Friction and Wear of Materials: Principles and Case Studies
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Lecture – 5
Lubrication

This is the fifth lecture in the series.

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In this specific lecture I will be discussing some of the fundamentals of lubrication. I think in the beginning of this course, I have categorically mentioned that tribology is a subject which is being widely pursued by mechanical engineers and to much less extent by material scientist. In the mechanical engineering domain, significant research is also being conducted on lubrication aspects. So, lubrication is also a subject where mechanical engineers often interact with chemists or people from chemistry department to develop new lubricants.

I reiterate my statement in the very beginning that tribology is truly an interdisciplinary subject. So, it cuts across the mechanical engineering to material science to chemistry also. Also, some of the mathematicians they also work on the lubrications, particularly the lubrication involves the solution of many complex mathematical equations to find out the life of a lubricant, to find out the lubrication efficiency and so on. There also mathematicians play a big role.

Since this course is particularly main for the senior undergraduates and the graduate students primarily in the field of material science and also to some extent in mechanical engineering. The purpose of this lecture is not to get into a significant depth into lubrication but to discuss fundamentals of the lubrication, different type of lubrication, how the friction coefficient is reduced as a function of speed, sliding speed and so on what we call as Stribeck curve;

So, what is the qualitative description of the Stribeck curve? and how that curve tells you that how the friction coefficient varies in different lubrication regimes? Different lubrication regimes that is also important. So, all these aspects will constitute in this particular lecture on lubrication.

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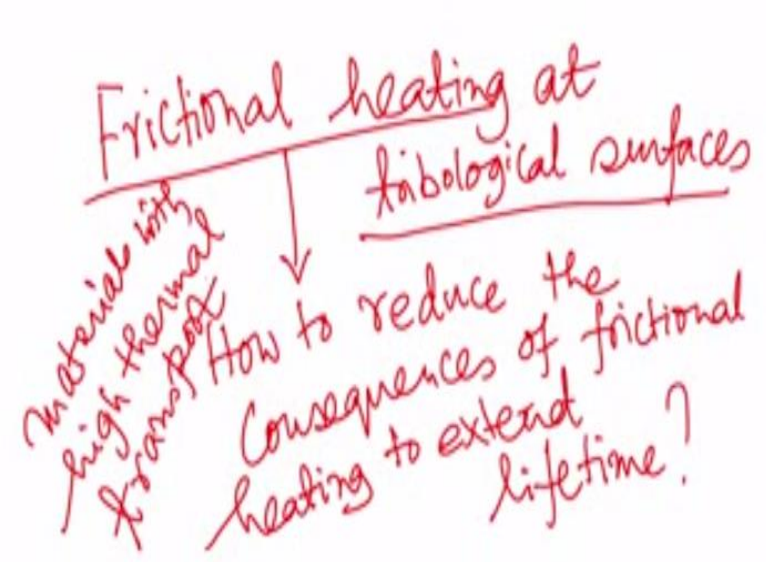

Now let us quickly recap. In the last lecture, I have told you that frictional heating at tribological surfaces. This frictional heating at tribological surfaces that is very important and it can be quantified using multiple formulas and multiple equations that I have shown in the last lecture. Now this frictional heating, the point is that how to reduce the consequences of frictional heating to extend lifetime? Lifetime extension is also very important for many machine structures and machine elements. So, there are 2 ways you can do from materials perspective, one can use materials with high thermal transport properties.

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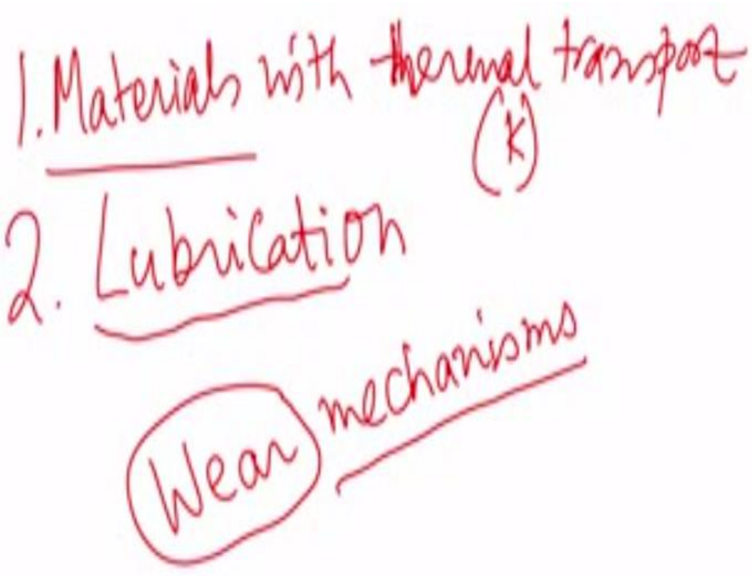

So, there are two scenarios I am trying to explain. One is using materials with high thermal properties. With high thermal transport properties means that thermal conductivity should be higher. So, this k value should be higher. So that heat is dissipated by more conduction. And number 2 is the use of lubrication. So, this option 1 essentially lies in the domain of material science and option 2 lies in the domain of mechanical engineers and chemists.

