**Video Course on Tribology**

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**Model No. # 04**

**Lecture No. # 13**

**Lubrication Mechanisms**

Welcome to thirteenth lecture of video course on tribology, present topic is lubrication mechanism in previous lecture. We understood boundary lubrication mechanisms, we discuss two modes of boundary lubrication mechanisms to compare all lubrication mechanisms one convenient method is stribeck curve.

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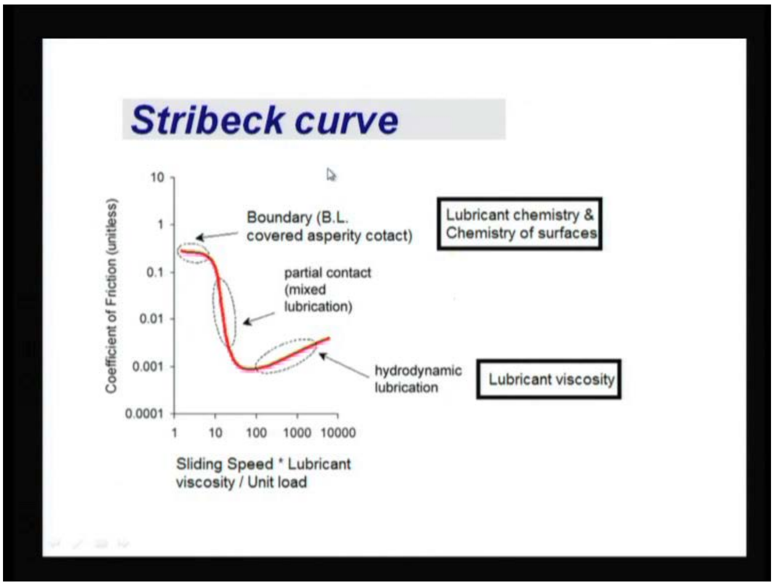


Stribeck curve is a basically a curve between coefficient of friction and a bearing number. Bearing number can be defined as sliding velocity, what we are talking about the relative sliding velocity lubricant with viscosity per unit unit load. Unit load means the applied load divide by projected area, when we plot a coefficient of friction with bearing number, what we get at different domains, and different regimes of lubrication.

Here, we have we are able to see a broken line or there is no continuity from 0 to some point, that is indicated when relative velocity is 0 than, this system will not act as a tribos system, that means we cannot plot this results with a 0 velocity, that is why there is discontinuity coefficient of friction does not mean for the 0 velocity. Other than what we talk about the static coefficient of friction, what we have we are talking about kinetic coefficient of friction, and coefficient of friction is unit less it is force divided by force.

Now, this curve this curve red color curve as three domains indicated with dashed elapids first is a boundary lubrication, second is a partial contact lubrication, third one is a hydrodynamic lubrication. We can extend this also; we can say initially it will be dry contact or when we are not intending any lubrication mechanism. Lubrication is happening is own or it is happening, because of the environment we are not giving any lubricant to the surface.

When, we do intentionally some lubrication on the surfaces, than it will be call a boundary lubrication mechanism. Boundary lubrication mechanism basically is a solid lubrication; solid form of the lubricant remains intact with surface. If, it is one molecular thick liquid layer than, it will act as a solid. And, it can be call as solid lubricant; it can be called as boundary lubrication. Other domain here it is shown hydrodynamic lubrication, where the relative velocity is essential and lubricant viscosity plays, major role if I compare hydrodynamic lubrication with boundary lubrication. What we can say, if boundary lubrication lubricant chemistry and chemistry of the surface of metal, which are interacting plays an important role. The chemistry important well, in the case of hydrodynamic lubrication is viscosity or resistant to flow is more important.

We know very well there nothing will be absolute, there is a possibility mixture of this thumb few surfaces asperities are covered with boundary lubrication, and few asperities are not covered or if it is covered. They are not in contact; they remain separated due to the lubricant film that is why they call hydrodynamic lubrication. There are other domains also, what we call we minimum domain of the lubrication here. When the coefficient of friction is minimum often, it is known as a elasto hydrodynamic lubrication. So, depends on bearing number, we can divided lubricant regime in four categories, in four board categories.

What we call as a boundary lubrication, and if you want to develop new categories with dry lubrication, and there is no intended lubrication that is also possible. Second one is a mixed lubrication or partial contact lubrication mixed; lubrication mechanism is more common, or is very commonly used compare to the partial contact lubrication.

And finally, it comes to the hydrodynamic lubrication over here. Intermediate will be elasto elasto hydrodynamic lubrication, where in the basically mechanism will be hydrodynamic lubrication mechanism, but in along with that, we will be considering elastic deformation of surface, and viscosity thickening effect. That will increase the load carrying capacity in fact, what we say almost every element need to have elasto hydrodynamic lubrication mechanism. If, we are really worrying about, cost if you are worrying about optimum performance, optimum performance happens at that point.

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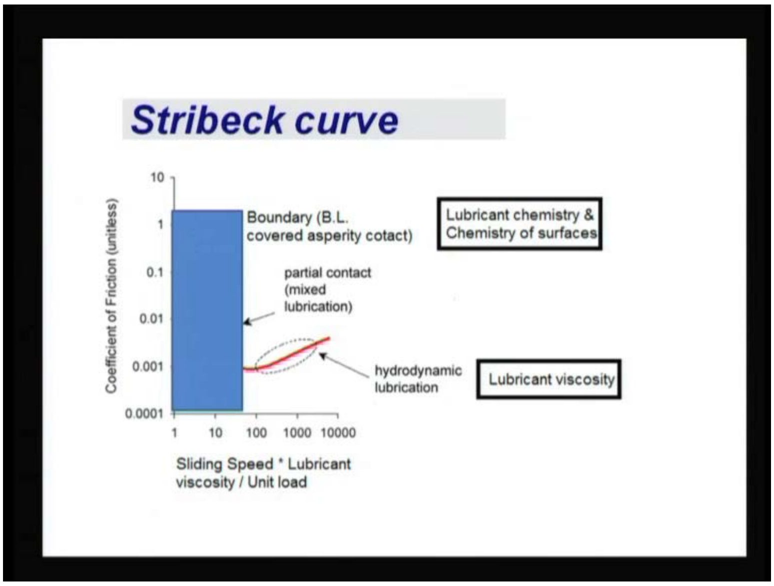


Now if, I think from stability point of view stability means as, if system is disturb it, should come back to it is original position or regain its position without going unbound vibration or going through was failure. So, if I go ahead with that kind of thinking stability thinking, I can say this is boundary, this is alloy. If, I see the right hand side of this line this is a stable domain, stable regime. What is the why we are saying is stability or why, we have emphasizing this domain is stable. Let us taken an example, we want to operate at this point, lubrication mechanism is getting operated at this point where that sliding velocity lubricant viscosity and unit load.

Now, because of the hit temperature will increase, and because of increase in temperature separation between molecular will increase. That is going to cause a lesser viscosity that means if we started point point here. It will decrease because of very lesser viscosity bearing number will decrease, and then coefficient of friction will decrease. As, a coefficient of friction is decreasing, naturally heat generation will decrease or heat production will decrease, as well as heat generation will be decreasing, that will lower the temperature. If, the temperature is lower it is going to gain back the normal position, or what we say that even if, we operate somewhere here. Stability will be remaining there, it is not going to unbound; it is going on better condition; it is going to be self helping; its it is system helps itself in that case, so it is a stable domain.

