Nanostructres and Nano Materials: Characterization and Properties

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Lecture - 45
Nanotribology

In this lecture we learn about nanotribology, so with the advent of nano materials we learned about know how nano mechanics is really essential in terms of detecting the mechanical property at nano length scales.

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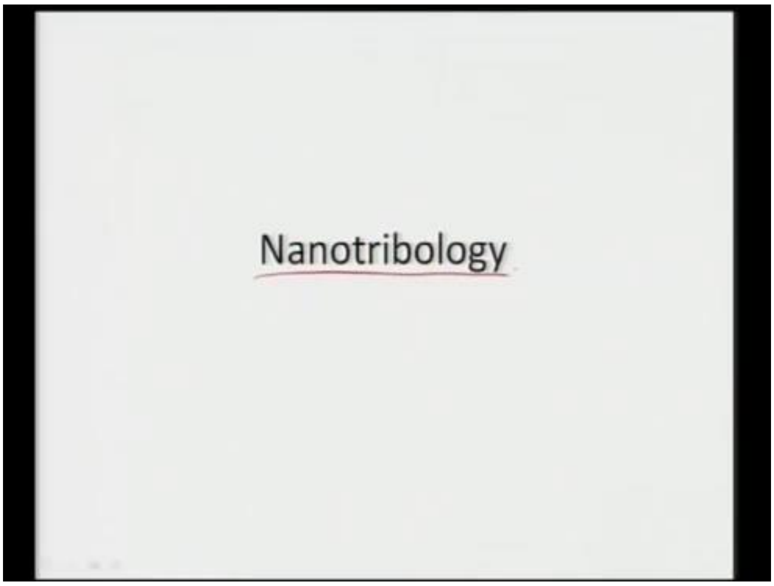

Similarly, for when we have some meeting surfaces and when we have some intermediate contact between two surfaces we need to learn about how the response of one surface with respect to other will be. So, that we can design engineering materials with much more effectiveness like, if you want to induce some lubrication or we want to see the response of one material with respect to other or see what will happen between two articulating surfaces we need to learn about Nanotribology and Nano Mechanics actually goes hand in hand with Nanotribology.

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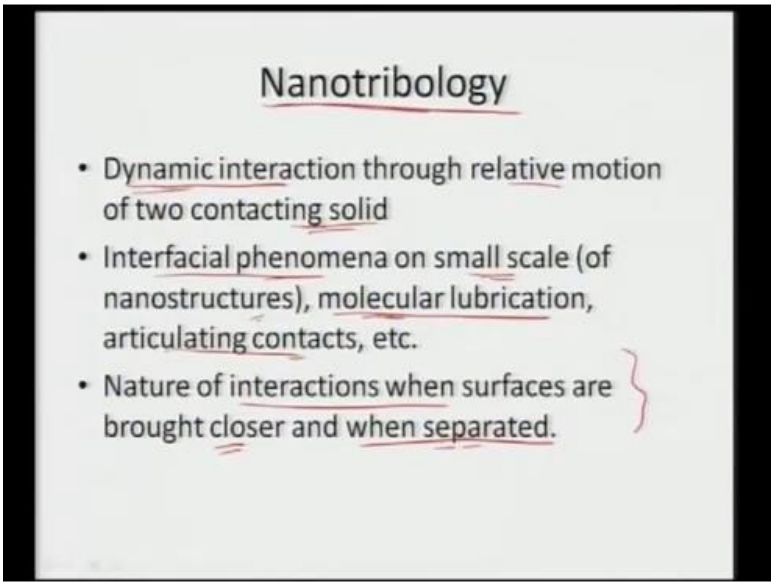

So, if you define Nanotribology it is a dynamic interaction through relative motion of two contacting solids and it automatically involve how the response of material with respect to other material will be when the materials are in contact. And they have some relative motion between those two contacting surface sand in Nanotribology the interfacial phenomena of small scale basically of Nano structures is very critical. We can also talk about molecular lubrication like if we can assemble some mono layers on top of particular materials. And we can see this response of the contacting surfaces than in that case learn about how we can reduce the friction and enhance the life of a particular for a particular component.

Also in terms of articulating surfaces the bulk response the micro response and the nano response they can be very different mechanism might be operating at those three different lengths scales. So, it becomes very essential also to see what is the initiating mechanism because that will dictate how the crack will basically initiate and then the later on the crack propagation. And more at micro length scale and then the ultimate failure at macro length scale. So, be able to relate be able to relate them at three different scales very essential. So, that is why we need to learn essentially how the contact is inducing damage at nano length scale, so that is why Nanotribology becomes very important.

So, again a Nanotribology not only related to when the two materials are closer, but also that how the interaction will occur when even when the surfaces separated. So, nature of interactions when the surfaces are brought closer as well as when they are separated, so that that is how we define Nanotribology. So, first of all it is a dynamic interaction to relative motion of two contacting solids. So, we need to see the two articulating surfaces are in contact and then it is defined by interfacial phenomena specifically at small length scales of nanostructures, because nanostructure will again define the contact between two meeting surfaces.

So, that also is very essential that what is the structure at nano length scale and that can be helpful in dictating in molecular lubrication or engineering the articulating surfaces or articulating contacts or even in microelectronic mechanical system. So, that we can see how the contact leading to such damage. And also the nature of interaction when the surfaces are brought closer or when they are separated it also both of these entities are constituted in the Nanotribology.

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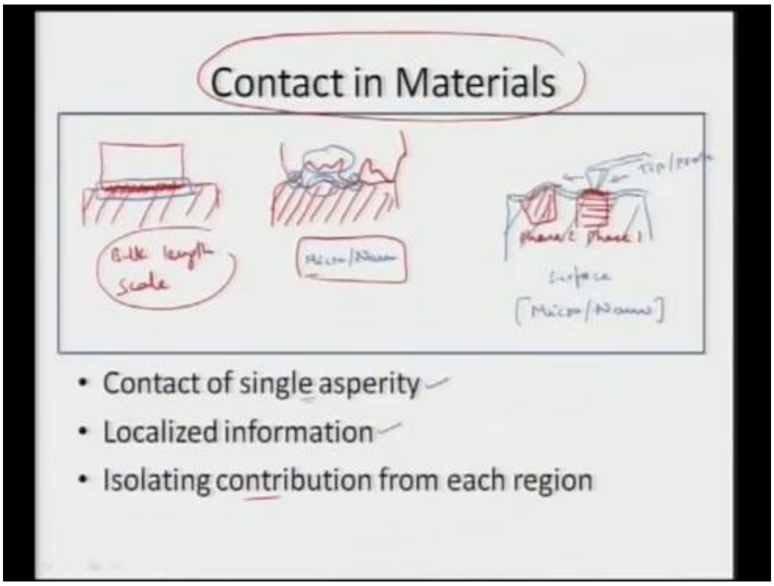

Essentially the contacting materials when we have when we see things at much more at a bulk scale we realize that the contact is complete. So, we can see we have one surface and then we have second surface the contact between them is very nice for a flight surface. But, again if we can start zooming it to very high magnification we will realize that the surfaces are not smooth they are not optically smooth, but they have some perturbations. These perturbations can be at micro length scale or they can again be at nano length scale. So, we can see that we might have some contacts which are very different from those are defined by a bulk scale.

So, in this in this case bulk length scale we might see that we have complete contact where as in the case of micro or nano we will we will realize that the overall contact surfaces gone drastically down. So, essentially where we had a complete contact like in the bulk scale at nano scale we will realize that we have only a limited contact. So, once we are talking about Nanotribology what we do we take the surface we capture surface roughness as it is and we utilize a probe which is small enough to contact each and every asperity.

So, in this case we can utilize an indenter with certain cantilever. So, we can see this is our surface again we are talking about micro or nano asperity and we have a tip which is small enough tip or probe. Which is small enough for capture each and every entity or each and every point of this particular surface.

So, in this case what we talking about we talking about contact of single asperity, so all these nominal points which were kind of abrupt. And then they may not they were not in contact in the bulk scale because if you see at the bulk scale these are certain area which are not contact at all. So, like this surface this surface they are not in contact at all, but again they also will dictate the overall friction that will occur in a material. So, what is happening at nano scale we can now capture the contact of single asperity as we can scan this strip along the surface. And it will try scanning the entire surface without losing any contact.

So, what we can get here is we can get a localized information in this particular case. So, also in this case if we find that if we have to more than one type of a material what we can do is we can, now say in this case we had phase one on this region and phase two on this region. So, the tip is moving along it can capture easily the values the kind of friction which will occur in phase one and in phase two. Now, we can differentiate what is happening with respect to the isolated contribution from each region or each phase even the orientations can also differ from surface to surface.

So, what can happen is that their contribution might also be very different. So, what we are seeing in respect to contacting material what is happening is, now we can capture the local asperity contact.

