Dynamic Behaviour of Materials
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Lecture-30
Shock Wave Induced Phase Transformations 3

Hello everyone, so, in the last lecture we have discussed about phase transformation, shock wave induced phase transformation. And we have seen that relation between this phase transformation and rank and hugonoit goals. So, today we will continue these discussions and we will see some of the examples of the materials that undergoes Shockwave induced phase transformation. So, there are some common Example of free software windows phase transformation one is already mentioned about this.

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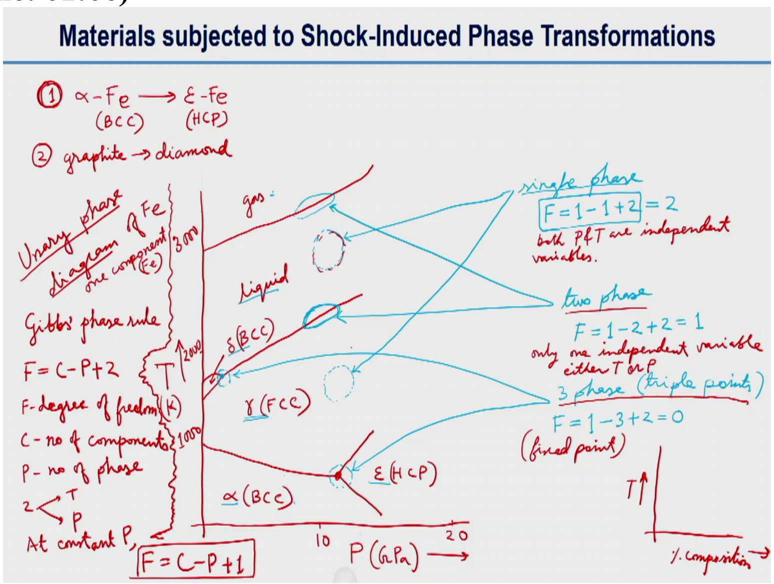

Alpha iron transformation to epsilon iron. So, as you know, this first one is BCC and then after transformation it will be hexagonal clothes pack structure and the second example is graphite to diamond phase transformation under shock loading graphite to diamond. So, we will first talk about the number one phase transformation that is Alpha iron to f7 iron. In a previous class, we already have shown that this phase diagram unary phase diagram of iron.

So, this is gives me unary phase diagram of iron FE. So, these phase diagram is in the y axis temperature axis and x axis is Pressor access pressor is in terms of Giga Pascal and temperature is in terms of kelvin. So, for this phase is the gaseous phase, this is the liquid phase and here in this phase the small area small region will be delta phase Delta iron, which is BCC and this area is gamma iron this is Gamma phase FCC.

And the lower temperature it has BCC crystal stocks, that is alpha phase and then f7 phase which hexagonal closed structure at very high pressure. So, this pressure is 10 Giga Pascal, 20 Giga Pascal here and then temperature is like thousand Kelvin, 2000 Kelvin, 3000 Kelvin. So, and as you know I think all of you know about it about the phase diagrams and about gives phase rule.

Am sure that you have studied in your undergraduate courses are basic material science Great gives phase rule. Which is equal to f c - P + 2, f is the degrees of freedom, number of degrees of freedom. So, I not ride the number what here because due to less space here with you please understand these all our numbers of degrees of freedom and sees numbers of components here I can right number of components and the system.

And then P is number of phases and then they too and they are not actually temperature and pressure, if we have at fixed freezer at fixed freezer or at constant pressure at constant pressure, the GIFs freeze rule will be c - p + 1. As you know some other phase that comes at constant pressure to you have seen that I will draw in the right hand side. So, at constant pressure you have in the y axis temperature and x axis is percentage composition.

So, this is a these type of diagram phase diagrams are generally drawn at constant pressure and for that this phase rule will be f = c - b + 1. So, here I want to just remind you, the term component means for example, we have we have a water and ice system. So, there we have a single component because water and ice both are H2O and also, but in there. There are two phases one is solid phase and one is liquid phase.

So, you should understand the difference between components and phases. So, in this case in this diagram, we are calling it as a unary phase diagram, because it has one component only what is the component is iron one component that is iron okay. So, I will draw a line so that this diagram looks nicer. So, what we want to discuss now is we will discuss how this phase rule is obeyed in these phase diagram.

So, first we will see the single phase region this is a single phase region and where the only liquid exist and here it is another single phases and we are we have on the gamma phase. Similarly, in this case and then gas in the in this region and then gamma sorry alpha is in BCC that region and upsell and they all are single vision, but for our, this illustration, we will only show on the two single phase reasons.