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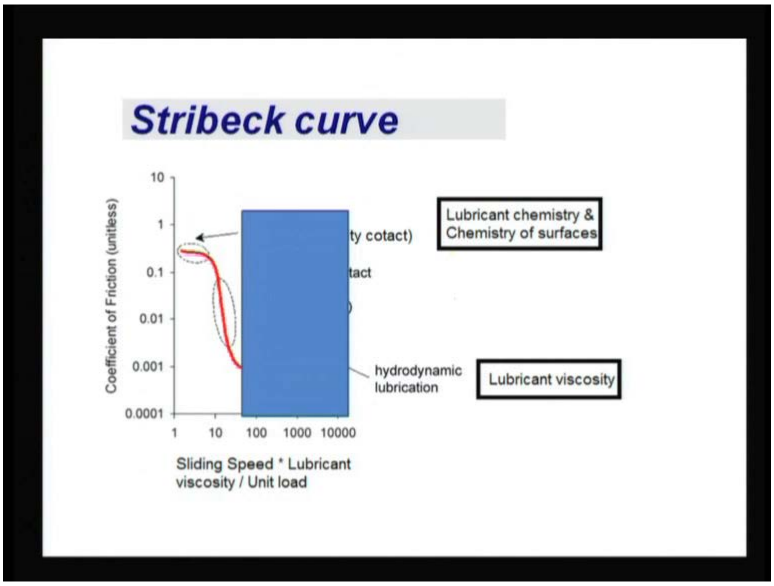


If, I see the other side left hand side of this line. If, I do not consider right hand side and consider only on the left hand side, now if in this case heat generation is high temperature is high and because of the voscos that viscosity is decreasing, decrease in viscosity will reduce the bearing number. The bearing number is decrease this is going to further increase coefficient of friction, increase in coefficient of friction will increase heat generation increase in heat generation will increase temperature, that will reduce a viscosity.

So, it is compounded effect once it is disturb. It will ultimately reach to this condition, whether the coefficient of friction, will be Nemours maybe say 0.5 0.6 and the system, which was not suppose to design or we will not designing the system. And coefficient of friction more than 0.1, in that case coefficient of friction reaches to 0.5 0.6. Naturally, system will collapse system will fail, that is reason why we call this domain is in stable domain in the stable regime, that is why whenever we want to operate any system. We should operate of the right side of this line, not the left hand side of this line.

But if there are restrictions if there are restriction, that system cannot be operated at right hand side, because of the some lubricant restriction or supply of the lubricant or we cannot go ahead with weaker lubricant at all in that situation. We need to design a system with a narrow band assuming, and need to keep a control on the temperature, that means we need to provide artificial cooling so temperature should never go beyond certain limit. Now, that is that was the stribeck curve, it can conveniently describe what are the regimes, and how 1 regime will be differentiate with the other regime.

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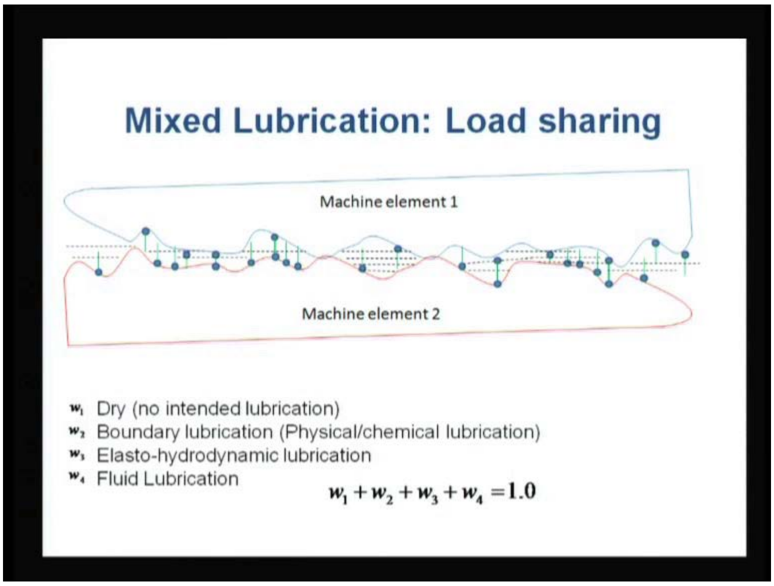


Now, come to the mixed lubrication case, why we are saying the mixed lubrication, because in this contact bear. When, you say machine element one and machine element two, when they are at the interface or we are making interface, we are able to see, there are few asperities which are directly in contact.

There is no lubricant or there is no boundary lubricant at term few asperities, where the boundary lubricants are acting few, at few asperities only the liquid lubricate is there, that means there is a possibility of dry friction, without any boundary additives. There is There are few contact with boundary additives, few contact with liquid lubricant and few contact with the elastic deformation, as happen you can see this this surface is a elastically deformed. It is showing more smoother is a surface compare to the valleys, and peaks which are shown at the surface.

Similarly, there is an elastic deformation over here. So, there is a elastic deformation there is a boundary additives, they are liquid interfaces also, and there is dry contacting that is why, we calling is as mixed lubrication there is part dry lubrication. There is boundary lubrication, there is a liquid of fluid film lubrication are there. If, there is a relative velocity then, it will be call as a hydrodynamic lubrication, and there is a possibility of elasto hydrodynamic lubrication. We can say, there is a dry contact boundary lubrication, elasto hydrodynamic lubrication and fluid film lubrication. If, I mix all together, that mix mixed lubrication and that, was shown in a previous slide mixed lubrication.

That is a longer 1 lubrication mechanism, where almost all mechanism are interacting with each other, and giving overall results. We try to analysis whatever the system, you pick up then if you analysis that lubrication mechanism ban large, it will mix lubrication mechanism. Now, there is a possibility only one percent is a dry lubrication, five percent boundary lubrication, ten percent elasto hydrodynamic lubrication and remaining fluid film lubrication depends. Which mechanism is dominating, if fluid film lubrication is dominating with nineteen ninety five percent asperities are separated, because of the fluid film lubrication than, it will be called as hydrodynamic lubrication or fluid film lubrication.

I am using the word the fluid film lubrication compare to hydrodynamic lubrication, because there is a possibility of separating to surfaces, by inducing outside pressure or supplying pressure from outside. That will call as hydrostatic lubrication, it will not be call hydrodynamic lubrication that is why to differentiate that, we are talking about the fluid film lubrication fluid is there from wear, and what is the source.

We are not talking, there is a possibility viscos film action also, hydrostatic viscos film hydrodynamic lubrication all they try to separate the surface completely, and there is no asperity contact in a situation. Now, as I mentioned there is a possibility of change in weight age, what we say that weight can given w 1 w 2 w 3 w 4 and summation of weight, should be equal to 1. That means if, there is a 1 percent. That means w 1 is a 0.01 w 2 is a 0.05 as a 5 percent w 3 is a 10 percent 0.1 0 that remaining remaining 85 percent, that will be w 4 that can come from this equation. Now, depends on the mechanism and how we are lubricating the surfaces, this overall equilibrium can be established, and that is going to decide what will the friction and wear characteristics of that interface.

If, w 1 as a higher value if, w 1 is a higher value, naturally friction will be higher wear will be higher. If w 4 is a very on higher side then, naturally the lubrication is effective, the wear will be turn to be 0 or negligible friction done. They will depend on the viscosity of the lubricant, we are operating the viscosity higher thick, using the thick lubricant and operating at higher speed. Friction will be higher side that was also indicated from the stribeck curve. If, friction is a sliding velocity is a higher and that, 2 in fluid film lubrication mechanism or in hydrodynamic lubrication mechanism in that coefficient of friction will be on higher side.