We can also differentiate what will happen once a tip is now in contact with the each and every individual phase. So, we can find out the contribution from each and every individual phase rather than the complete interaction. So, in micro or bulk where we are getting an approximate of the average property of the material where as in case of Nanotribology what we can do we can find the overall response from each and individual area. Now, we can combine it and then we can correlate it to the micro or the bulk scale there might be a very different phenomena because at micro scale there might be certain contributions, which might enhance because of the presence of grains because the grains can also orient they can also induce some damage via the rotation or the swirling or any such even their growth.

So, that can be captured at micron scale not at nano scale nano scale will only find out what is happening within the particular grain micron scale will tell contribution of the individual or localized response plus the grain response. And at bulk it can be multiple number of grains which can lead to damage it can be even three body where which can occur in a bulk materials. So, we can see the contacting material is very essential component because at bulk length scale we are talking about only a flat contact. And we can we assume that it is in complete contact, but in reality in micro or nano length scale we can see that asperities are not in contact. So, we to extract the information localized information what we are doing we are allowing a tip or probe to scan through the surface and give us the provide us the localized information isolating it from the bulk.

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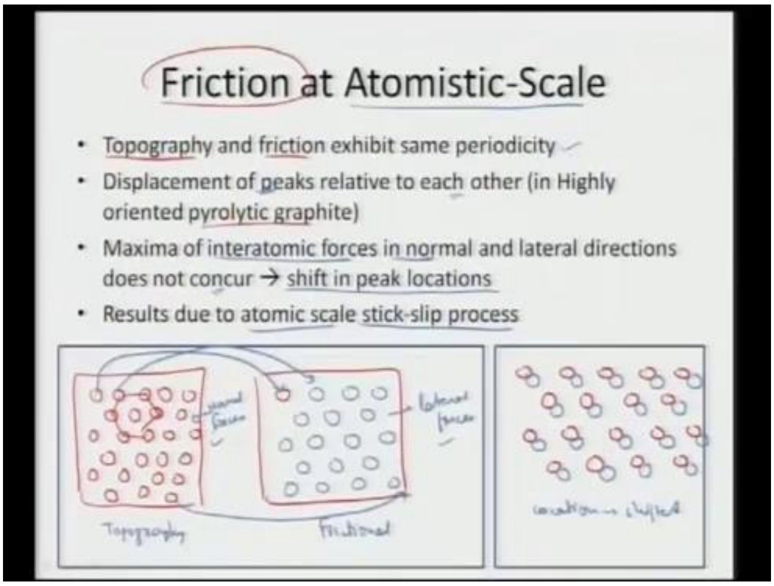

So, learning about the friction at atomistic scale what is happening here is we can utilize two techniques we can either have the topography or the frictional contributions topography is nothing but scanning the surface and finding out what is the local arrangement of atoms. So, if we take a highly oriented a pyrolytic graphite. So, what will happen is we will see the regularized hexagonal structure it will be highly regular highly regular pyrolytic carbon structure. So, we will see that that we have this atomistic position I am not drawing it that regularly, but we will see that we have very regular arrangement or hexagonal type of arrangement of atoms in the in through the topographical scanning.

But, once we talk about frictional forces if we can scan the same thing because there will be some frictional contribution from this atoms and say if we have a tip which is very fine. And it can capture the contribution from the atoms what will see we will see the same periodicity. So, if we if we capture the image again by utilizing frictional forces what we can see that we have the similar arrangement same periodicity can arise from the scanning. So, we can see the same periodicity from the scanning, now the same hexagonal type of a structure will appear. But, we will realize that the location of this atom and this atom corresponding atom through topography and through frictional forces they do not match.

There might be some shift between those two atoms, so what we can essentially see is the displacement of peak with respect to each other can occur in the highly oriented pyrolytic graphite. Because the maxima of the inter atomic forces in normal condition because in this case we are utilizing normal force sand in the second case we are utilizing in the lateral forces, because we are considering friction. So, the maxima of the normal forces and the lateral forces they do not concur at the same void, so that is why we can see some shift in the peak location. So, essentially what we will see in the first case what we had we had position of all these atom, so we can draw that.

Let me just draw one or two layer, so that it become little clearer. But, once we utilize start utilizing the frictional forces what will happen we will see that there is some shift. So, these positions would have shifted to certain extend, but it will now maintain the periodicity will not be affected the periodic it remains the same it is only the location which has been shifted. Now, and that occurs because of some atomic scale stick slip processes. So, the tip is in contact with the atom it will have some sticking and slipping process which can occur when it is in contact. So, that is why we will see the difference between the normal and the lateral forces imaging.

So, that is the case with the frictional or the normal force imaging at the atomistic scale. So, we can see the topography and the friction they exert the same periodicity and the displacement of peak can occur once we are talking about the normal forces or the lateral forces that results in the shifting of the peak location. And that occurs because of the because of inter atomic forces and the frictional forces the maxima of these two forces does not occurs at the same point.

So, these positions differs in a normal and the frictional forces and that occurs because of the local localized or atomistic scale stick slip processes. So, that basically tells that once we are emerging it and once we doing the friction force analysis it means that we can attain the same periodicity, but without exactly locating the exact position of these atoms.

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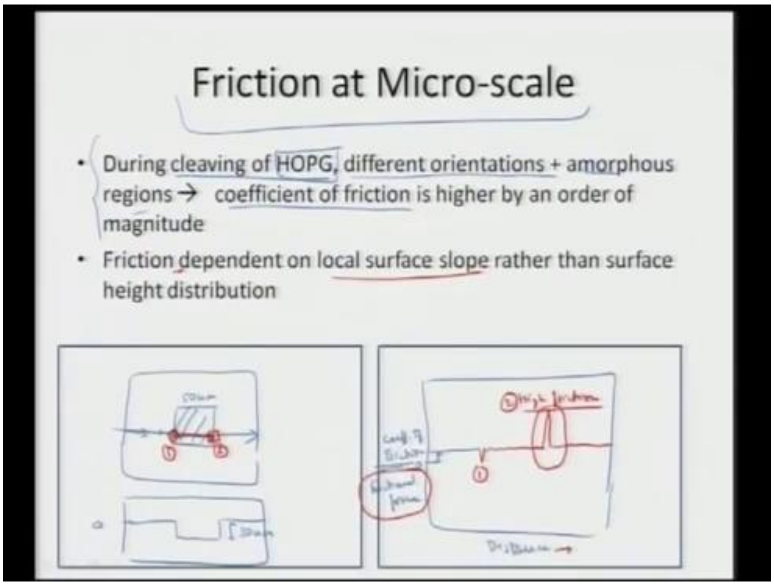

So, seeing the friction at micro skill we can see that once we can cleave the highly oriented pyrolytic graphite, we can see or because of different orientation. Which are present on a surface or because of amorphous region in the HOPG that is highly oriented pyrolytic graphite. What can happen is the coefficient of friction can alter to a certain extent.

So, once we are talking about the cleavage or presence of some amorphous phases on the graphite we can see the coefficient of friction. Now, drastically reduced by more than an order of magnitude. So, that that basically tells that the orientation of this crystals also very important in terms of identifying the slope or the coefficient of friction again it has been identified by the researchers that it is not the peak. If you have say if you have rough surface it is not the peak position or the height of a asperity it is a slope of the asperity that decides the dependence of friction on that particular feature.

So, once we are talking about roughness it is not the height, but it is slope of the asperity which decides the coefficient of friction how does it will occur will see in later few slides, but let me just give one example. See, if I take a surface and I have dig out a hole in it and that hole should be much smaller should not be very large. So, say if I have a small asperity at depth around say 50 nano meters not more. But, less around 50 nano meters as what we can do we can allow a tip to scan through this line. So, it will experience are very nominal coefficient of friction along the side, but as soon as it is touching this surface we will see a dip. So, if you just talk about the thickness of this one will have very smoothness goes down by 50 nano meters and then we again come to the surface. So, we can see that it is around 0 and this is around say 50 nano meters.

But, when we talk about friction going from left to right what we will see is that we have frictional force on this side and distance on this side, so as soon as it is going to certain values. So, we might have some value of coefficient of friction very marginal value of say 0.01, 0.02 very minimal 0.1 or… So, very lower value of coefficient of friction what we will realize is that frictional force will drastical or the coefficient of friction or this frictional force will drastically reduce as soon as it will touch this particular point. So, let me mark it red, so that you can see it more clearly.

So, as soon as it is reaching this point will see a dip in the frictional force and if we goes along will see some again back to normal. And it will go on as soon as it will touch again the ascending asperity what will see we will see a dramatic increase in the frictional force. So, what we are seeing very high friction at point number two and very low friction at point number one and then coming back to normal, so that is what we can see.

So, with the distance what we are seeing as soon as the tip is descending we can see a lower decrease in the frictional force as soon as it is seeing the ascending asperity. We can see very high level of friction very high frictional force that can occur at that particular point. So, that is point number two we can see very high friction at point number one we can see very low amount of friction. So, that is telling basically that there is some dependence of friction on the local surface slope rather than the surface height and that part has been already proved by certain researchers, but why does this happen will see in a slide or two.

