Nanotechnology Science and Applications
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Lecture - 14
Severe Plastic Deformation and the nanoscale: Experimental Utility

Hello, we will continue our discussion on a Severe Plastic Deformation, in particular, I mean we are looking at this whole discussion from the perspective of a utility in the nanoscale. And, the severe plastic deformation is a technique which creates a significant amount of strain inside the material and creates a whole lot of equiaxed small grains, several 100 nanometers across maybe even less than that in size. So, it is a very nice technique to create a sample that is reasonably macroscopic that you can handle and at the same time it has a nanostructure to it.

So, you can probe the effect of nanoscale in that system and there is no porosity in it; I mean essentially it is a continuous material. So, there is no porosity, there is no internal oxide formation and so on so. Many positives to the technique, we discussed that in significant detail in our last class. The also the I mean they may perhaps the only major drawback to it is that at least as of now, we do not have a simple way of extrapolating this into industrial production. And so, that is something that you have to keep in mind and, but within the scope of what it can do, it provides you with lot of ability to try out various things and so, that is what we will focus on.

We will be a focus more on the experimental utility of it. We will look at one more possibility that we can consider with it and then we will sort of summarize what we have done in the last two-three classes.

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So, our learning objectives for this class are how we would go about using this for modifying mechanical properties, the severe plastic deformation. We already did looked at it. So, I will let us we will let us look semantically as to what the data might look like and generalize what you might expect from it. And one aspect which we did not look at before is the wear property.

So, wear property is something that we will focus on and right try to understand how you can do a wear test with to figure out what the wear properties of a sample are and how you can put this severely plastic deformed material to a wear test and what you can maybe expect from it, it will, of course, vary from system to system. So, some generalization will try to do to bring those kinds of ideas together.

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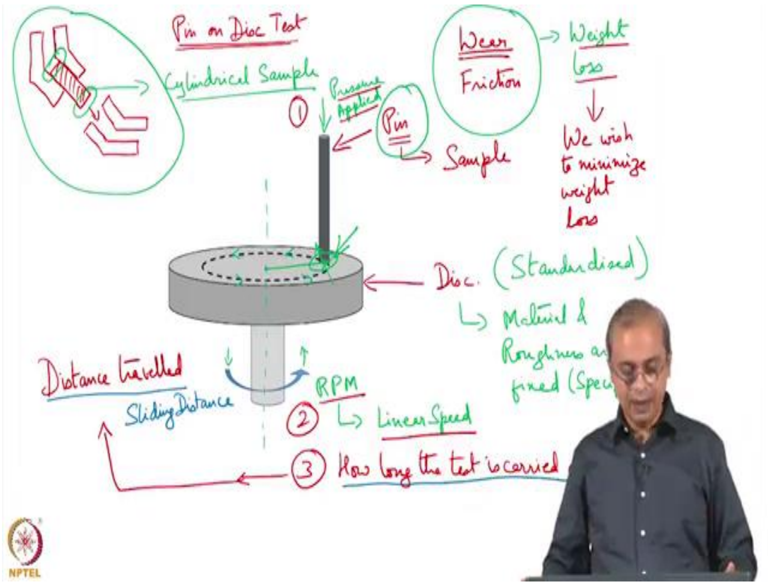

So, if you look at a severely plastically deformed sample as I said what you will get is you are having multiple passes through, I mean dice which are shaped like that. And so, the sample that comes out still has this cross-section that it originally had, but then it has already undergone significant severe plastic, I mean plastic deformation and then you can put it through one more pass like that.

So, this is just an example of what you could do. The angles that are there can be changed and various things you can do with it and that is your sample that you repeatedly send through this process. So, at the end of the process, you are going to have a cylinder of some form and you can do mechanical testing with it, just to see I mean again make a sample from which you can do a mechanical test and now look for some data from it and you could also do a wear test.

So, for wear, this is the kind of test that you would have. What you see on your screen is something called a pin on disk test. So, this is the kind of test we would do for a for wear properties and the basic idea is that wear property is important wherever you have friction. So, wear property is typically very important where you have friction. So, that could be any number of places; almost any joint in any engineering product any joint in an engineering product you are continuously going to have the joint move and because the joint moves, there is going to be some rubbing of one part of the joint with respect to the other part to the joint.

And so, there is a high I mean so, there is a lot of frictional activity going on there you going because of friction you are going to have heat being generated there and that friction will also keep creating a possibility that the material at the joint will begin to wear. So, that property of having to deal with friction is this wear.

Even in our body, we have every joint that we have in our body I mean our knee joint our elbow joint etcetera; every joint to the extent that we use the joint will have to subject itself to wear and we want it to have good wear property. So, all our joints have to have good wear properties. So, even people who are working with artificial joints which can be put to your knee joint that people do knee joint replacement and so on.

Those joint replacement activities are associated with materials that have very good wear properties. So, that is something that you have to look at. And so, even if you are working with biomaterials, then one certain area of biomaterial work may require you to look at wear properties. And so, therefore, this is a very important and fundamental kind of test that we need to look at.