So, depends which characteristics, we want we want higher lubrication or high coefficient of friction well lesser wear rate, naturally will keep high relative velocity and thick viscos fluid. So, that two surface is completely separated, but can be develop high coefficient of friction. It can give high coefficient of friction.

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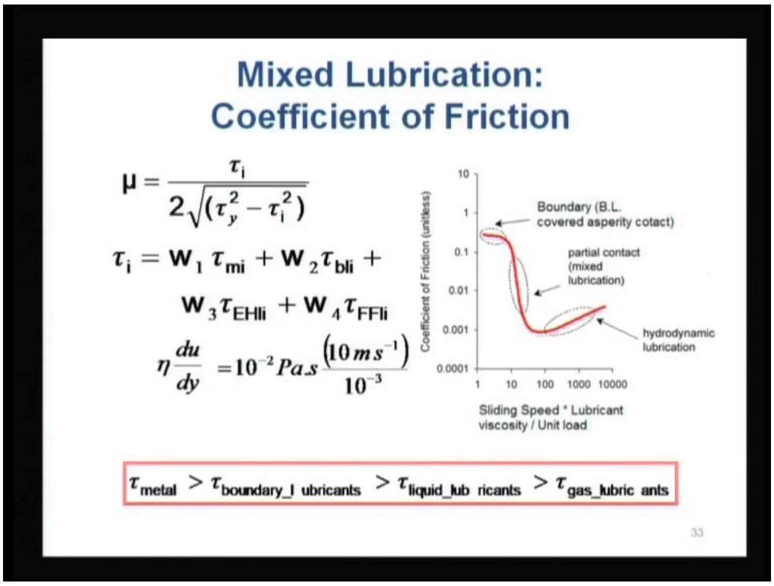


To find out coefficient of friction in mixed lubrication mechanism, we can go back to our previous relation. Which, we drive using junction theory or we say junction growth theory with the mu was expressed, in terms of shear strength of interface, and shear strength of bulk material or soft soft material material having shear strength in a bulk form. So, coefficient of friction was dry film using that relation, if know; if I think from mixed lubrication point of view. I can say this, tau I the shear strength of interface will be function of interface, which is made because of the dry lubrication direct metal to metal contact. So, I am expressing tau m I at the metal interface then, tau b l I that b is a boundary l is lubrication I is an interface. That means due to in boundary lubrication interface, what will theta than comes tau EHli E is elasto H is hydro and I is interface and l in this between is lubrication elasto hydrodynamic lubrication interface.

And, last 1 comes that is FFli that is a fluid film lubrication interface. Now, there is a possibility of generation of fluid film lubrication, and that will gave some friction because of the shearing of that lubricant, and if there is a elastic deformation. The deformation will consume some energy, and that is can be directly related to viscosity increase. What we can say depends on the relation; depends on the elastic deformation viscosity of the lubricant will increase, and that is going to increase coefficient of friction particularly.

In this situation then comes boundary lubrication that, can be estimated however if we are not 100 percent sure then, we can play; we say that we can use some sort of software to do iteration to find out w 1 w 2 w 3 w 4 by collecting the experimental data on that. And, this is a some note comes for here, we say that tau metal shear strength of metal will be greater than shear a strength of boundary lubricants, shear a strength of boundary lubricant will be greater than shear strength of liquid lubricant. We are not talk about the gas lubricant, but if there is a gas or maybe say; that air of may be gas maybe in nitrogen or hydrogen also then.

In that case shear strength of that interface will be lower or another case, we can say gas bearing any solid surface separated by the gas, as a lubricant will have lowest coefficient of friction interface separated. We say that two surfaces separate by liquid lubricant will be having intermediate or coefficient of friction greater than gas, but there is a possibility of lesser coefficient of friction compare to boundary lubricant compare to metal to metal contact lubricants.

Now if, a assume fluid film lubrication is a neutron and fluid lubrication. How is a fluid? Which use been utilized is a neutron lubricant, in that case tau FFli we can be represented and can be given in this form is a eta, and velocity gradient eta will be in a Pascal second or milli Pascal second u will be meter per second, and then in this y is a meters. So if, I take some magnitude analysis or some approximation, what we can say assume the oil. Which, we are used as a 10 centistokes as a viscosity, 10 centistokes is something like 10 milli Pascal second 10 milli Pascal is equal to 10 is to minus 2 Pascal. Seconds and velocity if, I can roughly estimate may be say around 10 meter per second that is why reasonable high velocity.

And, separation between two surfaces are which is happening is may be around 10 is to minus 3 or say 1 m m. If, I go ahead with this calculation, what we are going to get, it is something like 100 Pascal. 100 Pascal is very low shear strength compare to the boundary lubricant, which may have strength. When they are getting attach to the surface in mega Pascal also, 100 Pascal verses mega Pascal, even the one mega Pascal makes difference of 10 thousand or what, we can say that this leave this shear strength will be roughly 0.1 percent or much lesser.

Than that also will be lesser than, that now if I think about viscosity thickening effect, because of the elastic effect. Then, it will be twenty times may be say twenty or twenty is multiplied the 100, 2 kilo Pascal having 2 kilo Pascal will be much lower shear strength compare to solid material shear strength, which may reach around 200 mega Pascal.

In boundary additives or it may be around 120mega Pascal that is again very huge difference in shear strength. So, to be 1 easiest side I can assume these 2 terms are negligible, when we think about coefficient of friction and when, we are talking of the mixed lubrication of course. If, we talk only about the fluid film lubrication in that case, we need to account this even though whatever the lowest coefficient of friction.

We need to estimate through that or with EHl we need to estimate coefficient of friction but that will be not relative that will in absolute sense. When we are relating, it we know this coefficient of friction this fraction even though the 5 percent 10 percent may contribute significant factor, in over deciding overall coefficient of friction compare to FFli and compare to EHli.

Keeping that in mind, we will consider this factor. Whenever there is a mixed lubrication mechanism dominated with metal and boundary lubricant of course. If, it is 95 percent 97 percent FFli than, we should include all the factors when there is a possibility 50 percent or 25 percent coefficient of friction is given by the fluid film lubrication.

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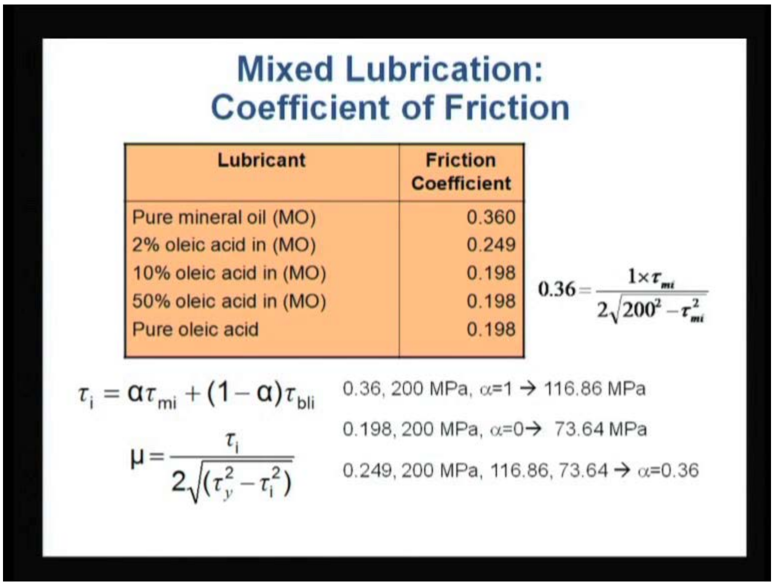

And some this example, or this experimental reading, where shown in 1 of the previous lecture I am just repeating it. So, that we can utilize our relation whatever, we have concluded from our previous slide and give some mathematical treatment, get result from that angel. In this case well, what we express earlier as a when pure mineral oil is used is, used at the interface coefficient of friction was 0.360.

