Video course on Tribology

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Lecture: 04

Friction Estimation

Welcome to fourth lecture of video course on Tribology. We are going to discuss on how to estimate friction with reliability, providing results as we get from experiments. In previous lecture we discussed three theories; adhesion, then plowing by conical theory and plowing by spherical asperity theory.

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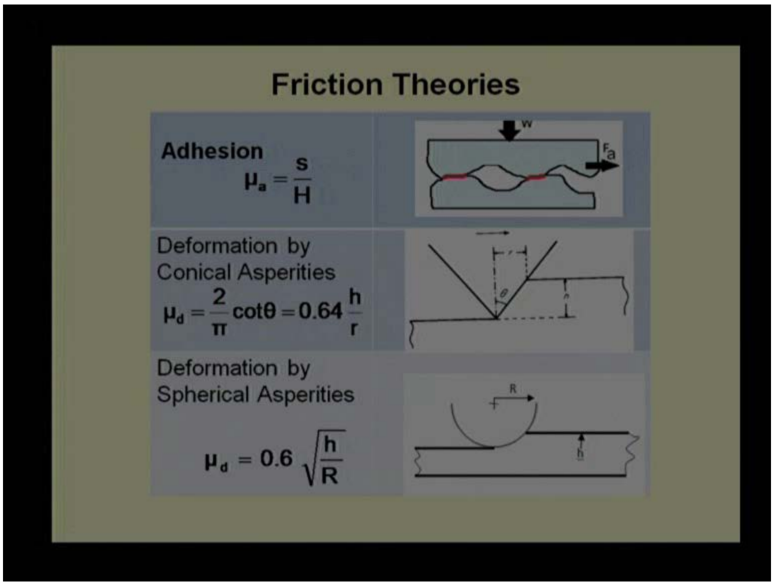

Friction Theories

Adhesion $\mu_a = \frac{s}{H}$

Deformation by Conical Asperities $\mu_d = \frac{2}{\pi}\cot\theta = 0.64\frac{h}{r}$

Deformation by Spherical Asperities $\mu_d = 0.6\sqrt{\frac{h}{R}}$

If we summarise those three theories what we get; in adhesion generally two surfaces get valid under pressure. That is why we call they these mode of friction as adhesion friction. In second and third it is a displacement of surface, displacement of material due to the asperities of hard material. And we develop mathematical relations for adhesion we say it is a ratio of shear strength to the hardness. Lower the shear the strength of material higher the higher hardness will provide lower coefficient of friction.

However, we discussed also what are the drawbacks that are mentioned that if same material has been used against a number of spheres this theory will provide same coefficient of friction for all material sphere which is not right. Then, we develop mathematical relation for friction by deformation or we say the conical asperity deformation deformation caused by conical asperity and we developed the relation as a 2 by pi into cot theta. It is a very sensitive relation and here the theta is a half angle half cone. If I simplify say the two divide by pi is equal to 0.063666 are the nearby 0.64 and express in terms of death or penetration and radius of the cone at interphone then I will get relation something like that 0.64 in to h divide by r. This is more or less same relation which we developed for spherical asperities. The same way mu d for spherical asperity was a 0.6 square root of h by r; r is a radius of spherical asperity.

So, there is a lot of symmetry between the second relation and third relation. Only thing is that, in second it is much more sensitive effect of h is much more dominant compared to effect which is shown in expression third deformation by asperity, a spherical asperity. In totality, all these three expressions are not providing very good results. That is why the (()) and Drabber who developed theory based on adhesion initially tried to modify it assuming that possible there is a possibility of this area to be extended or grow as we apply tangential force and other were friction force is going to increase area of contact. That was their hypothesis.

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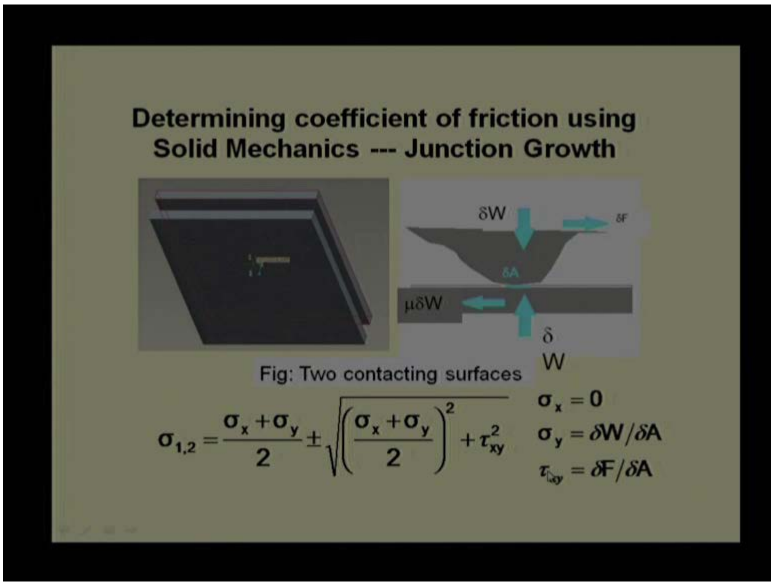

Determining coefficient of friction using Solid Mechanics --- Junction Growth

Fig: Two contacting surfaces

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x + \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

$\sigma_x = 0$

$\sigma_y = \delta W / \delta A$

$\tau_{xy} = \delta F / \delta A$

And then they tried to give some explanation, some derivation or mathematical derivation. To elaborate I am just taking these two spheres enouncing assuming both the spheres are of rough they come into contact only at the asperities. We can see there is a area of contact some force is been applied the normal force is been applied, some tangential force is been applied force equilibrium is shown in this element.

If I take a help of principle stresses or use a solid mechanics to drive the relation; what we can get principle stress one principal stress two is equal to average stress, stress in x direction and x stress in y direction plus minus plus will be for sigma one and minus will be for sigma two. Then this is the average plus there is a shear strength. If I simplify it we say that assume there is a normal load only in y direction and x direction there is no force then, sigma x will be zero sigma y will be the normal force divided by area or projected area while shear stress will be friction force divided by contact area. These are the simple expression. Difficult expression can be achieved, but, we want to find out initially or this is approximate relation which can give some results close to the experiment results.