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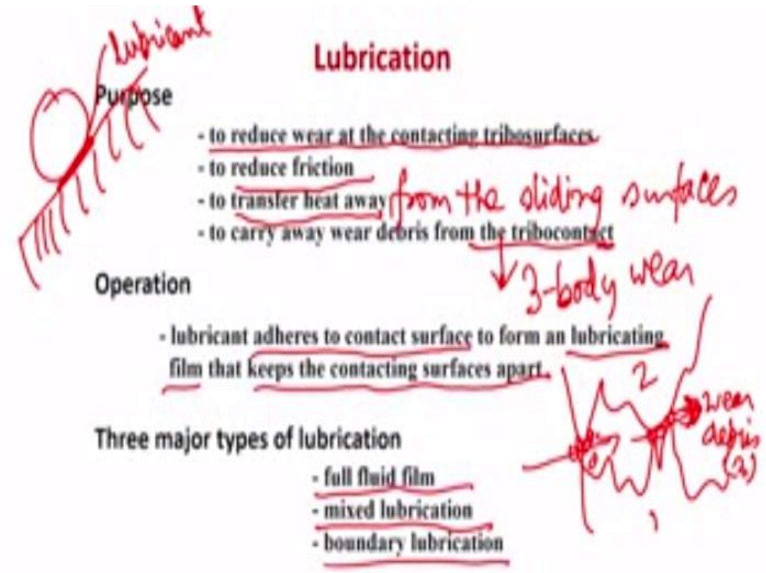

In this particular lecture, I will just describe that what are the very basics of the lubrication? Therefore, this slide actually connects my discussion with earlier two slides. The purpose of the lubrication is to reduce wear at the contacting tribosurfaces, to reduce friction and to transfer heat away from the sliding surfaces. In some cases when there is 3-body wear situation, 3-body wear means there are two fast bodies like mating solids 1 and 2 and there are debris particles. So, it is like 1 and then this is solid 1, this is solid 2.

If there are some debris particles, they are formed and they are getting entrapped. So, this is the wear debris particles. This wear debris particles in tribology literature, they constitute the third bod. This third body you can mention. You can see that how this third body can also take part in this wear phenomena. So, one of the purposes of lubrication is to flush away this third body, this wear debris particles from contacting surfaces.

So, what is the mechanism by which lubricants work? Lubricant essentially adheres to contact surface to form a lubricating film and that keeps the contacting surfaces apart. So, this is very important. Essentially if you have this is the first of two bodies; If this is your flat, now lubricants essentially make a film here. They make a film and this film is important that keeps these two bodies apart. Now, three major types of lubrication; one is full fluid film, second one is a mixed lubrication and third one is the boundary lubrication.

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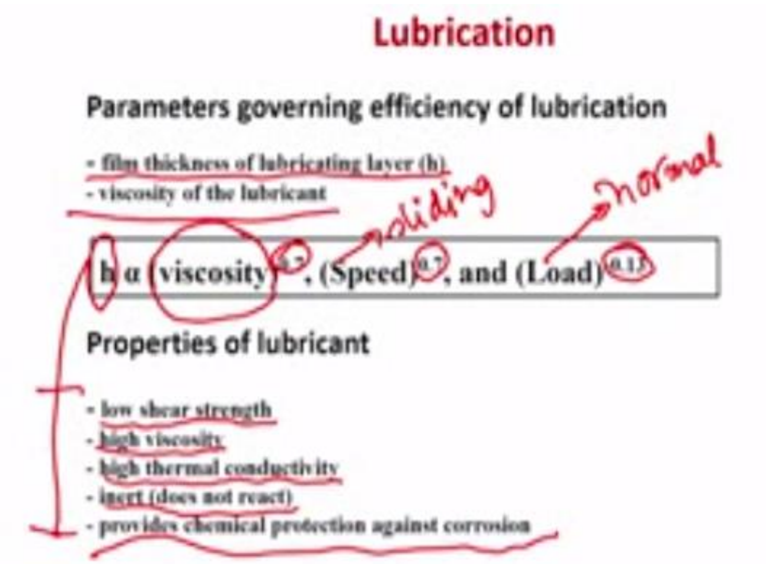

We will see all these different types of lubrication one by one in the next few slides. Parameters which govern the efficiency of lubrication: these actually depends on the film thickness of the lubricating layer h and viscosity of the lubricant. Now film thickness of the lubricating layer is h and this h depends on the viscosity$^{0.7}$. What is speed? speed is nothing but sliding speed $^{0.7}$. And what is load? load that is acting on, this is the normal load which acts on the tribological surfaces.