We are talking about, very low relative velocity. We are talking about very high load in that entire situation; boundary bearing number will be almost negligible. So, we can see the fluid film lubrication even at presence of appear mineral oil was negligible. Now, we added the 2 percent oleic acid, in that case what were happen coefficient of friction turn out to be 0.24 9.25 roughly, increasing on oleic acid is a decreasing the coefficient of friction, but not to the substantial level and subsequent increase in oleic acid is not going to give us much results.

So, as in this case fluid film lubrication is not dominating factor or elasto hydrodynamic lubrication is not dominating factor. I can use thinking about, this 1 also and more or less asperities will be in contact or aspartic covered, with boundary additives will be in contact. So, we have use the this relation alpha tau m I and 1 minus alpha tau b l I that means, we are assuming W 3, W 3 is equal to 0 W 4 is equal to 0. W 1 is equal to alpha and remaining W 2. Which can be find out, we can figure out from equation W 1 plus W 2 plus W 3 plus W 4 equal to 1. That will give as result W 2 is equal to 1 minus alpha, but we can utilize this relation along with this relation to find out.

What will be the interfacial strength for the metals, and liquid interface metal? Interface and what was the shear strength of boundary lubricant interface that means, if I use coefficient of friction 0.36. In this relation tau, I can be figure out. If, I know tau y for most of the metal tau y is known to us that means, if I know the coefficient of friction. If, I know the tau y I can figure out easily tau I let us taken example, in this case what we say that alpha is equal to 1, liquid lubricant was not acting at all and boundary additives was not mix in that.

So, alpha equal to 1 that means 1 minus alpha, will be equal to 0. This shear is 0 whatever the tau y it comes, because of the metal interface or we can say directly instead of writing tau. I can I can write here, that tau m I divided by square root of tau y square minus tau m I square.

If, you use this relation, so that 0.36 is equal to 1 is alpha is equal to 1 over here. tau m I divided by 2 the same 2 is getting repeated over, here is square root 200 square minus tau m I square now I can simplify this equation I can figure out what is the meaning of what is the value of tau m I what is happening because of the metal interface and that turn out to be 100 16.86 mega Pascal that means if the bulk module bulk shear strength was 200 mega Pascal this turn out to be 116.7 mega Pascal that is a seasonable high value.

Then, in the absence of boundary additives, but liquid lubricant acted very nicely. they have give some interface sliding interface or able to reduce that, shear strength of interface. And that happens always, whenever there is a adhesive bounding use a lubricant than, there will be slippery action happening and cool wield junction will not happen. If, during there is slider velocity of course, if it is a accessory load even in that case. In presence of liquid there is a possibility of cool wield, but if there is a some lubricant available load applied is high even, in that case interfacial strength will be lower than bulk metal shear strength.

Which is a ban large happening whenever; we do experiment in the lab. We found interface shear strength is lower than bulk module bulk shear strength. Well take another example; we know that coefficient of friction is not decreasing further here. 0.198 That means all the slides are been occupied by boundary additives, that is why the coefficient of friction is not varying. After that when all the sides are been occupied by boundary additives, there is no further side available. Which can be which was empty in that case I can assume that, alpha is 0, hold the surface in occupied by boundary additives.

If, I make alpha is equal to 0 that, means tau I will turn out to be tau b l I i can substitute over here. tau b l I tau b l I i know the coefficient of friction that, is turning out to be 0.198 and I can simplify; I can find out interface; shear strength that is turning out to be 7230.64 mega Pascal mind it it is mega Pascal. It is not kilo Pascal; it is not in Pascal. When, we talk about the fluid film lubrication, we are talking about the only Pascal not even reaching to the kilo Pascal. When, we are talking about the E H l and viscosity thickening effect then. There is a possibility of some kilo Pascal say 1 2 kilo Pascal, but in absence of those lubrication mechanisms.

When, you talking about boundary additives just a mono layer or very thin, lubricant layer on the surface may be say in some nanometers that coefficient of friction is reasonable, high whole the surface covered with boundary additives. Now, I can find out any value intermediate that means I can find out the mixed lubrication. What was happening in this case, that case was a 2 percent oleic acid that was a mixed lubrication in that case.

And, we are able to find out the results. In this case say the 0.2 4 is a 4 9 coefficient of friction 200 mega Pascal at the shear strength metal and finally, when we are using this relation or we are able to find out alpha there. We can go ahead wherever side, we can find out that? What is the tau? I substitute tau I; we know tau m I; we know tau b l I; I can find what will be alpha ill just repeated, it said I in third case when coefficient of friction is 0.249 substitute 0.249 tau y is known to us tau I is not known to us.

So, express tau I in terms of whatever the mu directly results or in terms of tau y and mu or you can directly interpret the result. What is the tau I, substitute tau I over here? We already know, what is the tau m I? Which came out to be 116.86? We know tau, tau b l I. Which come out to be 3730.64 is substitute this value. I can figure out what will be the value of alpha, that means either coefficient of friction is something like 2 4 6 9. I can figure out yeah what is what metal to metal contact is, it says that 36 percent asperities are directly in metal to metal contact.

There is a no boundary additive lubricant on that, or maybe it is depleted boundary additives. How reduced or more boundary additives can be added or this kind of methodology. This kind of method mathematical treatment allow us to do the optimization, how much lubricant additive should be mixed should be mixed at 3 percent, 4 percent, 5 percent it can be iterated accordingly of course, this is very simplified expression it does not holds always, but it give reasonably good idea about the boundary additives or percentage effect on surfaces.

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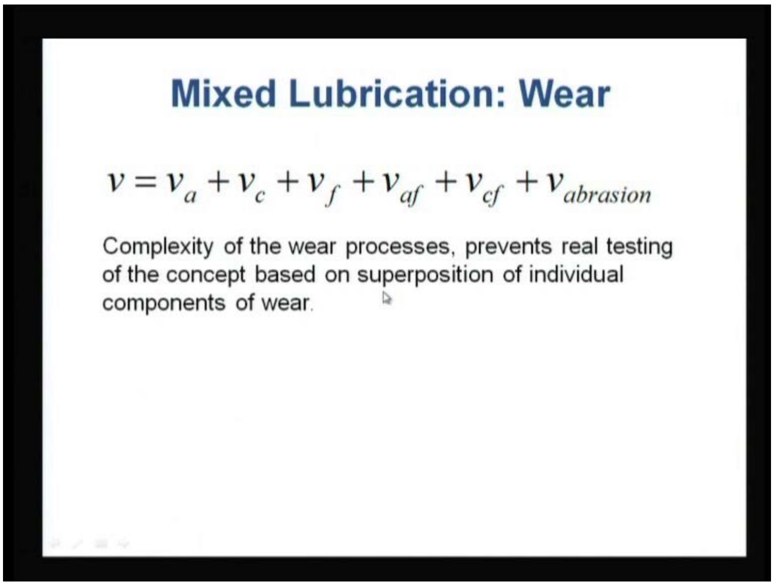


Now, will come to the wear mechanism. What we talking of the wear in mixed lubrication is interesting. First and final role says that wear will never occur; because of its own only one mechanism will not finally, lead to the failure is always a mixture of lubricant wear mechanism. Which will cause final wear first thing is that, in dry lubrication there is a possibility of strong abrasion is strong adhesion, but when we talk about, the lubrication mechanism or we talk about wear in lubricated conditions then, there is a possibility of some sort of adhesion. Whether asperities are still in contact some sort of curvesion may be lubricant is curving, the surface or some process fluid getting mixed with a lubricant causing the failure and finally, comes to the fatigue fatigue will be always there.