So, these single phase reasons I like his reasons, so, our F is equal to number of phases one sorry number of component is one and number of phases one because we have only liquid phase or only Gamma phase. So, you should be no I mean, you should be aware of that, although I am having two arrows here, but we are talking separately of liquid phase and gamma phase.

So, we can we can show for each single phase reason separately this this gives phase separately. So, this will give us f = 2. And similarly, if we talk about these two phase region. So, two phase regions on the on these lines as opposed this line can have both gas and liquid phases and this line we can have both liquid in gamma phases. So, these lines are two phase reasons Phase regions, So f is equal to component is one phases or two.

So this will give us degrees of freedom equal to one. So, we will see what is that degrees of freedom and before that, so, we want to show you these triple points where three lines meet each other and these are region of three phases. So, in this case, suppose these triple point there are three phases will coexist. So, one is liquid, one is delta phase and one is gamma phase. Similarly, in this triple point, so there will be three phases.

First one is the gamma phase, and then epsilon phase and alpha phase. So, to these triple points I will draw the arrow like this and these dribble points, these has three phase region and that points are called triple points, tree lines meet each other and for that points for those points, it will be only one component iron. And then, three phases plus two that gives us the degrees of freedom equal to zero.

So, now try to understand this in the single phase region F is equal to two that means, both Pressure and temperatures are independent variables and the single phase we got f equal to two So, both pressure and temperature are independent variable.

That means, you can vary P and T inside these single phase regions, but for the two phase case to two phase case.

If you see here F is equal to one. So, that means, only one variable is independent only one independent variable either t or p. So, if you see in on these lines that means the two phase regions. So, if you fix the pressure, then sorry if you vary the pressure you cannot vary the temperature because temperature is fixed on those particular areas of research similarly, on the other way also.

So, these lines, we can vary only one variable other variable is automatically fixed. And for these three phase three triple points, these are fixed points these are fixed points we cannot genes by varying pressure on temperature. So, suppose for example, this point is fixed at a particular pressure let us say pressure equal is equal to close to 13 Giga Pascal and also temperature is also fixed in this.

So, these are fixed points. So, I am sure that you all studied these in your material science course. But just to remind you all this for our phase transformation Chapter. Now, this alpha two of silent fees transformation was first reported by Bancroft and others in 1956.

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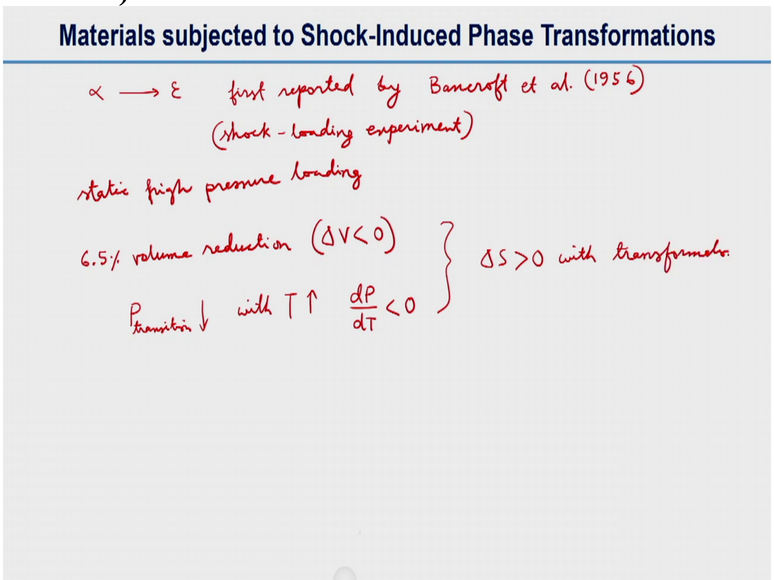

The first did that shocked loading experiment shock cloning experiment but later it was proved through static high pressure, loading experiment as well today that high presses alpha phase can be transformed into epsilon phase. So, and in this case in this transformation around 6% volume reduction happens means our delta V is negative volume reduction. So, from the imaginary phase diagram of the previous phase what we got is that the presser transition presser.

If you see here in these lines, the transition pressure decreases when we temperature when you increase the temperature, so, transition pressure decreases with increasing Temperature that actually what we found earlier dp dt is smaller than zero and these two from here, we can say that if you remember the earlier discussions. The entropy will increase with transformation.