So, to do the wear test basically you have to create the same situation of friction, you have to see how that sample behaves once it is subject to friction and you have to do this in some kind of a controlled manner; that is basically a what a test is. So, you have to set it up. So, that you can test one sample and then you can test some modification of that sample or some other sample and then compare results. So, that is the whole idea that so, the test should be somewhat should be reproducible; you should those conditions should be reproducible and there are some defined conditions for it.

So, the pin on disc test is meant for wear properties. It consists of a disc which you see here and a pin. So, and hence the name pin on a disc. Now the sample that we wish to test is the pin. So, whatever material you want to test for wear properties, you convert it to the shape of a pin; so, this pin. So, which is basically a cylinder of some dimension some fixed dimension will be available based on the standardization of the test. There will be one fixed dimension for that pin. So, you make your sample in that form.

So, as you can see the pin is basically one thin cylinder that is present and so, if you actually did no equal channel angular extrusion kind of process; this kind of a process out here, then you are getting that cylinder. So, you are getting a cylindrical sample and. So, it already has the kinds of dimensions required for it to fit this pin.

So, if you can know carefully tailor your sample preparation process, you will get pain. At the end of it, you will get a pin maximum maybe you have to chop off the two ends a little bit because usually the end will have some no it will not look like the end of a perfect cylinder; you will not you may not have a perfectly flat surface there very good chance. You will not have it because of all this twisting that you are doing. So, you may have to remove the two ends if it comes to that, but generally you are going to get a pin and that pin you can get in nanocrystalline, you can get it in microcrystalline form or a macrocrystalline form from some commercial entity.

And, then you can subject it to this severe plastic deformation such as equal channel angular extrusion and the same pin you can now get in nanocrystalline form. So, you can get the same sample microcrystalline or macrocrystalline and nanocrystalline and that is basically what we are always interested in if we want to study the effect of the nanoscale. So, you get the pin and you get the disc and the way the test works is that this disc is also some standardized disc. So, this is standardized in some form. So, which means material is fixed and roughness fixed or specified.

So, it is fixed or specified and so, I mean if you wanted to sort of purchase a pin on disc setup, then that is what it would be. So, you can get this pin on disc setup and what we have in our control are two things here the RPM. So, this disc is going to rotate. So, this disc is going to spin. So, it is basically going to spin. So, that what is your I am showing you here. So, this is going to spin. So, it is going to spin about this axis, the vertical axis. So, about that vertical axis, it is going to spin and therefore, we can control the RPM.

Now, once you control the RPM, this pin comes in contact with the disc at a particular distance from the center alright. So, once the RPM and the distance that the pin is coming in contact with distance of the position, the pin is coming in contact with the disc from the center of the disc you can convert that to a $v = \Omega r$, you can use and then you can convert that to a linear velocity or linear speed in this direction. In so, tangential to this, you can think of linear speed. So, therefore, this RPM will translate to a linear speed that is experienced by the surface of the pin that is now in contact with the disc. So, at this location, there is a certain linear which I am which I have encircled here there is a certain where the pin comes in contact to the disc, you have a certain speed.

So, therefore, so, that is something that we can define we can say that it is the pin is being subjected to so many meters per second speed that is defined. We also as part of the test; so, that is one part of the test the other thing that we specify is the force or the pressure. So, the pressure applied the pressure with which you are forcing the pin down on the disk. So, the disk is rotating and you force the pin down on that disk with some pressure. So, that is something that you specify. So, you specify this pressure with which it is pressed down and you also specify the RPM with which it is rotating.

So, those two things you rotate. So, this is basically the pin is now tracing an no circle. So, it is stationary this thing keeps rotating so, you see that path that it is going to see. So, this is what the pin sees on the disk. So, this is the way we test it. We also specify things like the temperature of the test, the humidity of under which the test is being conducted particularly the humidity temperature, there may be some local heating that is going on. But in principle, we specify the humidity because that is important because many times I mean as the rubbing action happens, you can have some corrosion also occurring. So, you need to be satisfied that you are setting the same kind of condition for a bunch of tests only then you can be satisfied with the resources that you get.

So, this is the test and as I said you can specify the pressure which means you have control on the pressure, you can change that pressure. So, the pressure applied should be known that is the point you should know what the pressure is and, in some test, you can apply one pressure, you can then change it on another test and change it on another test and so on. Similarly, this rpm is something that you control which means you can specify the RPM; you can specify higher RPM lower RPM etcetera that is another thing that you can specify.

You can also specify how long the test happens. So, how long the test happens is. So, this is one thing you can specify, this is another thing you can specify. The third thing is how long the test is carried out. Now, how long the test is carried out is something that we will get as a time element. So, you will get that as t time you can use it as time, but usually, it is much more useful to actually convert this how long the test is carried out to another parameter which is distance.