So, load you can see it is inversely propositional. But out of these what you see viscosity and speed is very strong influence 0.7 whereas load is little bit weaker dependence because it is

-0.13. From this expression you can very clearly see that lubricating film thickness would be higher for more viscous lubricant and also at higher sliding speeds. This is a very simple mathematical expression which can be correlated to find out what would be the lubricating film thickness.

In view of this particular equation, what are the properties of a lubricant? There are 5 properties I have mentioned. A good lubricant should have a low shear strength, it should have high viscosity, third one it should have high thermal conductivity, fourth one it should be inert and does not react and fifth one it provides chemical protection against corrosion. So, what it means is that suppose the 2 solids at the contact if they corrode each other, lubricant should stop this corrosion, should keep this protection.

A lubricant should not react with a material. So that tribochemical reaction should not happen. Why it should have a high thermal conductivity? If it has a thermal conductivity, then they can dissipate heat from the contacting surfaces. High viscosity means, if you look at this particular equation, higher the viscosity more would be h, more would be h means more would be film thickness, more would be film thickness means the 2 surfaces can be physically separated or 2 surfaces can mate physically apart from each other and that will reduce the friction and wear as well.

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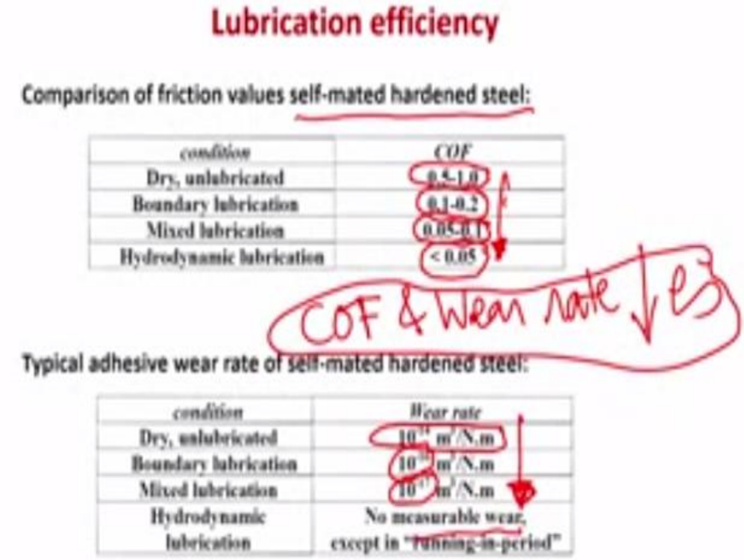

Just a comparison of the friction values of this typical lubricated and unlubricated conditions. Let us take the example of self-mated hardened steel. In the unlubricated conditions, it is 0.5 to 1. In the boundary lubrication, it goes down to 0.1 to 0.2. So, as you see that in the boundary lubrication, the coefficient of friction substantially reduced. In the mixed lubrication, it is even lower, it is 0.05 to 1. In hydrodynamic lubrication, it is even going down to 0.05.

The typical adhesive wear rate, as you can see the coefficient of friction goes down if you go from top to bottom. As you go from boundary to mixed to hydrodynamic lubrication, the coefficient of friction goes to even lower than 0.05. Now, how does the lubrication influence the wear rate of the similar metals? Let us say self-mated steel. This bottom table essentially shows you the order of magnitude of the wear rate. In tribology literature, it is not the exact value of the wear rate that is important but it is an order of magnitude that is important.

What you see here the first case that dry unlubricated condition, the wear rate is 10^{-14} m^3 /N.m, that is the wear rate. If it goes to boundary lubrication condition, two orders of magnitude lower 10^{-16} m^3 /N.m. If it goes to mixed lubrication, it goes to 10^{-17} m^3 /N.m and it goes to hydrodynamic lubrication, it says that no measurable wear. What it means is that wear rate is so small you cannot measure to any reliable manner by any experimental technique.

So, essentially it remains more or less flat, there is no wear on the surfaces. So, from both the things you can see that both the COF and wear rate that reduce. COF and wear rate systematically decrease as you go from boundary lubrication to mixed lubrication to hydrodynamic lubrication. So, this particular behavior it is more or less consistent in the case of the use of lubrication.

