression and for instability. So this will be, instability means when the stress-strain curve will you know decrease or go down at that instability, so this will be equal to 0 and that will give us the critical strain gamma C. We should understand that different materials have different behaviours like copper, nickel.

They are very resistant to shear instabilities and on the other hand quenched and tempered steel is very sensitive to shape and formation or susceptible to shear band. So we will use SB for shear band for now onwards SB. So one weakness of these method is as we have already told that we assume these as constants especially the B which may have a temperature dependent.

This can be a variable with temperature, but we are assuming it is constant. So this is a limitation of this model. What we will discuss next is the metallurgical aspects of shear bands.

**(Refer Slide Time: 07:45)**




So this shear strain gamma that can have a very high value, it can have very high value for some shear bands like most 1981 demonstrated that a value of 572 gamma is a 572 for a shear band. So that means sorry whereas actually shear strain this will be your u and this is y axis and x. So your gamma is equal to partial of u with respect to y that is the shear strain. So you can see that that high number 572 was reported in 1981.

So that means in the shear band region the severe shear strain localization region, the strain is very high as compared to the other part of the material. So there is another work of Grebe in 1985, it is very interesting so how you can see which are micrographs, we can see the exact micrographs and mark me as, I will just draw a schematic here. So suppose in this material titanium 6 Al4 V 6% aluminium, 4% vanadium material.

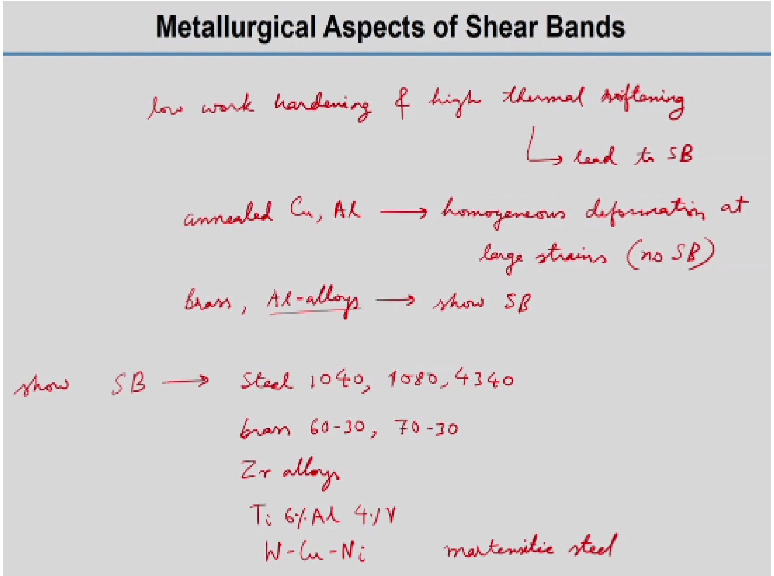
So what happens there is a shear band formation like this, this is the shear band, let us say this is we call shear band 1, because there will be one more shear band will build up here. So in the next case what will happen, there will be a second shear band and this first shear band will be you know it will like slide little bit. The first one will you know intersect the second one.

I will show you what is the second one, this is the second shear band, the vertical one, though this second shear band actually, sorry this one is 2. The second shear band intersects the first one, so producing a step here. So this is the step and this step is let us say, this distance is T and let us say the thickness of this shear band is t in the second shear band, you can see this is the first shear band and even this is also the first shear band.

So it was not like continuous now. So what is happening is, how we can calculate the engineering shear strain if you draw this part of the band in a bigger scale. So what it will look like is something like this, only the band area right, so only the band area. So if you compare it with this, let us say you have y here, you have x here and this is your u. So your gamma will be partial of u with respect to y.

And that will be T divided by t which is what the Grebe 1985 publication says that it pound to be 15. So that means the engineering shear strain is 15 which can be very well you know described by this intersection of the 2 shear bands. So this is a very interesting example how we can calculate with the help of these 2 shear bands. As we have discussed that the different materials can have different you know resistance or different behaviour regarding the shear band formation.