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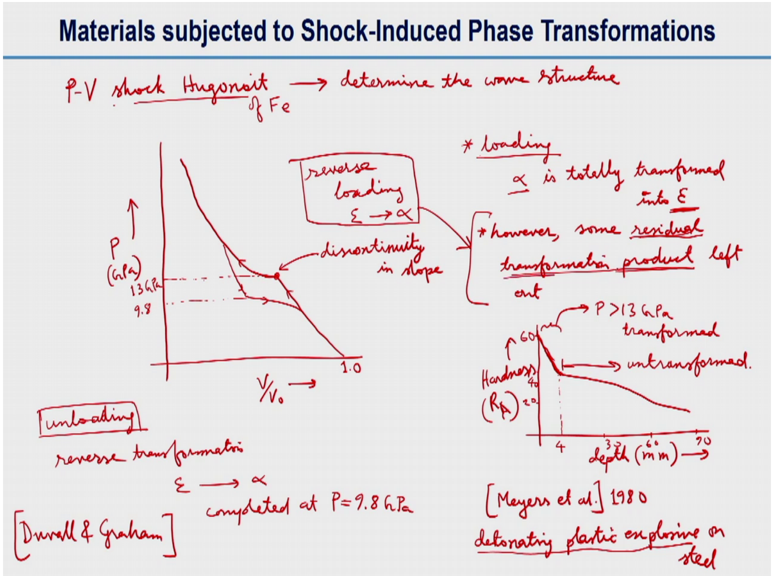

So, we can also see a presser volume shock who denied of this iron PV shock hugonoit for iron show you have volume, specific volume here presser in Giga Pascal So, it is 1.0 it starts from here and it goes like this. They will be discontinued it in slope ready like that. And this is not the loading case. And then in the unloading and unloading this looks something like this. So this during loading and this is unloading.

So, during loading this is as you know, it is close to charting Giga Pascal for the discontinuity of slope okay focus. You can see that during unloading during unloading the reverse transformation happens. So, during unloading, reverse transformation happens transformation that means, from f7 to alpha and it got completed at the pressure of 9.8 Giga Pascal here it is 9.8 Giga Pascal.

So, this by the way plot is from Duvall and Graham that our friends, we have earlier quoted from Mark me as book. So, this is the reference. So, you can see the discontinuity in slope and this point as I told you discontinuity in slope. So, from this shock would not go one can also determine the wave structure. We have discussed in the last lecture about the wave structure to two wave structures that two waves travel simultaneously.

So, we will also probably discuss later about these wave structures. So, here this is a shock hugonoit curve of iron. So, this reverse transformation happens when you do unloading. So, during loading during shock loading. So, alpha is totally transformed into a silent phase. However, some received will Transformation product left out. So, although I wrote that it got totally transformed.

But still sound the residual that transformation product left out. And so that is where the hardness. If you see hardness profile so there is a Marco micro hardness profile hardness RA local hardness with depth. Depth means actually this is a test Bamberg Mayer's group, so, this mirrors and others in 1980. So, what they did is they obtained these plot by donating, plastic explosive on steel the floor looks something like this.

So, depth is from the surface. So, if you see this is around four millimetre and if you go to the 6090 millimetre below. So, and this hardness number is around 60 at maximum and then reduces that is a 40 year 20 here. So, what happens you can imagine that during the detonation which fill a plastic explosive. The steel block after the pieces of that shock loading will be very hard at the surface that is up to four millimetre from the surface.

So, that means, at the surface this region suppressor will be very high p exceeds 13 Giga Pascal. That is right transformation happens. Transform that region is transformed and its way hardness is very high. And the other region is not transform the other part this side of the region untransformed, this is untransformed. So, you can see that the hardness can go up to very high. This is our number 16 because of this transformation of sorry.

So, what I wrote here is loading that is correct that for during I mean that is corrected during loading alpha phase totally transform to silent. But, what we talked about here is about the residual transformation product. So, that actually we should have written that this is actually about reverse loading. It is about Reverse loading, reverse loading from silent to alpha. So, that is what we discussed in this point.

Because as I told you the residual transformation product that means, the transformation product here is silent. Because we got upside in here from alpha two of silent and this is the transformation product and so, residual transformation product means some part of the silent we will left out will not be converted to alpha. So, that is what this residual transformation product means, and also in optical micro graph.