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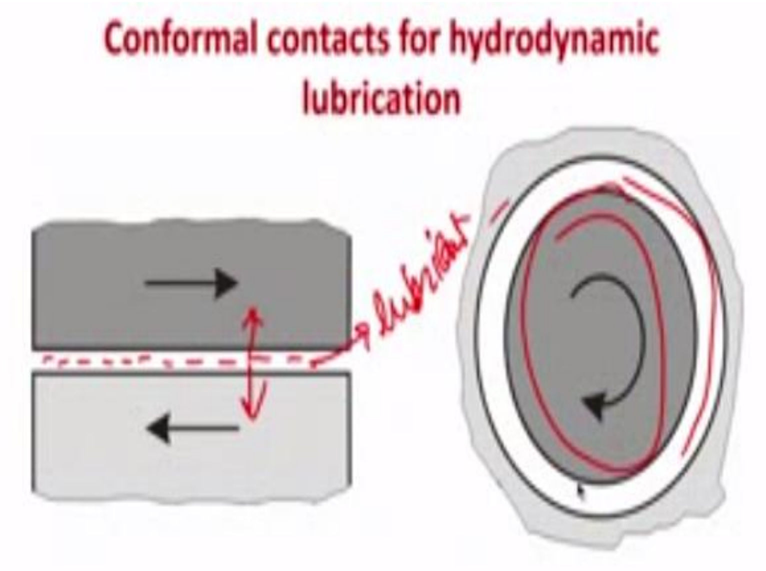

Now if you look at this hydrodynamic lubrication, there are conformal contacts. What you can see that two solids surfaces, they are in conformal contact with each other because essentially the surfaces, the two mating surfaces they conform to each other. Now if you put the lubrications here, this is the lubrication film or this is the lubricant here if you can use, then that will make this surface separate and this surface separate. Similarly, this is also conformal solid. So, these are two surfaces. One is rotating, and again there is very clear conformity and their hydrodynamic lubrication plays an important role.

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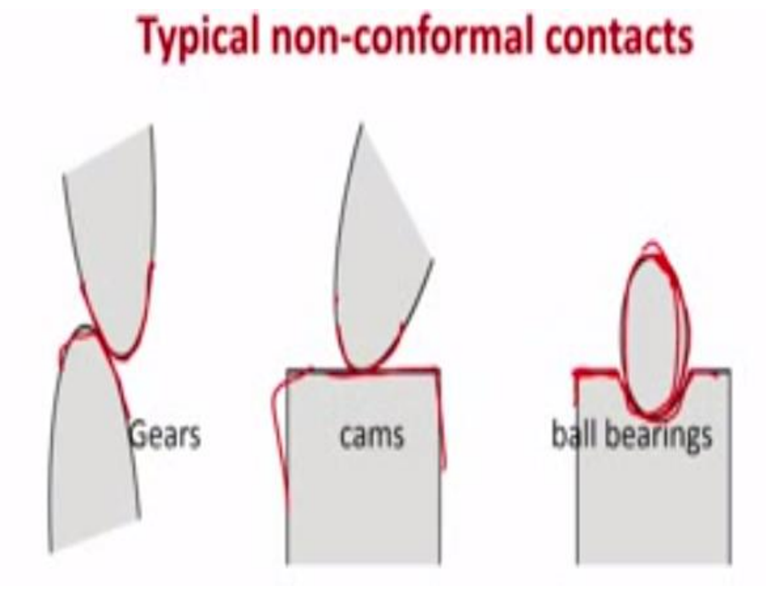

Typical non-conformal contact, for example gears. So, this is called gear tooth. So, these two teeth in the gears they essentially represent non-conformal contact. Here again cams. Again, it is a non-conformal contact. Ball bearings; This is one ball. In one of the earlier lectures, I have mentioned that one of the innovations that has happened in the field of ball bearings is called hybrid ball bearings like you have a metallic raceway and you have ceramic balls. Now ceramic balls can be either silicon nitride or sialon balls, which has a good wear resistance that is used as a ball and you have a metallic raceway that is a steel raceway.

