Video Course on Tribology

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Model No. # 04

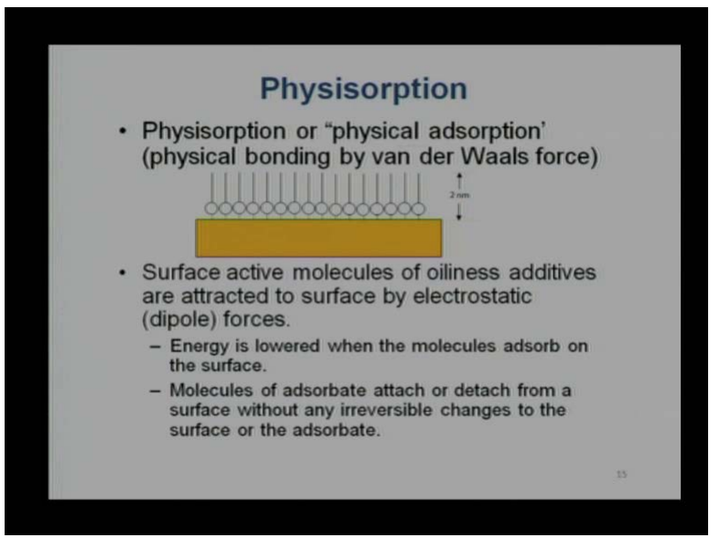
Lecture No. # 12

Boundary lubrication

Welcome to twelfth lecture of video course on Tribology. Today's topic is boundary lubrication. As appears from the name itself the boundary is marginal. We can say, it is marginal between dry lubrication and full film lubrication. Lubricant is present on the surface but not that much which can reduce friction substantially, wear substantially. There will be reduction in friction; there will be reduction in wear, but it will be more than what we get from full film lubrication. So, it is not true lubrication as such but, in many situations under high load, high load, low speed condition and high temperature condition, this kind of lubrication mechanism will occur.

Sometimes, it occurs at the start when the component is totally new. The surface roughness of the component is very high, during that time boundary lubrication will occur. End of this lecture we will cover one case study on that to show that initially wear rate is high and subsequently it comes down. As in the last lecture, we discuss their two modes of boundary lubrication; one is physical attraction or physical attachment of lubricant layer on the surface.

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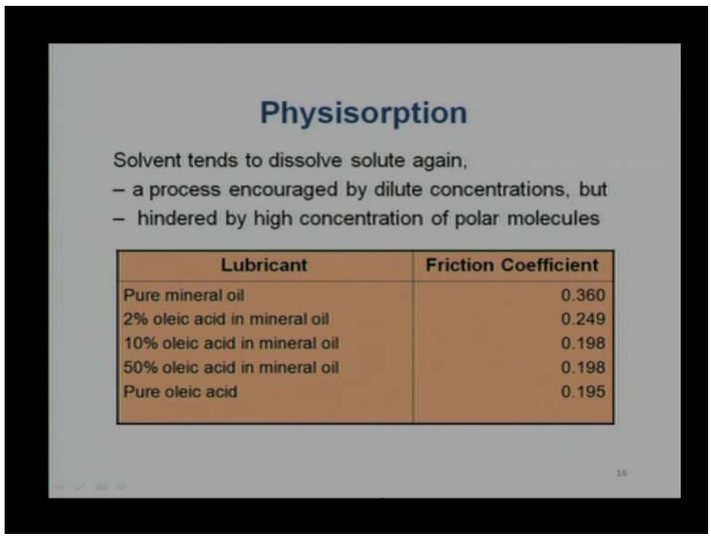


And the other one is chemical attachment. Chemical attachment is more like corrosion, what we use a word a “sacrificial layer”. Well physical adsorption is nothing like a sacrificial layer, it is an attachment and detachment, because of the molecular attraction the lubricant will get attach to the surface and under high temperature it will get detach or under sliding condition it will be disturbed or it will detach from the surface. As a first line says, this is known as a physisorption or attraction occurs because of the van der waals forces. This figure clearly indicates that the lubricant thickness is itself about 2 nanometer. It is very, very, thin layer. Many times oxide layer on the surface is more than this layer. In reality every metal is subjected to boundary lubrication, even in absence of liquid lubricant or in absence of boundary additive lubricants. That’s a natural phenomena, if material is open to environment, it will get oxidized or thin layer will be made or the thin layer will not be having very good chemical affinity towards the other metal. So, it will give at the interface much lower shear strength interface. Well in this case this sketch shows that this is polar end “O” shape or circle shape, this is the tail. As in my previous lecture, I mention this tail helps as a carpet. If you walk on this carpet it will simply bend, it comes back to their original position when you move away, same thing with the surfaces, if surface comes in contact with this layer this thin cantilever bends easily elastically and if surface pass away, then it move will come back to the original shape.

Sometime, we use a word “oiliness additives”, it sticks to the surface. Now, what is the theme behind; what is the physics behind this. It says that energy will be lowered, whenever molecular; whenever this additives is adsorbed on the surface, overall energy will come down. That means you need to provide some energy to remove this layer. That energy may be thermal energy, may be mechanical energy, but you had to provide to remove this layer and that is why it is advantageous. It reduces the overall energy, it bring some equilibrium. However, we say many times that, attachment and detachment is a continuous process that nothing is going to get damage on that, if it is under normal load and normal speed. You are not talking about severe load and severe speed. In that situation, it will not create any problem, it will not get damaged, it will only detach from the surface and after sometime, it will come back and

attach. So, it is a continuous process. We need not change lubricant oil frequently, if that is the situation, if that is the mechanism.

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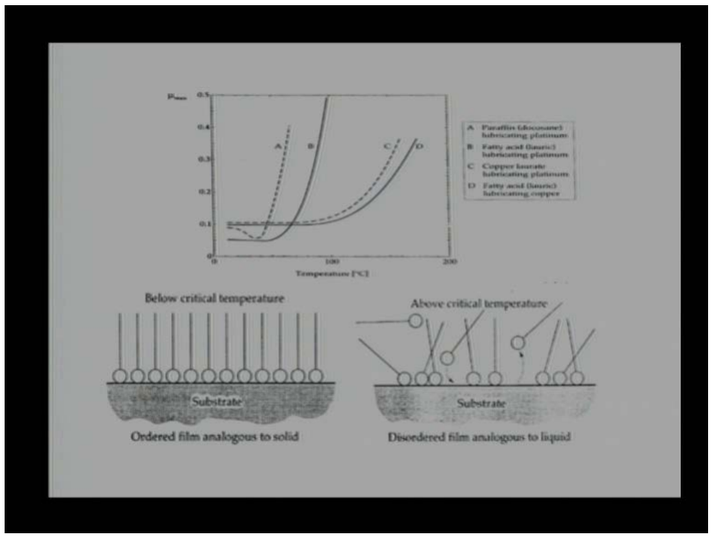


This slide was shown also on the last lecture, we say that when we want physical attraction then, it need to have some properties. First thing is that, it should get dissolve in solid. If it is not able to adjust with the lubricating oil, it is not get able to get mix with the lubricant oil, then, we cannot use that lubricant additive. Another thing, we say that with attachment and detachment is generally encouraged by the dilute concentration. Then if concentration is lower than, it will be frequent phenomena.