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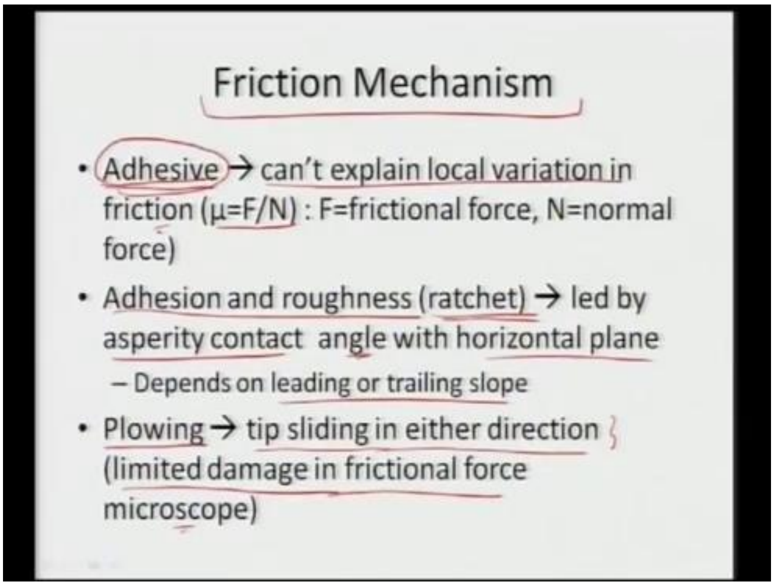

Talking about the friction mechanism which are dominant we can see that this difference in the coefficient of friction it can be explained via the certain mechanisms. So, adhesive forces only adhesive forces are present they would not be able to explain the local variation in a friction, because material is the same all the conditions are same. And the coefficient of friction is given by force by the normal force frictional force by the normal force. So, essentially it is not responsible for causing the change in the coefficient of friction.

So, adhesion cannot really explain what why this variation is occurring in the coefficient of friction then we talk about adhesion and roughness. So, we talk about this ratchet mechanism and that is basically lead by asperity contact and its angle with respect to the horizontal plane. Once we have an asperity then it will eventually makes some contact angle it will it the contact angle will not be normal any more it will have some angularity associated with that. So, that basically now depends on the leading or trailing slope and that in turn will affect the coefficient for friction again coefficient of friction can also be dependent on the plowing.

But, when we talking about Nanotribology the frictional forces are in the case of this imaging frictional force imaging or microscopy what is happening is that plowing is very much limited, because there is limited damage in the frictional force microscope.

So, tip sliding can occur in either direction and the plowing can be very it will be very limited and the damage will be very limited because of our forces are not exceeding the plastic deformation it is not leading to plastic deformation of the material. So, in that case it is the plowing is very much limited. So, we can see the alteration or change in the order of coefficient of friction is occurring because of the slope of the material. And that has been dictated by the ratchet mechanism that that is arising from the roughness of the sample.

So, we can see that frictional mechanism, which are dominant are adhesive or adhesion ratchet and plowing and adhesion is totally material dependent plowing also will depend on the kind of deformation or the kind of damage that is occurring. And in this case frictional force microscopy we can see the frictional force is very limited very low. So, in that sense it would not lead to the plowing of the material, so the eventual contribution is coming from the roughness and that is not detected by the ratchet mechanism for the friction. And that leads to some asperity contact angle and because of asperity contact angle we can see the horizontal angle basically changes it is the surface is no more horizontal. So, it has some angularity with respect to the applied force and that in turn leads to change in the coefficient of friction. So, that is what it is and how does it exactly depend we can see in the next slide.

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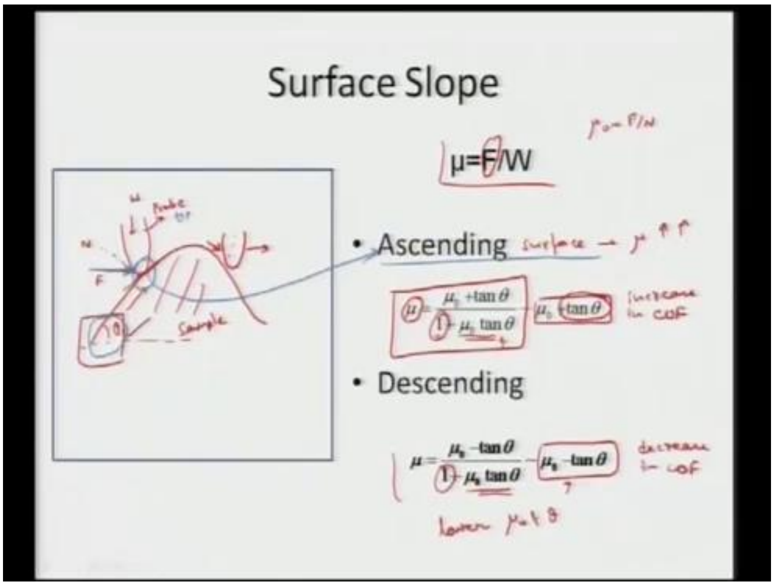

So, essentially we can see the coefficient of friction is given by frictional force by the normal force, but once we have a slanting surface what we can see let us say we have a slanting surface. Then what will happen we will have some theta with respect to that and this is the area where we are scanning it and then we have a probe tip. So, we are seeing this the tip is moving in the right hand right hand side from left to right. So, what we can see we have this frictional force which is arising out here then we also have a normal force contribution.

So, we have a normal force which is also existing out here, so in that case what is happening is if the tip is moving from left to right what we can see that in the case of ascending. So, when we are going from left to right this step this probe or tip is, now experiencing some additional contribution because of the resistance of the surface.

So, what we can see the coefficient of friction is, now given by mu naught plus 10 theta divided by 1 plus mu naught 10 theta. So, mu naught is nothing but the normal part without anywhere the surfaces does not have any slope. So, that part is now equal to mu naught plus 10 theta. So, there is some additional term, so as soon as the there is some contact of this probe with respect to asperity we see some increase in the coefficient of friction. So, that is why as soon as we see a ascending surface we see that coefficient of friction basically, now increases in case of descending what we can see is... So, in this case if we have the same contribution, but now tip is moving from left to right on the right hand side.

Now, we can see the similar forces which are acting on it, but now in this case what we can see there is some release because once we have contact surface there is some contact resistors because of the asperity in this case there is the drawing away from the surface. So, in this case we can see the contribution is mu naught minus 10 theta for lower mu naught n theta values. So, we can see that mu is equal to mu naught minus 10 theta; it means there is some decrease in the coefficient of friction. So, we can see for lower mu naught and theta values we can see that this term can be ignored. So, the denominator will become only one in both the cases, so this term can be ignored for lower mu naught and theta values.

So, eventually what we see the overall contribution is coming, because of the ascending and descending surfaces and because of this theta value, because of this angularity because of this particular slope. So, we had this sample and the sample surface we had certain theta value associated with that. So, we can see there is some theta value angularity and then we have force which is, now being provided to the probe tip against the surface. So, when it is working against the surface in an ascending fashion, so we can see for an ascending surface we can see there is some additional resistance which is occurring because of that and that is given by mu naught plus 10 theta.

Whereas when the tip is getting retracted or it is moving away from the surface, now it also finds a release. So, that is being given by the descending surface and we see a decrease in the coefficient of friction. So, that is that is how the coefficient of friction depends on the surface slope.

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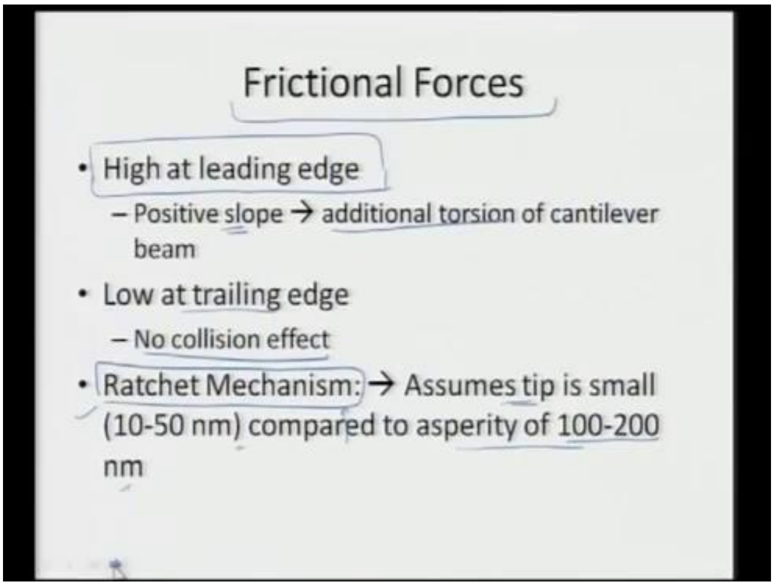

And again if we can see the frictional forces the same the same way, so high they are higher at the leading edge. So, once we have leading edge or ascending surface we find that we have a positive slope and that induces some additional torsion of cantilever beam also, once we have a slanting material. So, slope is positive, so as soon as strip will encounter that it will experience some additional torsion of the of the cantilever beam. And that in turn will induce very high frictional stress or the shearing of the material will require much higher stresses. So, that is the reason it also experiences the increase in the coefficient of friction.