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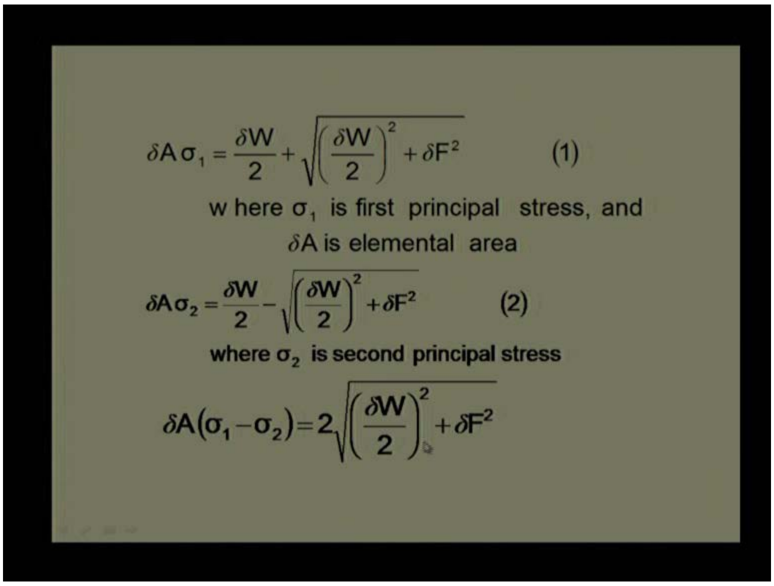

$$\delta A\sigma_1 = \frac{\delta W}{2} + \sqrt{\left(\frac{\delta W}{2}\right)^2 + \delta F^2} \qquad (1)$$

w here σ_1 is first principal stress, and

δA is elemental area

$$\delta A\sigma_2 = \frac{\delta W}{2} - \sqrt{\left(\frac{\delta W}{2}\right)^2 + \delta F^2} \qquad (2)$$

where σ_2 is second principal stress

$$\delta A(\sigma_1 - \sigma_2) = 2\sqrt{\left(\frac{\delta W}{2}\right)^2 + \delta F^2}$$

Now, if I use a expression sigma one with a plus sign and sigma two with a minus sign, I will be getting relations something like this and we know very well if we subtract expression two from expression one; I will be getting the difference in principle stress and that should be the minimum yield strength of the material which is supporting that kind of load or supporting the w load. So, you subtract and we get expression something like this you can see there is a normal force divided by two plus tangential force and this is sigma one minus sigma two which I am saying that this should be equal to a minimum value of yield strength should be equal to this. It can be more than that, but, minimum value should be like this.

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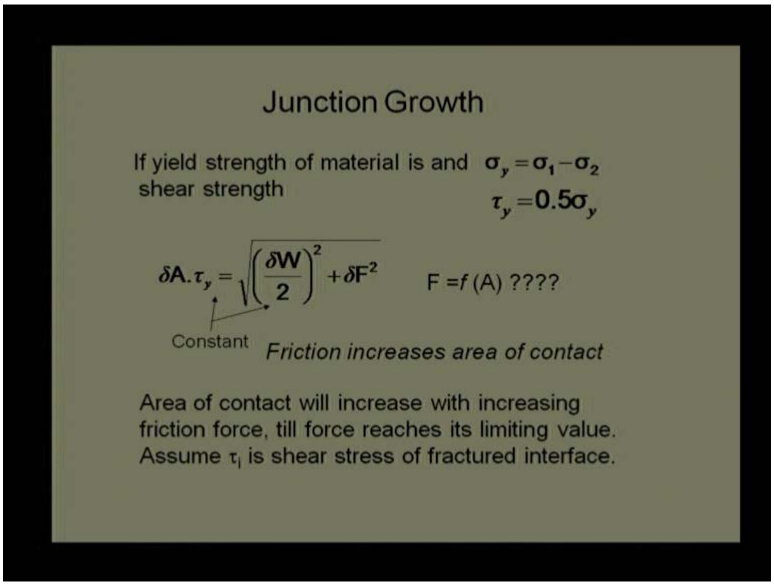

Junction Growth

If yield strength of material is and shear strength $\sigma_y = \sigma_1 - \sigma_2$

$\tau_y = 0.5\sigma_y$

$$\delta A.\tau_y = \sqrt{\left(\frac{\delta W}{2}\right)^2 + \delta F^2}$$

F = *f* (A) ????

Constant

Friction increases area of contact

Area of contact will increase with increasing friction force, till force reaches its limiting value. Assume τ_i is shear stress of fractured interface.

We can substitute those values sigma y is equal to sigma one minus sigma two and if I use a shear strength approximation we say that shear strength is generally fifty percent of yield strength. Depend on the which theory I am using or which component maximum shear stress or Tresca theory I am using. If the Tresca theory then this is will be the .577 sigma y while one might say that will be .75 .7577. While in case of Tresca theory it will be 50 percent of yield strength.

We substitute these values what we get expressions something like this as the area or elemental area into shear strength of material, expression for normal force or is fifty percent of normal force is square of that and then tangential force. For present case we are assuming the normal load is not going to change. It remains same. Material sphere is not going to change it remains same. What is the meaning of that this w and tau y is not going to change. So, this indicates if we increase value of f, value of a need to be increased to give reliable results or we can say friction force is a function of area of contact. Friction force is function of area of contact. With increase in a friction force area of contact will continuously increase. But, there will be a limiting value. Beyond certain area it cannot be increased further. If we can say the limiting value of e is equal to a max right.

So, it will reach to one level and to differentiate between the shear strengths we can say that, lets take a shear strength of a interphase and represent as a tau I where friction force or we say one surface will be getting separated from other surface. There will be a breakage of contact or breakage of cool welds which were made during the normal load or initial load. Then only the sliding will start. We can we can represent f as a tau I, shear strength of interphase into area of that is a limiting area a max. If we substitute those values what we get? Half limiting or our friction force is equal to tau I into area maximum area which can be developed, which can be grown to the maximum value.