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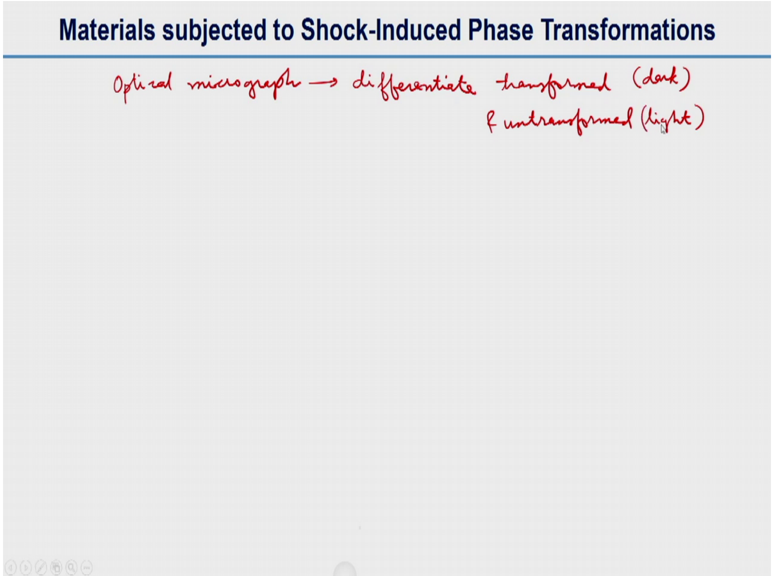

You can see that optical micro graph you can differentiate the two region transform And I am transform region. So, the transform region we look darker and then the untransformed will be lighter in opinions. So, we were discussing about shocking news transformation of iron from gamma iron to f7 iron. So, now again we will discuss another phase transformation

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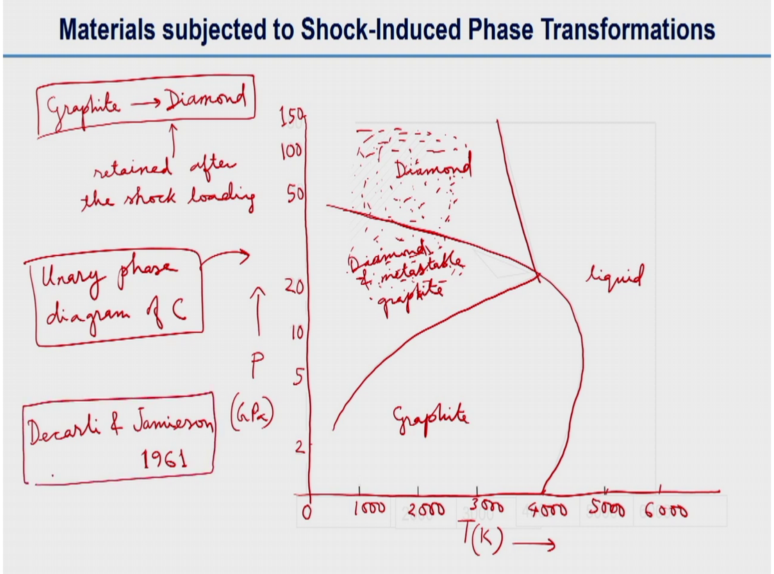

Example of a phase transformation shocking used phase transformation that is graphite to diamond. So, graphite to diamond So, this stands for me. We can retain after pieces of the shockwave. So, we can retain it can be retained after the sharp loading or the passes of the shockwave sharp loading. So, before going to the details we will see how the unary phase diagram of carbon looks like show unity phase diagram.

If we have preserved in Giga Pascal in Y axis and if we have the temperature in Calvin in x axis so, simple rewriting in two Giga Pascal and 6000. So, the phase diagram looks something like this. So, here in this region at high pressure we have diamond is stable state.

And then in this region, we have good fight at low pressure, good fight. And then at high temperature, we will find it as liquid state.

Now here we can see that this in between diamond in graphite, so diamond in matters they will give it stays. So, Diamond and Mater stable graphite and basically the diamond reason is if we see So, these reasons, even above this line above this line or mostly and even some below this line also we will we can have diamond. This is what we have drawn is in nearly phase diagram that in theory means one component.

The only one component is carbon in if a diagram of carbon this diagram and the first researcher to report this gamified to diamond using sharp loading the transmission using shock loading was reported first by DeCarli and Jamierson. Mention the me So, did you the first person they reported in 1961 on that shocking new phase transformation of gamified to diamond.