Whereas in the case of trailing edge, so when we are retracting or when we have a negative slope there is no collision effect. So, there is no additional torsion or shearing that is occurring in the tip and that leads to lowering of the coefficient of friction. And the ratchet mechanism is considered out here because also we assume that the tip is small enough when compared to the asperity which is around 100 to 200 nano meter assuming that. So, the tip also has to be small enough to capture the ratchet mechanism. So, if the tip is pretty high it cannot it will encounter more number of asperities altogether.

So, in that case we the contribution of ratchet mechanism may not be that large, but again it will be substantial. So, again we can see that for higher frictional force that the leading edge are caused by the torsion of the tip itself also very high shearing forces are required for the friction. And that term we can see the increase in the coefficient of friction whereas in case of trailing edge we have a negative slope. So, there are no collision effect on the tip with the sample surface. So, in that sense we can observe a very low coefficient of friction and we assume that the ratchet mechanism is dominant because the tip is assuming the tip is pretty small around 10 to 50 nano meter. The tip radius will be around 10 to 50 nano meter whereas the asperity the asperities are generally 100 to 200 nano meter. So, assuming that we can assume that the ratchet mechanism is the dominant factor in controlling the coefficient of friction.

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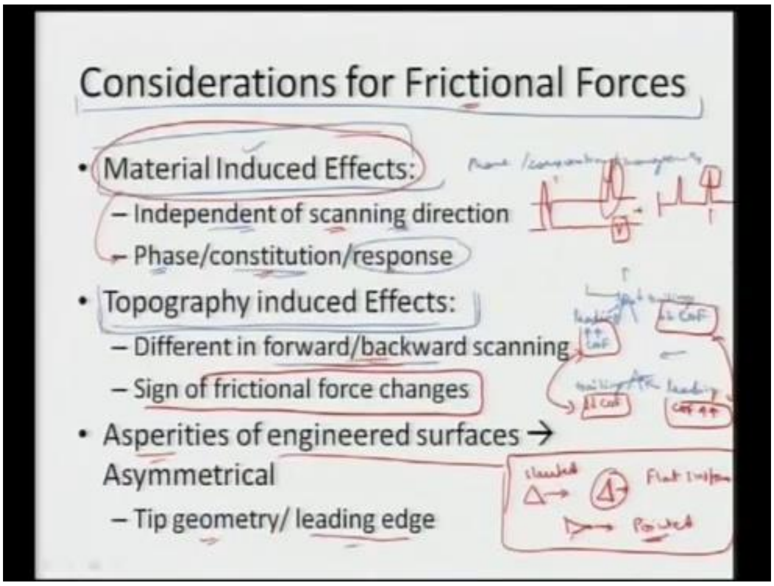

Again now there can be various considerations for calculating the frictional forces. So, there can be two main effects which can come by they can be many more, so main one main mechanism is material inducer effects or topography induced effects. So, once we are talking about material we are talking about the phase its composition its homogeneity such aspects. So, once we have a material contribution they are independent of the scanning direction. So, does not matter if we are taking the tip from left to right or right to left and we are worried we are not worried about the topographical features anymore, so we just worry about the material composition.

So, does not matter whether we are going from left to right or right to left the features will come out the overall properties will come out to be very similar because those are dependent on the material and not on its feature or the topography of it. So, what essentially we are worried about is the phase what is the constitution of the particular phase what is the composition what is the homogeneity? And also what is the final response of the material with respect to a force which is applied by a certain tip. So, we can see the first is the material induced effects second can be topography induced effects it means we find some slope we find some cavity we find some hill in a feature that can also induce some changes.

And those effects will change as we are talking about forward or backward scanning. So, as we saw earlier if I have a feature like this and I am scanning from left to right then I will observe it I will observe the initial point as a ascending asperity. And later on I will find it at trailing edge trailing and the first one will be the leading edge. But, once I am scanning from left to right I as see that the overall frictional forces will totally change because. Now, I will find this one as the leading edge and as this point as the trailing edge, now initially when I had the leading edge I saw an increase in the coefficient of friction and the second case reduction in the coefficient of friction.

Whereas in the second case what is happening is the coefficient of friction is now increase in the leading edge on this side the trailing edge I can see reduction in the coefficient of friction and these are totally opposite. So, that is what we can see that once we have some topography induced effects the sign of frictional forces changes completely. So, that is the importance of these topographical induced effects, so it very much depends on the direction of the scanning. And again one more consideration which is to be given necessarily for engineered surfaces all these features all the topographic features are not symmetrical they may not be symmetrical. And also it depends on the geometry of the tip also if say I have a cone-spherical tip it is fine spherical tip it is fine.

But once I have a non symmetric tip say if I have a Berkovich tip and I am scanning it like this it is the features will be very different because, now I have some different area which is now coming in contact or if I do scanning like this. So, in this case I have a pointed area which is now scanning the surface in this case I have a slanted surface and in third case I have a flat surface which is now leading to scan the material. So, all the responses in all the three cases might be very different depending on the material response. But, definitely there will different, because in one case I have a pointed tip second case I have a slanted slanting tip and third case I have a flat tip which is now scanning against the surface.

So, I have see very three different responses, so that is also very critical that what is the leading edge of the probe or the scanning tip. So, we can see for considerations for the frictional forces these can be material induced effects. But, they will not affect the affect the overall properties they are independent of the scanning direction they depend only on the phase its constitution and its response. Whereas, topography induced effect they are very much dependant on the scanning direction whether forward or backward scanning is being done. Somehow we can now combine these two together and subtract the effects which are coming from each other.

Say in one case I saw a response like this that means I have a trailing edge in this case and in the second case I had a leading edge then I do a reverse scan it means the leading edge becomes a trailing edge and the trailing edge becomes a leading edge. So, in this case I will see a response which is like this. But, if when I combine them together what I am seeing is I have see an overall response which is like this, because the resistor forces are very dramatic it should be the other way actually. So, the trailing edge it is a negative side on the top hand side, so let me rewrite.

So, what happens in the in this case in the trailing edge as the reduction in the coefficient of friction and in the leading edge I will see a enhancement in the coefficient of friction, once I am do I do a reverse I will see the exact opposite trend. So, in this case my now forces will be very high.

So, once I combine them together what I will see is something like this because in this case the leading edge the overall coefficient of friction or the frictional forces are dramatically high in comparison to the trailing edge. So, I will see a response which is more like this. So, it is very hard to correlate them that oh this effect and this effect they are similar of trailing and the leading edge. So, combining them is little more trickier rather than, so simple. So, we cannot really combine these two forces as it is. So, it require some engineering as well some understanding of this as well. So, those are topographical effects and also asperity effect can also come into picture because of the tip geometry or the leading or the trailing edge of the tip itself.

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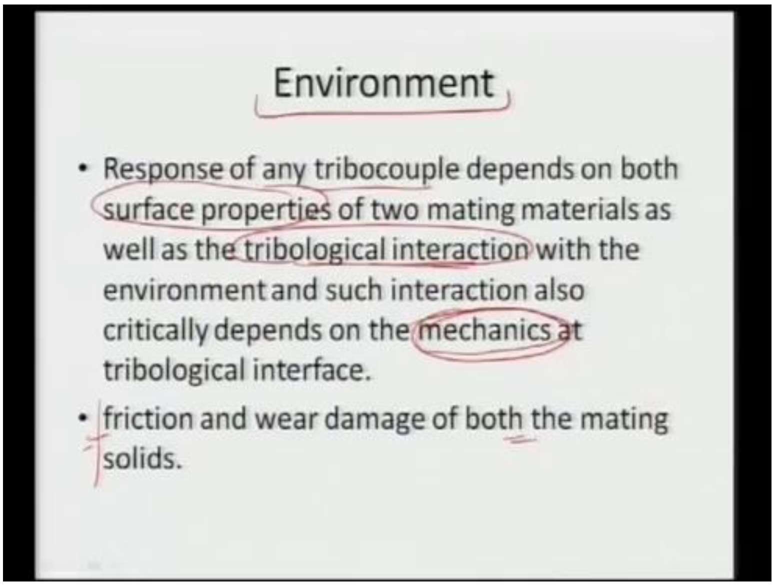

Also on the environment also very dramatic effect because response of any tribocouple will depend both of the surface properties of the two mating surfaces as well as the tribological interphase with the environment, so depending on that. So, first thing is the surface properties biological interaction tribological interaction and what is happening exactly at the mechanics what is the dominant mechanics which is leading to the contact and the response of these two. So, those couples of properties which are very important are the surface properties how this tribological interaction is occurring at the interphase. And also what is the mechanics dominant mechanics that is leading to this particular response at the tribological inter phase.