**(Refer Slide Time: 12:16)**



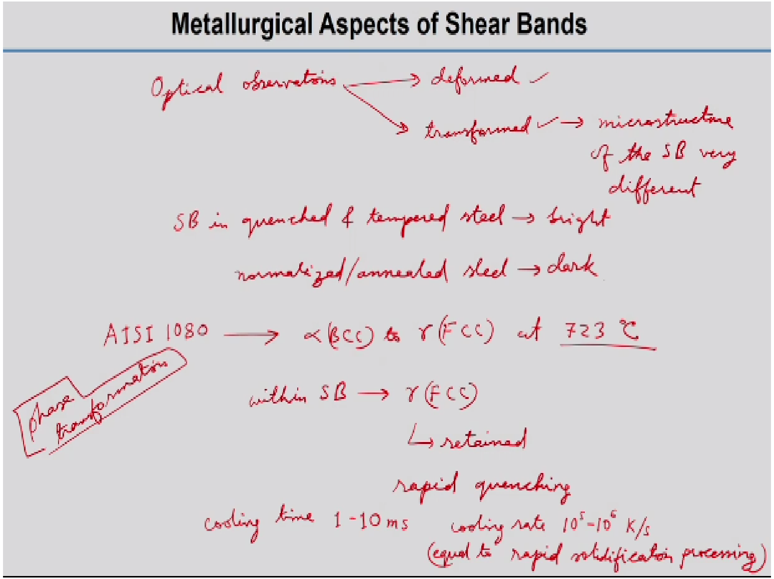

So the basic idea is the low work hardening or strain hardening and high thermal softening will lead to shear band as we are writing for shear band. So if we see different materials let us say for annealed copper or aluminium, this show homogeneous deformation at large strains that means, no shear band, so but otherwise if you see some alloys of copper, some brasses, and let us say aluminium alloys, which is like is hardened aluminium alloys, they show shear bands.

So why it is happening because in annealed copper or aluminium there is less dislocation density and then the work hardening can be more and that is why that the homogeneous deformation can be seen at very large trends, but for these alloys it is suppose for aluminium alloy, it is over as the aluminium alloy that means it has precipitated already it has strengthened and strain hardening will be less.

So you know significant shear band formation, so there are some other alloys which shows shear band, I mean permanently like steel 1040, 1080, 4340 and brass I think and brass 60-30, brass 70-30. So and then zirconium alloys, then titanium as I showed you, titanium 6%, aluminium 4%, vanadium and then tungsten alloy like which copper and nickel. So also martensitic steels like which are quenched and tempered, martensitic steels.

So these show shear bands, most of the materials at very high strengths show shear bands, but not all are so significantly you know I mean undergo shear bands or maybe sometimes the shear bands for some material may not be very in a well-defined with a well-defined shape like bands, but it can have shear strain localization.

**(Refer Slide Time: 15:49)**




So from optical observations the shear bands can be classified into 2 different categories. So I mean that is the classification used by the Meyer's book, but it may not be very universal classification. So this one is deformed and one is transformed. So the transform is a means that that microstructure of the shear band is very different than the other part, the surrounding areas.

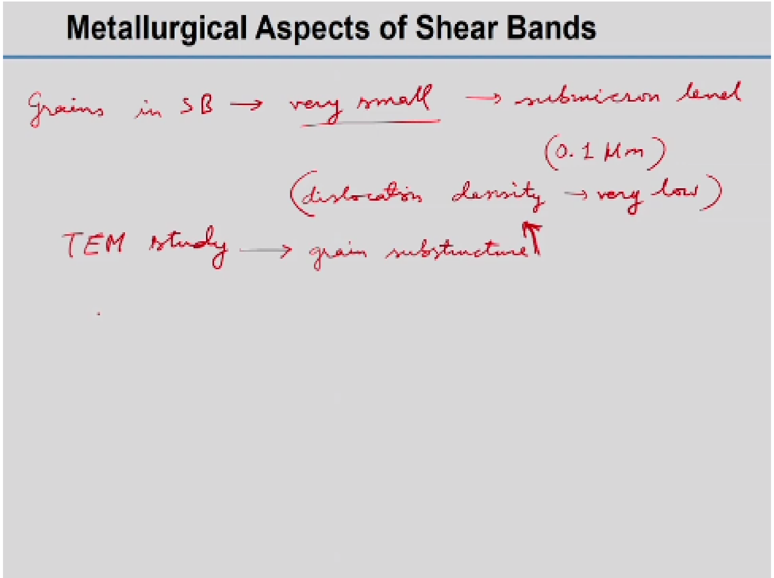
So for example, shear banding quenched and tempered still is bright and on the other hand normalized or annealed steel or annealed steel have dark appearance. Annealed steel have shear bands, those are dark. So it is important to note that some of the materials actually undergo transformation like the steel 10 AISI 1080 that is the eutectoid composition so that has a phase transformation from alpha BCC to gamma FCC at 723 degree Celsius.