However, if the concentration is higher, there are many molecules available for the few sites, than even though attachment and detachment may be continuous process, but that will not reflect in the experiments. We will not be able to find much difference in coefficient of friction, much difference in wear rate. This table indicated, if you do not use any additives, any boundary additives, in this case we took example of oleic acid, which is one of the boundary additives having oiliness properties. If tribo surface is operated with pure mineral oil (no additives in that simple base oil) and coefficient of friction estimated was 0.36. I am using the word estimation because we can never get exact value of coefficient of friction. It is only estimation, it will having some sort of probability.

When, we add 2% of oleic acid, you can find a substantial change in coefficient of friction from 0.36 to 0.25. That is substantial change. But after that, increasing oleic acid is not going to change significantly. So, that's why we require little bit of boundary additives to get favorable results. We do not require complete oil to be boundary additives because that will be very viscous, difficult to form, difficult to move, that's why we do not use hundred percent unless until, it is required from the situation.

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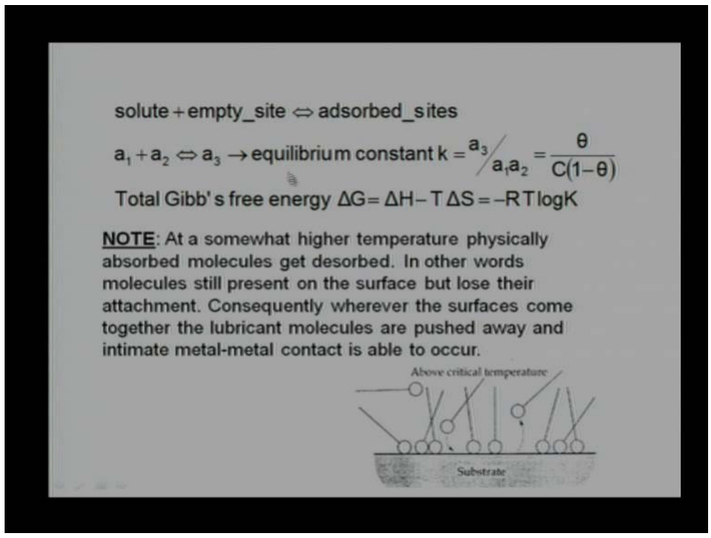
This figure shows how the coefficient of friction varies for different oil and oil additives. The A figure, it shows clearly that with the increase in temperature, viscosity decreases, the decrease in the viscosity coefficient of friction also will decrease.

But it after certain temperature (what we know as a critical temperature) after critical temperature, it will get unbound, coefficient of friction is going to increase continuously, assuming or treating that lubricant is completely removed from the surface. Even though lubricant remained there, but it will not be effective interlock at the interface. That is the A curve, what see, that is paraffin based, if you use boundary additives, fatty acid is a boundary additives then coefficient of friction is increasing after certain temperature, and that critical temperature is greater than critical temperature for paraffin oil.

However, when it reacts with the copper it makes some chemical layer. It is corroding the copper making some boundary additive layer then, this temperature is increasing substantially

from here may be say, it is around 70°, 80° it may reach, 150°, 140°. Similarly, for other oils it can change different, it can show different behavior, what is happening with the temperature? Why this kind of phenomena is happening that can be explained, using these two sketches. It shows that ordered film on the substrate or substrate and substance and it is a below critical temperature. Almost all the sites are occupied surface is not free from this molecule. However, if the temperature increases then, thermal forces will be on higher order compared to van der waal forces. So, molecular attraction will come down or we say that relative molecular attraction will come down or will force will be lesser compared to thermal forces and we will be getting disordered lubricant film on the surface. That is the reason why we do not get very good performance at a higher temperature or temperature above critical temperature. In that situation we need to see, need to think that lubricating oil should satisfy our requirement. If we know the operating temperature is high than, we need to choose proper lubricant additive, it will not that you whatever you choose lubricant additive, it is going to survive, will work. It works only after works below some critical temperature, it does not work beyond that and its known that this kind of thermal equilibrium can be estimated or it can be guessed using the Gibb's free energy.

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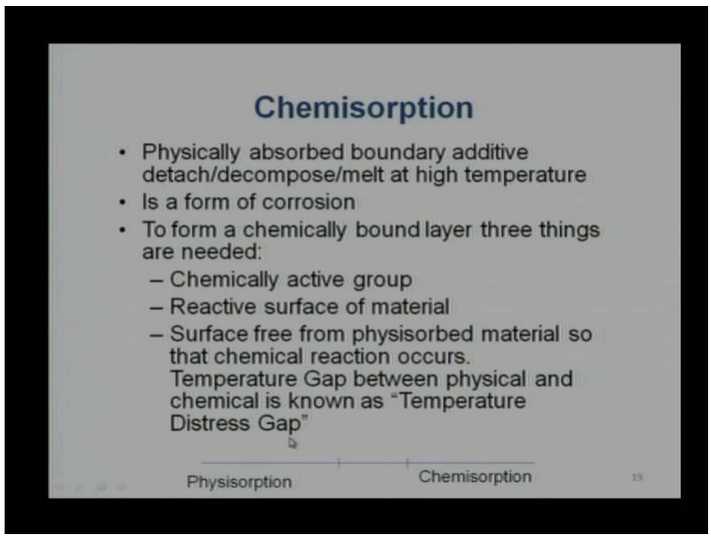


As I mention in last lecture that Gibb's free energy is more like potential energy even require. Some energy to remove this lubricant layer from the surface, and that Gibb's

energy can be estimated, using this relation. This clearly says, as the temperature increases Gibb's energy is going go down. If Gibb's energy is lesser that means, you need to supply lesser energy to disturb the lubricant film. If this energy is more then, you require more energy to disturb the film or it will be more stable compared to stability at the high temperature, that is why we says that in high temperature, it is getting desorbed, and that is shown again through this figure which we showed in previous slide.

