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 at appears from the name itself the boundary is marginal. We can say, it is marginal between real lubrication and full film lubrication, lubricant is present on the surface, but not that much which can reduce friction substantially wear substantially, there reduction and friction; there reduction and wear, but it will be more than, what we get and full film lubrication. So, it is not true lubrication as such, but in many situations under high load speed, high load low speed condition and high temperature condition. This kind of lubrication mechanism will occur.

Sometimes, it occurs they start when the components, totally new the surface of roughness of the component is very high, during that time boundary lubrication will occur. So, end of this lecture will cover, when necessary on that it show that initially wear rate is high and substantially it comes down. As in the last lecture, we discuss their 2 modes of boundary lubrication; 1 is physical attraction or physical attachment of lubricant layer.

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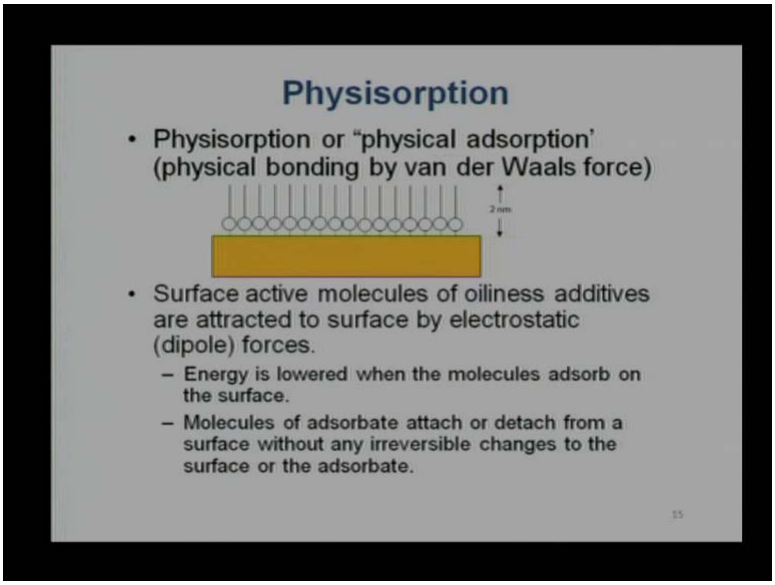

On the surface and other 1 is chemical attachment, chemical attachment is more like curvesion what, we use a word as sacrificial layer well physical adsorption is nothing like sacrificial layer. It is an attachment and detachment, because of the molecular attraction the lubricant will get attach to the surface.

And under high temperature, it will get detach of under sliding condition, it will be disturbed or it will detach from the surface. As a first line says of 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 all about 2 nanometer. It is very very thin layer many time, 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 is natural phenomena. If material is open to environment, it will get oxides or thin layer will be made on the thin layer will not be having very good chemical, affinity towards the other metal. So, it will give at the interface much lower shears strength interface, well in this case this is stretch shows the, this is polar rent o shape or circle shape, this is the tile. As in map previous lecture, I mention this tile 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 can deliver bends easily elastically and the surface is surface pass away, then it move will come back to the original shape. Sometime, we use a word is an oiliness additives is a stick to the surface. Now, what is the thin behind; what is the physics behind; This, it says that energy will be lowered, whenever molecular; whenever this additives is adsorb 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 this advantages. It reduces the overall energy it bring some equilibrium. However, we say many times that, attachment and detachment is a continuous process that is nothing is going to get damage on that, if it is under normal load and normal speed. You are not talking about server load and server 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 frequent, if that is the situation; if that is the mechanism.

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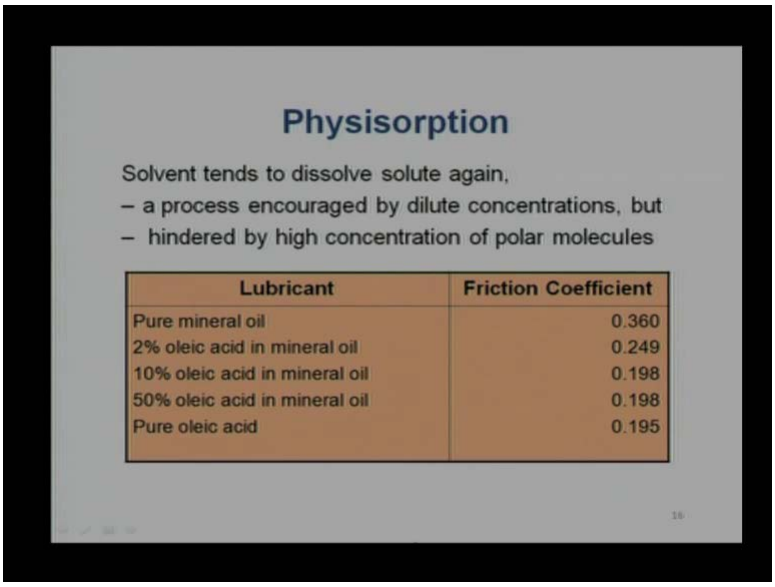

This slide was shown on the next lecture last lecture, we say that when we want physical attraction than, it need to have some properties. First thing is that, it should get dissolve in solid. If, it is not able to adjust with the lubricating oil, it is not get able to get mix with the lubricant oil.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

However the concentration is higher, there are many molecules available for the few sides, than even though attachment and detachment may be continuous process, but that will not reflect in the experiments, will not be able to find much difference in coefficient of friction must difference in wear rate. This table indicated if I, if you do not use any additives, any boundary additives in this case, we took example of oleic acid, which is the 1 of the boundary additives having oiliness properties. If, it is operated tribo surface is operated with pure mineral oil no additives in that simple base oil and coefficient of friction estimate. Coefficient of friction was point 3 6, 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 percent of oleic acid, you can find a substantially chain in coefficient of friction from point 3 6 2 point 2 5 that is substantial change, but after that increasing oleic acid is not going to change significantly. So, we required little bit of boundary additives to get favorable results, we do not require complete oil to be boundary additives, because very viscose difficult to form; difficult to move, that is why we do not use hundred percent unless until, it is required from the situation.