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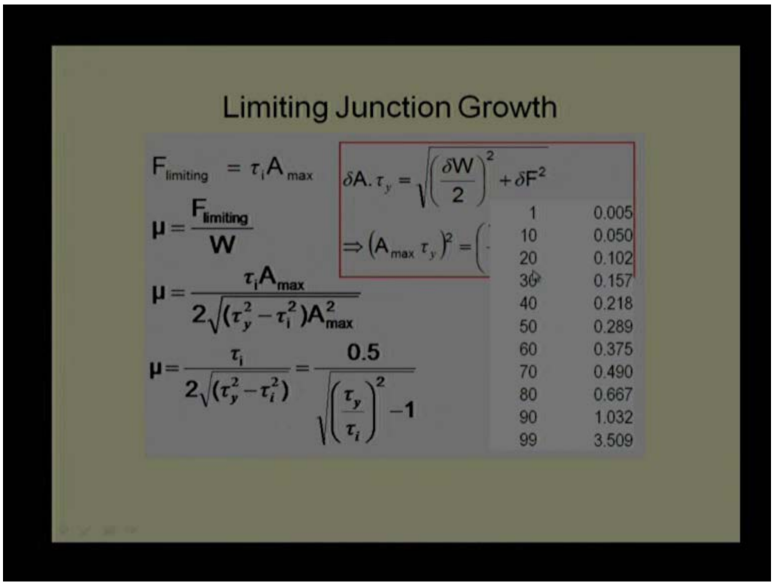

Limiting Junction Growth

$$F_{limiting} = \tau_i A_{max}$$

$$\mu = \frac{F_{limiting}}{W}$$

$$\mu = \frac{\tau_i A_{max}}{2\sqrt{(\tau_y^2 - \tau_i^2)A_{max}^2}}$$

$$\mu = \frac{\tau_i}{2\sqrt{(\tau_y^2 - \tau_i^2)}} = \frac{0.5}{\sqrt{\left(\frac{\tau_y}{\tau_i}\right)^2 - 1}}$$

$$\delta A.\tau_y = \sqrt{\left(\frac{\delta W}{2}\right)^2 + \delta F^2}$$

$$\Rightarrow (A_{max}\tau_y)^2 = ($$

1	0.005
10	0.050
20	0.102
30	0.157
40	0.218
50	0.289
60	0.375
70	0.490
80	0.667
90	1.032
99	3.509

And if I substitute these values in this expression which we derived in previous slide what we gave something like this; a max into tau y square the area is continuously increasingly, this normal force will remain same or term which contain the normal force will be the same. And last expression is a friction force. We can rearrange, we can find out the value of w from this what will be the maximum value which we can be applying or it can be applied on this interphase. And we know coefficient of friction can be represented as a friction force divided by normal load. I can substitute this tau I into a max over here and w after rearranging can be represented in this form, two square root of tau square tau y square minus tau I square in bracket and multiply with a max square. a max and this a max will cancel out and what we will get the expression in terms of shear strengths. Shear strength of the interphase shear strength of soft material that is the difference. We are saying that there is a difference.

If interphase is getting fractured at the value of shear strength of material then coefficient of friction will be very very high. However, if the shear strength of the interphase is very low, irrespective of what is the value of the tau I the coefficient of friction will be lesser and this is the reason why we provide lubricant. If we provide lubricant at the interphase shear strength of interphase will be almost negligible compared to the solid material strength. Just to get a feel of that we did some calculations. We say let us take a example the tau tau I by tau y this can be given in a some ratio.

Let us take a tau y tau I divided by tau y is one percent or .01. If with that is the case, if interfacial strength is just one percent of soft material shear strength, coefficient of friction is almost negligible. It is a .005. If we increase that to the ten percent, we say interphase is made in such a manner, interfacial strength is ten percent of soft material shear strength and coefficient of friction increases also ten times. Earlier it was .005, now here it is a .05. We further increase to 20 percent what we get? It is almost double from 10 to 20 is almost getting double from .05 to the .1.

Similarly, we can do more number of iterations and we come to the result. See when is a ninety nine percent, interfacial strength is a ninety nine percent of the bulk shear strength of soft material coefficient of friction is predicted as a 3.5 and this is very close to the what we got the result from experiments. Experimental result shows that they are two soft materials are used. Their interphase shear strength will be very high almost equal to the one of the weak material shear strength and coefficient of friction can be very high may be say 3 to 4 or 3.5 what we are getting from here right.

So, we can interpret our result, the stabile result in such a manner the ratio of shear strengths decide mu. It is not a absolute value of tau I or tau y. Decide the what will be the, what will be the coefficient of friction or what will be coefficient of friction due to adhesion. But, it is a ratio which decides if its strength interphase is strong and bulk material is also strong then, we will get a one kind of shear strength. If the interphase is weak; weak in the sense it having a cold junction, form cold junction then, again the shear strength of the material will be comparable to interphase again. The coefficient of friction will be very high.

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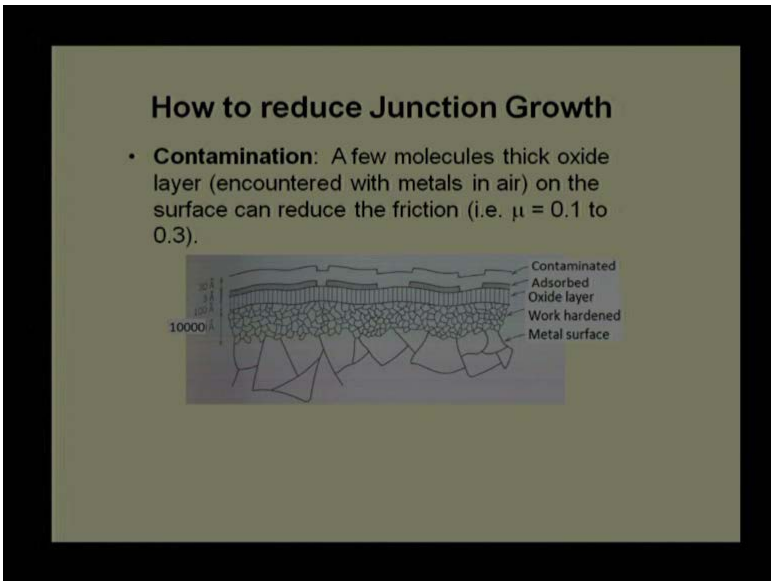

How to reduce Junction Growth

- **Contamination**: A few molecules thick oxide layer (encountered with metals in air) on the surface can reduce the friction (i.e. $\mu = 0.1$ to 0.3).