Whenever, the lubricated wear adhesion can be avoided, abrasion can be reduced, but fatigue will be dominating factor in that situation. So, what we are writing in this case as a volume per unit length. Per unit sliding distance is kind getting contributed by v a or that is volume wear due to the volume. Per unit sliding distance wear due to the adhesion hear a volume wear, because of the curvesion volume wear because of the fatigue. And, there is a possibility of interaction adhesion and fatigue. They are interacting together curvesion and fatigue, it has happened that whenever, there is a curvesion environment fatigue will be Nemours or maybe say that fatigue. Effect will be Nemours and finally, comes abrasion, whatever the particle are getting detach or coming from the environment.

They are causing the wear of the surface and losing the wear material that, means can be added on this, now question comes how many experiments really will be required to get all this parameters huge huge numbers of experiments are required to conclude that way.

That is why, it is not very common approach of course, this is ideal approach, but it is not a common approach reason being that. This a complexity of wear processes protecting, the results with 100 percent accuracy from wear experiment is, it still not possible accept in nano level. Now when, things are not 100 percent sure that we will not be able to get good results from that. That is reasons why, we are considering I will be say whatever we do you are not get a fluid film? Results from this kind of approach that is why we not going out of this approach what, we say we are not going at the super in position of individual component of wear. We need to think from several other angle.

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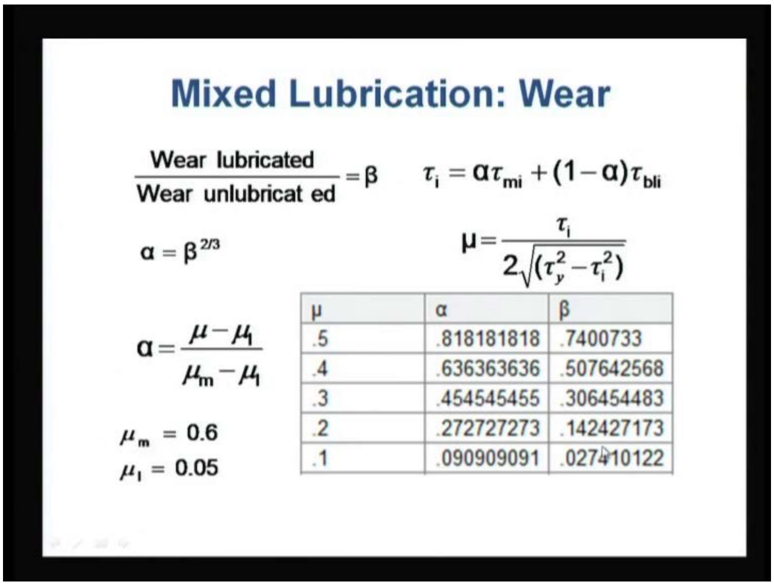


And previous slide, we are shown that friction calculation, and how we can go ahead with this kind of calculation. That is why; this is another weight to treat a company. It say that get a comparative results, when we talking about the wear lubricated or wear under lubrication. Wherever, there is a lubricant available and still wear is happening 100 percent that, will cause lesser wear compare to un lubricated because abrasion more and more rolling action will occur, and in that situation abrasion will wear will decrease similarly, they will not be many junction due to the adhesion.

So, wear will go down, that is why we say that wear lubricated by wear un lubricated will be equal to some friction. That is a beta and this beta will be lesser than 0 ah lesser than 1, but greater than 0 and few experimental. They have done a exchange experiments and then, they could relate beta with alpha say basically wear is happening, because of the friction junctions. If, there is no friction junction at all, they will not be any where if there is a adhesion that is what the wear happen adhesive wear. If, crashing happens or we say the plugging is happening that, is happening because of the friction mechanism that is what abrasive wear comes into picture similarly, fatigue will happen because of the some sort of confinement and some sort of coefficient of friction that is causing some adhesion losing some particles from that.

So everywhere wear is related to friction we are not talking the direct relation magnitude relation there is a possibility of change but, when lubricated condition it can be related again this is a hypothetical concept whatever the experiment was done based on that this judgment come it will not be 100 percent true for each and every case if this is the situation I can utilize this expression to find out alpha once alpha is known we can find out what will be the wear volume reduction or we can say whether the beta is equal to 0.01 0.1 0.2 0.3 that can be judged relatively not absolutely relatively in terms of alpha that is the good approach instead of going with the extensive experiments based on super in position of individual wear mechanism this required much lesser number of experiment and then give some sort of conclusion which is reliable from most of the materials there is another possibility that if we do existence experiment in the lubrication mechanism and in absence of lubrication mechanism alpha can be figure out using this relation also we do we know there is a alpha will be statistical

And then, we can find of the mean value from that, if I know mu under lubricated condition mu in absence of lubricant and mu under normal condition. Which we are operating? We are not we are talking about, the mixed lubrication where, there is a some sort of lubricant. The liquid lubricant will be there to separate, the asperities some sort of metal to metal contact will be there, that is why we are going higher with first absolute sense volume liquid lubricant completely separated. What is the coefficient of friction what is the coefficient of friction with mu coefficient of friction on the metal to metal interface when there is no lubricant at all.

And, what is the coefficient of friction under actual condition, which is required to perform experiment in that case. If, you know the mu, we can find out alpha. If, I know the alpha; I can find out the beta that, will give us as a result. How much friction; how much wear can be reduced by using the lubricants or lubricant additives, or we can find out effectiveness of the lubricant. Let us take one example, you say suppose we did experiment with and found coefficient of friction, and metal to metal interface with the 0.6 taken an example of steel, mild steel was mild steel can give coefficient of friction equal to 0.6.

Now, you have given keepers flow you have completely separated two surfaces and shearing is happening or there is a relative velocity. That is causing some sort of shearing of lubricant, and that is causing coefficient of friction equal to 0.05. That means I know the mu m; I know the l; I can find out if there is a mu, different mu in the different regime. I can find of alpha that will give beta lets historical study what, we say that let us take example of mu is equal to 0.5 that means. Whatever the real condition mixed lubrication condition, we did some some sort of liquid lubricant and some boundary additives coefficient of friction turn out to 0.5 again it as hypothetical.

In that situation, if we substitute value and figure out. Alpha is standing out to be 81.8 percent or you say compare to metal to metal lubrication 80, it is reducing by around 18 percent 18 0.1 percent. So, coefficient alpha is 80.8181 or maybe say 0.82, but beta is lesser that means, wear having lubricant as more effect on the beta compare to alpha same thing. If, I got to the different kind of, boundary additives and coefficient of friction is standing out to be 0.4 instead of 0.6 than, this alpha value is decreasing because metal to metal interface is decreasing. In that case, it is come out turn out turn out to 0.64.

Well beta is 0.1 0.51 again, the beta is lesser than alpha keep going doing the same thing and coefficient of friction is reduced to 0.1, and we say that coefficient of friction 0.1. Alpha is also 0.1 is only 10 met percent metal to metal contact, well in this case it is turning out to be only point. 0.03 that means instead of 10 percent, what with the metal to metal interface, but wear is happening at only at 3 percent. That is what we are trying to conclude is lubricant as a more role, more effect on the wear compare to the friction. That is why we say, that we are not agreeing with the definition of lubricant.

If, you see the definition of lubricant in a common English dictionary we say that substance which reduce the friction, but here we can take the substance. Which, we reduce the wear as per dominantly and the friction also. So, it reduces the friction as well as wear more emphasizes is given on the wear. You can see comparison here 3 percent and 10 percent production is ban 97 percent well, in this case reduction is by 90 percent.