Again friction and wear can lead to damage of either one or both the materials of both the mating surfaces. So, frictional force will be dominant at both the both the surfaces and that will lead to some damage accumulation in the two mating surfaces.

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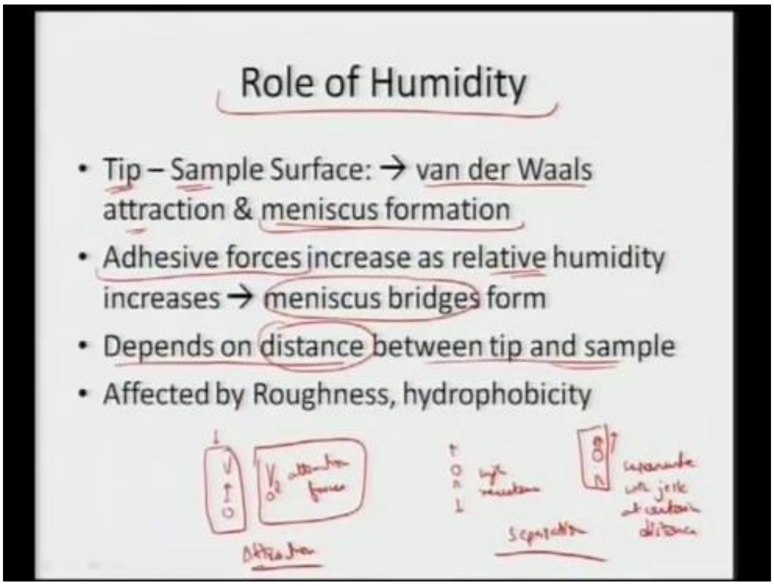

Now, let us see the role of humidity, so we can see that the role of humidity how it can really occur. So, the interaction between tip and sample surface they are very many van der Waals forces or the secondary forces of attraction. And also there is some meniscus formation once we have humidity always there will be a formation of some meniscus. So, what will happen that adhesive forces will start increasing as we start increasing the relative humidity, because of formation of meniscus bridges?

So, once we have a tip and a sample and there will be some secondary forces between the tip and the sample van der Waals forces of attraction or it can be even meniscus formation, so once we are contacting the surface. So, once we are contacting it or when we are separating it we can experience those forces come into play it also will depend on the distance between the tip and the sample as well. So, that is what is very critical that depends on the distance also between the sample and the tip. So, as soon as we see as soon as it is coming closer we might have some attractive forces, but once we are very close there will be very sudden increase in the attraction forces.

Similarly, when they are trying to separate initially we will find a very high resistance and there will be a sudden jerk a sudden jerk. So, with very high jerk these two surfaces will now separate at certain distance. So, we can see once they are farther apart very smooth transition from very higher to lower distances and is sudden grasp or sudden capture of these two surfaces with a sudden force even for attraction. And when they separating out you see the same phenomena you will see a same phenomena that they will now separate with a very sudden force they will separate far apart.

It is more like a magnet once we are trying to bring the two magnets closer they will find a sudden at certain point they will combine together with a very high force. Similarly once we are trying to pull them apart it will be hard initially to separate them apart. But, as soon as you reach a certain distance they will go much farther apart with a certain force. So, that is what we can see that the role of immunity it induces some attractive forces which are van der Waals forces and also, because of meniscus formation. And as soon as we increase the humidity we will see that adhesive forces will also start increasing and it happens because of the formation of meniscus bridges. It also depends on the distance between the tip and the surface and again the role of humidity also basically gets affected by the roughness or even the hydrophobicity of the material. Because once we have a hydrophobicity or the wetting of the material in hydrophobicity we would not allow a continuous film formation. So, in that what can happen we can form a local islands of water film and that in turn is not covering the entire surface. So, we can see enhancement in the shear forces or the frictional forces, which can occur out there.

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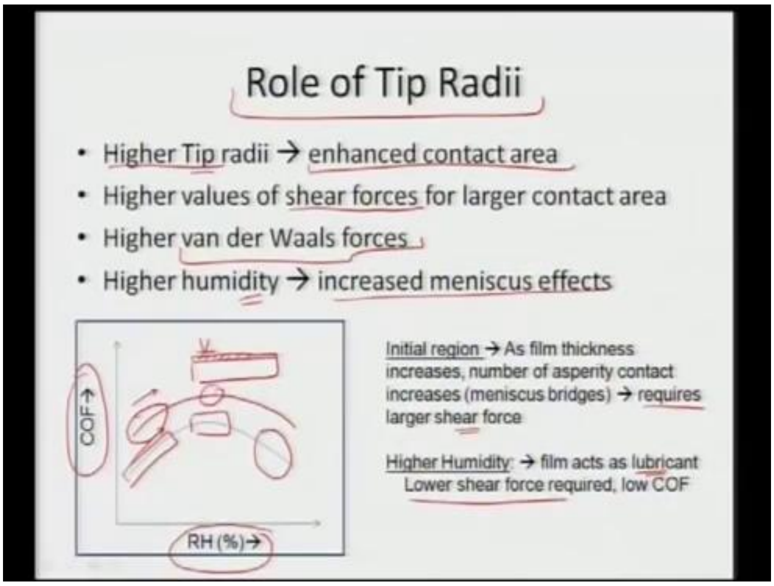

There can be again role of tip radii, so apart from the effects of the environment like humidity we can also find role of tip radii. So, what is happening here is when we have a higher tip radii, we find that the contact area also increases. So, once we have higher contact areas, now we require high shear forces because, now we have higher contact area. So, once we have once we have higher shear forces in addition we also find that the van der Waals forces also will increase because of the enhanced contact area. So, eventually what is happening is the overall shear forces or coefficient of friction also starts increasing.

In addition once we have presence of humidity we also see increased meniscus effects. So, what is happening is if we for a particular tip if we see the relation between the coefficient of friction and relative humidity in a initial region. We can see the increase in the coefficient of friction because in the initial region the number of asperity contacts will increase because of formation of meniscus bridges. So, in a starting region we have more meniscus bridges very high adhesion forces very high Van der Waals forces, now we require very high shear force.

But at later on some time what happens is now this film starts making complete coverage and because of that it starts acting as a lubricant and now the contact will require. Now, the tip is submerged and now it will requires very lower shear forces for moving along and in turn it renders very low coefficient of friction. So, we can see the role of tip radii, so as soon as we have very high tip radii it means we have enhanced contact area which eventually means we have very high van dar Waals forces all. Now, we require larger contact area we require very high shear forces we have high van der Waals forces.

So, eventually we will see an increase in the coefficient of friction humidity also we can see there is there is a downward bell type of a curve. So, initially we see that with enhancement in the relative humidity we see increase in the coefficient of friction because now we have very high meniscus bridges very high contact area. So, that in turn will start increasing the coefficient of friction, but at certain stage it will start forming a continuous film and it starts acting as lubricant. So, in turn it now starts reducing the coefficient of friction.

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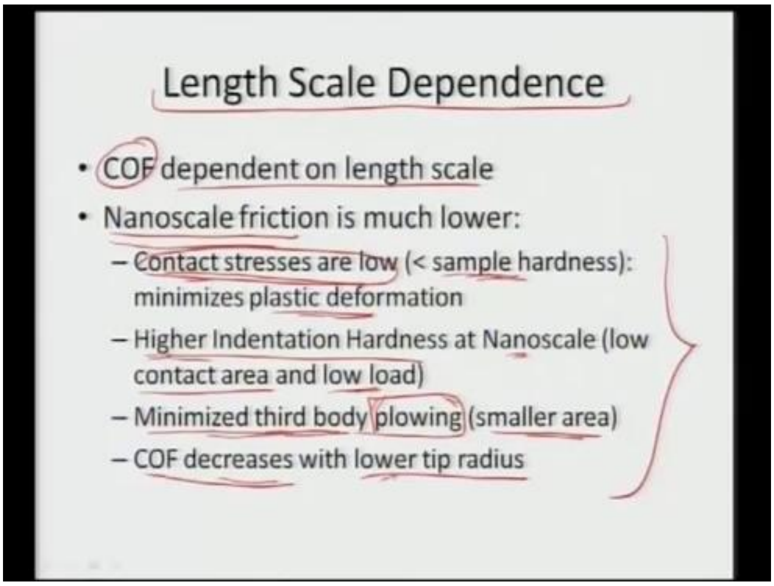

Also is dependence of coefficient of friction on the length scales, so coefficient for friction depends on the length scale as well what is happening what has been observed is that nano scale friction is much lower than that of the micron scale friction. And that is basically results because the contact stresses are very low.