So, you can convert that to another parameter which is the distance traveled which is basically as the disk rotates once the location that the pin is pressed on and the arc that the or the circle that the pin is basically tracing on the disk then for every revolution that $2\pi r$ is that distance it has travelled. If the r is the radius and so, if it if there are 100; I mean if it is rotating at 100 RPM, then it has travelled 100 into $2\pi r$ distance per minute. And so, you can say if you run the test for 10 minutes, you have basically done 1000 into $2\pi r$.

So, $2000\pi r$ is what you have done in terms of. So, if r is whatever. So, some distance you can put for r, then you multiply this you will get the answer that is the distance the pin has travelled. So, if you want to test it for ten minutes you put the sample down there for 10 minutes, press it against that disk for 10 minutes at some pressure that you have fixed. So, you fixed the pressure that with which you are pressing down on it, you set the RPM, wait for 10 minutes, then that it has travelled a certain distance.

And, similarly, you take another pin you again put it on this test and make it run for 10 minutes and then again it is travelled the same distance and so on. So, then you have these a bunch of pins which have all travelled the same distance on this test on this test rig with the same applied pressure and the same level of humidity and you can compare the results. And typically, what are you comparing? The general aspect associated with wear the general aspect that is associated with wear is basically weight loss

So, the general aspect associated with wear is weight loss. So, essentially with friction slowly material wears off and then you are having less and less of that sample and eventually in a technological circumstance, what this means is that at some point it will go below some tolerance value and it may no longer be useful in that technological application. So, if you are looking at taking some material on to some technological application where it is likely to be subjected to frictional conditions.

And therefore, a likely to experience friction and therefore, be subjected to wear as an activity that is happening on it then we would like to know what is the weight loss and as you may imagine we want the weight loss to be as minimum as possible. We basically do not want any weight loss because that is something that is undesirable. So, when you want to compare different materials essentially what you are comparing is you are running the test and you are comparing to see if you can minimize the weight loss.

So, we want to minimize weight loss. So, anything you do to the sample and you are trying to say that you have improved it; from the perspective of wear, this is what you want to do you want to run a pin on disk test and then at the end of the test you want to see what is the weight loss that happens and you want to compare it against a variety of different samples maybe the sample before you did some treatment to it and then and after you did some treatment to it.

And then see what your weight loss is and then see if you actually if you say you have made an improvement, then under the same test conditions you should have less weight loss that is the and in a repeatable manner that is the basic idea that we want to do. So, this is the basic test and we will see what kind of data we will get from it and then see what we can make of it.

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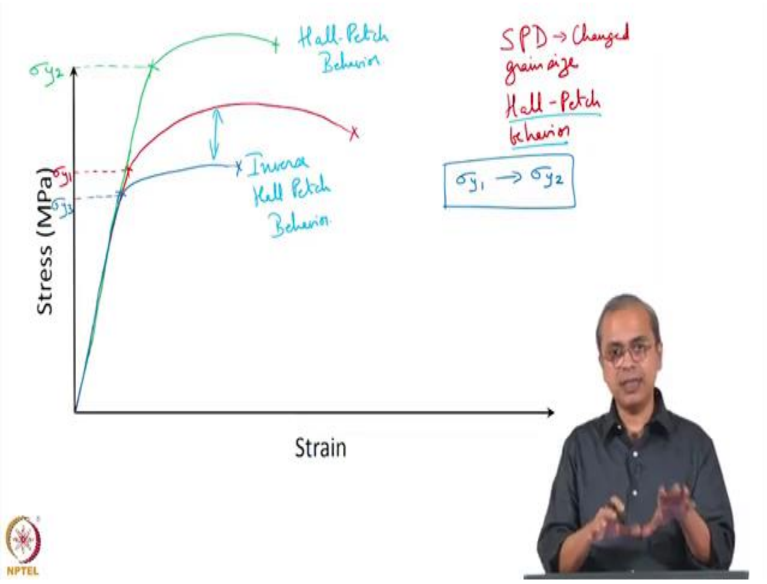

So, if you see here if you look at mechanical properties in general, you are looking at a stress-strain curve. Of course, you can have a true stress true strain curve or an engineering stress engineering strain curve in a true stress true strain curve, you are looking at the instantaneous length and instantaneous cross-sectional area and so on. In engineering stress and engineering strain, you are looking at your starting cross-sectional area and starting length so, to speak.

So, in general, you are going to have data that looks like this. One linear section and then at some point it will deviate from the linearity and then you see something that looks like this and then its sample fractures. So, this is your yield point. So, this is σ_y that is your real point stress versus strain is what we have. So, when we do severe plastic deformation, we have basically changed grain size. So, now if you look at the Hall-Petch behavior, you are expecting that as the grain size goes down the yield stress will go up.