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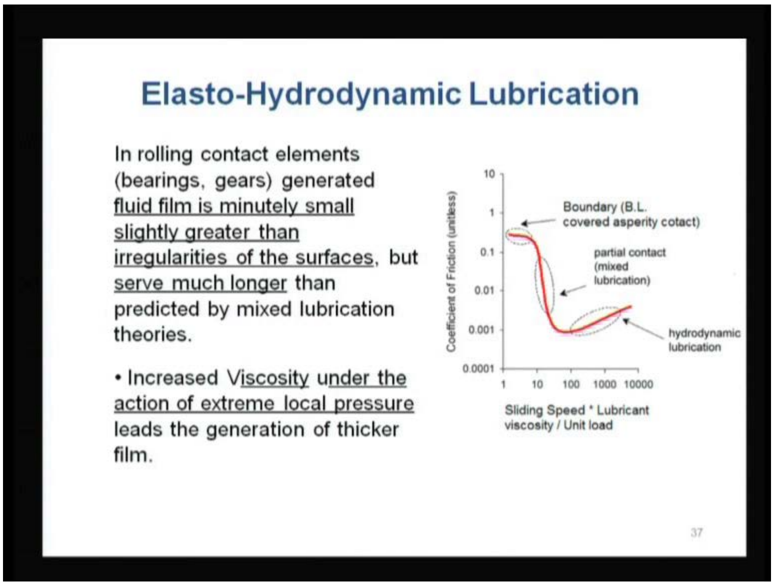


Another domain as I mentioned, in the mixed lubrication and hydrodynamic lubrication comes elasto hydrodynamic lubrication a few lines are written over here. We say that in rolling contact element, whatever the rolling action is happening. What we studied earlier that fatigue is the main wear of wear phenomena, in that case what will happen in fluid film will it not be very high, liquid lubricant film will not be dominating, and whatever theoretical analysis. Simple theoretical analysis will do what, we find in that case is something like. We get film thickness much lesser lesser magnitude.

But naturally case, when we do experiment; we found film thickness is greater side theoretically. We are not able to get the results. If, we go ahead simple with hydrodynamic lubrication mechanism how, we will be treating then in the next module. When we exclusively come up with equation theology equation, and elastic equation try to solve the equations. If, we do that whatever the if use only the hydrodynamic action then, film thickness will be much lesser, but in reality when we do experiment.

We find film thickness is greater than that or this is what, we are talking about that this domains somewhere here elasto hydrodynamic lubrication. It is not reaching to hydrodynamic lubrication bearing number is not, that high as a required for hydrodynamic lubrication 1 guess rough guess say that because of the high pressure.

Because of the high pressure, liquid to molecule will come closer and closer if molecules are coming closer and closer. They will give more and more resistance to the fluid flow a more resistance to fluid flow. That means viscosity is increasing effective viscosity is higher, in this cases that means if viscosity is higher from thickness will be higher. That is one good guess and a person was given he develop also relation.

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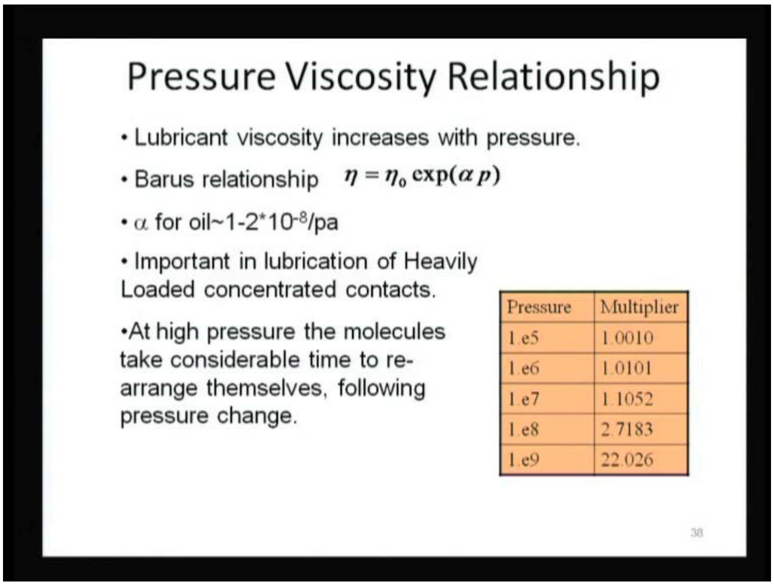


And, what we call as a barus relation barus relation says, that viscosity will increase with pressure and this exponential relation. There are number of other relations also was not not always such as coming to the same conclusion.

And, we are here to explore this lubricant regime. We are not going with strict trend is a more like learning and then, may be subsequently implementing according to that. What you say that, there is a alpha what we called as a pizza viscosa coefficient and that is generally expressed in terms of per unit Pascal for most of the liquid. There is well, range between one to two a mineral oil is 1 or synthetic oil, it will be slightly higher or if a some viscos thick oil is made be higher.

So, alpha have value of alpha means higher viscosity, at the high pressure to just elaborate that, that I given this table over here, we say that lets assume alpha is equal to 1 alpha is equal to 1 and increase the pressure pressure is only 10 is to 5 Pascal, that means ah this is a 1 10 is to minus 8 into 10 is to 5. That means it will be 10 is to minus 3 even 10 is to minus 3 the viscosity will be almost same as a eta 0, that is the ambient pressure that is what, we find the multiplication factor is 1.001 was a negligible is comparable to 1.

Now, we increase the pressure, but 10 times instead of atmosphere pressure. We increase pressure to 10 times, that is the almost 1 mega Pascal 1 one mega Pascal. We are able to see there is a increase in a viscosity by 1 percent. 1 percent increase in viscosity what, we say that this is a multiplication factor is a exponential alpha p is factor. That will instead of 1 it will be turn out to be 10.01, when the pressure is 10 bar. Now, pressure increase to the 100 bars, this factor turn out to be 1 0.1 that means 10 percent increase in viscosity instead of 100. It goes to 1000 again that means, 100 mega Pascal in case of 100 mega Pascal the sector as increased substantially it is coming out to be 2.7.

That means, there is a increase in viscosity by 1 100 seventy percent and that is thickening effect further. If, a goes in Giga Pascal when Giga Pascal even see the viscosity increase in twenty 2 times, and that is the reason given for the rolling element may be rolling element bearing of the gears. Whenever we required increase in viscosity, because the load is very high, and we do not want the lubricant turn out to be or quizzed , out of the lubrizol interface.

We want viscosity increase at that point and it as happen, because of the lubricant propagates self. We are increasing the viscosity tremulously from 1 to reaching to twenty 2 times 22 times increases the viscosity of course. It is a when the contact pressure is 1 Giga Pascal, which is not very uncommon contact pressure can reach to even 3 Giga Pascal, 4 Giga Pascal, because of very high loading. And, it is interesting to load that most of the load is shared by liquid in this situation.

What we say that, this is important this kind of fact is important. Whenever there is a heavily loaded concentrate contacts, and they down the each on the one problem comes. You say that even high pressure, it will take some time to rearrange the molecule. It will not be in spontaneous, it will not happen in 1 Nano cycle it may take few millisecond to the second to reach to that equilibrium. It will take some time that is why the effect may not be that dominating at what, we are showing their effect. If, it is happening talk talk about the example, of rolling element bearing it may take hardly 1 second or lesser than 1 second in a concentrate contact, and after that the boll goes out of the willing element goes out from the contact.