When is a disturbed than, what will happen surface can easily push, this lubricant or lubricant molecules from the surface, leave surface without lubricant layer wear rate will increase in this situation temperature or we say that, it as temperature increases wear rate will increase. When we are treating or when we are using boundary additives, but that is not hundred percent true, few lubricants, they work at the high temperature; they do not work at the low temperature; you make it very high coefficient of friction at the low temperature, but when you go for high temperature, when you operated those lubricant additives at high temperature coefficient of friction will come down, that is generally known as a extreme pressure additives or additives, which work with chemical action or they react with surface, they make some product.

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The cover the surface, they make sacrificial layer, but they protect the surface or reduce the coefficient of friction compared to dry friction or compare to unstable film. We can

studied that, we say that chemisorption is a happening because of the chemical action and as the first line indicates, physically absorb boundary lubricant or boundary additives, either will get detach, decompose or melt, any of the situation is possible. It can get detach, because of the very low molecular attraction compared to their thermal forces. It can decompose also (quite polymers get detach as well as decompose). Decompose means long molecular arrangement structure gets broken.

And it may melt also it can change as a strict from solid to semi solid to liquid or completely disturbed the chemical structure, anything is possible that is why we require chemisorption at the high temperature, and as I mentioned earlier that it is a form of corrosion. We are doing purposely, we are introducing corrosion purposely. Say to make this kind of boundary layer, what we require? We require a chemically active group, something chlorine, sulphide, phosphorus, they are chemically active. If you leave this chemical along with the metals, they will make some chemical region on the metal surface, which will be having low coefficient of friction and low wear rate compared to metal surface itself.

So, this is chemical active group, in addition, we require reactive surface of material. All the metals have reactive surface by and large ceramics. They do not have that much or polymers; they do not have that much reactive. So, chemical additives will be useful only for the metals, and large, for the metals not be very effective for ceramics; not very effective for the polymers. Another word, chemical composition required for the metals will be different. The chemical composition which is required for the ceramic materials, for polymer materials.

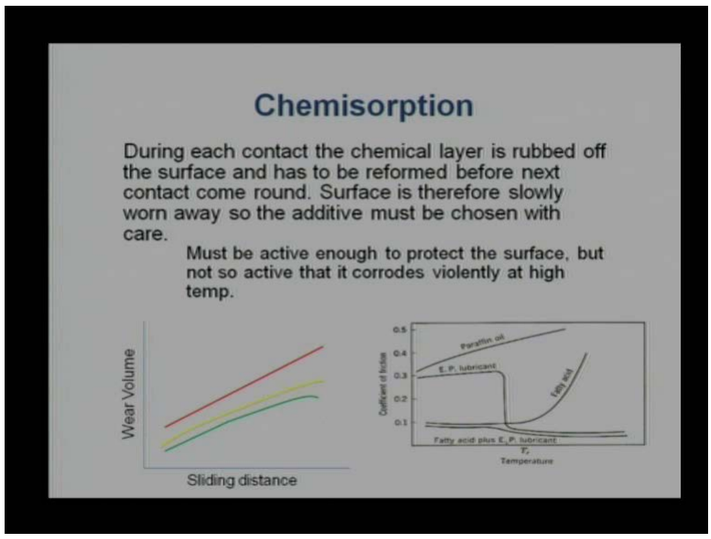
And, there is another one guideline given over here, we say that try to use both the process physical absorption as well as chemical absorption, both are possible, if I choose a surface, which is chemically as well as physically acting with the lubricant additives as, I can get good results at a low temperature physical attachment; at a high temperature chemical attachment same lubricant additives can be used. That is why we can show with the diagram, we say the physical adsorption below one critical temperature.

This blue color line I am showing as a temperature line or from left to right. I am trying to show, this temperature is going to increase. At the low temperature, physical absorption is sufficient at the high temperature chemical absorption is sufficient, and

there is always gap between. We generally, they do not over lap reason being, if there is a physical absorption, if there is a lubricant layer already, there then chemical absorption will not happen unless it is clean completely. If there is a something already on the surface, it will not be reactive towards the chemical active group.

So, there is need to be some gap and that gap is known as a temperature distress gap. You should never operate the equipment in that gap, either this lower side and higher side. We need to design or otherwise, this temperature distress gap need to be minimum or we should not use one metal or one additive, we may use composition. Active group for a physical absorption at the low temperature, another group at high temperature. So two different groups are used in that case quite possible, they will not be temperature distress gap. It can be without that gap.

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Now, some mechanism is specified as I mention on this slide, we say during each contact, the contact layer is rubbed off, it is nothing like that wear is stopped completely. It is getting rubbed of that is why we are using the word boundary lubrication.

And after rubbing off it get exposed to another corrosive media or we say corrosive liquid or corrosive substance in that case next layer will come immediately. So, it is again a dynamic process rubbing off of lubricant layer and reformation of the lubricant layer on the surface. But in that process, what is going to happen? Slowly, slowly chemical additives is going to deplete, it already reacted with the surface, and it will get depleted.

So, it is not as good as physical absorption, what we say in physical absorption, there is no change it can be reabsorbed again on the surface without much problem.

However in the chemical case, it does reacted made oxide layer, it is removed. Now, we required a new percentage or some additional percentage for the next reaction. So, what we can say whenever we are thinking about the chemisorptions lubricant additives depletion, need to be accounted. It will get depleted with time; it is nothing like that once you add lubricant additive, it will survive forever. It has certain duration after that duration lubricant additive will be depleted, you need to refurnish that.

And that is, this point says clearly, they need to have good balance, good trade off. They should be active enough to protect the surface, but it should not be active too much active so that increase a corrosion rated high eliminate. Now, if I compare if I compare dry lubrication, I compare boundary lubrication by physical absorption or we compare chemical absorption. So, we can compare on wear and sliding distance chart, we studied wear rate. We know that as a sliding distance increases total wear volume will increase wear rate we are not talking; we are talking of the total wear from this surface ; how much wear as occur.

If I plot this first, this line is clearly showing Archard's law. In dry condition, they are in proposition sliding distance and wear volume will be having by and large linear profile, linear variation by and large. Now, when you come to the mixed lubrication, we come to the chemisorption or chemical layer than, there is also loss of chemical, loss of the metal surface, because of the additive is reacting with metal. When it is acting with reacting with metal, that is means fraction of the metal is also getting removed from the surface. How fast and how slow, that will depend on the chemical composition of the additives and the material. That can be decided, but generally that is a non-linear, it is not as linear as Archard's law states; it states can see here. That wear rate is lesser wear volume is lesser compare to the dry case, when comparing it.