So, if you have if the system is following hall Hall-Petch behavior, then after you have done severe plastic deformation; you will see its behavior look like this and something like that. So, now, its yield strength will be like this. So, if we call this σ_y the original one as σ_{y1}, it now becomes σ_{y2}. So, it has gone up and so, that is how the strength will change and the amount of plastic deformation that it may. It may undergo before failure may change it may not necessarily be the same. So, you may usually when the strength goes up to some degree the ductility comes down. So, I mean these things are not this is the general trend that you tend to see, but this is what you are likely to see.

In case the inverse Hall-Petch relationship is in a vogue you may see that it actually deviates from linearity sooner. So, you will see a behavior that looks like that. So, you may see a behavior that begins to look like that. So, you may have a lower σ_y. So, those kinds of things can happen. So, this is what we are looking at. So, generally we want better mechanical properties. So, when we do severe plastic deformation, we would like to go from σ_y, σ_{y1} to σ_{y2} this is the preferred state that we wish to accomplish and that is what we are trying to do in most conditions.

Now, in some applications where you are essentially looking for wear properties improved wear properties, this is useful to have, but in addition we also want to wear property to improve. So, that is something that we want to do. So, it is always of interest to see if by improving the mechanical properties have you also improved the wear property. So, that is that combination is always an interesting thing to look at. And so, that is something that can be examined and for that as I said we do this spin on disk test and we look for weight loss under different experimental conditions.

So, for example, if you see here, we are looking at one possibility of this experiment where the variable is the sliding distance. So, as I said here if you go back to this plot here that variable is this distance travelled that is the sliding distance. So, this means it is important for us to control how long the test is being carried out. So, we control how long the test is being carried out and at that under that those conditions you have the, you have you are basically controlling the distance travelled right and then we want to look for weight loss.

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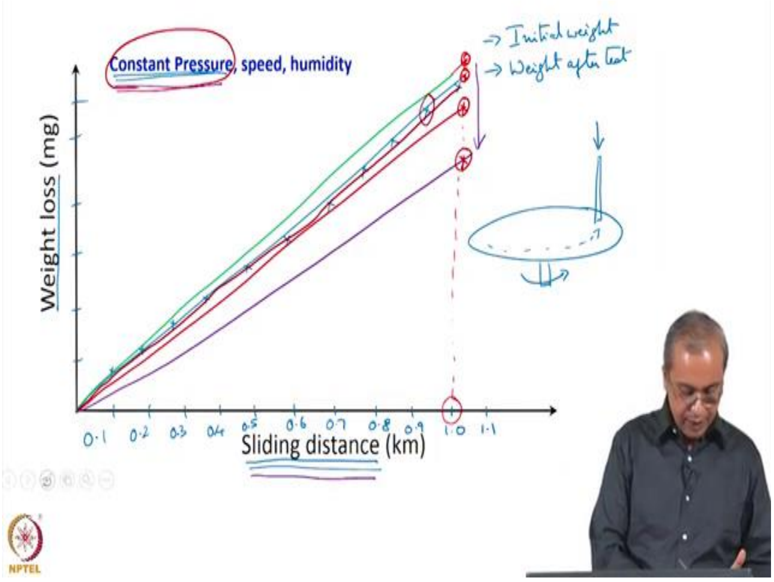

So, what is typically done is that you have weight loss here and you have sliding distance on your x-axis. So, what is typically done is the test runs for I mean it runs for 10 minutes and then so, it has travelled some distance; it has travelled we just say it. For example, it is travelling in meters say this is 100 meters, this is 200 300. So, this is marked in kilometre. So, we will mark it as 0.1 0.2 0.3 0.4 0.5; so, 0.5 kilometers. So, you can have 0.6. So, that is easier for you to see 0.1 0.2 0.3 0.4 0.6 and then we will just put it down to up to one.

So, we have 1 kilometer. So, this is the distance it that is travelled and then so, at every point; so, at when you start off with; obviously, there is no weight loss you start that is your starting weight whatever is a weight that you measure of the sample that is your starting weight. So, at every100 meters that the sample has travelled on the pin on disk test you haut the test take out the pin and then weigh the pin. So, you have initial weight and you have and then you have weight after test and therefore, you can get weight loss. So, after it has travelled 100 meters, we check what the weight loss is we put some value here.

So, there is some value there 200 meters you have some weight loss 300 meters you have some weight loss something like this and really I mean I am just showing you a plot which looks linear and so, but basically, it depends on the system you are studying. So, you are going to get some plot like that which shows you weight loss as a function of you know.

So, some milligrams it is losing and that milligram as a function of distance. So, every100 meters, you stop the test you take it out check its weight figure out what weight loss has happened, put it back on test again run for another 100 meters take it out. Again, now with the second weight that you have again compared with your original weight of that sample and you have a weight loss. So, you make a plot like this.

So, this is now at constant pressure. So, which means that load that you are putting on that pin is constant. So, your pin is here this, this pressure that you are applying is constant, but you are halting at different distances. So, you allow it to run for some number of revolutions you halt you take it out and you make this measurement. So, this you can do for a bunch of different samples. I mean so, you can do this for some sample I mean let us say, you have done your brand new sample is that it is a red curve, you have done it for the for after it has undergone some level of severe plastic deformation and then you do something more.