However, if I say in terms of strong interphase, strong in the terms it is related to material and it is attached firmly to the material or one layer which is firmly attached to the parent material in that case, there is a possibility of low interfacial shear strength. To elaborate that lets take one picture and see this is one of the soft, one of the material metal surface which has a work harden surface then oxide layer due to availability of oxygen and environment and some absorption, some contamination. And these layers are a very very thin. We are talking about the thirty Armstrong, that 100 Armstrong and in this case may be roughly ten micron.

So, when the material is a virgin, behaviour of the material will be different. If it is a work harden, if we say ten micron work hardening layer on that then its interfacial strength will change or interaction with other material will change. In that next one is that oxide layer if there is oxide layer may be say even hundred Armstrong, that can change the interfacial strength. In short these layer decide the behaviour of tribe surfaces. If all three layers, all four layers are removed from the surface then we will be getting very high coefficient of friction and in fact, it happens in the soft materials like a gold, indium they do not get the those many layers. However, in the steel chromium we can get a good number of layers, good, excite layers on the top of the surface and they prevent adhesion they make interphase, weak shear strength surface or shear strength of interphase is almost negligible in those cases. That is why we get a low coefficient of friction.

However, if we remove these layers coefficient of friction will increase. We can do this kind of experiment in the laboratory when the shaft is machined and if we immediately we try to run at the high speed, we will find there is a high coefficient of friction and complete welding on that. However, if we grease it and then run in bearing or a soft surface we will find coefficient of friction is much lesser. Reason being the lubricant layer or this layer has a thin or coat of thin layer on the shaft surface and reduce the interphase shear strength, that interphase shear strength compared to the bulk shear strength of a steel shaft and then we will get a good result.

And in this case, feasibly that if the surface roughness of the other surface may be say they are two surfaces and one surface has a coating this kind of layers and other surface has a high hardness with high surface roughness. This may damage the protective layer; that means, if surface roughness is very high there is a possibility of damaging those protective layers and increasing the coefficient of friction in those cases. We somehow do not want that kind of thing that is why we are always preferring low shear low surface roughness of the surface as well as some protective layer. In short adhesion theory which was tried using the junction growth is applicable along with asperity contact where the asperities need to be much lesser in size in height as well as in hardness. So, that they do not create cavities or ploughing effect on the soft surface.

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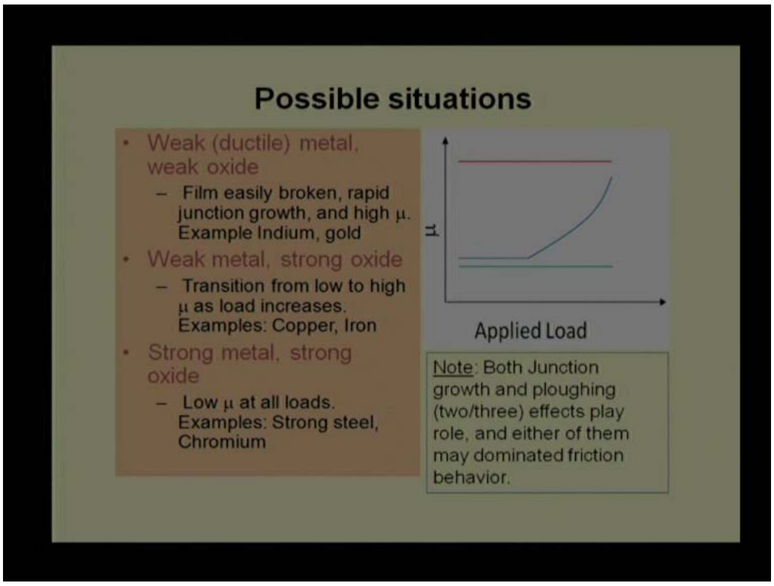

Possible situations

- Weak (ductile) metal, weak oxide
  - Film easily broken, rapid junction growth, and high μ. Example Indium, gold
- Weak metal, strong oxide
  - Transition from low to high μ as load increases. Examples: Copper, Iron
- Strong metal, strong oxide
  - Low μ at all loads. Examples: Strong steel, Chromium

Note: Both Junction growth and ploughing (two/three) effects play role, and either of them may dominated friction behavior.

I can think over some possible situations; we say that assume the metal is weak and oxide layer is weak. Here when we are talking about the weak oxide it is not in obsolesce, it is only relative sense. This layer attached with ductile material and strength of that layer over ductile material is low we are not talking any other thing that. This is the only attachment or adhesion to the parent material to the this ductile material is weak; that means, it will be simply removed or abutted or delaminated if there is a some surface roughness or some tangential force on applied by some harder surface.

So, what we are able to say in from that, the this film which is made as a weak oxide film it can be easily broken because in bonding to the parent material is much weaker and this kind of material with oxide weak oxide layer will undergo rapid junction growth. Result very high value of mu, high coefficient of friction. Couple of example on which belong to this category are indium, gold. Gold to gold we found a coefficient of friction very high. Indium to indium we found the coefficient of friction very high. Even if the indium versus gold will be having high coefficient of friction.

We can take another example we assume that there is a weak metal the shear strength is low. But, there is a strong oxide here a strong oxide is adhesion of oxide layer on the material exclusively that in that case what will happen initially there will be coefficient of friction will be very low or we say reasonably low value. After sometime if the interphase or rupture, interphase between the weak metal and oxide layer; we are not talking tribe sphere we are talking about the metal and oxide layer if that is rupture then there will be transition and that due to this transition coefficient of friction will increase drastically.

Examples are in this case are the copper and iron, we have found many times oxide layer on a iron and if it is a deform excessively it will be removed from the surface and coefficient of friction will suddenly increase. What we known at termed that as a transition load. The last which is a most most favourable is a strong metal and strong oxide both surfaces surface as well as oxide layer are firmly attached. They have a strong bounding or oxide layer has a strong bounding on metal. In that case what will happen irrespective of the loads because the strength of that bond is very high, all the loads it can sustain. I mean I say all the load in is there is a reasonable extent of region is not going to immediately rupture under slightly higher load or moderate load.