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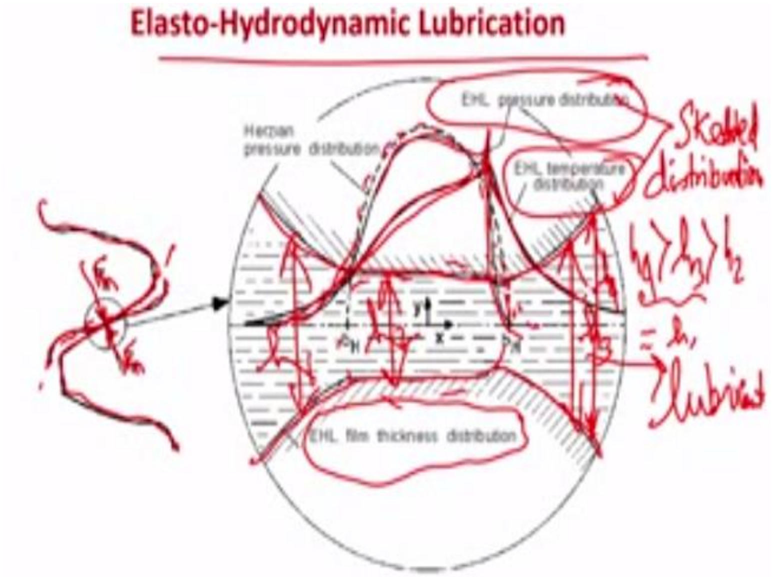

Now, comes to the elasto-hydrodynamic lubrication. If you look at these two non-conformal contacts, this is being blown up here. This is one tooth kind of things, gear tooth and this is another gear tooth. Now this is pressed against other. According to Newton's law every action has an equal and opposite reaction. If it is F_n here, it should be F_n from the other tooth also. Now, use lubricants here.

This lubricant will penetrate into the interface between the two teeth. And if you blow it up and see here in this particular lubrication regime, you can now solve some of the basic equations of the fundamental lubrication equations to find out that what is the elasto-hydrodynamic lubricant film thickness? and how it is distributed inter spatially? Like if you go from one end to another end, there are two things you can see here.

Essentially this surface would correspond to this particular surface and the bottom one corresponds to this one and this is your lubricant. This regime that we are operating is the elasto-hydrodynamic lubrication. So, there is Hertzian contact stress distribution which you have seen earlier that is modified in the presence of lubricant. And also, there is elasto-hydrodynamic lubricant pressure distribution because of the lubrication that how this elasto-hydrodynamic lubrication that is changing. And there is temperature distribution.

Temperature distribution it showed a very skewed. So, in both these elasto-hydrodynamic pressure distribution and elasto-hydrodynamic temperature distribution, you see it shows more skewed distribution. So, this skewed distribution is very clear from this non-conformal contact. However, Hertzian pressure distribution, it shows more symmetric distribution the way it is also expected.

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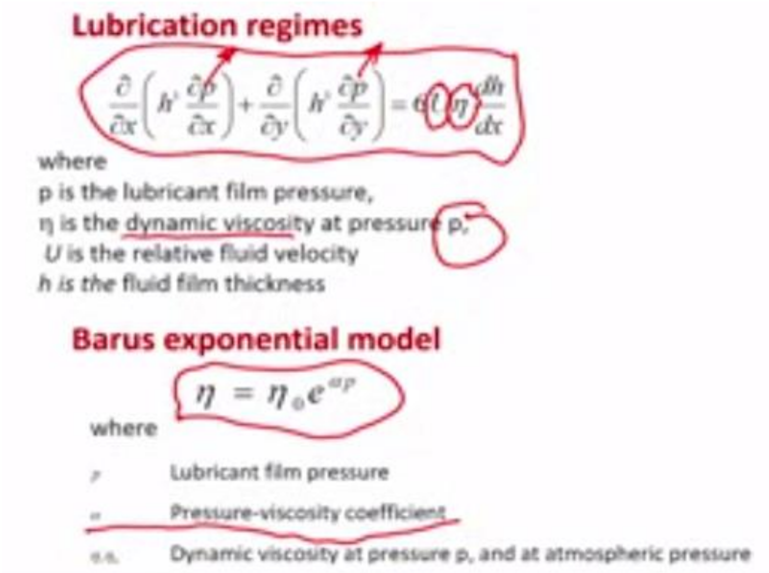

In this lubrication regimes, one of the fundamental equations that one has to solve is partial differential equation and what you see that is in the x, y coordinates; the Cartesian coordinates.

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(h^3\frac{\partial p}{\partial y}\right)=6U\eta\frac{dh}{dx}$$

h is your fluid film thickness. ∂p is your lubricant film pressure. This is not your Hertzian contact pressure remember. U is your relative fluid velocity, η is your dynamic viscosity, and dh/dx is that how the fluid film thickness that varies with respect to x.