So you know about that I think from your iron carbon phase diagram. So if within shear band area that temperature is achieved, then so this phase will be converted to gamma FCC that gamma phase and it will be retained at room temperature, it will be retained because it undergoes rapid quenching because the heat conducts you know to the surrounding areas once the plastic deformation is stopped.

And then this cooling time is cooling may be very fast, cooling time can be let us say typical cooling time is in millisecond order 1 to 10 millisecond and this is may be cooling rate, the average cooling rate can be achieved like 10 to the power of 5, 10 to the power 6 Kelvin per second. So these are like equal to the cooling rates obtained in rapid solidification process kind of equal to repeat solidification processing.

So what we have discussed here is about the phase transformation, phase transformation so phase transformation can be seen in some materials where the transformation temperature is not very high and then due to the high standard loading in the shear band region that temperature can be reached and that is how the some of the phases got transformed into you know another phase and then those new phases can be retained because of the repeat quenching.

**(Refer Slide Time: 20:27)**

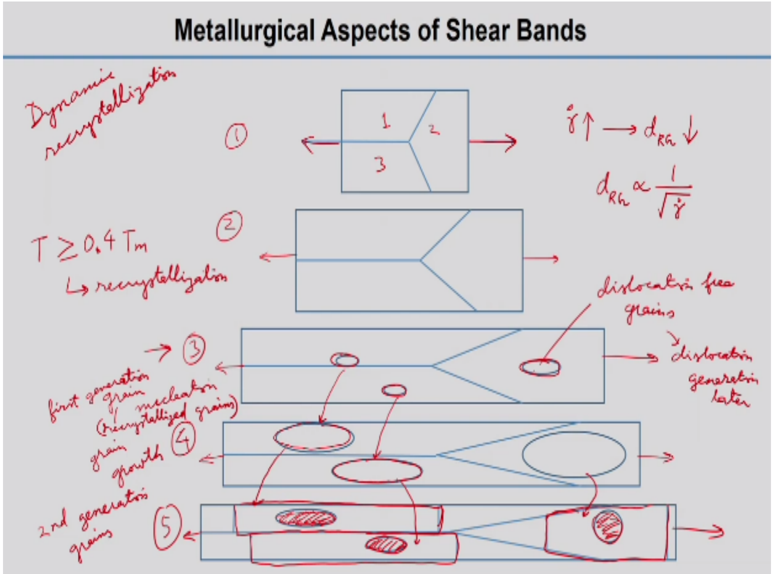



It is interesting to note that that the grains in the shear band regions are very small, grains in shear band are very small, not like the you know the parent material or the original material. So they are submicron level. Some of the grains in the literature if you find it like 0.1 micrometre level because in general a metallic material may have a very big grains like big means as compared to this, it can be 50 micron or 100 micron, but in the shear band area.

So this are in mostly in you know less than a micron or you know very small grains. So also dislocation density in many of the research work was found to be very low and many of these grains. So for that as you can understand transmission electron microscopy study is required to understand all these mechanisms because even the grains are very small. So if you want to see inside the grains, so you need to go for TEM study, transmission electron microscopy study.

So those micrographs will give you about the grain morphology or grain substructures like what is inside the grain and that will include even dislocations density we can see that. So basically what is happening here why these grains are very small because there are some recrystallization mechanism which we call dynamic recrystallization because during the deformation the recrystallization happens.

**(Refer Slide Time: 22:27)**




So we can see that with the help of this diagram which is from the Mac Meyer's book and so this says that when a material undergoes some deformation, let us say this is the material undergo some deformation there are let us say 3 grains here. So these are the grains we are showing only a small part of it, this is 3 grains and then it is continuously under deformation. So these are now the material is elongated and then at step 3.

So we have step 1, step 2, 3, 4 and 5 at different you know deformation. Now you know the step 3, what happens in there are new grains are generated. So as you can understand if you know about the recrystallization. So if the temperature is equal to or greater than 0.4 of the melting temperature, the recrystallization can happen, recrystallization can happen as you know that shear band produces very high temperature that can be possible that we can reach some temperature which is more than 40% of the melting temperature.