Example in for this category are this steel and chromium where they make a strong bounding with oxide layer or layer which is formed due to environment due to contamination that is a strong or bounding of that oxide layer is strong. If I plot this on the diagram what we say that this red colour line belongs to the first category that is a weak metal and weak oxide. While coming to second one the weak metal and a strong oxide can be plotted something like a blue line we say that there is a stationery or may be say initially cost and coefficient of friction and then there is a rupture of the layer and then that is why there is a sudden increase in coefficient of friction or finally, we say that the green colour line which is most favourable, we accept this is having a combination strong metal and strong oxide. That layer is always appreciated whenever we design any tribal sphere we should aim for this kind of layer so, that we can get low coefficient of friction. However, if we want high coefficient of friction then we can choose first case, but, in that case wear rate will be also very high and then we need to provide appropriate action or appropriate tools to get solution.

Now, this is a note finally, coming when the slide is a both junction growth and ploughing effects. Here why I use a word two and three? Two and three; that means, ploughing is generally occurred due to the two body and three body. When we are talking about two body is something asperities which are firmly attached to the surfaces and one if asperities and asperities are in coming into contact. When we are talking about the three body ploughing in that case we are assuming there are some debris at the interphase and that is creating some sort of ploughing effect. Let us take an example of the sand. If sand comes between the two soft materials then the sand particle will start ploughing or start digging either material one and material two.

So, that that will causes some frictional losses. We are talking that that the ploughing due to three body and when we are talking about only asperities the two body ploughing effect. They play important role and depend on the situation; either of these mechanism will play dominated role if there is no lubricant extra smooth surface, high high adhesion between the material sphere or high cohesion between the similar layer. Then coefficient of friction due to adhesion will be very very high and ploughing will be almost negligible

However if there is a partial lubricant adhesion component can be reduced to almost negligible level. But, because of a surface roughness there will be some ploughing effect and if there is a clear separation between two surfaces then the ploughing as well as adhesion will be negligible and then that can be treated as a full film lubrication which is not a topic in this category. We will be discussing that topic in later when we start film film lubrication mechanism.

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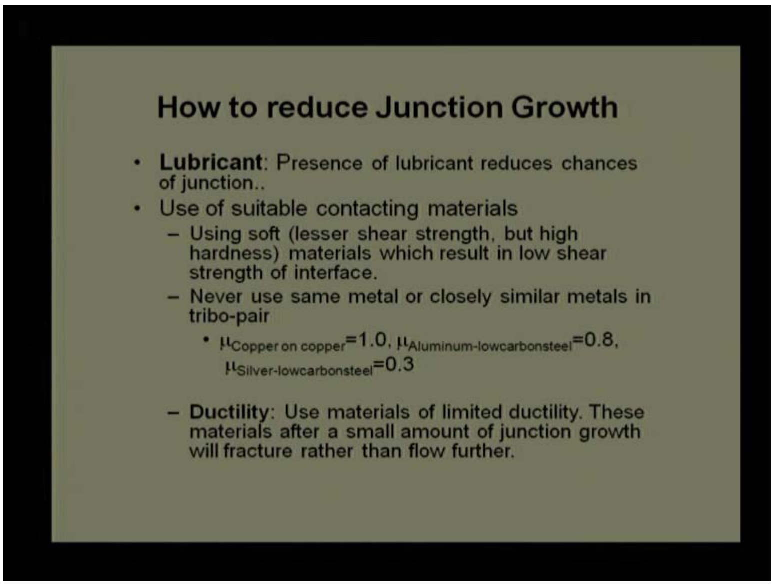

How to reduce Junction Growth

- **Lubricant**: Presence of lubricant reduces chances of junction..
- Use of suitable contacting materials
  - Using soft (lesser shear strength, but high hardness) materials which result in low shear strength of interface.
  - Never use same metal or closely similar metals in tribo-pair
    - $\mu_{\text{Copper on copper}}=1.0$, $\mu_{\text{Aluminum-lowcarbonsteel}}=0.8$, $\mu_{\text{Silver-lowcarbonsteel}}=0.3$
  - **Ductility**: Use materials of limited ductility. These materials after a small amount of junction growth will fracture rather than flow further.

Now, how to reduce a junction growth? Note it down few points few suggestions, not necessary everything will work in one situation, but, one of the suggestions will work to reduce the junction growth. Say if you want to really reduce the junction growth, do not think about the dry lubrication. Provide some sort of lubricant either powder lubrication, solid lubrication, semi solid lubrication or liquid lubrication which reduces the interfacial strength between two surfaces is fine, is something like when we play carom board. We use a powder lubrication, we provide a powder form similar kind of action which has a loose strength lower shear strength that will work on this.

And there is a possibility to choose appropriate material. We say that when you choose low soft material as a third material that it may provide as a low shear strength and that may work. That is why many a times we are using a molybdenum disulphide between the two contacting surfaces which has a very low shear strength. We can sustain the, molybdenum disulphide can sustain high compressive load, but, shear strength is negligible, shear planes will simply move unless some load. So, that is appreciated.

Next suggestion is that never use a same metal or metal which have a similar kind of chemical structure or they have a high molecular attraction. To explain this we can take example of copper or copper, the coefficient of friction is 1.0. Reason being if they are not this particular sphere are not oxidised and they are version materials they will come in a contact they will form cold conjunction unless shear force the junction will grow and finally, a limiting shear strength will come which is by and large equal to bulk material of copper or shear strength of copper itself.

Coming to the second spheres; aluminium with the low carbon steel again in this case the both material of soft material and when they make a junction that junction will grow under tangential load. Coefficient of fraction in that case will turn out to be .8. However, silver and the low carbonate steel is some good example here their shear strength their interfacial strength is relatively low and that is why they give low coefficient of friction.

Sometime we play with the ductility also. So, we say, we use this low ductile material which can easily rupture. Apply it slight force on that we can easily ruptured at the interphase and that will provide a low coefficient of friction. However, there is a problem if that rupture happens to be very rapid or it deteriorate the surface roughness then we should not use this kind of suggestion, we should use some sort of lubricant or many a times we use water to lubricate the surfaces.