But it has a non-linear profile, this gap may increase; may decrease depend on how fast the distance "L" has been travel. If it is very fast there is a possibility, it goes down, it goes up also and this is shows as physical absorption. We know the physical absorption case most of the time the wear of the lubricant layer is happening detachment of the lubricant; layer is happening, it is not reacting with the substance, it is not reacting with

component; it is not reacting with material, naturally, wear rate increase case of the physical absorption will be lower than chemisorptions. May be, whatever be the situation in that case, if I treat without considering the temperature or without accounting the temperature in that case I will be getting always this curve.

However, if I think from other side say that physical absorption will not work when temperature is high then in that case physical absorption in case. Whatever, the coating we have it will turn out to be red line or you say that these two will not occur simultaneously that is why, they should not be compared. Temperature will be always there temperature factor always, need to be accounted. So, whenever physical absorption happens; chemical absorption should not happen; whenever chemical absorption happen physical absorption should not happen they need to be having two separate situations. If I compare I may get wrong results or wrong conclusion.

That is why we use this kind of curve; we say this is mineral oil without any additives. It shows the better performance compared to the dry lubrication, because there is lubricating oil and it cools the surface, distribute the stresses equally, well coming to physical absorption, it is fatty acids can see clearly, there is a transition temperature T_m beyond that temperature fatty acid coefficient of friction is increasing substantially. Now, if I neglect or if I use some sort of lubricant additives, where the temperature gap is not there, it is acting instantaneously wherever, the fatty acid is failing EP additives or EP lubricant or we say that extreme pressure lubricant is acting immediately.

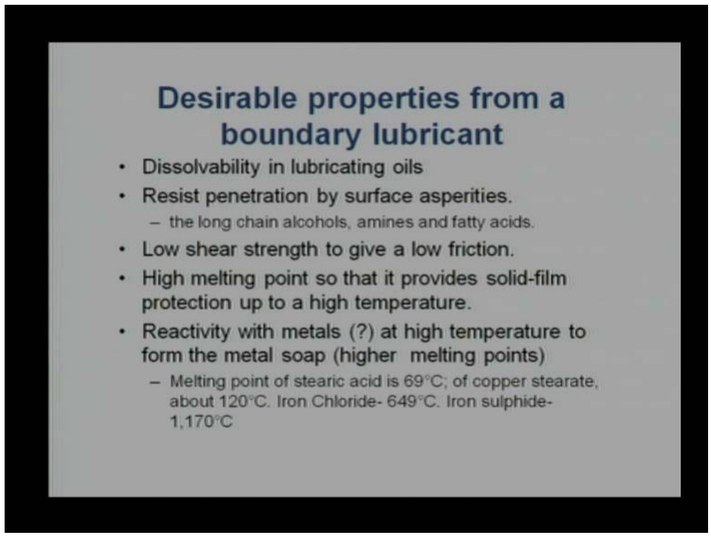
And that is why I can see that, coefficient of friction is constant. It is not changing or we say that EP additives are ineffective at that temperature. At low temperature they do not have any chemical reaction with the surface, but as a temperature increase. This, they are going to react with surface, that is why I mention, you know in my last slide also whenever, we make lubricant. We generally add chemical related to physical absorption, chemical related to chemisorption and e p additive is another form of chemisorptions. We say that, it is happening under the high temperature and extreme pressure. If pressure is very high, temperature will also increase there, so they are related or chemisorptions phenomena can be said as extreme pressure phenomena.

So, overall if I want to make lubricant good, lubricant package I will be using mineral oil or carrier fluid with fatty acid plus EP additives. So, overall package gives satisfactory

performance to us, because of low coefficient of friction compared to pure base oil, compared to EP additives and base oil compared to fatty acid and base oil. Overall package need to have all together.

So, whatever the transient case, if the temperature is going very high EP additives can react, however they will remain silent they will not work. Even though the cost is increasing by delta, but overall we need good results and there are always uncertainties in machines, if the local temperature is going beyond certain temperature, then EP additives should work.

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Now, we say that whatever the desirable properties from boundary lubricant, I am talking boundary lubricant from the both the point of view is, physical absorption as well as chemical absorption. We say that need to have dissolvability in lubricating oil, if they are not able to get dissolved in the lubricating oil, they do not have any use, if they are not totally getting mixed than there is no use. If we are able to see additive separate lubricating oil separate than, it does not have much utility.

And it should be able to resist the penetration of the surface asperities, when one surface asperity is approaching to other surface, these asperities should be covered with lubricant additives, so that it is not getting touched or it is not coming in direct contact with the surface as far as possible. In that case wear will be in mild region, if there

are asperities are able to penetrate in other surface and then wear volume will increase; wear rate will increased.

So, that is why we prefer to use long chain alcohols for physical absorption, amines or fatty acids, is oil react for the physical absorption. Chlorine, phosphorus, sulphur offer the chemical composition. Well the as we discuss in friction chapter or friction lectures, that we need to have low shear strength of the interface. If interface does not have low shear strength, well tribology comes to the zero. It does not have any use then, we need to make interface having low shear strength and that is a necessary condition for using any lubricant. If they are these kind of boundary additives are not able to give us low shear strength of the interface then, they does not have much use.

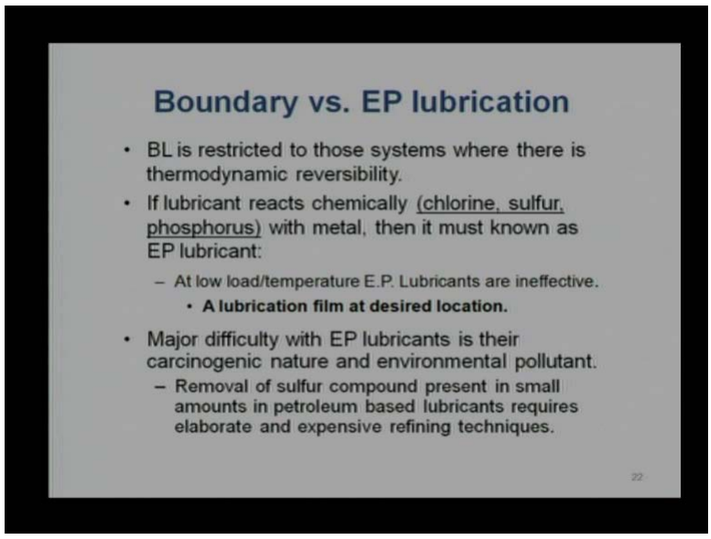
So that is why, we need to have low shear strength, either directly getting attach to the surface or when chemically attaching in the surface. In addition, what we can demand that at high melting point, they should not get disturb as the temperature increases. So, if physical adhesion or physical absorption is able to sustain up to 250°, 300°C that will be preferable choice, in that case, we are not going ahead with chemical absorption, because we know chemical absorption is going to corrode the surface and the lubricant additives will get depleted and we need to refund the lubricant and is a finally, says that it need to suit the metal, which, we are using here, the word you and I am using the metal, because mostly this kind of additives are effective with metals. They have are less effective with polymers and the ceramics.