So when we continuously deform this material then we are deforming even here and then you know we are deforming the material then what will happen is this will generate again new grain, so we can see these grains are now growing bigger. So this grain is now here, this grain will look like this. Now it will, the grain growth, so this we can write as grain growth in the steps and then this is grain nucleation or start of the recrystallization process.

Grain nucleation and probably what we can write here this is we are talking about dynamic recrystallization, we call it dynamic because it happens during the deformation. So this is what happened is, these are the first generation of grain nucleation or we call them these grains, we call them recrystallized grains, so but then again these grains suppose this grain is now converted to this.

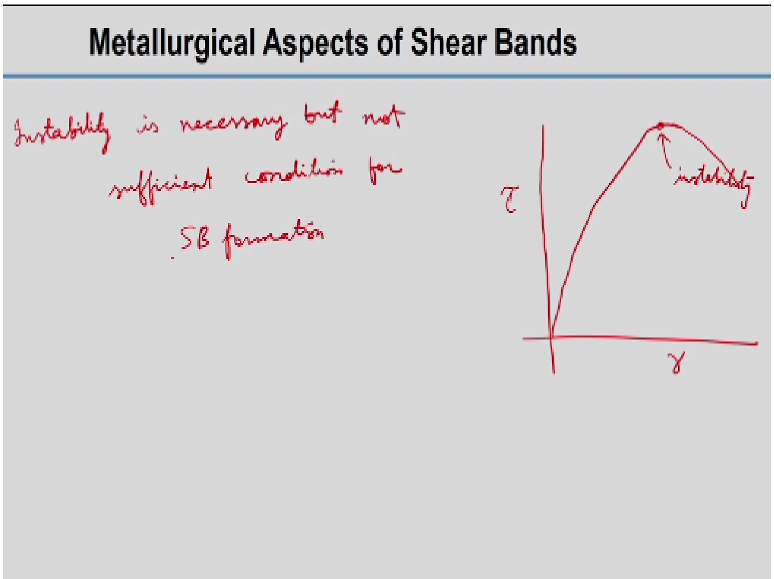
You know it is now bigger and then this grain forms this grain, and similarly, this grain from the new grain this one okay. So what happened again because we are continuously deforming it and we are talking this inside the shear band, we are talking about the inside the shear bands because there are high temperatures involved in it and the shear strain is very high. So what will happen there is next generation of the grain that means this is the grain, new grains, the second-generation grain will come up.

The second generation grain will come up, so I should write second generation grains. So here we can write first-generation. So this process will continue if we will deform more and if the temperature is high enough and the strain is high. So this will continue to do so and if you can understand that if you know about the recrystallization we have not discussed much in this course, but recrystallization will give you first with dislocation free grain.

And then dislocation free grains, but then dislocation will generate later, it will happen, but ultimately probably this shear band region can give you small grains with less dislocation density as compared to the surrounding region. So another observation is if the strain rate increases the you know size of these grains this recrystallized grains I will just write drz, drz means let us say the size of the recrystallization grains will decrease.

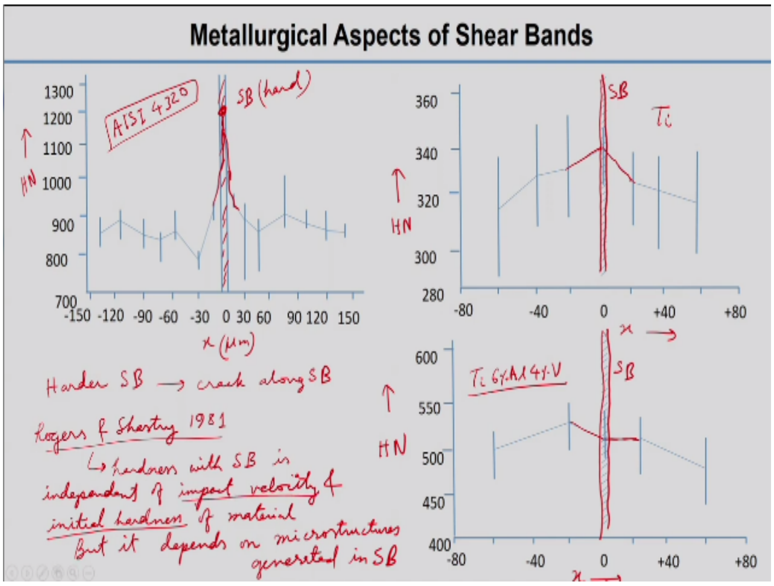
Some of those researchers actually found some relation of these size of or the diameter of the recrystallization grains is proportional to 1 by gamma dot that is 1 by square root of gamma dot that means if the shear strain rate increases that size of the grain will be even you know smaller.