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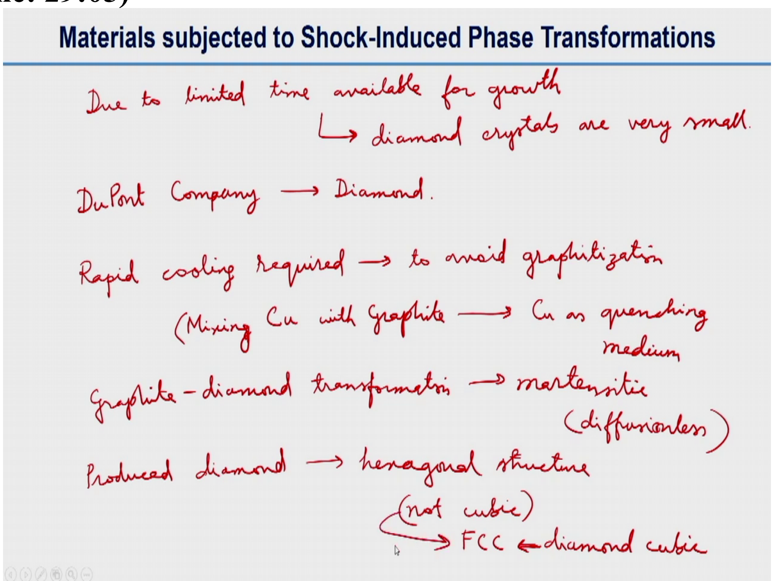

So, to diamond if you see it starts at a low pressure even this reason as you know this diamond from graphite to diamond at the lower temperature, it can start as early as 2.3 Giga Pascal start forming diamond. So, these phase transformation. The result is results a very small greens and also the small particles which are polar crystal that means, the particles are also small size.

Which are properly crystal and even one grain also has small size due to a limited time available for growth. So, due to limited time available for growth every level for growth diamond crystals are so, the very small table crystals produce produced by shock loading

DuPont company used to produce diamond using these methods. They use this method as a commercial method of commercial method that means using sharp loading in these methods.

Rapid cooling is required rapid cooling is required to avoid graphitization. So, that means, it can be again you know convert into great afraid. So, to avoid dead, the rapid cooling is required. And sometimes the mixing copper with graphite hills in quenching, so, copper is Quincy medium Quincy medium and this graphite diamond transformation these transformation is a modern city transformation modern society modern society that means it is diffusion less difference understands formation.

And the diamond produce is hexagonal and crystal structure has exact structure they are going to be a structure not cubic. cubic as you know FCC it has absolute is with diamond cubic actually structure that is the crystal success called diamond cubic and it has a as an FCC. Lettuce does it usually one, but in this case, it is not to be this is hexagonal suction with help of shock loading. Whatever we produce that has an XML structure as we already mentioned.

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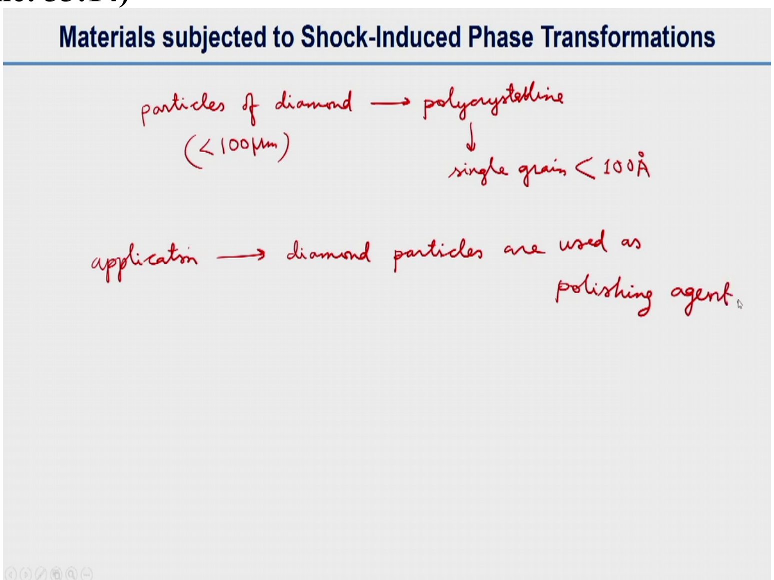

That the particles are particles of diamond produce with this method are poly crystal and frolic is still in. So, they have even particle size even, are probably lived in hundred micrometre and these greens, one single green let us a single green has seen the green or you can call it the crystal has even less than 100 Enstrom diameter and applications. If you are concerned about the application of these small particles, they are these diamonds particles are used as polishing essence is as polishing it, polishing is not agent we will not talk about drop more about these two wave structures.