This is an example, which shows the stearic acid which is boundary additives, it has a melting point around 69° degree centigrade, when we are talking about the absolute, without any reaction. However, when it reacts with a copper surface, copper stearate, it melts at 120°C, which is the relatively higher compared to 69°C. Similarly, if there is a chloride or chlorine available as a chemical additives, which goes higher with chemisorption than iron chloride, which as a solid form as a sacrificial layer temperature is very high is a 649°, that means this can sustain above 500 degree centigrade temperature without failure.

However, if you want to further go the higher side, then sulphur should act or we say the iron sulphide, which will melt at the 1170°, because it is very high temperature, they can be using the high temperature additives. They are giving good

results at high temperature. However, we know very well the pollution is an additional consideration, whenever pollution comes or we had to think about pollution, we need to discard chloride; we need discard sulphides. So, overall we can say the physical absorption should give a future or will be better for future compared to chemical absorptions right.

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Now, this slide shows, because there I found some disturbances and books, people or a researcher have written boundary lubrications separately, extreme pressure lubrication separately. I am just trying to compare over here, we say that boundary lubrication as per them is restricted to system. Where, there is a thermodynamic reversibility, that means attachment and detachment is thermodynamically reversible at high temperatures lubricant will detach. So, this is what they have quoted that boundary lubrication should be named, if, there is a thermodynamic reversibility, if there is no thermodynamic reversibility, which mostly happen in chemisorptions in that case we should not be calling that the boundary lubrication, they should be call as extreme pressure lubrication, because this kind of mechanism acts under high temperature and generally high temperature occurs, because of the high pressure.

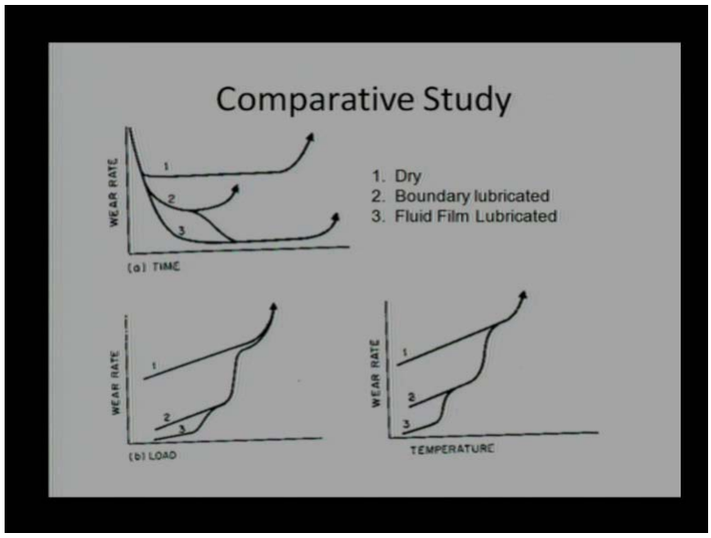
So, what we say in this case we are other examples, chlorine, sulphur and phosphorus. They act with the surface and there are known as EP additives, EP lubricant. They are ineffective or these all 3 are ineffective

at the low temperature case, low load and low temperature case. It is a interesting point, should be noted for here, that people say this is a low optimization wherever I need lubricant film EP additives are able to form it where as at high temperature, we require lubrication effective lubrication which can be sustain there for sometime and EP additives are able to make it.

So, that is going to give us or this kind of additives are giving us optimum performance as per the requirement, wherever it is requires it gives it does not make lubricant film everywhere, if the gear pair is coming in contact, wherever, the contact point comes lubricant film is made at that point there, because of the high temperature, high pressure and corrosion occurs for some fraction of second, there itself. However is that clearly mentioned clear over here, that they have good properties, they are nice, they are probable from commercial point of view, but some society point of view they are not encouraged; they are carcinogenic nature; they are harmful; they are polluting environment, that is why there is a problem. Interesting story about this is that in a common petrol sulfur will be there and sulfur acts as a chemical absorption agent. It can react with the surface, it can make lubricant film and that is going to give us protective layer that is useful, but because of the pollution. Now, it has been emphasize the petrol should be free of sulfur or it should be below certain limit or sulfur percentage should be minimum to this percentage; it is a costly in two fronts.

First you require process to separate the sulfur from the petrol first thing; second you require some lubricant additives to be mixed with the lubricating oil. So, that surfaces can be prevented from the wear. Because of the pollution picture or pollution consideration, cost is going to increase that is, why we have always problem, whenever, we use this chemical absorption technique than it may survive for 5 years 10 years and after that environmental issue will come again, we have to remove one thing something else.

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There is a comparative study with between these three kind of lubrication mechanism, which dry 0 lubrication or maybe say, whatever the naturally form layer on the surface. Second boundary lubricated, which we are studying in this lecture and third which will be discussing may be in next lecture, that is the boundary; that is fluid film lubrication. Surface is completely separated by the fluid film, if we plot curves for this three condition 1 for dry; second for boundary; third for fluid film lubrication; then, what kind of cause we get for the wear rate. If I plot wear rate with time as the time increases, this is clearly showing about the trend wear rate decreases, it remains stationary and then goes up after certain duration. Well in boundary case anything is possible.

You say wear rate in decreasing initially is reaches to 1 point after that, it can go and merge with 1 or can merge with 3 that means, if the surface roughness has decreased substantially, boundary lubrication, may turn out to be full film lubrication mechanism or if the surface is disturbed, irregularities have increased it can go and merge with dry case or boundary lubricant will not be effective in that case.