So, I am just showing you some curves here that I mean straight lines in this case which you represent schematically what you might expect after you have done different things to the sample. And essentially if your wear property is improving right in if your wear property is improving, then you should actually see behavior that is in this direction let us say. So, this would improve this means improving wear property. If you are going the opposite way then that it if the graph that you are getting goes to higher and higher values of weight loss, then you are losing wear property or your property is becoming worse.

So, this is the data that kind of data that you have to get this is one way in which this wear data is plotted there is another way in which we could do it which is changing the variable a little bit here, we have put constant pressure and we have changed the distance that it is travelling opposite thing you can do I mean you can sort of invert the experiment where you are having constant distance that you are travelling, but you are changing the pressure.

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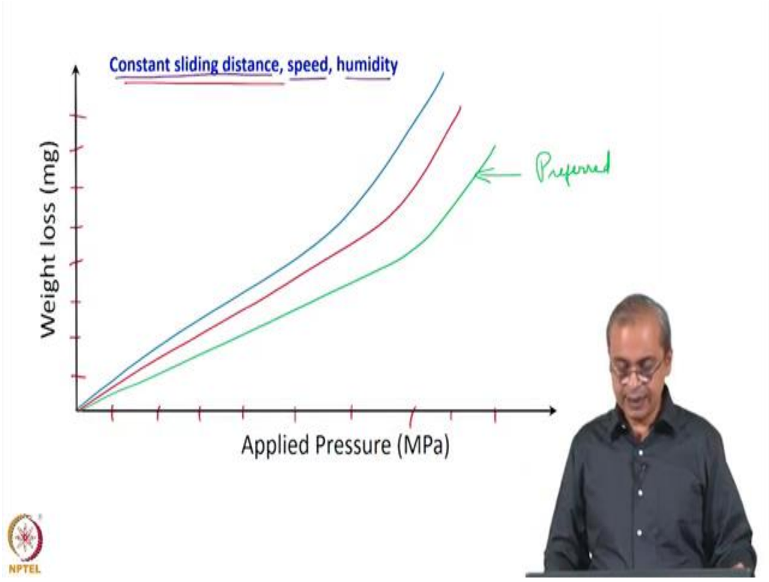

So, that is what you would see here. So, constant sliding distance and other things are constant also speed is constant humidity is constant. So, in other words, if you go back to this curve here, it is like saying that you are always travelling 1-kilometre distance. So, you will let the test run for the same amount of time, you are always travelling to a 1-kilometre distance and at that distance you see for the different samples what is the weight loss.

So, you will get one weight loss value here weight loss value here, weight loss value here, wherever those curves meet. So, you have so, in this schematic, you can already see at that 1-kilometre distance. You have one sample that gives you this value of weight loss a higher value of weight loss, then third sample gives you higher value of weight loss and so on. So, you get this and this is at this particular value of pressure

Now, I can run another test where I change the pressure to a higher value and again run the test, again run for the same amount of distance look at the different weight losses. So, that is what we are plotting here. So, an applied pressure is on this x-axis. So, you have different values of applied pressure and again you are looking at weight loss, but distance travelled is the same. So, you will again have some curve that I mean you may see something like this because as an at higher and higher pressure you may see a behavior that deviates from your original linearity for example, and you may start seeing much higher weight loss as the pressure you apply goes beyond some threshold value and once again you are comparing samples.

So, you have various samples. So, you have some sample that looks like that and some other sample that looks like that and so on. So, in this these three samples clearly the green one the sample that is represented by this the green data here is your desired sample because it is having less weight loss. So, this is what we are interested in. Now, why should the weight loss be high or low or it should why it might end up being the same? So, these are things that we need to think about and really to understand that it is important to look at what is happening to that sample.

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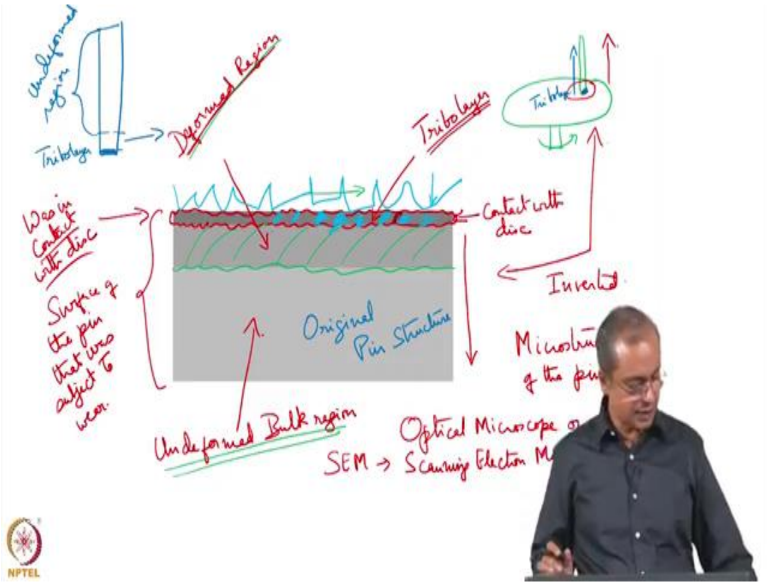