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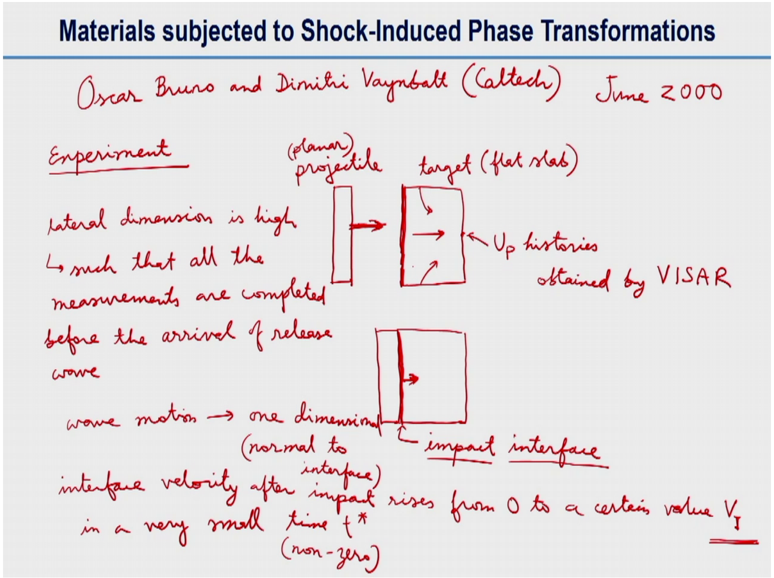

So, we will see the most of them. These discussions were taken from one of the reference that is Oscar. Bruno Dimitri rain belt there from Caltech, California Institute of Technology. So that is a technical report published in Zoom 2000 So, that is titled as shocking news Martin static phase transformation transitions critical stresses and to have structures that solve the remaining problem. So, this is the reference will be discussing.

Suppose, a typical experiment we know that we do produce a shockwave is we have a flyer play that is we can call it a projectile. This is a projectile and the target is this one target and when you get the particle velocity history. So, we get the up history particle velocity histories obtained by VISAR we talked about this that is velocity interferometer system for any reflector.

So, on the back surface of the target that up history is can be obtained by this it was in this technique and when the projectile will hit the target, so we will see what kind of Shockwave will be propagated. So this is what we are discussing is related to shocking new phase transformation. So, this is a planner project tell by the way this is planner projectile, and let us say the it is hitting the free surface free surface of the target.

That you consider a flat target is let us say, flat slab when it hits, suppose projectile hits the target. So, this surface, this is not surface this interface. This interface is we will call it as impact interface impact interface or simply we can call for our discussions we can call it as only interface even. So, in this example, so, the ratio of the literal to the language a new dimension it chosen says that.

So, the literal dimension is high such that the all the measurements are such that all the measurements are done are completed before the release. We, before the release, we arrived from the literal surface of the target that means when you were hitting when you were hitting the target, so the shock will propagate in this direction, but there was some relief from the surface literal surface.

So these really with waves, we do not want to any interaction from these releases. So, that is why what we assume is that the literal dimension is very high, so that the release waves cannot interact with the primary Shockwave. So, that is that is the assumption here. And that assumptions mean that that that Dimensions would be infinite and wave motion is with motion is one dimensional.

One dimensional means, normal to the interface, normal to impact interface or outright just interface. After this impact this interface velocity that interface velocity after the impact after impact rises from zero to a certain value. So, interface Velocity. Let us say VI at in a very small time small time letters MD stir small time Easter. So this is the value VI. This is the interface velocity.

It is this is a very small time but it is nonzero, not zero not equal to zero. So, that means the rise of these interface velocity is very quick. So it is a very small time it rises to velocity VI. So,

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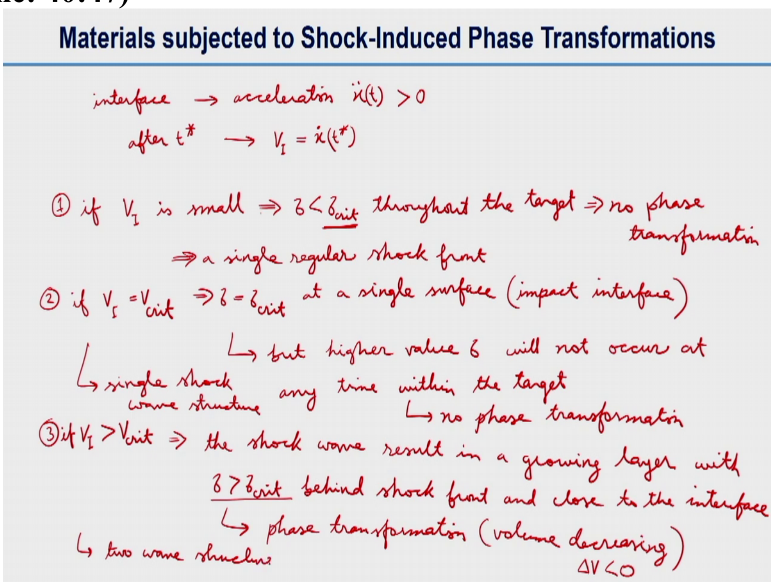