(Video Starts: 18:34) What it means that, this fluid film thickness is h here. Now as you go here, fluid film thickness is reduced. But as you go here fluid film thickness again increases. So, if you see h_1, h_2, h_3, and if you say this is h_4, h_1 to h_4 this will increase. So, $h_4 > h_3 > h_2$ and may be h_4 to h_2 is more or less similar to h_1. So, this fluid film thickness how it is increases with respect to x that is also calculated. **(Video Ends: 19:12)**

So, if you solve this equation then you get the solution and then that would be very important and other point that you must notice here that eta is not a simple viscosity it is dynamic viscosity at pressure p. How this dynamic viscosity also changes with pressure? Now Barus exponential model tells you that

$$\eta = \eta_o e^{\propto p}$$

So, α is the pressure viscosity coefficient and η is your dynamic viscosity at atmospheric pressure that is p = 1 atmosphere.

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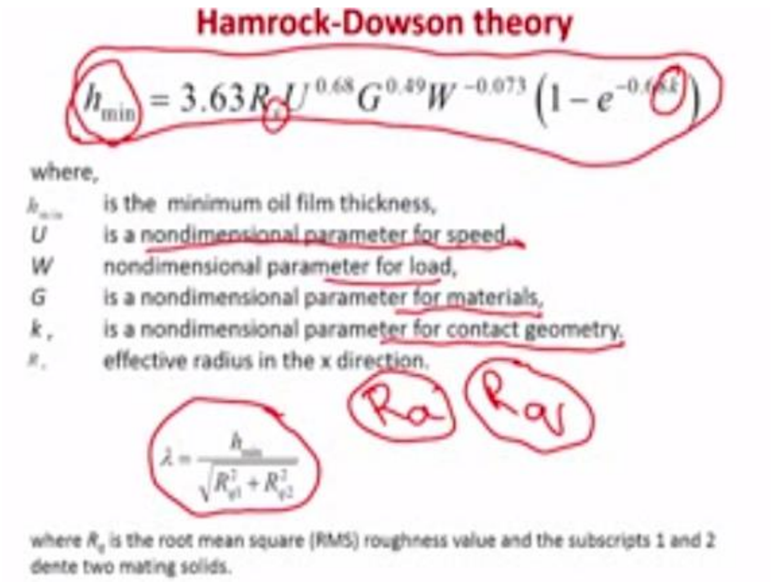

Now, all those things the equations that I have shown you in the very beginning of the last slide if you solve it with even boundary conditions then what you get minimum film thickness, minimum lubrication oil film thickness can be expressed by this particular equation.

$$h_{min} = 3.63 R_x U^{0.68} G^{0.49} W^{-0.073} (1 - e^{-0.68k})$$

R_x is the effective radius in the x direction, U is the nondimensional parameter for speed, G is nondimensional parameter for materials, W is your nondimensional parameter for load, and k is your nondimensional parameter for the contact geometry.

And you also see here R in the λ.

$$\lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

What is R_q? You remember in one of the lectures, I have told you about the R_a and R_q. R_a is your average surface roughness and R_q is the rms roughness. So, you have to take R_q here to calculate the value of λ which you have to put it in this particular equation. So, this will give you that what is a minimum oil film thickness.

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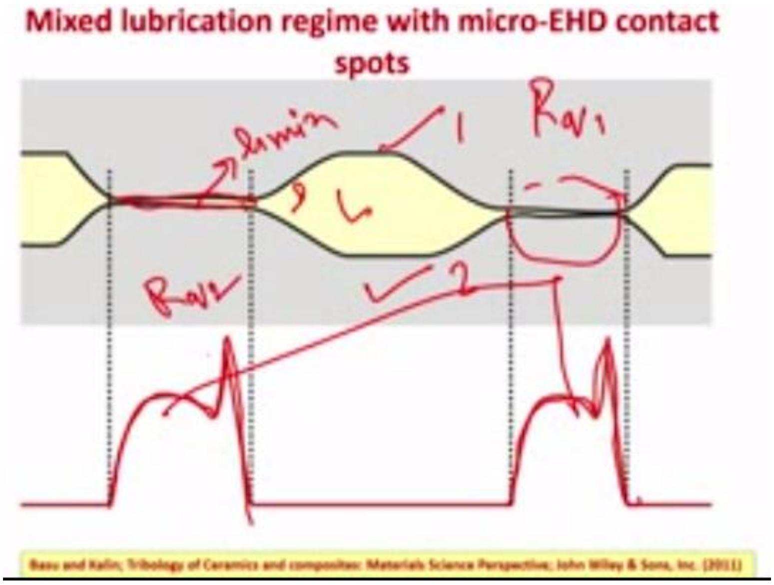

In the mixed lubrication regime, you will get a very interesting picture in terms of how the elasto-hydrodynamic pressure that goes through a transition? Now these are the 2 mating solids; two non-conformal contacts 1 and 2 and this is your lubrication L in the yellow marks. Now if you look at this particular contact region the way it goes, it is little bit tapered in this minus x direction and then pressure it goes through nonsymmetric manner it changes and it is repeated again in the fluid space in this particular region.