So, it means the contact stresses are stresses are much lower than the sample hardness. So, what happens is because of that is that is that the overall plastic deformation is much more limited at nano scale friction. So, we can see nano scale friction is the overall coefficient of friction is much lower than that of a micron scale and that essentially arises from the contact stresses which are very low much lower than the sample hardness. So, we can minimize the plastic deformation that occurs at nano scale friction also higher indentation hardness which is which is observed at nano scale because of low contact area.

And low loads which are utilized in the at the for the nano scale at Tribology also the surface property is also, because the surface property is itself we observed very high indentation hardness at the surface than in the bulk. So, that also results higher indentation hardness at nano scales third thing is because of lower loads and lower contact area we can minimize the third body plowing, so the because the overall stresses are. So, low at this scale that it minimizes third body wear it means that we do not allow and debris to form at this at this nano scale friction. So, the plowing is also very minimal the loading also is very minimal there is no third body wear. So, in that case and again if even if we find some particle to get embedded the smaller area of the tip disallows any major damage because of third body wear.

So, that also reduces the overall dependence of this coefficient of friction on the third body interaction and also we have seen that the coefficient of friction also decreases with lower tip radius because of lower contact area.

So, eventually what we can see is that nano scale friction or the coefficient of friction is very low in comparison with that of micro scale friction and that occurs because the contact stresses are very low. Because the loading kind of loading we are applying is very low it means it is much lower than that the sample hardness. So, we are minimizing any plastic deformation in the material secondly the surface itself will have the higher hardness higher indentation hardness at nano scale.

So, because of lower contact area and low load that also eventually reduces the frictional forces at the at the nano scale friction also there is minimize third body plowing because of lower loads and smaller area. And also we have seen that the when we have the tip radius is also very fine we also see a reduction in the coefficient of friction.

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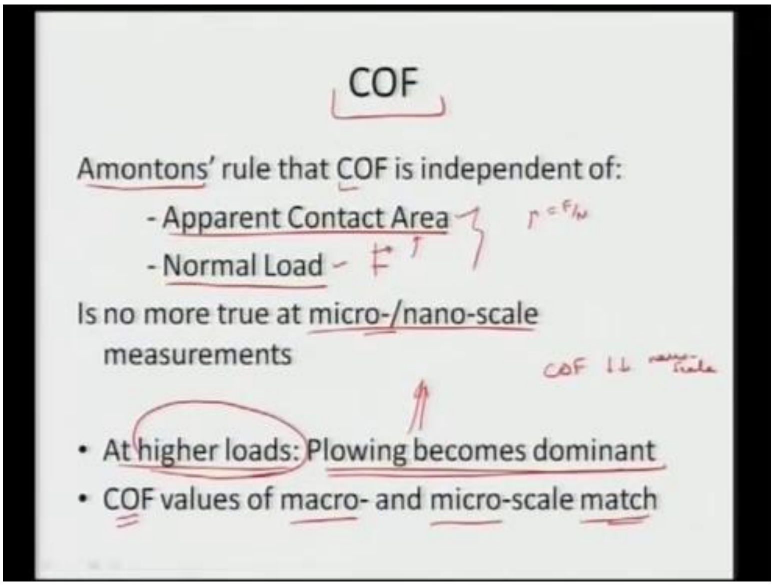

And the coefficient of friction basically is detected by Amontons rule that coefficient of friction is independent of any apparent contact area or normal load. So, that thing has been very well established for the micron or the bulk scale that the coefficient of friction will not depend on the apparent contact area or the normal load. So, whatever will the normal load it automatically will set the apparent contact area and that in turn will make the new constant. So, it is not dependant on the normal load or even the apparent contact area that is basically being adjusted automatically.

So, but this is no more true at the micron or nano scale because what is happening at the at the bulk scale we all we are also inducing some plasticity the force or the stresses that high enough to cause the material deformation at that length scale. So, it automatically takes care of the normalization of this normal force and apparent contact area, but that is no more true in the micron or nano scale because in this case we are limited by the lower force lower contact area. And there is no more plastic deformation also we are limited to surfaces. So, surfaces also will have a very high indentation hardness limited plowing limited contact area, so what is happening is. So, at higher loads only the plowing becomes dominant that is for the macron scale or the bulk scale and also the. So, basically the overall coefficient of friction will be very lower in the case of nano scale.

And if you want to match what is happening at nano scale and at micron scale we need to now see that we utilize very high loads. So, in it higher loads this plowing mechanism becomes dominant and then only the coefficient of friction values at macro and micro scale or even the nano scale they will match. So, we can see that the Amontons rule which states that the apparent contact area in the normal load do not affect the coefficient of friction that is no more true in the macro or nano scale measurements. So, for achieving that we need to make plowing also become dominant mechanism that can occur only at higher loads and that only will make coefficient of friction to be similar in both macro as well as nano length scales.

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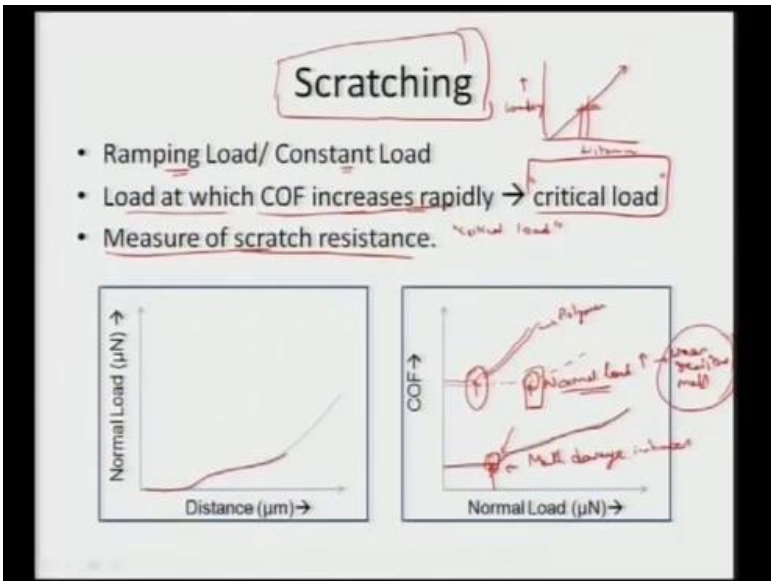

So, again we can do scratching both at ramping load or even at constant load, but if we are utilizing a ramping load then we can essentially see the response of loading condition as we go along. So, we start increasing the load, so we have a distance and then we have a loading. So, we start increasing the loading as we going along a distance, so we can see with that with increased loading at what point we can see increase in the sudden increase in the coefficient of friction. So, we are seeing a normal loading which is being applied, so we can see a normal loading which is being applied to a material as the distance is going along.

But, at certain point what we can see is at a certain point the coefficient of friction suddenly starts increasing it is now increased to certain extend and it will keep increasing further. So, at this particular point we can see that the material damage has initiated and this particular point is the one where we can see this is the critical scratch resistance. So, we can find this is a critical load at which the material start scratching dramatically. So, if with the ramping load we can see load at which the coefficient of increases rapidly that is called critical load. So, this is nothing but the critical load which is being applied on the material and this is a measure of scratch resistance because the after this point there will be very heavy damage to the material.

So, we can see the scratch will start inducing to a very larger depth and that is the that is the responsible culprit for enhanced coefficient of friction and we can see the load at which the coefficient of friction will increase very rapidly that is called critical load. And this critical load is a measure of scratch resistance of the material. So, we can realize that if you are using a very soft material this normal load will suddenly start increasing at very low normal load itself we can see the coefficient of friction start increasing. But, for a very highly resistant material we can see that the normal force can be very high and still the coefficient of friction can be very low.

So, we can see the normal load can be very high for can be very high for wear resistant material or in other words we require very high normal loads for causing the scratch in the material. So, once we have polymeric sample we can see that the normal load is occurring at very lower normal loads whereas the for ceramics or very high hardness material. We can see that the normal load is pretty high for with when the coefficient of friction starts increasing rapidly. So, that is the difference between the soft and the hard materials and we can utilize this concept of coefficient of friction with respect to normal load to identify the behavior of materials also.

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Again the wear mechanism can have can take various forms, so initially it can start making some wear marks or it can also induce indent marks. So, once we allow a tip to interact with the surface because of the contact between the tip and the surface if the tip is very hard it will induce some wear marks on the sample surface and eventually what can happen is it can also induce some debris wear debris. So, once it is plowing the material we can see there is some material removal that also occurs in a occurs because of the tip to material or sample interaction. So, first thing is we can induce some marks damage marks if the marks if the tip is hard enough load is high enough it can start plowing the material that will lead to material removal.

Also generally it has also been observed that there can be formation of thins film as well. So, once a load is being applied and because of localized heating or disturbances or local oxidation also can occur. And that may lead to thin film formation or there might be reorganization of the material soft material and it can also lead to formation of a thin film also local deformation can also occur depending on the tip geometry. So, those can lead to formation of deformation bands or it might also lead to straining of the material eventually if the material is brittle enough it can also lead to crack generation and propagation.