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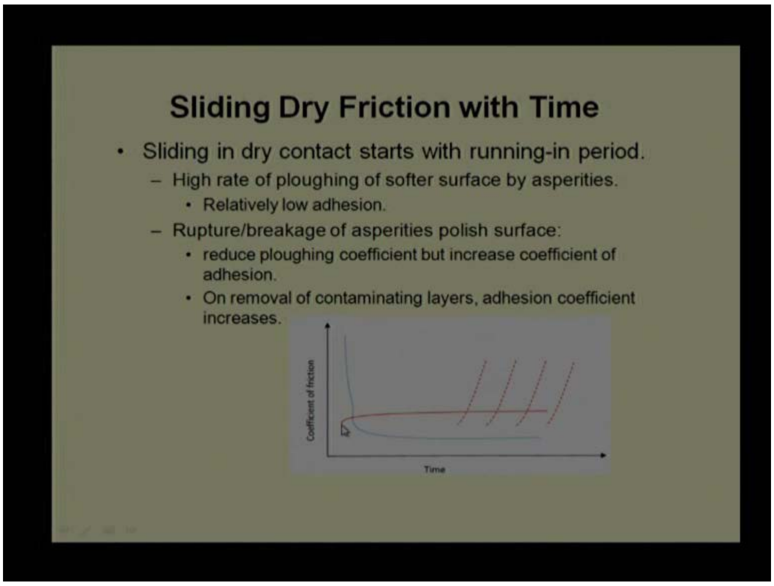

Sliding Dry Friction with Time

- Sliding in dry contact starts with running-in period.
  - High rate of ploughing of softer surface by asperities.
    - Relatively low adhesion.
  - Rupture/breakage of asperities polish surface:
    - reduce ploughing coefficient but increase coefficient of adhesion.
    - On removal of contaminating layers, adhesion coefficient increases.

And there is some observation which we got at the lab is that coefficient of friction is not necessary remain same throughout the time from the start of operation to the end of operation. Of course, we have already explained in the previous lecture what is the kinetic coefficient of friction and what is the dynamic and what is the static coefficient of friction. However there is a slight change in the terminology. Many times in a write in a book you find steady coefficient of friction. Steady coefficient of friction is equal to the kinetic coefficient of friction. What is the meaning of that? At the start there will be some coefficient of friction, but, that will change that will be different than steady coefficient of friction or kinetic coefficient of friction. So, there is a slight change in terminologies, a slight confusion in terminology. That is when we say steady coefficient of friction that is in the start before running in time.

When we see steady coefficient of friction; that is a kinetic coefficient of friction. It is going to happen during the working life of a component. Running in time we are not counting and remaining whatever the number of hours which that tribe pair can sustain that will show a steady nature of coefficient of friction. We are talking about that; however, there is a possibility of change in coefficient of friction even under steady running condition. What we say that when we are bringing two new surfaces, just fresh surfaces they will there will be higher ploughing effect at the start and relatively low adhesion. If the surfaces are unpolished the surface where having a super finish they are perfectly polished then possibilities will be high adhesion and low ploughing effect. But, we are talking about the normal manufacturing surfaces which have relatively high roughness. In that case ploughing effect will be very high initially compared to the adhesion.

And if this process continues there will be some rupture some breakage of the asperities. Due to that there will be a reduction in ploughing effect or coefficient of ploughing will decrease. But, this due to this there will be increase in coefficient of friction. Due to adhesion yeah more and more asperities are keep coming in contact due to rupture or we say that rupture of high level or high magnitude asperities is another possibilities the these wear debris come between the interphase and that will increase the coefficient of friction.

So, if I start again we say that initially two, as two body ploughing effect will be there subsequent to that there will be rupture of asperities wear debris will be at the interphase. There will be adhesion and increase in adhesion coefficient of friction because more and more asperities are coming into contact. So, there will be overall dynamics, few asperities will be ruptured. So, ploughing a fracture reduce few asperities more number of asperities will come in contact. Then adhesion coefficient will increase and few debris will come at the interphone and coefficient of friction should increase. That way there is a transition behaviour if I try to plot it.

So, ploughing effect initially I am showing going down with the rupture of asperities. After that it is reaching to the one dynamic situation by enlarge giving constant coefficient of friction. Here even though there is possibility of further rupture of asperities, but, those asperities there is a possibility that they will remain as a debris between the interphase. So, two body and three body overall will come to the equilibrium will give a steady value of coefficient of friction.

Coming to the second one; there is a red colour line. This red colour shows that adhesion will increase with a rupture of asperities more asperities will come in, will come into contact and there will be more and more junction formation, but, junction formation and junction rupture will be a continuous process. So, finally, they have to come to one equilibrium position that is why blue colour line and red colour line when we average will give us some steady behaviour. However, there is a problem. If situations are not under control; the speed is increasing suddenly, load is increasing suddenly then any of this line can terminate the component life any of this line will and the life of a component or which causes excess very high coefficient of friction.

So, that is why we are keeping this as imaginary lines. They depend on the load condition, they depend on the temperature, they depend on whether the lubricant layer was initially there and got was removed from the surface because of the starvation, because of pump failure, because of miss alignment or some other reasons. So, there is a possibility of this kind of hypothetical lines. It can be may be say similar to pairs. One pair can show life is starting coefficient of friction is decreasing, reaching in the steady state condition and then again coefficient of friction increasing at the component or similar component or similar material pair and at that condition you can show reaching to this condition moving to straight condition and finally, ends with this line.

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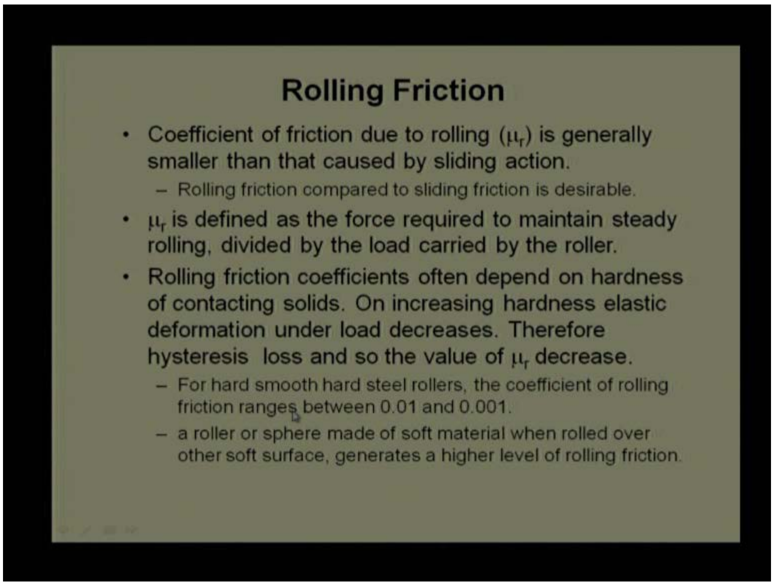

Rolling Friction

- Coefficient of friction due to rolling (μ_r) is generally smaller than that caused by sliding action.
  - Rolling friction compared to sliding friction is desirable.
- μ_r is defined as the force required to maintain steady rolling, divided by the load carried by the roller.
- Rolling friction coefficients often depend on hardness of contacting solids. On increasing hardness elastic deformation under load decreases. Therefore hysteresis loss and so the value of μ_r decrease.
  - For hard smooth hard steel rollers, the coefficient of rolling friction ranges between 0.01 and 0.001.
  - a roller or sphere made of soft material when rolled over other soft surface, generates a higher level of rolling friction.