So, this behavior is kind of repeated and this is called elasto-hydrodynamic contact spots.

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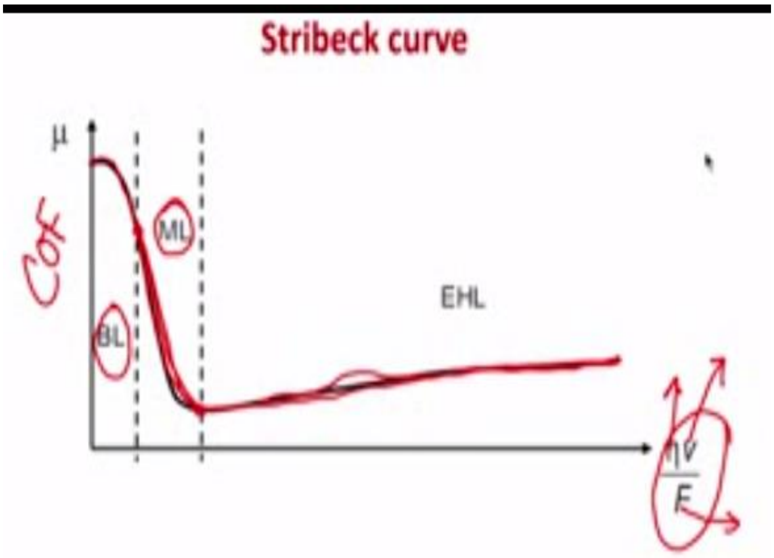

This is fairly important curve Stribeck curve. So, along the y axis it is the coefficient of friction that is being plotted and along the x axis it is plotted ηv/F. η is your viscosity, v is your sliding speed and F is your force. And then how this η value changes? η changes in a very nonlinear manner in the boundary layer. Boundary lubrication regime η drops to some extent, but this decrease in the boundary lubrication regime is much at lower extent compared to the mixed lubrication regime.

If you see, that decreases very significant and very substantial the way it goes down from boundary to mixed lubrication. In the elasto-hydrodynamic lubrication regime, the coefficient of friction does not increase to a much significant extent. It is more or less constant, but it increases to some miserable manner with parameters which are plotted around the x axis. For example, if the sliding velocity keeps on increases, so therefore ηv/F also increases but that will not cause significant increase in the coefficient of friction. That will cause only minimal increase in the coefficient of friction.

So, essentially low coefficient of friction will be maintained under a longer window or much larger window of the sliding speed in the elasto-hydrodynamic lubrication regime.

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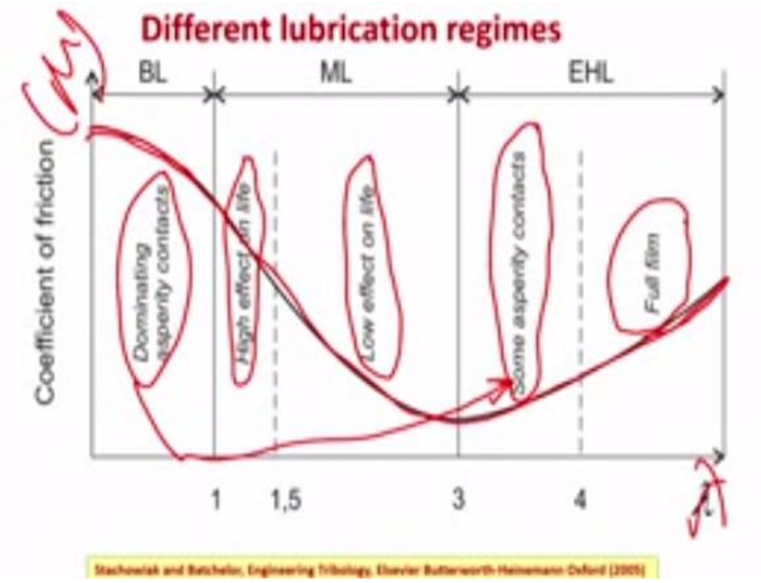

These other things that you know at the beginning of this lecture on the lubrication. I have also mentioned that this coefficient of friction not only is reduced in lubrication regime but also the wear rate is reduced. I have given you few examples for the self-mated hardened steel and then I have shown that how the orders of magnitude of the wear rate decreases in different lubrication regime. Now, what you see here coefficient of friction µis plotted against λ and what is λ?