This impact interface, I would just write interface will have undergoes exploration we will right X and the T exploration, which is positive exploration and after a small time interval t *. So, the target boundary tables at a constant speed and the target boundary means the free surface or the impact interface. So, that means that VI is equal to have this so we can write it that way. For we have let us say three cases here.

If VI is small or we can call sufficiently small then this means Sigma is smaller than a critical value sigma critical throughout the target throughout the target and that means, note phase transformation, transition or transformation. So, what is critical means, so, if it is below the critical the stress is below the critical limit. Then no phase transformation and that is true for VI for less than a some value that is VIV critical.

You can see. So, if VI is equal to be critical, then sigma is equal to sigma critical. So, sigma critical at a single surface. So, it is it is the impact interface. But although the stresses sigma has the value the critical value. So, higher value of sigma that means, the Sigma critical higher than the Sigma critical will not be will not occur at will not occur at any time within the dark it within the target.

So this means also that the new phase transformation this means that no phase transportation like the earlier case and number three cases. If VI is if we is slightly even higher than the critical value, if he is higher than even if it is slightly higher NV critical, what will happen is the shock wave will result in a growing layer with the material that has sigma is good and sigma critical behind this rock from behind the shock front.

So, which is Close to the impact interface and close to the interface always mean input interface here. So, in this case the impact interface acceleration will induce volume decreasing phase transformations. So, what will happen is there will be a growing layer with sigma critical and that means, it will favour a phase transformation that is as we know it is a volume decreasing phase transformation delta V smaller than zero.

So, now we see these three cases. So, first one if the VYVI is small there will be no phase transformation toward the target. So, what will happen is here in this case a single regular shock wave will travel single will say regular. So, there is no phase transformation regular shock wave in the second case also because there is no phase transformation. So, because of that.

In this case also there will be single Shockwave structure like the first case single software structure, but in the third case that there are this case is different than earlier two cases. So, it will have to weigh structure to will structure now, we will see how it has the two wave. So, we will explain these plots later.

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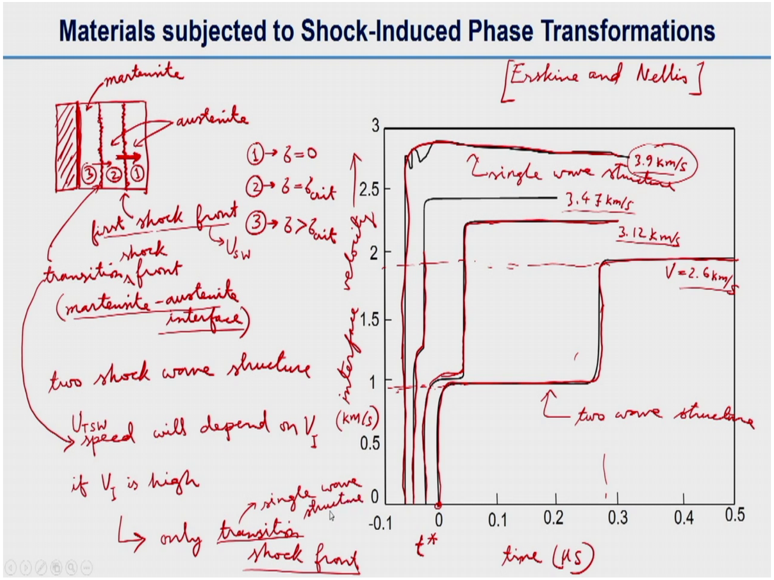

But before that, what we want to draw this again with the projectile and target. So, what will happen is in the third case when sigma critical, so, what will happen is, this is the project tell, so, will now talk about the target only. So, first the entire the target has the Austenite structure we call Austenite I take structure then after in the third case when the Sigma will be sigma critical and the velocity VI has a slightly higher value than and we critical So, in this case we are going to see again.