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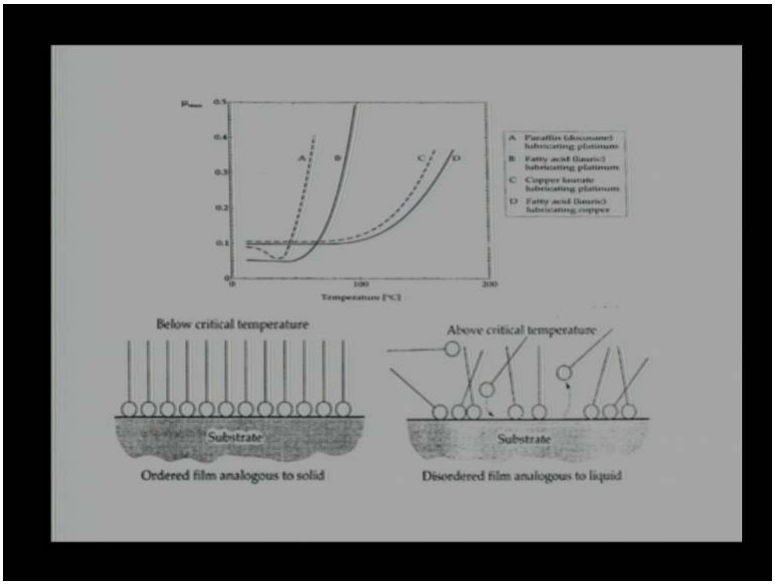

This figure shows the how the coefficient of friction, varies for different oil and oil additives, the A figure it shows clearly, that with the increase in temperature viscosity decreases, the decrease in the viscosity coefficient of friction also will decrease.

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 retreating that lubricant is completely removed from the surface. Even though lubricant remain there, but it will not be effective interlock at the interface, that is the A curve what see, appear of in this however, if you use boundary additives fatty acid is a boundary additives than, 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 copper it makes some chemical layer. It is curved in copper making some, boundary additive layer than, this temperature is increasing substantially

from here may be say, it is around 70 degree, 80 degree it may reach, 1 00 51 100 40 degree. Similarly, for other oils it can change different, it can show different behavior, what is happening with the temperature? Why this kind of phenomena happening that can be explained, using this 2 catches. It says that, order film on the substrate or substrate and substance and it is a blow critical temperature almost, all sides are occupied surface is not free from this molecule. However, if the temperature increases than, thermal forces will be on higher order compare to van der waal forces. So, molecular attraction will come down or we say that relative molecular attraction will come down or will to force, will be lesser compare to thermal forces.

And will be getting disordered lubricant thin or 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 is 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 survey; it will work. It works only after works below some critical temperature; it does not work beyond that and this kind of thermal equilibrium can be estimated or it can be goosed using the gift free energy.

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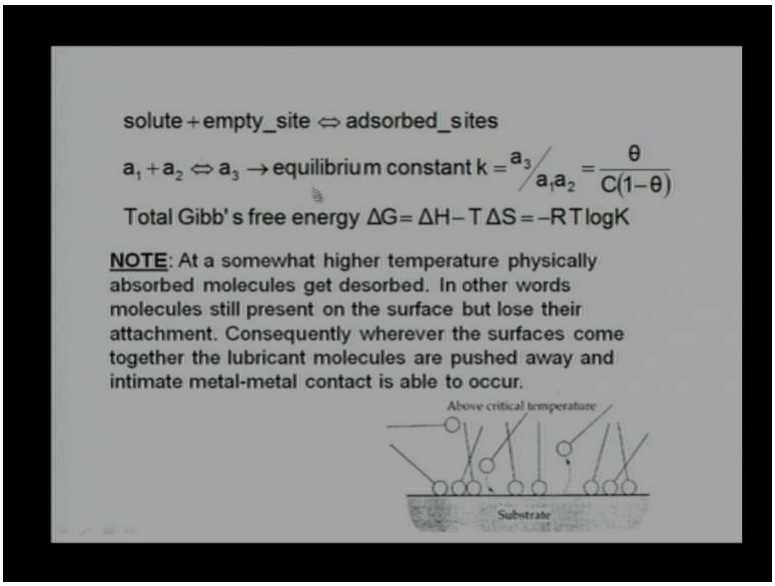