So, will not be able to reached to this effect. If, I may be fifty percent forty percent seventy percent depend on relative velocity, that means whenever we go for very high load bearing, should not be operate at very high sliding a speed. They should be operate that low sliding is speed, whenever there is a very high load under the those situation only this viscos viscosity increase will be substantial. If, we are operating very high load and very high speed then, this will not be dominating factor and for only friction of this factor will be factor. We should use some other relation, which can account velocity effect in that.

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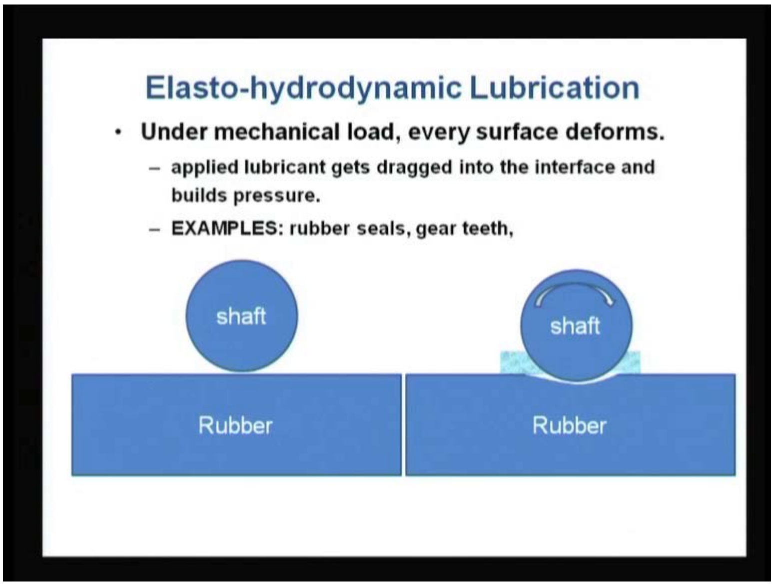


Now, some interesting thing about elasto hydrodynamic lubrication or some sort of mechanism, which can be purpose. What we say that under mechanical loads every surface deforms, there is a ban large true deformation may be nano level, but deformation will be sheared them. And, we say that if there is a deformation. There is a possibility of dragging that, lubricant into that interface. And, if there is a dragging of lubricant at the interface pressure will increase.

These are the common example for the rubber seals and rubber itself is the very soft even 10 mega Pascal can deform the rubber substantial level similarly, this kind of mechanism occur the gear teeth with the viscosity thickening effect occurs. Now, to illustrate that let us take 1 rubber material rubber sheet, and there is a shaft may be say assume a steel shaft. Which will not deform or is a young is module as a far far higher compare to rubber material. So, if there is load on the shaft deformation of the rubber will happen something like this. If, there is a deformation and if you pour the lubricant, because of the rotation lubricant will be will be brought into this this kind of interface. Which can return the lubricant some self, some time compare to straight surface it is making shape in a manner. So, it can act as a reservoir for lubricant that is helping us, but deformation and then further subsequent to that is a viscosity increase that both will act together.

And, then can give as a very favorable environment for the tribo interface with the friction will not go very high value, because there is a change. And, there is a change in film thickness itself, I am just trying to compare. When the shaft comes in a contact with rubber, they will not be any film thickness of liquid, but because of the rotation as well as a deformation of rubber. We are able to see some sort of interface here or some sort of film thickness over here, that is cause because of velocity deformation, and that was in previous slide. When we mentioned about effective film thickness will be larger side, what we can estimate from hydrodynamic lubrication. If, we are estimating hydrodynamic lubrication some x unit and because of the EHl, there is a possibility of 5 x film thickness increase in film thickness.

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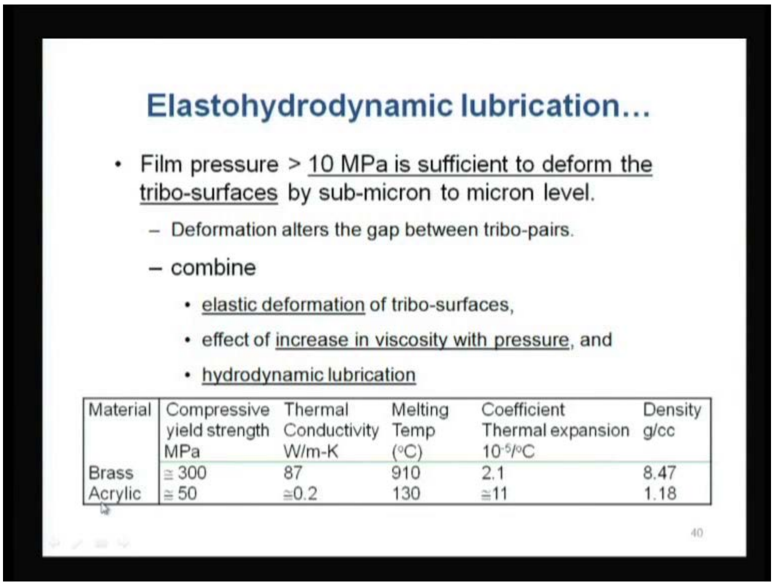


That is happening, because of the elastic deformation as well as because of the viscosity some conclude. Conclusion marks from the elasto hydrodynamic lubrication is a film pressure, even though 10 mega Pascal is sufficient to deform the surfaces to some micron to micron level. And, this is causing the alteration in the gap between tribo surfaces tribo pairs the gap is happening, because of that to analysis to come up with some results on elasto hydrodynamic lubrication. We can combine elastic deformation of tribo surfaces increase in viscosity as well as hydrodynamic lubrication.

So, we have treating in three ways first is that, we required elastic deformation. We required in increase in viscosity and we required hydrodynamic lubrication, but this says clearly, that the increase in viscosity from previous table were shown to us is that, the viscos pressure is not very high than. There is a possibility of increase in a viscosity, but not to greater level, but when we talk about something like 100 bar or 10 mega Pascal. We found increase in viscosity is only 10 percent is not very high percentage.

And in again, if there is a relative velocity effect, velocity is higher that means the rolling contact is not happening for the longer duration then, that because viscosity effect will not be dominating also. What we are hypocritically think about 10 percent, it may not turn out to be ten percent may be two percent three percent depend on the relative velocity. So, that may not happen a substantially, that is why we differentiate between elasto hydrodynamic lubrication.

What we call as soft E H l and hard E H l soft E H l means elastic deformation can be considered, but not viscose not viscosity, effect not viscosity thickening effect and other mechanism. what I talk about high p H l. where the viscosity as well as deformation need to be considered, both the surfaces are hard require substantial pressure to deform the surface.

If, surface pressure is very high than viscosity effect also will be dominating of course, to some extent it will be decrease, because of the velocity effect. Right Now, we did some cases study and in our la, what we picked up 2 bearings 1 is made of brass material other is made of acrylic acrylic is soft a surface. That can be also figure out from this 1 see compressive strength in the acrylic is a roughly fifty mega Pascal, what the brass is 300 mega Pascal compressive strength and there density acrylic as a very low density. So, that is advantages there are some factors which, we say the melting point of the acrylic is a lesser than 1 30. That means we should not apply to high ambient temperature or should not introduce too high ambient temperature.

Another, reason to avoid high temperature application is low thermal conductivity of acrylic material. Now, what we did we did experiment by making brass bearing and acrylic bearing 1 test item, what we can name as a journal bearing test item.