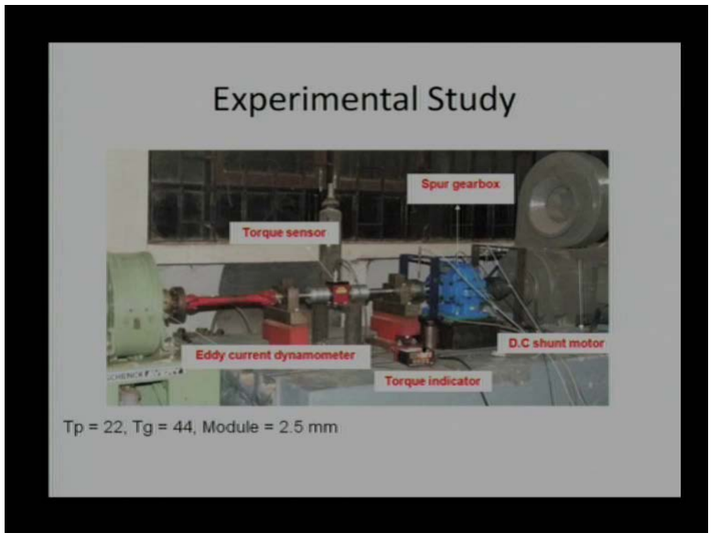
So, both the possibilities that is, why we say many times. Whenever, we are buying any new car or new automobile, we need to operate vehicle at the lowest speed, this boundary case is over or second comes and matches with 3, then after that only, we should operate with high speed. Now, there are 2 other curves also, we say that wear rate verses load. As the load is increasing, even though fluid film lubrication will can

sustain up to certain limit beyond that, it is going to be a boundary lubrication and the further the load is increased further, then it may merge with the dry lubrication or in other words as a load I is continuously increasing lubricant may not be retained at the surfaces at the interface. It will be simple squezzed out from the surfaces.

And if there is no dynamic load; if there is no reversible position change, then lubricant will not be suck back, it will be simple moved out whenever lubricant comes; it will be simple moved out of the interface and will be getting very high wear rate or we say, that every lubricant need to be designed, as per the load, for high load will be, we will be designing the different kind of lubricant for low load condition, we will be designing different kind of lubricants. Coming to the temperature, which as a more or less same factor or same effective as load. As a temperature increases, we know that, detachment from the surface will increase even for chemisorption case the temperature suppose is very high than, rate of the wear will increase, because of the more and more reaction with the surface. So, that fluid film lubrication is merging with an increase temperature, the boundary lubrication and beyond certain temperature is merging with the dry lubrication case.

So, this comparative study indicates clearly, whenever we design a system we should keep in a mind for how long we want to operate it. If for the longer duration, we want we should operate under some condition which gives favorable surface condition to the equipment, and then it should be operate to the other condition. Same thing, if we want we know surely, what kind of load are going to come and how much load is going to come, and then we should design boundary additives or boundary lubricant or fluid film lubrication mechanism accordingly.

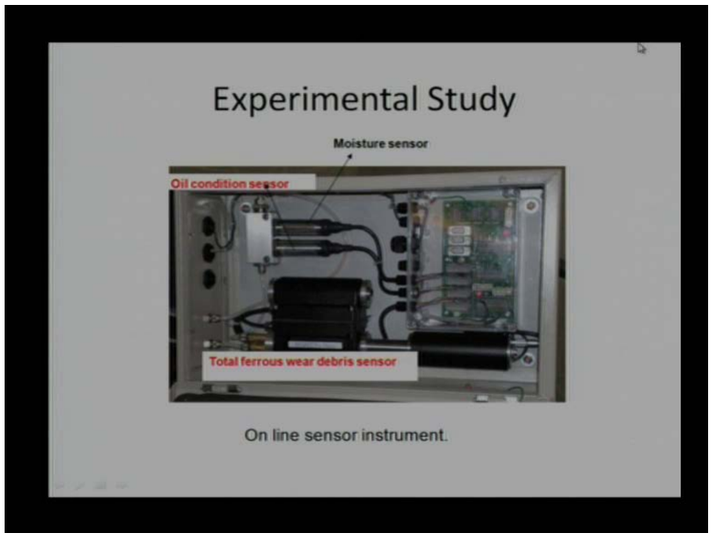
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So, I will just covered one experimental study, which we did in our lab and results are related to our boundary lubrication mechanism. You can see this figure has Eddy current dynamometer, which applies a load and net load applied in this case is from 0 to 75 neuton meters. There is a Torque sensor, which can measure how much torque has been applied and what is this is a gearbox, which is a test box with the gears are going to get tested. There is a motor to drive the gearbox, we are using both the things. We are using motor to drive; we are using dynamometer to stop or apply the load; we are using the both the combination.

And Torque Sensor to measure how much Torque is been applied, and then is a display unit over here, which will give display of the Torque. What we are talking the gearbox is 2 to 1 ratio or we say that pinion nine gear as 22 teeth well gear, teeth gear. Now, number of teeth on the gear are 44.So, this at 44 divided by 2 in 22. It gives 2 to 1 ratio and there are standard involute profile having pressure angle 20° and module is define as 2.5.

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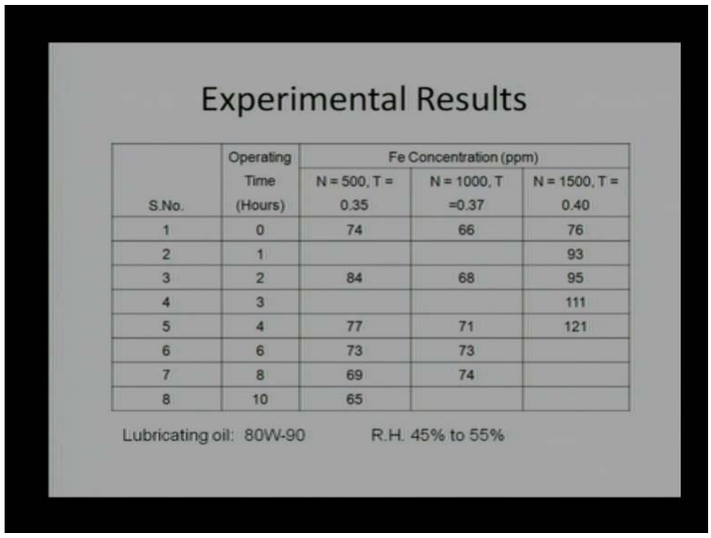


We to find out online, ahead with online measurement, we use sensor unit what we know as a online sensor instrument can see, there is a oil condition sensor. What is the meaning of that oil will get disturb oil, will can change quality continuously.

If it is getting more and more acidic then tan numbers will decrease on that, tan numbers will increase. Similarly, there is a possibility of corrosive wear, so there is a moisture sensor clearly, indicate if the related humidity is very high, than we should not conduct experiments, because the major governing factor will be corrosion and there is a mechanical action. So, there will be corrosive wear however, if you want to do corrosive studies or we want to do study on corrosive wear, than we should be able to use with some moisture environment with higher Moisture environment. Above all, there is one unit what say as a total ferrous wear debris sensor. It is generally, finds iron particle, how many iron particles are getting circulated through the lubricating oil.