As, I mention a last lecture that, gives free energy is more like potential energy even require. Some energy to remove this lubricant layer from the surface, and that gives

energy can be estimated, using this relation. This clearly says, as the temperature increases gifts energy is going go down. If gifts energy is lesser that means, you need to supply lesser energy to disturb the lubricant film. This energy is more then, you required more energy to disturb the firm or it will be more stable compare to stability at the high temperature, that is why we says that in high temperature. It is getting dissolve and 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 wear 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 there 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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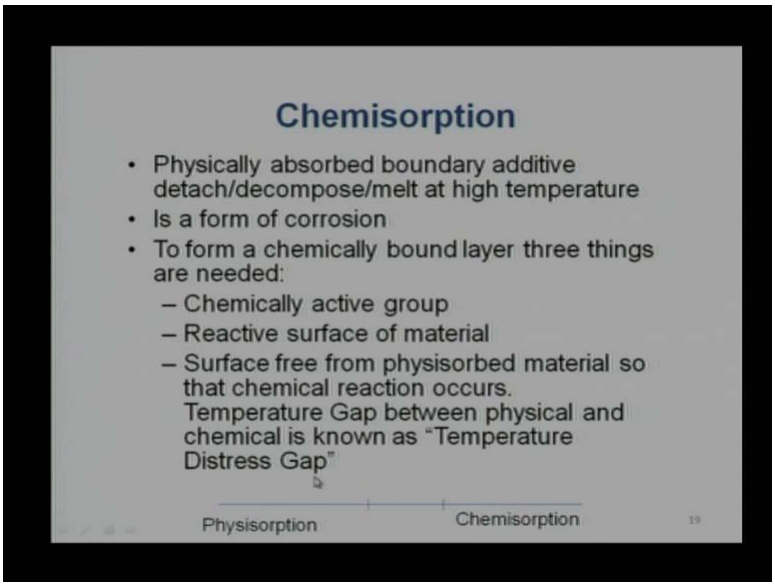

The cover the surface, they make sacrificial layer, but they protect the surface or reduce the coefficient of friction compare to dry friction or compare to unstable firm. We can

studied that, we say that chemisorption is a happening, because of the chemical action and as a first line indicates, because 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 compare to their thermal forces. It can decompose also quite polymers, get detach as well as decompose. Decompose means long molecular arrangement structure gas broken.

And it may melt also it can change is a strict from solid to semi solid to liquid or completely desorbed the chemical structure, anything possible that is why we require chemisorption at the high temperature, and as I mentioned earlier that it is a form of curvesion. We are doing purposely, we are introducing curvesion purposely say to make this kind of boundary layer. What we require we require a chemically active group, something chlorine, sulfide, 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 compare to metal surface itself.

So, this is chemical active group in addition, we require reactive surface of material all the metals have reactive surface ban 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 a ban 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 and the chemical composition, which is require for the ceramic materials, for polymer materials.

And, there is another 1 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 or 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 blow 1 critical temperature.

This 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 lab 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 1 metal or 1 additive, we may use composition active group for a physical absorption at the low temperature, another grow high temperature. So, 2 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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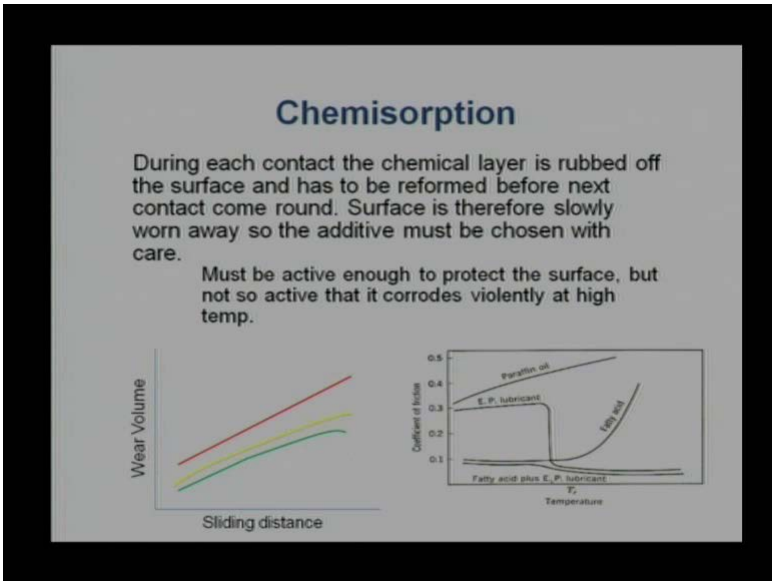

Now, some mechanism is specified as I mention on this slide, we say during each contact, the contact layer is rubbed off. It is nothing like that wear is a stop completely. It is getting rubbed of that is why we are using the word boundary lubrication.

And after rubbing of it is get expose to another cursive media or we say cursive liquid or cursive 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 med oxide layer, it is removed. Now, we required 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. We need to be accounted it will get depleted with time; it is nothing like that once you add lubricant additive. It will survey forever it as certain duration after that duration that lubricant additive will be depleted, you need to refinish that right.

And that is, this point says clearly, they need to have 1 good balance, good trade off. They should be active enough to protect the surface, but it should not be active too much active, that increase a curvesion 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 chat, 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 stretch ; how much wear as occur.

If I plot this first, this line is clearly showing archard law in dry condition. They are in proposition sliding distance and wear volume will be having ban large linear profile, linear variation ban large. Now, when you come to the mix 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 friction 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 an non-linear. It is not as linear as archard law; it states can see here, that wear rate is lesser wear wear volume is lesser compare to the dry case, when comparing it.