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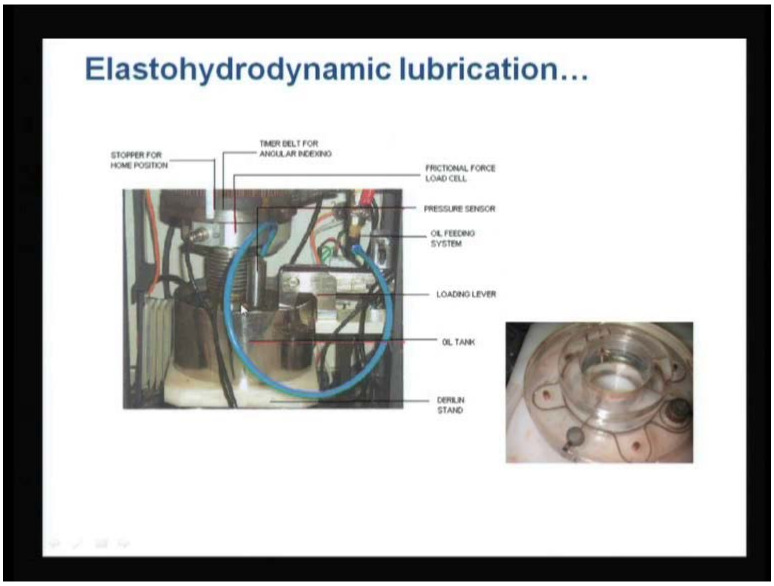


That looks like; something like this the journal bearing test item there is a bath. Where filled with lubricant that means, whole bearing will be some much and there is a bearing attach to this load same as bottom. This is brass bearing there is some load arrangement the load lever, we can apply load from 1 end it will be pushed with leverage mechanism on other end. We can regulate the speed of pressure sensor what, we have applied pressure sensor to measure the pressure of what is the pressure at the interface.

So, then we can find out whether they will be elastic deformation or not that is what pressure sensor comes and this bearing rotates. After, certain durations that can fixed as per the our whole algorithm at every 9 degree; it will rotate or at every 9 degree; it will change its position after certain duration may be say time t is equal to 0. It is as a 0 degree maybe after time t is equal to t even, it will rotate by 9 degree and again it will stop. So, that we can cover whole circumference to find out the pressure profile and this is the 1 brass bearing here. And similarly, bearing was a meet for the made of the acrylic material, which is soft a material having compressive strength on a fifty mega Pascal. Where come in this having compressive strength of film we say 300 mega Pascal.

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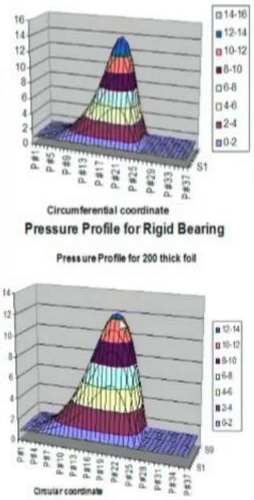
## Experimental study on soft & hard bearing materials

| Combination | Acrylic Bearing | | Brass Bearing | |
|---|---|---|---|---|
| | μ | $P_{max}$ Kpa | μ | $P_{max}$ kPa |
| 500rpm-300N | 0.0106 | 572 | 0.0296 | 696 |
| 500rpm-450N | 0.0069 | 655 | 0.0131 | 1013 |
| 500rpm-600N | 0.0042 | 1337 | 0.0105 | 1441 |
| 500rpm-750N | | 1331 | 0.011 | 1620 |
| 1000rpm-300N | 0.0179 | 717 | 0.0226 | 765 |
| 1000rpm-450N | 0.0124 | 1151 | 0.0206 | 1000 |
| 1000rpm-600N | 0.0111 | 1041 | 0.0249 | 1241 |
| 1000rpm-750N | 0.0102 | 1062 | 0.0223 | 1792 |
| 1500rpm-300N | 0.0362 | 772 | 0.1003 | 772 |
| 1500rpm-450N | 0.017 | 1007 | 0.027 | 1096 |
| 1500rpm-600N | 0.0065 | 1248 | 0.0257 | 1386 |
| 1500rpm-750N | 0.011 | 1345 | 0.0163 | 2565 |




Now, we compare the results when we comparing the results of a coefficient of friction and p maximum if p maximum. Which are occurred in an acrylic bearing and p maximum which are occurred in brass bearing both are in kilo Pascal's.

And may be of course, few places only it has reached to the mega Pascal, but acrylic material is a soft material. It will be deformed at the low contact pressure, itself few experiments what done in 500 r p m 1 thousand r p m and then 1500 r p m again the 4 kind of loads 300 neutron 450 neuter 600 neutron and 75 neutron coefficient of friction is not very dominating factor. In this case, it was happening at the decimal level as a second decimal is not be very important. What is the more important for us to find out the pressure maximum pressure, what we find the maximum pressure and first load situation first load and it is p situation, is around 572 kilo Pascal well that case this maximum pressure is 600 96 mega Pascal.

So, it is interesting thing is that material property is are playing important role in finding out, what will be the maximum pressure this is a good to learn from mechanical engineering point of view reason being many times in mechanical engineering. We design component and subsequently, we select the material based on the maximum pressure without thinking the maximum pressure itself. It will decide by the load component or material, which is getting deformed or we generally avoid the deformation.

And then calculate maximum pressure, well in reverse case or in reality or a practical situation deformation will change of maximum pressure volume. This is happening over here same load situation same speed condition, but maximum pressure. In this case, is happening around 696 mega kilo Pascal well, it is happening here may be say around 20 percent lesser and 572 Pascal?

Same situation of the as speed is capital same, but load is increase we can see from 572. It as reach to 39 to 31 as a 150 neutron meter well brass case, it is reaching to sixteen 170 kilo Pascal have we say 10.62 mega Pascal well in this 10.3 mega Pascal. So, again twenty five percent difference in maximum pressure, happening because of pressure. Now, if we increase the speed from 500 to 1000 pressure is increasing, which is a clear in hydrodynamic bearing cases increase. In speed will increase maximum pressure value it is a load carrying capacity will increase.

And, there will be pressure profile will be in the much lesser accident not much lesser as a lesser accident. So, in this situation what is the greeting and slowly slowly it is increasing and then subsequently decreasing in the elastic deformation case. Now, this is interesting to know here the surface is also getting deformed or surface is getting deformed.

It will flat in and if it is flattening the most of the surface not most of the surface reasonable surface will be having maximum pressure, it will not be any 1 point pressure but having surface pressure well, in this case it will be see able see that pressure as increase and is a increase to 1.8 mega Pascal.

Now, if you further increases speed from 1000 to 50 to 100 what we are able to get something like maximum pressure here as 10.3 mega Pascal well in case of the brass is standing out to be 20.6 mega Pascal 10.3 mega Pascal verses 20.6 mega Pascal. That is the interesting thing were brass, maximum pressure is going on higher side compare to acrylic material, because acrylic material is deforming and it is adjusting. It is that is the reason why, we say that elastic deformation should be considered. Whenever we are analyzing any practical situations if, the pressure is sufficient to deform bearing or deformed bearing asperities than factor, lubrication mechanism is a elasto hydrodynamic lubrication mechanism is not having hydrodynamic lubrication mechanism.

And, this is what I am trying to conclude present lecture with two graphs. We are showing here, in the this is more like for rigid case and this is for say elastically deforming surface even though material as same. If, the material thickness is roughly three mm material thickness is reaching slightly lesser lesser on 200 micron size. You can see clearly over here, there is a flattening and will elaborate this in our lecture elasto hydrodynamic lubrication mechanism. That means deal with number of mathematical equation thank you for your attention will continue next lecture with hydrodynamic lubrication mechanism thank you .