**(Refer Slide Time: 28:10)**




And one thing to mention here is that that instability, so whenever that means we are talking about a shear stress, shear strain curve, so this curve when it will decrease from the maximum stress. So this is the point of instability. So instability is necessary, but not sufficient condition for shear band formation I will write SB. So that is an important conclusion from the researchers. So that means the instability can start, but that does not mean that shear band will form.

**(Refer Slide Time: 29:18)**




And also there is another very interesting finding is that some of the materials if we compare the hardness let us say this hardness number we have here is increasing and this way the distance this is the shear band region. So this is in micrometre level and then similarly, here also this is in micrometre and then this is some hardness number. Yeah, this hardness number. So what we can see that these are the shear bands.

So we will show that what is this because these are for different materials first I should draw these lines. So that you make sure that this is the shear band region, so shear band, shear band and shear band. So what are these 3 materials, so first one is AISI 4320, which is quenched and tempered steel and the second one is titanium and the third one is titanium 6%, aluminium 4%, vanadium.

So this is as you can understand it is a very common titanium alloy which is even nowadays used in 3D printing, metal 3D printing it is a common material in metal 3D printing. So what happens if you see only this still it has this steel has a very high hardness you can see that the hardness curve goes like this and this is the peak hardness here. This is the peak hardness here and then it goes down again.

So in the case of this titanium this is not that high that hardness in the shear band region is not that high and even in case of this alloy this is very less even lower in a surrounding region. So different material will show different behaviour, but we should understand that if we have a harder shear band that means in this case you can see that very hard shear band. If it is hard shear band that can lead to crack formation along the shear band.

So that is one important aspect we need to look for, another one the conclusion from the very early research work of Rogers and Shertry in 1981, they have concluded that the hardness within the shear band region is independent of impact velocity and initial hardness of the material or the parent material that means. The parent material and but it depends on micro structures that generated within the shear band in or within the shear band.

So what they did they did an interesting experiment, so what they did, they heat treated 4 different steels of different carbon contents, let us say 0.2%, 0.4%, or you know 0.6%, 0.8% of carbon and that they heat treated these 4 steels to the same hardness and then they tried with you know tried to produce shear band with high strain rate loading then what they found is that with different carbon content the shear band hardness is different.

And shear band hardness vary linearly with carbon content that means the initial hardness as we have wrote here, the initial hardness and the impact velocity were same and but because of the microstructure that generated due to high carbon content are different. I mean due to variation of the carbon content are different in different samples and they found that the hardness will very high hardness vary with you know with carbon content.

So that is an interesting result and that means we can say that the initial hardness of the material and the impact velocity has no effect or very less effect on the hardness of the shear band and that will depend on the microstructure generated in the shear band area. So with that we are closing this chapter that means the shear band instability, what we discussed is that the shear band is nothing but the shear strength, severe shear strength localization.

But when it is a kind of a very thin strip in the micrometre level then we call it as a shear band, but some materials may not show very well defined band structure, but still it goes you know a severe shear strength localization and the basic idea of shear band is that there are high temperature generation because the less time for you know the temperature to diffuse or conduct away from the shear band area.

So due to high strain rate so at a very less time so the high temperature generated and that temperature it you know makes the material soften that called stumble softening but thermal softening and work hardening are there competing mechanism. So and then the instability of the stress-strain curve does not you know always say that the shear band will form instability is necessary, but not the sufficient condition for shear band formation.

And we have also showed that the microstructure inside the shear band can be very different than the surrounding region it has very small grains because of the dynamic recrystallization and also the hardness of the shear band in some material can be higher and that can lead to crack formation. So with that, so this is all for shear bands. So the next chapter will be dynamic fracture. We will discuss on dynamic fracture in the next lecture. Thank you.