But it as non-linear profile, this gap may increase; may decrease depend on how fast the distance as been travel. If it is very fast there is a possibility; it goes down, it goes up also and this is show as with physical absorption. We know the physical absorption in 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 chemisorption may be whatever, 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 cam.

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 this 2 will not occur some, intensely that is why, they should not be compare temperature will be always, there temperature factor also 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 2 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 dry mineral oil without any additives. It shows the better performance compare to the dry lubrication, because there is lubricating oil and it is cool 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 that temperature gap is not. There, it is acting instantaneously wherever, the fatty acid is failing e p additives or e b 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 e p additives or in fatigue at that temperature, 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, 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 e p additives. So, overall package gives satisfactory

performance to us, because of low coefficient of friction compare to pure base oil, compare to e p additives and base oil compare 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 e p additives can react, how was 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 all always uncertainties in machines with the local temperature is going beyond certain temperature, then e p additives should work.

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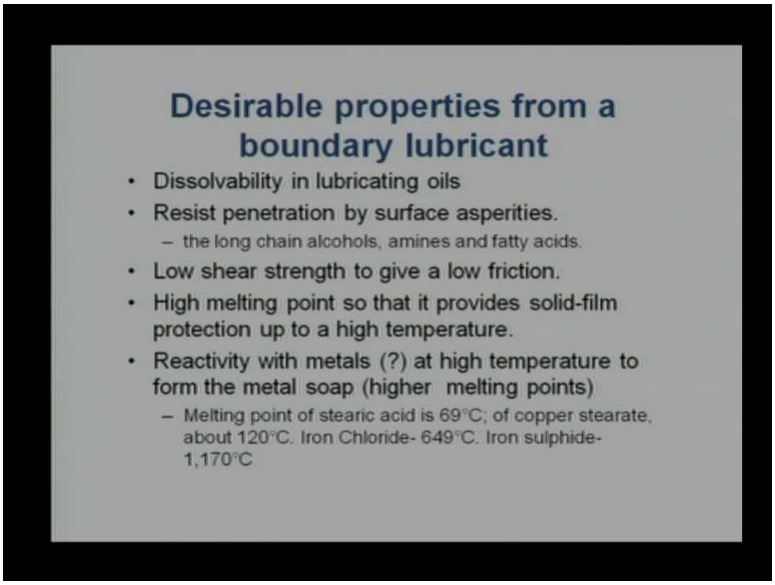

Now, we say that whatever the desirable properties from boundary lubricant, I am talking boundary lubricant from the both the point of view is, physical absorption as well as chemical absorption. We say that need to have dissolvability in lubricating oil, if they are not able to get dissolve in the lubricating 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 right.

And it should be able to resist the penetration of the surfaces asperities, when is 1 surface asperity is approaching to other surface this asperity should be covered with lubricant additives. So, that it is not getting touched or it is not coming direct contact with the surface, as per as possible in that case wear .Where, wear will be in mild region, if they

are asperities are able to penetrated another surface and wear volume will be increase; wear rate will increased.

So, that is why we prefer to use long chain alcohols for physical absorption, amines or fatty acids is all the react for the physical absorption. Chlorine, phosphorus, sulphur of the chemical composition well the as a 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 0. It does not have any use then, we need to make interface having low shear strength and that is necessary condition for using any lubricant. If they are this kind of boundary additives are not able to give as low shear strength of the interface then, 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 attachment in the surface in addition, what we can demand we say that high melting point, they should not get disturb as a temperature increases. So, if physical adhesion or physical absorption is able to sustain up to 200 50 degree 2 hundred 300 degree centigrade that will be probable choice in that case. We are not going higher with physical chemical absorption, because we know chemical absorption is going to covered the surface at a lubricant additives will get depleted and we need to refund is 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 very less effective with a polymer and the ceramics.

This is example, you show the stearic acid which is boundary additives, it as a melting point around 16 90 degree centigrade, when we are talking about the absolute without any reaction. However, when it reacts with a copper surface, copper is stearate it melts other 120 degree centigrade, which is the relatively higher compare to 69 degree centigrade. Similarly, if there is a chloride or chlorine available as a chemical additives, which goes high with chemisorption than iron chloride. Which as a solid form as a sacrificial layer temperature is very high is a 6 100 40 9 degree centigrade, that means this can sustain above 500 degree centigrade temperature without failure.

However, if you want to further on the higher side, then sulphur should act or we say the iron sulphide. Which will melt at the 1170 degree centigrade, 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 politician an additional and consideration, whenever politician comes or we had to think about politician. 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 compare to chemical absorptions right.

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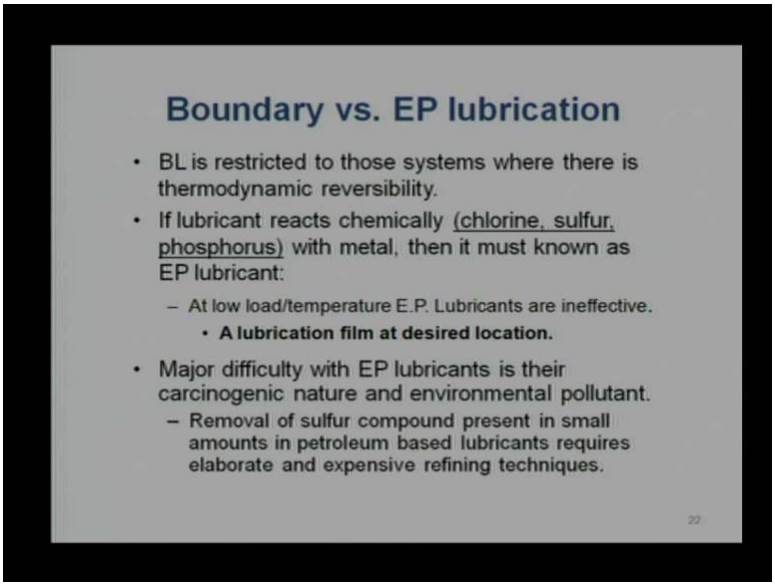