So, it gives us an indication of wear rate higher the number of particle; higher the wear rate that is, why this unit is useful. When it get attached with this stress set of we can see, there are number of tubing is going on from this and this tubing one connected to this unit. You can see the tubing is over here in previous slide here tubing are going and the unit is place somewhere here. So it gives overall reading to us.

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Let us start with some maximum the readings, we say that we bought a new gearbox and we know whenever the gearbox is new it should not be loaded completely. So, what we selected almost 0 load and 500 rpm speed and is given in rpm that is a 500 and we are not using units over here, because rpm is common unit and torque as 0.35N.m. We did not have applied any torque from the dynamometer but we know during the assembly there will be always some sort of misalignment there will be some resistance from assembly.

And that is given as a 0.35N.m as a torque, we have not done anything purposefully but it is coming, because of assembly and this gives iron percentage or iron concentration, in ppm. Number of experiments and this experiment was done in lubricating oil, what say, the 80W90 is a motor oil and it has a good EP additive package. This kind experiment happen and whatever the experimental result what we got is that is show the relative humidity, where ending from 45% to 55% that means, it is not going beyond certain limit. We can conduct this kind of experiment without much problem.

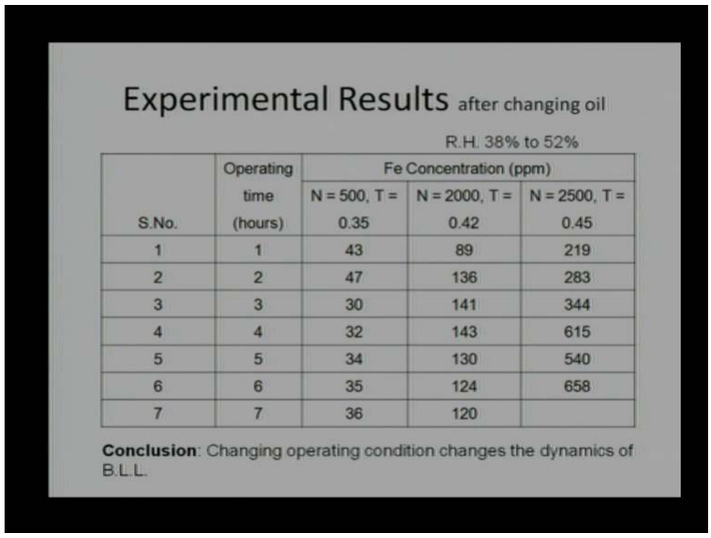
Just after doing experiments just starting the experiment, we took the reading and we found there is 74 ppm as an iron percentage or concentration, after 2 hours operation, this percentage increased to 84 after that it remains almost a series 77, 73, 69, 65. Interesting thing is that, when we do this kind of thing. It is always in a mind after that if I want to

operate, this percentage should come down, because bath-tub curve says, clearly initially wear rate will be high subsequently it will come down, but it did not happen to others we increase the speed from 500 to 1000. You can see the minimum weight, this is in sequence after operating of the 10 hours, we 11^{th} hours was with this speed they are in sequence all this experiments are in sequence. This is a 11^{th} this shows the 65 well, this shows 66% increase of course; there will be always some inner accuracy, so, we cannot differentiate between 65 and 66, but as we are increasing more and more number of operating hours, we are finding more and more particle percentage coming in.

Either there is not filter system, or is not working well or something else is problem or another possibility is that at the high temperature, high speed means high temperature and high speed, there is a some plus temperature is happening and chemical additives or we say EP additives are reacting with surface. They are corroding the surface and then they are removing the top asperities that's why the percentage is increasing. To confirm that, we increase speed also, you say from 1000 rpm to 1500 rpm keeping almost the same load no change in the load aspects. This is happening because of the misalignment or some inner accuracy in the surface.

Now, what we are getting over here, this percent percentage is continuously increasing this means, more and more corrosion happens with the surface or even, we know the gear lubrication mechanism other this lubricant additives is known to you one of the very good gear lubricant and still that we are getting this kind of wear particles that means gears will never work in hydrodynamic domain. It will never work in fluid film lubrication mechanism now, working in mix lubrication or boundary lubrication, that is why we are getting wear particles and the particle percentage is increasing with increasing speed if the mixed lubrication case percentage will not increase, will come down. So, that is why we feel that this kind of experiments is showing the results related to the boundary lubrication mechanism.

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Let us see other results, second set of results after changing the oil, we have changed the lubricating oil here that oil with old particles, whatever were getting dumped in the lubricating oil have been removed. Fresh oil, fresh oil, we are getting good readings at the 500 rpm you can see 43, 66 or another word, you can say it has reach to steady state condition or running in period is over for 500 rpm , but it should continue for the 1000 rpm also, 2000 rp m also, but what we got and when we are operating at 2000 rpm. We are getting different environment, we were getting different results you can see 89 from 36 it jumps to 89.

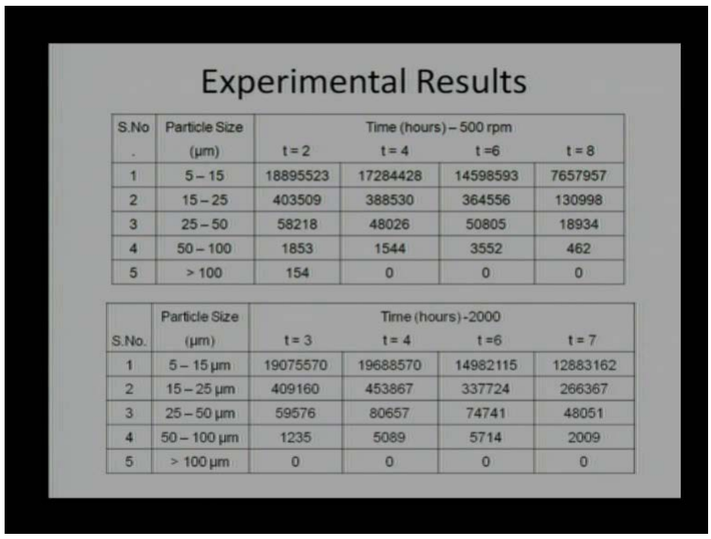
After operating for the 7 hours, when you are operating that equipment for the 8 th hour, we are getting 89 ppm that is much higher almost 3 folds compare to 36 and this percentage is increasing to a certain limit and after that its decreasing. To get a confirmed result, we operate at one higher speed further and we can find there is a unbound lubrication, unbound ppm level from 219 to 658 that means, a more and more temperature is getting induced to the surface or some sort of load is coming on the surface which is creating higher wear, number of particles.