So, please remember our orientation is you essentially have the disk which is spinning and on top of it the pin is put in contact with it. So, this is the pin. So, the wear is actually occurring at this place the pin is the sample and the wear is occurring at the tip of the pin the where the pin comes in contact with the disk. What I am showing you is the likely microstructure that you might have at the top of that pin. So, this is this set of three layers that I am showing you is a schematic of what you can expect of the at the top of the pin. So, this is actually if you look at the orientation with respect to this test, this is inverted.

So, this is the top of the pin the whole thing is the top of the pin or I will not say top of the pin surface of the pin that underwent wear that was subject to wear and this top layer is was in contact with the disk. So, it is inverted. So, this region which was in contact with the disk is the topmost layer that you see here; in contact with the disk. So, which is what I have put here also. So, it is in contact with the disc and then, this is heading down here is heading up there. So, it is inverted. So, to speak and generally when you do a wear test you find that the and once you finish the wear test you take the pin and you look at the pin under the microscope.

So, so, you have to look at microstructure. So, you look at the microstructure of the pin under the microscope usually say, you can use an optical microscope it also depends on what magnification and resolution you are looking at you can also use a scanning electron microscope. So, you can use either an optical or an SM which is basically your Scanning Electron Microscope. So, when you do this on the wear test, we find that there are three major layers usually seen in a typical wear test. This is called the topmost layer is called the tribe layer and then we have a deformed region and then we have the undeformed bulk region

So, this is what we have a tribo layer and then we have a deformed region and then we have a undeformed bulk region and the reason this happens is as you can imagine this pin is pressed against that disc and the disc is rotating. So, the maximum effect of that friction happens on the surface layer of that pin which is in direct contact with that rough disc.

And there multiple things are happening you have the surface layer is being damaged because of the friction there is a lot of friction rubbing happening at that surface layer and so, that surface layer keeps getting damaged and not just getting damaged. When I say damaged it means the surface layer is scratched and then depending on the material that you are testing, a scratch surface can also get oxidized.

So, for example, if you take stainless steel the reason it is resistant to rusting. So, when you take stainless steel and you use it does not rust then that is why we call it stainless steel the reason it is like that is because there is a chromium oxide layer that is formed on the surface of that steel. And that chromium oxide layer is a continuous layer, it is a very thin layer, but it is a very continuous layer and it prevents oxygen from penetrating into that sample and oxidizing the steel underneath it. So, that is how this stainless steel remains as stainless steel.

Typically, if you take stainless steel and keep scratching it right if you keep scratching it then steadily the interior of that surface will keep getting oxidized and then eventually the whole sample fails. So, that is called any abrasive action a continuous abrasive action on a stainless-steel structure will eventually break down that structure and this is because of this surface oxide being a protective layer. And so, for example, if you have a pipe if you have just a smooth liquid flowing through the pipe, then the surface is not scratched or the interior surface of that pipe is not scratched.

On the other hand, if you have some muddy water which is flowing through it, then you have a lot of mud particles that are flowing they are continuously bouncing off that the pipe as they go through the pipe especially if it is a turn. If you have a straight pipe and then it makes a turn, then at the turn at the outer periphery of the turn continuously those particles are rubbing that surface. And then so, you are cutting you are scratching that protective oxide layer repeatedly damaging that oxide layer and forming a fresh oxide at an interior layer.

So, this process continues and then you eventually keep creating oxide, oxide and then eventually you oxidized all of that iron that is present there and then essentially that is you have basically damaged that sample. It is no longer that stainless steel that was there it is a heavily oxidized sample. So, the same thing happens when you do a wear test the layer that is directly in contact any kind of oxide layer it has that oxide layer gets damaged and then whatever is the exposed layer that also gets oxidized.

So, you usually have a sort of damaged debris like layer which sits on the top. And so, even though I have shown you as I know in this, it is just a schematic its shown as some kind of a uniform layer actually it will be a rough layer it will be a somewhat damaged and uneven layer that you will see out here and that is your tribo layer this is called tribo layer. It is the layer that is having some kind of broken-down material of the parent material that you are testing and a fair bit of it is going to be oxide because of its oxidation you exposed it to conditions that are favourable to oxidation. So, it is very likely that it will be in oxidized form.