Now, this slide show may be, because there I found some disturbances and books people or a researcher have written boundary lubrications. Separately extreme pressure lubrication separately, I am just trying to compare over here, we say that boundary lubrication as per them is restricted to system. Where, there is a thermo thermodynamic reversibility, that means attachment and detachment is thermodynamically reversible at high temperatures lubricant will detach. So, this is what they have coated that boundary lubrication should be named. If, there is a thermodynamic reversibility, if there is no thermodynamic reversibility. Which mostly happen in chemisorptions in cases 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 author examples, chlorine, sulphur and phosphorus. They act with the surface and there are known as e p additives, e p lubricant. They are ineffective or this all 3 are ineffective

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

So, that is going to gave us or this kind of additives are giving on optimum performance as per the requirement, wherever it is require 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 meet that point there, because of the high temperature, high pressure and curvesion occurs. First some friction of second, there itself, however is that clearly mentioned clear over here, that they have good properties.

They are nice, they have probable from commercial point of view, but some society point of view, they are not encourage; they are carcinogenic nature; they are harmful; they are polluting environment, that is why there is a problem interesting history about this is, that in a common petrol sulfur will be there and sulfur, acts as a chemical absorption agent. It can rate with the surface, it can make lubricant film and that is going to give you as protective layer that is a useful but because of the pollution. Now, it has been infest side the petrol should be free of sulfur or it should be blow certain limit or sulfur percentage should be minimum to this percentage; it is a costly in 2 phones.

First you require process to separate the sulfur from the petrol first thing; second you required some lubricant additives to be mix with the lubricating oil. So, that surface is can be prevented from the wear, because of the politician picture or repletion consideration, cost is going to increase that is, why we have always problem. Whenever, we use this chemical absorption technique than it may survey for 5 years 10 years and after that environmental issue will come again, we have to remove 1 thing something else.

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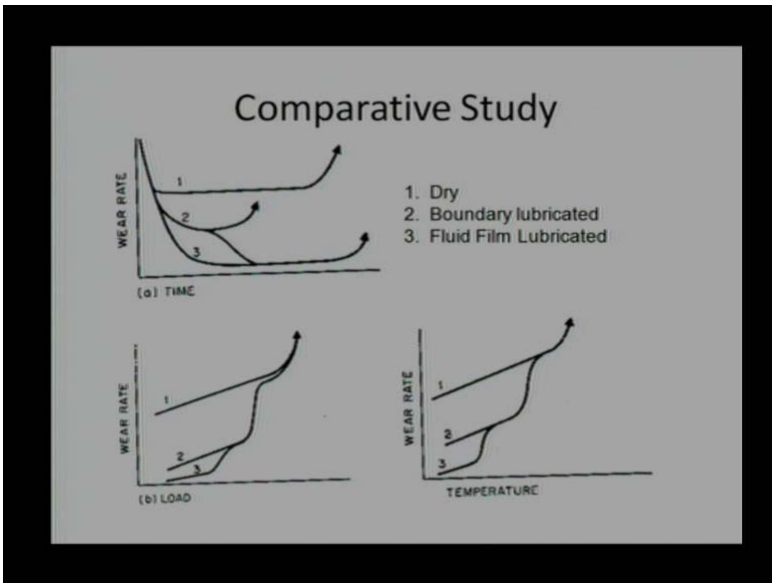

There is a comparative study with between this 3 kind of lubrication mechanism, which I dry 0 lubrication or maybe say, whatever the naturally form layer on the surface. Second boundary lubricated, which we are studying in this lecture and third which will be discussing may be next lecture, that is the boundary; that is fluid film lubrication surface is a completely separated by the fluid film, if he plot curves for this 3 condition 1 for dry; second for boundary; third for fluid 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 tracker wear rate decreases, it remains stationary and then goes up after certain duration well in lubricants anything is possible.

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

So, about the possibilities that is, why we say many times. Whenever, we are buying any new car or new automobile. We need to operate vehicle of the lowest speed, this boundary case is over or second comes and matches with 3, then after that only, we should operated 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 boundary lubrication and the further is a load is increase further, then it may match with the dry lubrication or in about the as a low discontinuously increasing lubricant may not be retain of the surfaces. It will be simple quizzed out from the surfaces.

And if there is no dynamic load; if there is no reversible position change, then lubricant will not be shut back. It will be simple moved out whenever lubricant comes; it will be simple mode out of the interface and will be getting very high wear rate or we say, that every lubricant need to be design, as per the load for high load will be, we designing the different kind of lubricant for low load condition, 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 surface 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 matching with an increase temperature, the boundary lubrication and beyond certain temperature is matching with the dry lubrication case.