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$$\lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

That means if it is R_{q1} here and if it is R_{q2} here and this is your h_{min} here. So, this h_{min} divided by the square root of these two terms would give you the λ value. And if you plot this coefficient of friction as a function of λ, again it shows a very nonlinear manner. It essentially decreases and that to significant extent **(Video Ends: 25:29)** followed by very small increase in the coefficient of friction in the elasto-hydrodynamic lubrication regime.

And in all those things what you see, the mechanism of the surface interaction also changes. For example, in the boundary lubrication, the asperity contacts; the interaction that will dominate. And in the mixed lubrication, it has a very high effect on the extension of the life. In the later part of the mixed lubrication that will have considered low effect. In the elasto-dynamic lubrication at least some asperity contacts, some means it is much lesser than this one. And in the later part of the elasto-hydrodynamic lubrication, it is full film. That means this lubricant film will be completely maintained and that will separate out the two mating solids from physical contact.

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So, this is one of the industrial examples like Four Ball Wear Tester to study the lubricants and this four-ball wear tester is very important to screen various commercial lubricants in the industry. So, what I am going to do in the next couple of lectures is that we will apply this particular knowledge that we have gained so far from the friction, wear, and lubrication. And then we will also now start with the next thing that is wear mechanisms.

So, wear mechanisms. The way this term is defined wear is the constant material removal from two contacting surfaces which are in relative motion. So, the whole spectrum of tribology is essentially the friction and wear of the two contacting surfaces in relative motion. So therefore, wear which involves the material removal that must takes place when the two solids are in relative motion that is absolutely important. Now, the other things as we go along the way that wear mechanisms and so on, we will also see that how the different materials can be developed.

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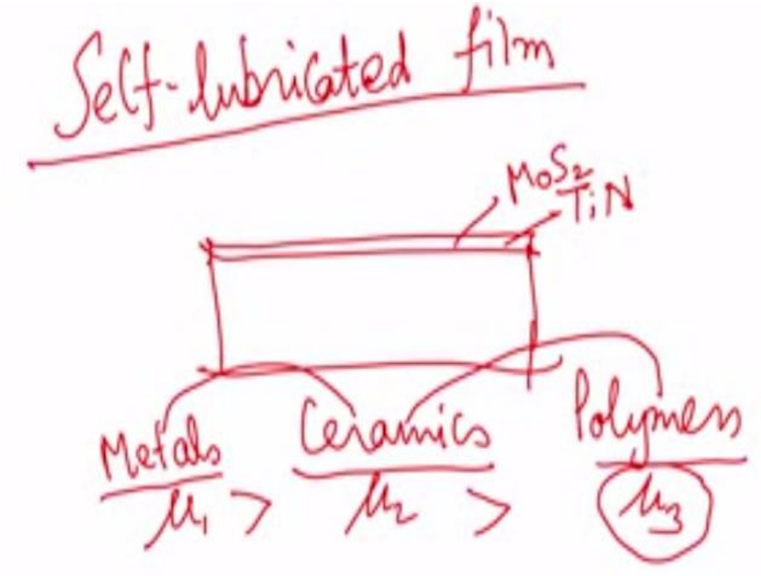

For example, I said the materials with high thermal conductivity or thermal transport properties. There is something called self-lubricating materials, self-lubricated film. Now this self-lubricated film, one of the approaches can be that you can use the self-bulk material. But on the bulk material you can deposit a thin layer of let us say titanium nitride just for example. So, this titanium nitride or you can use some MoS_2 (moly disulphide). These moly disulphide or titanium nitride coating can act as a lubricating layer.

So, there are plenty of examples I will explain to you later. But self-lubricated film often used in the application scenarios where you do not need to use a lubricant as such. So, without the lubricants you can use a self-lubricated film to realize or to achieve similar level of reduced coefficient of friction and similarly reduced wear rate which is important in the technological field. If you remember that three material classes, I have discussed earlier. one is called metals, another is called ceramics, and third one is called polymers.

And when they are used in the tribological contact, what you see here that ceramics and metals, they are different in terms of bonding and then also they are different in terms of elastic modulus. But in terms of the coefficient of friction; suppose it is μ_1, this is μ_2 and this is μ_3. So $\mu_1 > \mu_2 > \mu_3$. So, if you use the polymeric materials, often you can achieve the coefficient of friction which you can otherwise achieve in case of metals with boundary lubrication.

So, without boundary lubrication you can achieve similar level of coefficient of friction in case of polymers. So, we will deal with these most of the materials which are used for tribological applications and what are the different classes of new materials that are being developed with reduced friction and wear in the subsequent lectures of this NPTEL course. Thank you.