So, that is the tribo layer that is usually relatively thin because that is how far the oxide penetration happens oxygen penetration and so, on that happens. Below that you have this thing called the deformed region and that is because of the mechanical stresses that are there on the pin because it is being subject to this test of a pin on disc. So, as you can imagine with the pin-down and as the disc is rotating, you are trying to push the material in one direction. So, let it getting pushed tangentially. So, the surface layer of the pin is getting damaged, the layer just above that surface is also getting pulled in the direction of which the in the direction in which that disc is rotating.

So, let us assume that the disc was rotating in that direction. So, if you assume that the disk was rotating in that direction, then what you will see is in this region you will see the microstructure having shift gone in that somewhat in that direction. So, lot of microstructure gets sort of pulled in that direction. So, you will see that you will see evidence that the material has been pushed in one direction and it is that deformed region.

So, that deformed region is looks like that. Then if you go further deep again, this is not there will not be a very hard and fast line at which this happens. So, this is also going to be some slightly non-uniform line and then below that when you go deeper than this deformed region, you will have the undeformed bulk region. So, this is your original pin material. So, the original pin structure will be there towards the interior of this spin. So, as you go away from this contact region as you go up, you get these different regions. So, tribo layer will be here. So, let me make it a little bigger. So, it is easier to see.

So, if this is your pin, this is where you will have your tribo layer, then you will have a region which is the deformed region; the same as the deformed region there and then above this from here to here undeformed. So, this is how we get it and the same thing like I said we have inverted here which is inverted as what you see. So, this is what we see and ever so, often we stop this test we take the sample and we look for what weight loss has happened and we see.

So, now people have studied this for variety of applications and as I said it really depends on your sample and what is happening to that sample which tells us whether or not you are going to see a difference or not. So, typically this difference that you are seeing in this plot here. So, this means if I take a value here and if I just draw a line here, this means there is a significant improvement. So, this is weight loss has been coming down and this means if this was your original sample, let us this is your original sample, then this means weight I mean it is an improved state of affairs.

So, sometimes in some systems when you go from the say macro scale to the nanoscale, you may see a behaviour that looks like this. On the other hand, you may also have a situation where they actually overlay so, in which case you are not really seeing any improvement. So, that blue line was your original sample and if after you have done all the testing it looks like this with essentially within the range of the noise.

After having done a lot of severe plastic deformation, you are still seeing essentially no difference between those curves and those curves are basically here; that means, there is no improvement. So, you can have people have seen in studies situations where if you look at the plots, then you are not really seeing any major difference between these plots. So, again here you do not see any big difference here and, but you may actually end up seeing a difference in the mechanical property. So, that possibility is there.

So, there is a possibility that you will see an improvement in mechanical property because you have gone to the nanoscale, but you may not see an improvement you may or may not see an improvement in the wear property even though you have gone to the nanoscale. And so, people have studied those kinds of systems and the typically the reason that they use for that if they see this kind of a situation is got to do with the state of your tribo layer and if the tribo layer which is this oxidized material, it really depends on what is the condition of that oxidized material.

If that oxide is extremely hard and is it is also very abrasive, then what happens is this oxide layer that you form this oxide layer you form which has lot of oxide particles that will also dig into the deformed region. So, it is basically it is like thinking you know, it is like you have this muddy water as I said that is flowing through a pipe and it breaks off some particles of the oxide layer of that stainless steel, then those particles also further corrode I mean further impact the pipe further down the line. And so, both the muddy the mud particles in the water as well as this debris that has come from that from an earlier location in the pipe, both of them act on the later location of the pipe.

So, similarly, you can have a situation where this as you are doing the test the roughness of that. So, if I say this is the this is where the roughness of that wheel or the disk is actually pressed against the pin, then this roughness is actually trying to erode I mean is trying to provide I know a wear action on that surface. But in addition, any debris that has been formed here the debris that has been formed due to the wear that debris is also participating and assisting this wear process.

So, like I said if you have an oxide layer and that oxide layer is protective, then it is helpful. But if you if the oxide layer breaks down and it also forms a hard particle that can actually impact the degradation process, then it is not helpful; it actually makes the situation worse. So, you can have circumstances based on this testing that you do where you can have an improvement in a mechanical property if you are in the Hall-Petch region of the behavior mechanical property itself may decrease if you are in the inverse Hall-Petch behavior. So, this is Hall-Petch and this is inverse Hall-Petch.

So, in fact, first of all, if you want to improve both mechanical and wear properties when you do this as you go from micro-scale to micro-scale to nanoscale, you, first of all, want to make sure that you have you are still staying in the Hall-Petch region of that behavior of that sample. We saw earlier that in the same system, it can show Hall-Petch behavior up to some point in time and then start showing you inverse Hall-Petch behavior.

So, you want to stay in the Hall-Petch behavior of that system; if you want to improved its mechanical properties and then while you are still in that Hall-Petch behavior of the system, you want to test for wear properties and then see if the wear property is improved or not. They're depending on the kind of tribo layer that you get here based on what is happening with respect to the tribo layer, you may see an improvement or you may not see an improvement.