So, this comparative study it indicates clearly, whenever we design system. We should keep in a mind for how long wear 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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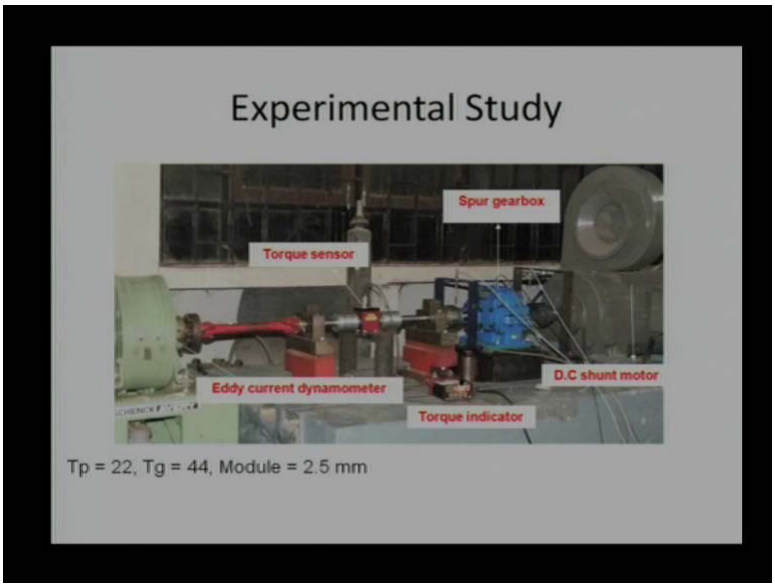

So, I will just covered 1 experimental study, which we did in our lab and results are related to our boundary lubrication mechanism. You can see this figure as an Eddy current dynamometer, which applies a load and lead load applied in this case is from 0 to 75 neutron meters. There is a Torque sensor, which can measure how much torque as been applied and what is this is a gearbox, which is a test box with the gears are going get tested. There is a motor to drive the gearbox, we are using the both the things. We are using motor to drive; we are using dynamometer to stop are applied the load; we are using the both the combination.

And Torque Sensor to measure how Torque is been applied, and then there is a display unit over here, which will give display of the Torque what we are talking the gearbox gearbox is 2 to 1 ratio or we say that pen nine gear as 22 teeth well gear, teeth gear. Now, number of teeth on the gear are 44.So, this at 44 divide by 2 in 22. It gives 2 2 1 ratio and there are standard invalid profile having pressure angle 20 degree and module is define as 2 point5.

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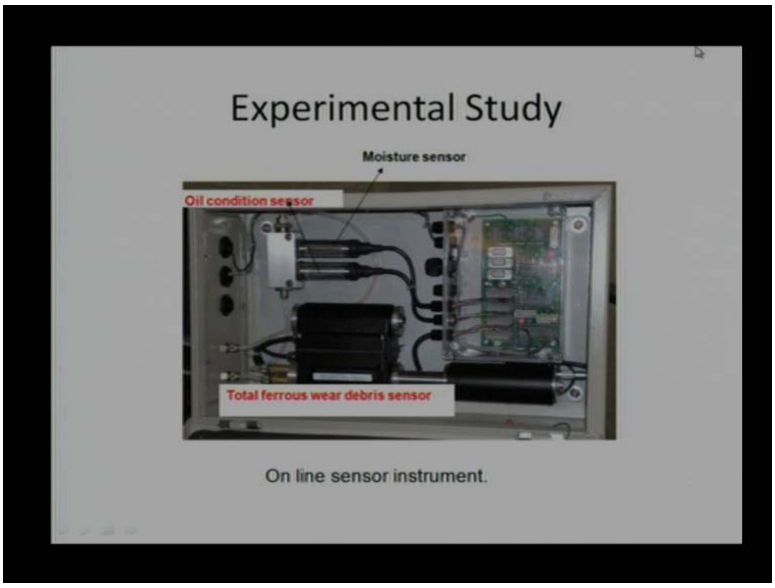

We to find out online, it go ahead with online measurement, we use sensor unit what we know as a online sensor instrument can see, there is a oil condition sensor. What is the meaning of that oil will get disturb oil, will can change quality continuously.

If it is getting more and more acidic then 10 numbers will decrease on that, 10 numbers will increase. Similarly, there is a possibility of cursive wear, there is a moisture sensor moisture sensor clearly, indicate if the related unity is very high, than we should not conduct experiments, because the major governing factor will be curvesion and there is a mechanical action. So, there will be cursive wear however, if you want to do cursive studies or we want to do study on cursive wear, than we should be able to use with some Motor environment with higher Moisture environment above all, there is a 1 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 as an indication of wear rate add the number of particle; add 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 is or connected to this unit you can see the tubing is where over here in previous slide here tubing is as going and the unit is place somewhere, here so it gives overall leading to us.