Depends on environmental condition this line will be selected or there is a possibility or extended life or many times we get the infinite life. There is also possibility of infinite life. It will show coefficient of friction as a steady value throughout this life there is a possibility. We have been discussing about the sliding friction but there is another option what we call the rolling friction. From history we know very well that rolling friction is always preferred compared to sliding friction. What we say, as far as possible avoid sliding friction. Bring rolling friction into picture. You have heard about the sliding bearings are been replaced with the small small balls.

So, the coefficient of friction is steady and gives reliably low value and we can say coefficient of friction due to rolling that is represented here with a mu r is generally smaller than that caused by the sliding action. This is always desirable for machines. If I have choice I will prefer rolling friction compared to sliding friction if friction reduction is my main aim. So, that it can be defined as a ratio of forces also or it can be defined as a ratio of movements also. In this case we are assuming as a ratio of force the force required to maintain steady rolling divide by the load which is applied on the roller or tribe pair.

One of the interesting thing is that rolling coefficient or rolling friction coefficient depends on the hardness. So, there is a symmetry, there is a similar behaviour. Sliding friction also depends on hardness higher the hardness by enlarge higher the hardness; coefficient of friction will be lesser. Same behaviour is adopted or opted by the rolling coefficient of friction also higher the hardness lesser will be the coefficient of friction and reason behind this is that there is high hardness there is a lesser chance of what we say that magnitude of deformation will be lesser. Death or penetration will be lesser in that case.

So, if the death or penetration is lesser; there is a chance that material will show lesser stresses. If I think from stresses loop point of you from the loading and unloading point of you if materials have stresses behaviour, it does not regain its position without losing energy then coefficient of friction will be high. However, it gains the same position without losing much energy then coefficient of friction will be lesser. We have a couple of example we say that if we start with a hard steel roller or steel ball also, then if it is roll or on a flat surface or in convex or concave surface the coefficient of friction may be in the range of .01 to .001.

We are using the word here smooth; that means, surface roughness is not accounted. If the surface softness accounts then there will be surely some sliding on that. It will not be perfect rolling. And we are talking about the hardness. If the surface is hard, if the surface will turn out to be soft then there will be excessive deformation and due to that excessive deformation there will be loss due to and that will be counted as coefficient of friction. That is why in second line it is written a roller or sphere or the ball over here made of a soft material when rolled over other soft surface intended high level of coefficient of friction or rolling friction will be high. So, even resistance will be high in that case if the material pair is soft and strong.

If the hard material is a rolling over the hard material deformation will be lower. In that case coefficient of friction will also be lower. If I see the all mechanisms I can divide this coefficient of friction due to four mechanisms. We say that even under rolling condition there is a possibility of micro slip. Micro slip between the material pair, there is a possibility of elastic deformation, there is a possibility of plastic deformation and if there is a thermal change or behaviour change due to the temperature then again there will be coefficient of friction; so, four mechanisms.

But, we are assuming for time being that we are not going in a plastic domain. The plastic domain coefficient of friction is neglected in this case and there is a very low chance of micro slip, very low chance of excess of heating.

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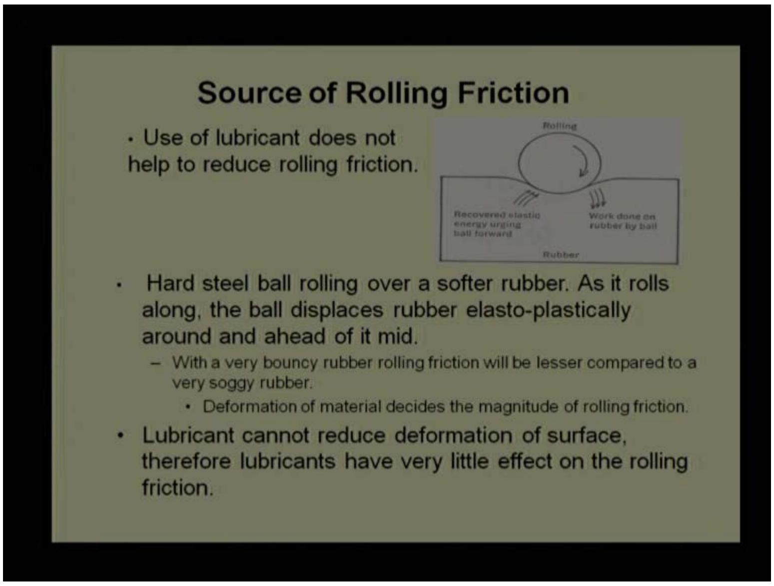

Source of Rolling Friction

- Use of lubricant does not help to reduce rolling friction.
- Hard steel ball rolling over a softer rubber. As it rolls along, the ball displaces rubber elasto-plastically around and ahead of it mid.
  - With a very bouncy rubber rolling friction will be lesser compared to a very soggy rubber.
    - Deformation of material decides the magnitude of rolling friction.
- Lubricant cannot reduce deformation of surface, therefore lubricants have very little effect on the rolling friction.

So, we will consider only the elastic case surface. Elastic itself is going to give coefficient of friction. So, to demonstrate that, there is diagram which shows that the roller rolling in clockwise direction. When it start rolling what it will be what happen to the material it will be going to the some pressure and if there is a rubber material then there will excess deformation of surface.

Now, what will happen if the surface is not straight, it is going under deformation? That means, a point contact is converting getting converted to the area contact or line contact is getting converted to the area contact. So, there is a substantial area of area contact in that that introduces some sort of micro slip then the as well as the stresses losses. In this case it is shown when it is relief at the backend if the recovered energy whatever has been given initially it has been recovered at the backside. But, due to rubber which has heat dissipation capabilities or heat absorption and capabilities or energy of the absorption capabilities; in that case energy will not be given back completely as some portion will be lost and that will cause a coefficient of friction.