So, if material is enough strain harden or the material is highly brittle and the loading is pretty high it can lead to crack generation as well it is as well as its propagation and that might eventually lead to some material removal as a debris also.

So, we can see that we have various wear mechanisms it can have wear marks might arise because of indent marks we can have wear debris that might lead to material removal. We can also have thin film formation because of local disturbances or heating or oxidation or even disturbances we can see local deformation. So, leading to deformation bands or straining of the material or even plastic deformation of the material which can eventually also lead to crack generation and even propagation of even brittle materials.

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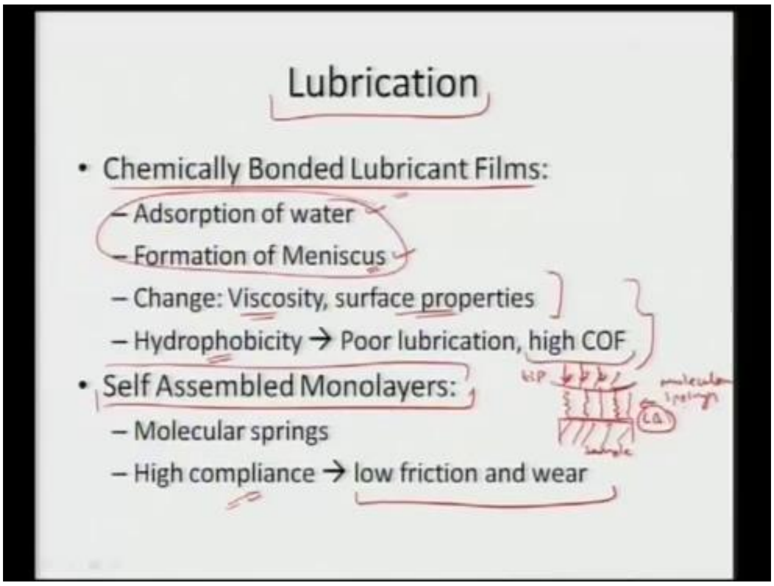

And one more important concept in tribology is also lubrication, so we can various types of lubrication we can have some layer lubricant layer and those lubricants can be either chemically bonded. So, we can have or they can be also self assembled monolayers. So, we can see that chemically bonded lubricants it is mainly by the adsorption of water on the surface it leads to formation of meniscus. So, we did see that with enhanced relative humidity initially it starts inducing very high frictional forces, but at certain time it becomes a lubrication. And then it starts reducing the coefficient of friction and this choice of this chemically bonded lubricant also depends the way it changes the viscosity or of at the surface properties.

So, those are also important contributions in choosing a particular lubricant which can be chemically bonded to a particular surface and also talking about hydrophobicity. Once you have hydrophobicity the lubricant will not stick evenly to the surface it will start forming certain islands and in turn it is not covering the surface properly. So, in turn it will lead to poorer lubrication and it will enhance the surface stasis and eventually it will lead to enhancement of the frictional forces also we will observe a very high coefficient of friction.

So, again the lubricant what we are choosing the it has to be wetting in a further surface, so that can spread out and it can protect the surface from the wear damage also we can have Self Assembled monolayers on the surface, so they also act as molecular spring. So, once we have a surface we can have some protection because of the monolayers they can be langmuir blodgett films as well or even ((Refer Time: 48.46)) or there can be many self assembled monolayers. So, they can stay on the surface and any tip when it interacts with the surface these act as springs molecular springs.

So, the overall loading which is being incurred by the tip does not reach the sample directly via ((Refer Time: 49.08)) via through a langmuir blodgett or langmuir blodgett or self assembled monolayers, so what we can see the damage to the sample now is restricted. So, if the molecular spring is they have very high compliance it can take very high loads or very high shocks, so in turn we will see a very low friction and wear in those cases. So, we can see we can have a chemically bonded surfaces but, then it also is detected by the super hydrophobicity or hydrophobicity the viscosity of the of the of the film or even surface properties.

Those are being changed by the chemically bonded lubricant films also the self assembled monolayers such as langmuir Blodgett, so they can what they can do they can act as a cushion they can act as molecular springs. So, the kind of loading which is being supplied by the probe or the frictional tip, that is being absorbed by the molecular chains or molecular springs. And when the compliance of those springs or those molecules is pretty high it can reduce the coefficient of friction and reduce the wear damage.

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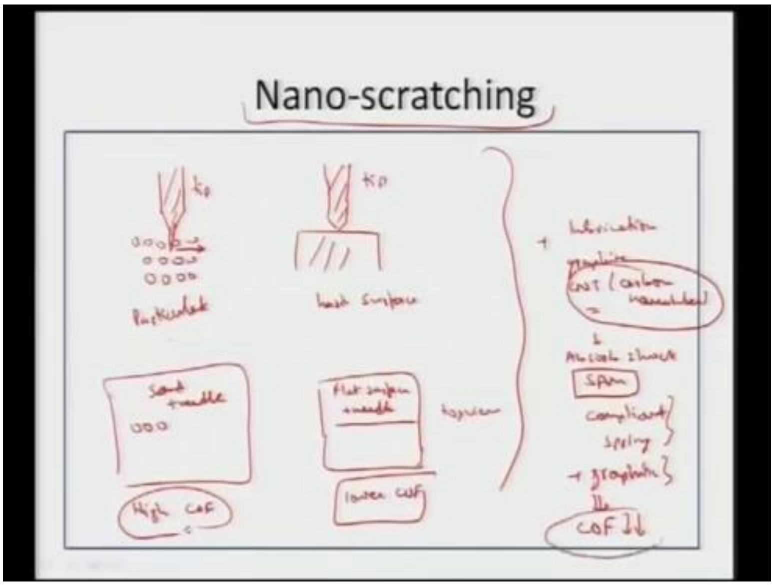

So, nano scratching can be observed as a tip which is basically being interacting with the matter. So, depending on whether the matter is pretty like a particulate. So, it can basically penetrate through and depending if the surface is pretty hard surface is pretty hard this is the tip this can be particulate it can be even hard surface. So, depending on how the response of this particulate or the hard surfaces it can either leave a scratch. So, it can leave a scratch in the material. So, just seeing the top view or it can get embedded much deeper into the particulate and eventually can lead to very high coefficient of friction.

Because in this case what is happening? The tip can pierce through the material and in turn it will become very hard for the tip to walk across. So, once we are very high it is more like a sand and we are putting a needle inside and we are trying to move the needle. So, if we take a tip inserted into the sand box and trying to move it will be very harder for the tip to move. Whereas if we take a surface with let us take a glass surface and take the same tip same needle and trying to force it over the glass surface and move it along.

So, we might realize that the hard surfaces might result a lower coefficient of friction in comparison to that of sand surface. So, those can also come into picture additionally what can happen we can also add some lubrication like generally people utilize graphite or now these days we people also utilize carbon nano tubescarbon nano tubes. And because of the graphitic nature they also can induce some they can also act as lubrication and they can also absorb shock. So, as we saw in the self assembled monolayers that if we have a compliant spring it can also absorb the shock plus the graphitic nature of this carbon nano tubes it can also tend to reduce the coefficient of friction can be dramatically reduced.

So, we can see that the overall feel of adding the aspect of nano scratching it depends on the surface directly that whether it is a particulate or a hard surface. And how are they interacting with the surface it is more like a sand and a needle kind of a relationship in this case it can be a flat surface plus a needle. So, we can see that the lower coefficient of friction can be obtained when we have a flatter surface. So, higher perturbations will cause very high coefficient of friction and these days people have adding some ((Refer Time: 52.54)) also as a lubricant because it can also acts as a absorber for the shock. Similar, to that of self assembled monolayer also it is very compliant also, because it has a graphitic nature it can also reduce coefficient of friction.

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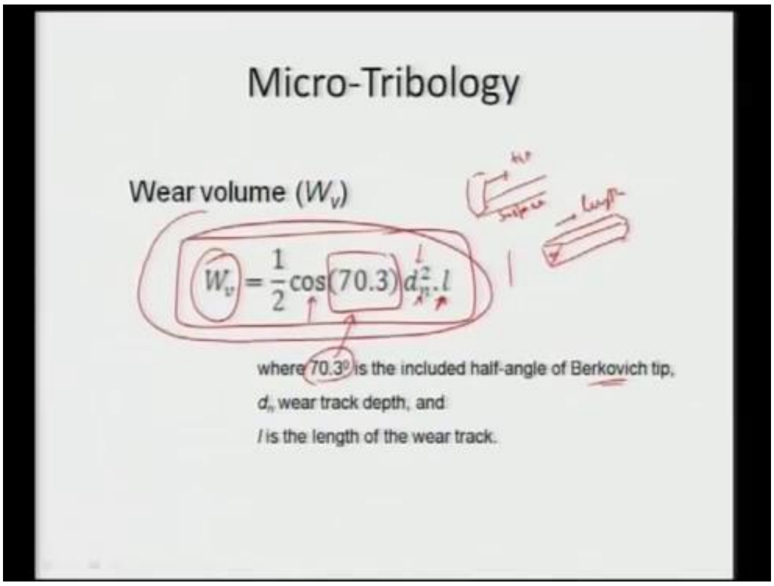

So, in if you utilize this nano scratching or micro scratching and say if you utilizing say a Berkovich tip we need to utilize the equivalent of this conical angle. So, the conical angle equivalence of this Berkovich tip is around 70.3 that is being utilized here. So, we can see if the tip is scratching the surface we can utilize the rule that it is forming a conical entity or a semi triangular entity throughout the length. So, defining its depth and the length we can always calculate what is the wear volume? So, depending on the geometry of this particular cavity which has been created by a moment of this particular tip on a surface we can always calculate what is the wear volume that is being arising from the nano scratching or even at a micro scratching. So, that is the wear length this is the depth and then we have a equivalence of this particular conical angle for the Berkovich tip, so from that we can always calculate what is the wear volume.