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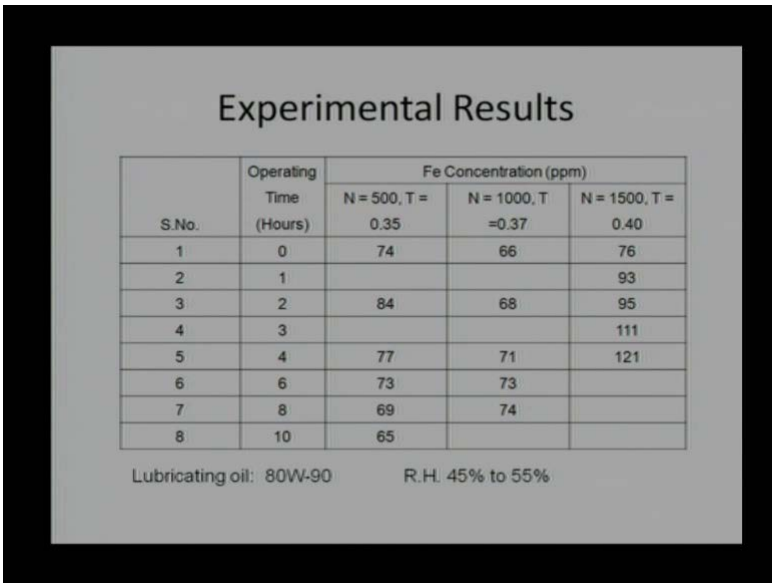

Let us, start with some maximum the leadings, we say that we brought a new gearbox and we know whenever, the gearbox is new we should not be loaded completely .So, what we selected almost 0 load and 500 R p m is speed and is given in R p m that is a 500 have, we are not use units over here, because R p m is common unit and Torque as a point 3 point neutron meter. We did not have applied any Torque from the dynamometer, but we know during the assembling there will be always some, sort of misalignment there will be some resistance from assembling.

And that is given as a point 3 5 neutron meters as a Torque, we are done anything purposefully, but it is coming, because of something and this gives iron percentage or iron concentration, in p p m number of experiments and this experiment was done in lubricating oil. what say, the 80 w 90 is a motor oil and it as good e p additive package this kind experiment happen and whatever, the experimental is what we got is a that is show the related immunity, where ending from 45 percent 2 55 percent that means, it is not going beyond certain limit. We can connect this kind of experiment without much problem.

Just after doing experiments just starting experiment, we took the reading and we found there is 74 p p m as an iron percentage or concentration, after 2 hours operation. This percentage increase 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 both of the curve says, clearly initially wear rate will be high, it is 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 in sequence after operating of the 10 hours, we 11th hours was with this speed they are in sequence all this experiments are in sequence. This is a11th this shows the 65 well, this shows 66 percent 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 us either, there is not filter system is not working well or something else is problem or another possibility is that at the high temperature; high speed is high temperature and high speed, there is a some plus temperature is happening and chemical additives or we are e p additives are reacting with surface. They are curved surface and then, they are removing the top asperities that is, what the percentage is increasing to confirm that, we increase speed also, you say from 1000 R p m to 1500 R p m keeping almost a 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 curvesion happens with the surface or even, we know the gear lubrication mechanism other this lubricant additives is known to you 1 of the very good gear lubricant 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 a speed if the mix 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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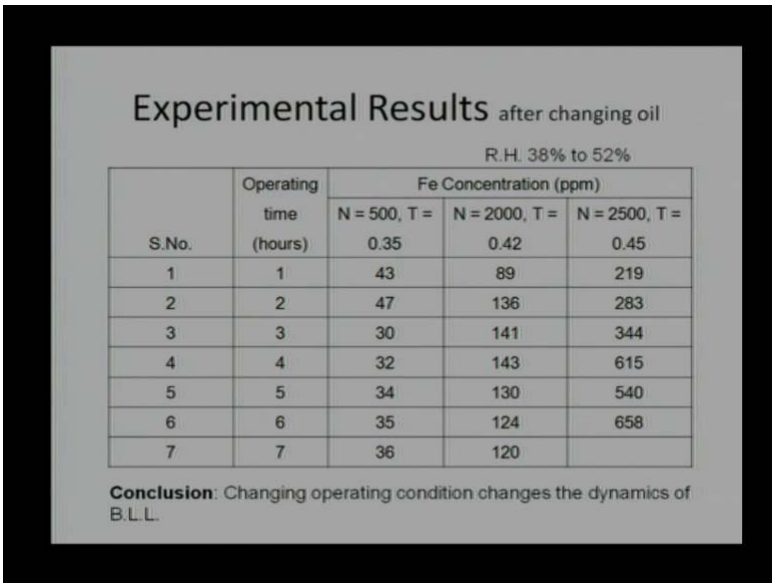

Let us, take other results second set of results after changing the oil, we changed the lubricating oil here that oil wolf particles. Whatever, the work work getting dammed in the lubricating oil are been removed fresh oil. fresh oil We are getting good readings at the 500 r p m can see 43 66 or another word, you can say it as reach to steady state condition or running in period is over for 500r p m , but it should continue for the 1000 r p m also 2000 r p m also, but what, we got and when, we are operating at 2000 r p m , We are getting different environment. We were getting different results you can see eighty 9 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 8 9 p p m that is much higher almost 3 4 inch compare to 36 and this percentage is increasing to a certain limit and after that it decreasing to get confirm results. We operate at 1 higher speed further and we can find there is a unbound lubrication, unbound p p m level from 200 19 to 6 00 58 that means, a more and more temperature is getting induce 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 no I can think I can think in different way, I can say when the speed is increasing vibration level is increasing and load level is almost 0 to additional vibration, phenomena is

happening and that is going to increase the fatigue failure or is a 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 dynamic or boundary lubrication layer. It is continuously changing it is not a stationary if 500 r p m, it showing the steady state condition, but we are stretching to 2000 r p m it showing high wear rate as I mention, 1 possible reason is vibration continue a periodical loading and that is going to induce fatigue failure in a surface or at least top asperities are shaped off, we need to confirm that with a load.