So, VI has a value has hired him to be critical and then sigma is higher than the Sigma critical. So, what will happen is this is the impact interface right. So, this is the impact interface, the material close to this impact interface will be transformed to martensite. so and then I will it was Austenite. So, we will remote this so it is not transform too much inside.

And at the time the shock front we read somewhere here so this is our shock front. So here what is happening is the entire this or this young, we have both Austenite still we have Austenite and then is this is the shock front and the first in our regular shock front. But here, we will have one more shock wave. So that is the transitions front transition front or the transformation from because this is the interface of Martin site and Austenite marten site Austenite. So that interface we also be going forward in these direction. So this is the first shock point and that is transition.

We will say transition shocks and so there will be two shock frontier. So that is why it is called as to shop we structure so false front is this one. And in this region first reason, actually, I would write one, two and three. So, in the first region, the first reason sigma is equal to zero. Because the shock from the first rock forefront has not even raised yet and the number two region and that has it lets us sigma my equal to sigma critical.

But still the transformation has not occurred as you can see in the earlier slide. So, number two reason have sigma which is greater than sigma critical and transformation occurred. So, that is the Austenite structure transformed the martensite which is we told that this a diffusion less transformation, so that martensite and Austenite interface is also another shock front. Now, following the first or the primary shock front.

But in case if the velocity is Very high speed of a transformation struck fun. So, these transformational transitions are short run even bigger the same. So, transition short run the speed, will depend on depend on the VI you know the that impact interface velocity if VI is very high, if VI is high, so, what will happen that that will have a very high transmission shock with front speed this weekend right as you transition Shockwave.

So, you are for the first shock friend, we can write, U velocity, U Shockwave and here we can write U Transition Shockwave. So, the speed of the transition front. So, the speed as it is increases. So, what will happen? If VA is very high, there will be only transition sharp front that can be shown in this diagram. So, these Floor is the reference is are Erskine and Nellie are screening Nellie.

I actually forgot the year of the publication, where the new is So, this shows in the y axis it is in interface velocity that is written in kilo meter per second and in x axis It is time, microsecond it actually men these time the swing very close to zero. This is actually it is just staggered. You can see, I can think that this is a very, very small time it is close to zero.

That is a positive not zero, it should be positive actually, although it is shown as staggered like this. So, these forecasts are for four different impact velocities. So I would ride impaired Felicity SV. So, suppose for this curve is very equal to 2.6 kilometres per second, at a very high velocity, and the other one is, second one is 2.12 kilometre per second and the third one is 3.47 kilometre per second and the last one is 3.9 kilometre per second.

So, if you see in the first one 2.6 kilometres per second you can see there are some you know change of velocity after some time. So, and also similarly, in the second case also, you can see a similar structure although it is the changes happened in a very at a lower time. And similarly, in the third one also you can see changes, but then the fourth one looks a little different. The changes happen at the last one there is this is actually some fluctuation.

But, then you can assume that there is no change so, you can regiment like this. So, this means that this means that if you have to velocity interface velocity one is corresponds to let us say below one kilometre per second and another one is corresponds to below two kilometre per second or similarly for the other two 3.12 kilometre per second impact velocity and 2.47 kilometre per second the big velocity.

So, just to again remind you these velocities what I have written 2.6 or 3.1 to 2.47 does it impact velocity and then interface velocities impact interface velocities, and that can be produced from this is in the y axis. So, now, what is happening if you are seeing these change of velocities like we can see a very prominently in the first case. So, that means it has a two wheel structure we structure but in case of 3.9 kilometres per second.

In fact velocity it has a single wave structure, So, that I have already told only transition shopfront single we structure. So, if you want to again see the earlier slide. So, when the VI is very small then it has a single regular shock front. And then we are equal to be critical also we have a single shock with structure, but when we Why is equal to get an actually greater than we critical.

And that will create a stress that is actually the sigma is the compression normal stress we are talking about I forgot to mention that I hope that was understood comprehensive normal stress we are talking about. So, now, this if it is sigma is get it and sigma critical. So, that will give us a two way of structure, but, if the velocity in parallel is very high, then what will happen is the interface velocity is high.

And that will give the transition shock from will you know dominate and that will again eventually will get a single wave structure that is only the transition shock front that is all for the pretty. So, we have discussed about different phase transformation of iron and then we discussed about carbon phase transformation from graphite to diamond.

And then we discussed about to wave phase structure to a shock wave structure that is, we even discussed in an earlier class as well. So, we will continue this discussion on Shockwave a little bit on the next lecture and then after that we will go forward to some other chapter. So, thank you.