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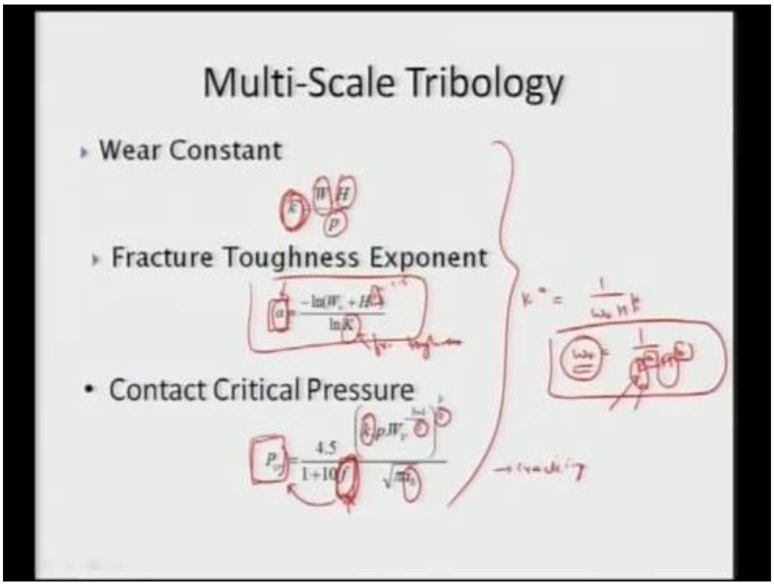

But, more essential is to be able to correlate what is happening at nano scale and at micron scale. So, we can see that the overall wear constant is dependent on the wear volume hardness of the material and the kind of loading that has been applied. So, we can obtain the wear constant and equating that. So, because we can also find the what is the fracture toughness for a brittle material when do see what is the crack length or what is the fracture toughness exponent.

So, we can see that it is it is the dependence on the K a. So, K this is the exponent for the fracture toughness this is the K is the fracture toughness. So, we can see that, so we can see this is K power a equal to H power b. So, wear volume is equal to 1 by K a hardness over B. So, we can see that the wear volume is inversely proportional to the when we have a high fracture toughness or when we have very high hardness we can see a wear volume can be very low. So, these exponents also are very critical a and b, because now if they are very high the overall contribution from fracture toughness will also be very high.

So, we want this fracture toughness exponent to also be very high. So, depending on which type of material is there we want a and be to be very high b is approximately 1.5 for ceramics. So, we can see that the contribution of a is also very strong. So, once we can identify what is the value of a and b then and from the wear constant we can also input this wear constant into K. So, what we can see the coefficient of friction which is arising because of the of the nano scratching a kind of crack and that is being generated we can always calculate the critical pressure which can cause cracking.

So, eventually what is happening we are utilizing to identify the fracture toughness hardness and from nano scale we can always find what is the frictional coefficient to cause cracking in the material. So, through this particular relationship we can we can identify wear constant we can get a and b exponents coefficient of friction from the nano scale experiments and eventually we can calculate what is the contact critical pressure to cause cracking. So, via utilizing the nano this particular technique of nano friction or Nanotribology we can always go back and identify what is the kind of force or pressure Required for causing this particular cracking.

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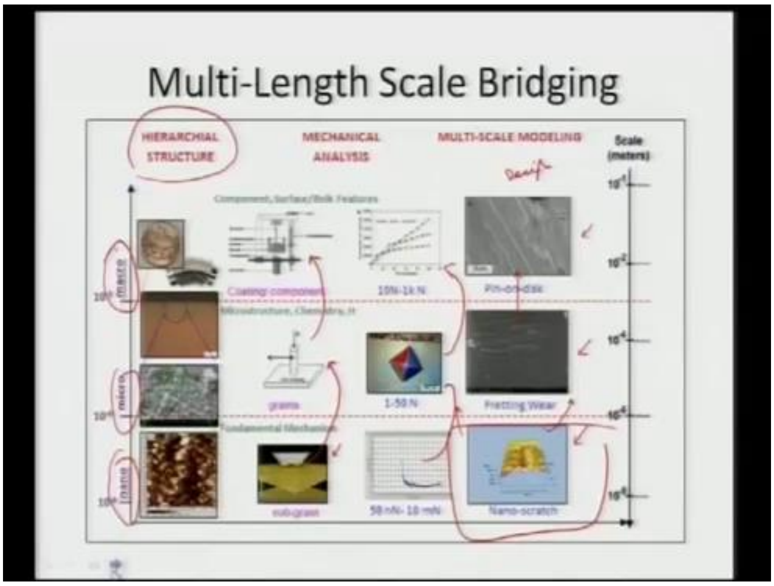

So, essentially what is happening is we have to correlate what is happening at nano scale micro scale and the macro scale. So, a kind of testing that is required, so at sub grain we are talking about nano indentation or nano scratching at micro scale we are talking about fretting and at macro scale we are talking about pin on disc. So, how we can correlate these aspects in terms of what is the fundamental mechanism in terms of the macro structure in terms of the component geometry or the bulk features. So, how we can correlate, so we can obtain properties or the fundamental mechanism at nano level we will do correlated to the macro structure and eventually form the design part via seeing the bulk features or the component properties. So, this becomes very essential in correlating the hierarchical structure which is dominant at three different length scales.

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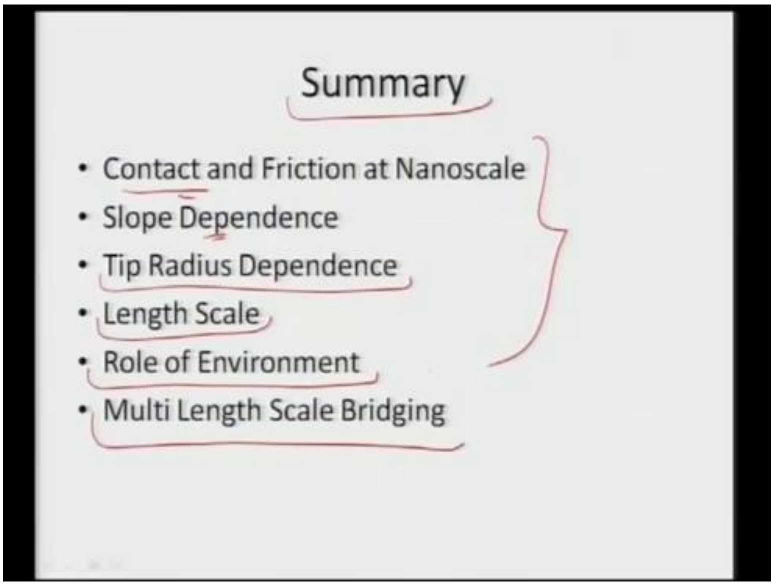

So, in summary we can see that the contact and friction at nano scale is very different because of the tip contact area kind of Van der Waals forces kind of contact forces which are dominant at that length scale. It depends more on the slope rather than the peak height or the peak depth also we saw that dependence of the tip radius as soon as we are talking about higher and higher tip radius we are enhancing the contact area. So, we are eventually inducing very high frictional forces which are to be required, so we can see increase in the frictional forces.

Also length scales also become very critical because of the kind of loading conditions the dominance of certain mechanisms like plowing is very limited in the nano length scale even the hardness of surfaces are very higher in comparison to that of bulk. So, length scales also contribute a lot in terms of detecting the frictional properties role of environment like once we have humidity it will also lead to enhancement in the overall meniscus bridges to a certain extent, but then it will start acting as a lubricant. So, then in turn it will start reducing the coefficient of friction and also how we can utilize all these concepts in going from nano to micro.

So, and nano we can find the mechanism in macro we can also include the overall contribution from the macro structure, and then we can come to the design of the component. So, in that case we can see the overall relation of Nanotribology eventually coming out with the mechanism in finally, designing a real life engineered component with this I end my lecture.

Thank you.