So, the mechanism of the wear is a very important aspect which decides how much wear will happen on the in a particular system and so, that is something that we have to look at. So, and in and therefore, as I said, in summary, you can do this process, you can test for wear properties, you can create a nanoscale material using severe plastic deformation and use it for testing wear properties.

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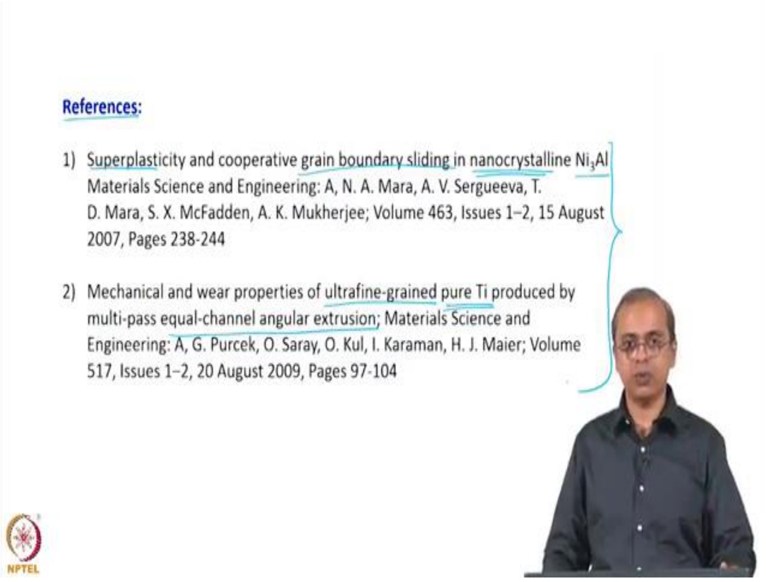

So, that is our discussion on using severe plastic deformation for some experimental application in this case for wear properties. I want to draw your attention to two references here. So, both in the last two-three classes, we have looked at severe plastic deformation either in the process of equal channel angular extrusion or in the through the process of this high-pressure torsion; both of them are doing severe plastic deformation.

They give you samples with which you can do a variety of different things, different tests and you can we saw a spoke about how you could do a tensile test, how you could do the tensile test in a transmission electron microscope the kinds of challenges that are involved in it and so on. And so, in fact, this paper here, you are welcome to look it up it actually looks at that kind of a study with the great detail and so, the specific data that they give the specific images that they show you where they can show you the various phenomena that we just discussed in general terms in our class those specifics, you can see in this paper.

So, if you get a chance please take a look at this paper and you can see how well they have put it all together the challenges they faced how they overcame it and also their data. So, you can all see all of that in this superplastic and cooperative grain boundary sliding in this particular Ni_3Al system. It is in material science and engineering it is a very good journal and you can also see the theory behind it and so on listed in this particular reference and again as I said it is nanocrystalline material that you are looking at.

There is another paper which also uses this severe plastic deformation but looks at it from the perspective of biomedical applications. So, particularly with respect to titanium; so, pure titanium so, their focus is on the idea that if you take typically the material that is used for biomedical applications, it is not pure titanium it is titanium which is alloyed with other elements and often those other elements are toxic. So, if eventually they start leeching out of that titanium or coming off the titanium it is not good for our body.

So, their focus was to see if you can actually make titanium mechanically suitable for applications inside the body by improving its mechanical strength as well as its wear properties by simply going to ultrafine-grained structure and again which means nanoscale structure. So, they look at this ultrafine-grained pure titanium and they are using multi-pass equal channel angular extrusion to get you that very fine grain size in the nanocrystalline range and then they study it for looking at both mechanical properties and wear properties.

They do the kind of testing's that testing that we have discussed in general in this class, you can see the specific data that they get the specific plots, they get the microstructures that they obtain and so on in that journal paper in that in that publication. And you can actually see in they have a particular situation where actually they are seeing an improvement in mechanical property, but not an improvement in wear property and they proposed the theories for it and so on.

So, these are both two very good references which you can see both looks at applications of severe plastic deformation in the nanoscale and one is focused on superplastic deformation, the other is focused on biomedical applications. So, I think that sort of is a summary of what we have discussed in the last two-three classes and it is a very useful technique and also these are very important materials phenomena and tests which all sort of come together in these discussions that we have had. Going forward we look at other properties and similarly look at impact of the nanoscale on those properties.

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So, in summary, we have seen what severe plastic deformation can do and that it can significantly alter mechanical properties and we saw that in the two different types of discussions that we had. And, that the pin on disc test is a very useful test to have for us to gage wear properties and that wear property may or may not improve in conjunction with other mechanical properties.

So, we need to understand what is the interplay between these properties to fully understand why it has improved in some cases and why it has not improve in other cases and I also drew your attention to some references, where these are discussed insignificant details for specific systems while we have presented some general trends that we have considered and looked at they are specific to their systems and they give you the data with respect to those systems. And therefore, that is a nice insight into how this can be looked at in a very scientific and thorough manner

Thank you.