However, this Torque sensor clearly indicates that misalignment was not that dominant, it is only the speed which is changing the phenomena and it is giving higher wear rate. Now I can think in different way, I can say that when the speed is increasing, vibration level is increasing and load level is almost 0. Additional vibration phenomena is

happening and that is going to increase the fatigue failure or is fatigue wear is going to increase with increase in speed. To confirm that what we did, we applied at load that the vibration phenomena can be reduce the vibration operated can be reduced, even for high speed it should not vibrate that much.

So, of course, before that we say that conclusion from this slide the changing operating condition changes the dynamics of boundary lubrication layer. It is continuously changing it is not stationary at 500 r p m, it showing the steady state condition, but we are stretching to 2000 rpm it showing high wear rate. As I mention one possible reason is as vibration continues as a periodical loading and that is going to induce fatigue failure in a surface or at least top asperities are chopped off, so we need to confirm that with a load.

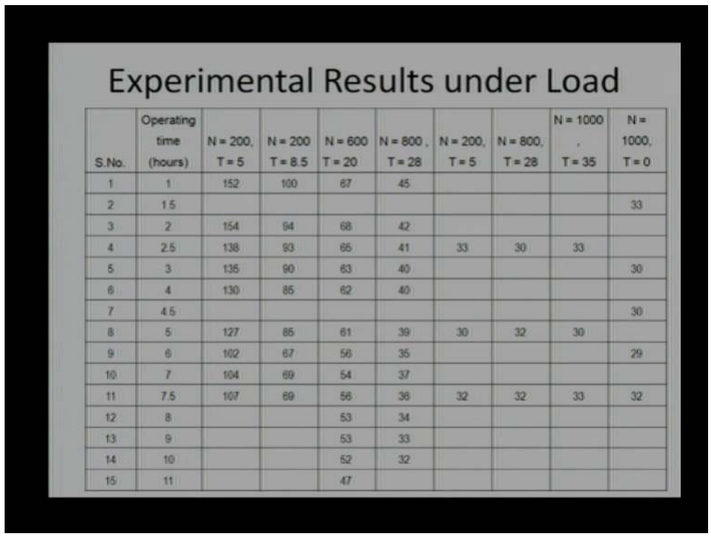
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If I increase the load what is going to happen and of course, before that we try to find out particle size, what is the range of particle size. To diagnose with particle size, minus size or under the mild wear domain the severe wear domain and interestingly we find too many particles for the size between 5 to 15 micron. Interestingly, this number of particles are continuously decreasing with time that is means is it is going for the betterment. It is going for the convergence continuously, number of particles are decreasing. Coming to 15 to 25 micron again the number of particles are continuously decreasing. So, that is favorable situation, we can say starting case may be severe wear, but it is still controllable case it is moving to the mild domain or mild wear side.

And interesting thing is that, we found couple of particles having size more than 100 micron and when we studied that mild wear and severe wear, you say that about 20 micron particles it is a severe wear, so most of the domain case. In this case, it will be the server wear, but they are not uncontrollable, they are controlled they are moving to the right direction that means, you do not have to worry too much and we know there is a running in time is bending in time wear particles will be larger initially. This is for the 500 rpm same thing must done for the 2000 rpm also what we find again the same thing that number of particle are decreasing except over this case, number of particles are decreasing which are in range from 5 to 15 micron and there is no particles size, no particle, which has a size greater than 100 micron, that is a favorable case. In all other cases also, we find that particles are decreasing in numbers, so these are the favorable situation their bedding in time is a many add. If you want to reduce wear rate or reduce, this kind of particles then we should applied load.

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And that is why we did experiment with load also. Say rpm 200, torque applied load is 5 N.m, wear rate or number of particles, ppm level is continuously decreasing.

So, 152 and 154 is coming to the 107 of course, 2, 3 ppm I am assuming that is inaccuracy or it is not giving that much reliable results. Now, if I increase load what's going to happen same increasing the load from 107 it is coming down to 100 and continuously decreasing to 69 that means load is working.

Whatever we are thinking vibration is creating some problem, is fatigue value or related failure of the related wear, because of that it is happening over here. Now, if we increases the speed and the torque, again we are getting lesser number of ppm or lesser ppm in this case same thing or same results for the 800 also 800 and load is higher side 20 N.m, it comes to result 32 N.m that is indicating, that is showing,; that bedding-in time is coming to the closer or almost negligible level.

After that we could not find any further improvement. This clearly shows the number of particles ppm level is reaching almost 30 ppm and beyond that we are not able to improve whatever load condition whatever the speed we are applying not remains on the situation. Or in other words, if the load is applied results are good. Now, here we have removed the load also, we have brought the torque almost is 0 level occurs, I am not using the word 0.3 N.m because all the torques are very high compare to 0.3, 0.4 N.mn that is we put value as 0. And this is 0 Torque and 1000 rpm, still we are getting good results.

Now, that is complete bedding-in completely in running in time or we say that running in behavior. Now, what is happening why vibration does not happen at 1000 rpm, now, we can say there is a number of asperities which were earlier there, they have completely got flattened or turn away or removed from the surface and there is somehow marginal lubrication keep coming or we say that there is a fluid film lubrication with some boundary lubrication. Some percentage is of boundary lubrication and major percent is of full film lubrication that is why the gear rate, gear wear rate is low in this situation.

That is a favorable situation for us or we say that when we study there is a boundary lubrication mechanism we are able to understand the mechanism in a different manner, we say that even though we know bedding-in time or bedding in behavior the wear rate should be very high, initially it should reach to steady condition and after that it should increase while in this case bedding in time it shows that even though running in behavior it is changing with, it is speed and changing with load condition. That is why we need to understand system completely. If there is a possibility of light load that is introducing vibration we should not introduce.

And that is a typical example for a rolling element bearing. We say whatever the dynamic load capacity of the rolling element bearing we should never apply load lesser

than 3% of that, reason being that there will be more clearance on less load, less deformation of surface that will cause a more vibration less load carrying capacity and pitting in that case will be much, much, faster compared to with load. In other words, what we say from the Archard's law as the load increases wear rate will go down, but when comes to the lubricated case particularly the the boundary lubrication, we are saying, it is not the case quite possible increase in a load may decrease the wear rate. It is not in that proportion itself.

With this I complete a boundary lubrication mechanism when next lecture will be discussing about the mixed lubrication mechanism, where are we been thinking about some portion of the surface undergoing boundary lubrication and remaining portion is undergoing hydrodynamic or Elasto-hydrodynamic or some other lubrication mechanism or when talking about some other mechanism it may be squeeze lubrication mechanism also. Thank you for your attention.