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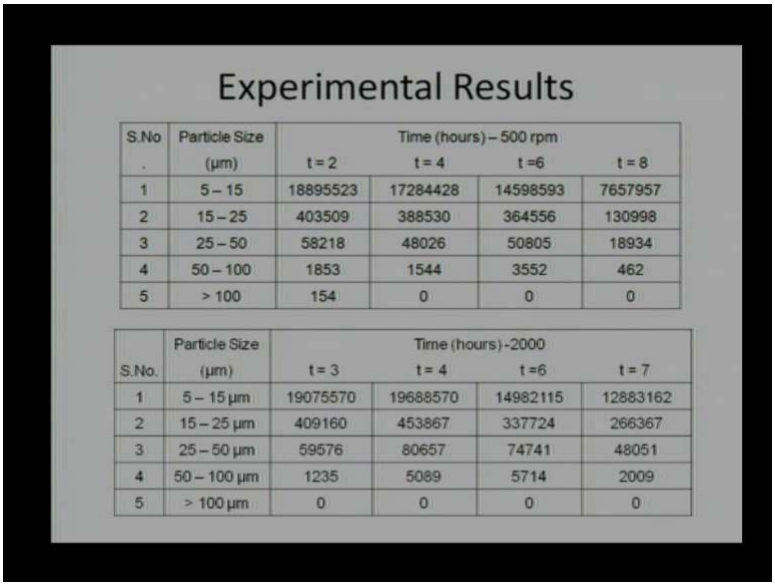

If I increase the load what is going to happen and of course, before that we try to find out particle size what is the range, of particle size to diagnose with particle size minus size or under the mild wear domain the server, wear domain and interestingly. If find too many particles for the size between 5 to 15 micron interestingly, this number of particles are continuously, decreasing with time that is means is a it is going for the betterment. It is going for the convergence continuously, number of particles are decreasing coming to 15 to 25 micron we gain the number of particles are continuously decreasing. So, that is favorable situation, we can say starting case may be server 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 articles having size more than 100 micron and when, we studied that mild wear and server wear. You say that about 20 micron particles are a server wears 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 r p m same thing must done for the 2000 r p m 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 film 5 to 15 micron and there is no particles size no particle, which as a size greater than 100 micron that is a favorable case in all other cases also, we find that particles are decreasing in numbers, this are the favorable situation they are bending 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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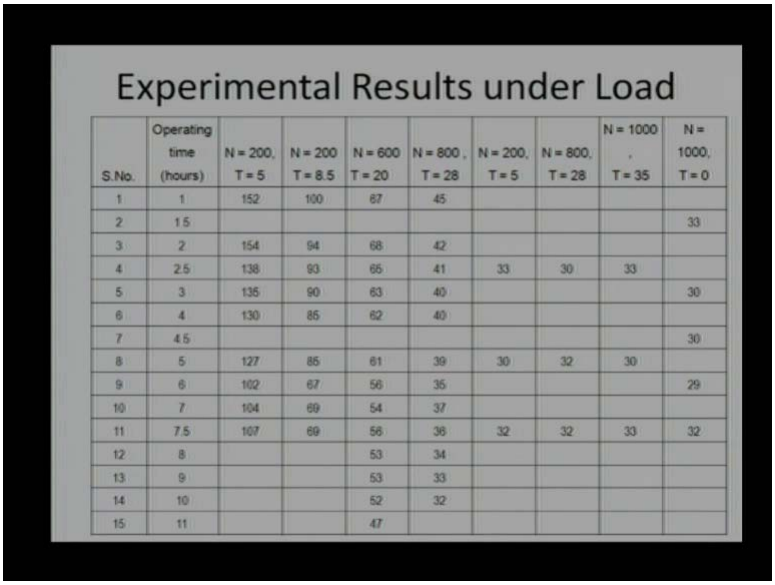

And that is why, we did experiment with load also say R p m 200 Torque applied load is 5 neutron meter wear rate or number of let say, p p m level is continuously decreasing.

So, 1 52 and 1 54 it coming to the 1 0 7 of course, 2 3 p p m have assuming that is in accuracy or it is not giving that is more reliable results. Now, if I increase load what is going to happen same increasing the load from 1 0 7, 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 Torque again, we are getting lesser number of p p m or lesser p p m in this case same thing or same results for the 800 also 800 and load is higher side 20 neutron meter, it comes to result 32 neutron meter that is indicating; that is showing; that bedding in time is coming to the closure or almost negligible level.

After that, we could not find any further improvement this clearly, shows the number of particle was p p m level is reaching almost 30 30 p p m 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 word, 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 point 3 neutron meter, because all are Torques are very high compare to 0point 3 0 point4 neutron meter that is we put value as 0 and this is 0 Torque and 1000 R p m still, we are getting good results.

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

That is the 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 different manner. We say that even though, we know bedding in time or bedding in behavior the wear rate should be very high initially, he 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 percent of that is an being, there will be more clearness unless load less deformation of surface that will, cause a more vibration less load carrying capacity and fitting in that case will be much much faster, compare to with load another word. What we say from the orchard law as away the load is increases wear rate will go down, but when comes to the lubricated case; when can calculated the to 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 preposition itself.

With this I complete a boundary lubrication mechanism were next lecture, will be discussing about the mix 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 quiz from lubrication mechanism are some thank you for your attention.