Now, if I think from the lubricant point of you we are able to save the use of lubricant does not help to reduce rolling friction. In this case even when we are providing a lubricant. It does not help much there is no adhesion it is only the deformation and we know very well liquid by enlarge if it is very thin lubricant layer it will not completely separating then it will not change coefficient of friction, it will not absorb any deformation and the load which we are talking in the rolling contact generally very high compared to sliding contact. In that case lubricant layer really does not play much role if only elastic deformation is causing coefficient of friction.

So, this is what we will mention here hard steel rolling over soft rubber. That it rolls along the ball displaced rubber elastic plastically around. If I assume only elastic deformation then it will regain perfect shape. However, assume elastic plastic then there will be permanent deformation on the rubber material. For simplicity we generally assume load applied load is much lower than which can cause a plastic deformation. Now, depends on behaviour of the material whether it is a bouncy rubber. If it is a bouncy rubber it is not a soggy rubber, it is not going under plastic deformation what we say that apply load in such a manner it retains a bounce space on the rubber then coefficient of friction will be lesser.

However the soggy rubber which does not have a good molecular bounding and when it is subjected to deformation it gets that shape and if it is getting that shape the coefficient of friction will be high. They will not be energy returned back to the surface. So, we can say that deformation of material will decide the magnitude of rolling friction whether coefficient of friction will be high, coefficient of friction will be low that will can be decided by the material behaviour. If the material is made of good rubber or we say that rubber is made of the good ingredient. In that case coefficient of friction will be slightly lower compared to the simple period time rubbers.

And again the line is coming out here we say lubricant cannot reduce deformation of the surface. Therefore, lubricants have very little effect on the rolling friction. It will not be able to reduce coefficient of friction substantially at case.

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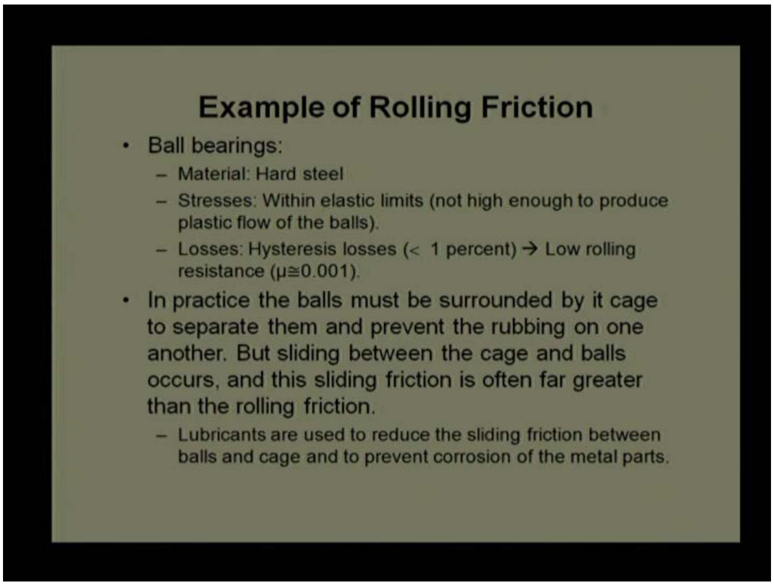

Example of Rolling Friction

- Ball bearings:
  - Material: Hard steel
  - Stresses: Within elastic limits (not high enough to produce plastic flow of the balls).
  - Losses: Hysteresis losses (< 1 percent) → Low rolling resistance ($\mu \cong 0.001$).
- In practice the balls must be surrounded by it cage to separate them and prevent the rubbing on one another. But sliding between the cage and balls occurs, and this sliding friction is often far greater than the rolling friction.
  - Lubricants are used to reduce the sliding friction between balls and cage and to prevent corrosion of the metal parts.

Now, we have number of expressions for the rolling element bearings or which define the, what will be the rolling friction. We will be discussing those detailed expressions when we deliver lecture or we discuss about the rolling element behaviours or rolling element bearing design and selection of the rolling element bearings that time will be discussing those detail expression.

However, I am just providing the two simple examples in on this slide is that ball bearing we are assuming they are made of the hardest steel. They are made intentionally with the hardest steel. So, the deformation is negligible. It can really roll harder, roll to sliding ratio is very very high. Now second assumption here we are seeing that which load which is applied is within elastic limits. It is not high enough to produce any plastic flow of the ball. There is no plastic deformation. What will happen in that case? If this is the situation with which we are providing, the hysteresis losses will be very low generally lesser than one percent. So, what will happen most of the cases? The coefficient of friction will be .01 to .001.

However, we know the rolling element bearings who have come through the cages, separators. We provide cage to separate the two rolling elements. Reason being if the one rolling element is disturbing other rolling element what we call the fully compliment bearings load carrying capacities will increase. But, there will be chances of more friction due to the rolling between two surfaces itself. It will start retarding each other motion and then it will get a high coefficient of friction at the interphase.

However to get a more uniform loading in that case, we are or we say that to keep separation between the rolling element, we provide a separator or cages and they have a much more area of contact with the rolling element. That is causing higher coefficient of friction at rolling element bearings. When sliding happens between the cage and the ball it will not be perfectly rolling, it will not be pure rolling, it will be rolling cum sliding then coefficient of friction naturally will be high. And if we do not provide any lubricant then coefficient of friction will be really high .2 to .3.

Here, we can say rolling and lubricant is playing a role because there is a sliding between the cage and rolling element providing lubricant has a meaning. It is a meaningful to reduce the coefficient of friction due to sliding. But, rolling lubricant otherwise cannot reduce the coefficient of friction due to perfect rolling or which is happening due to the elastic deformation and regaining it. The deformation, the only the rolling element play the deformation. Then lubricant cannot be used or we say that even if it is used it is going to create some churning lose it will be on the negative side. It will not give any benefit to us, but, it will give only drawbacks to us. First is that high cost of the lubricant then again churning losses and then displacing from the contacting pair which will happens is own. That is they will not be very clean surface. Lubricant cost as well as churning losses high friction losses.

So, we are providing lubricant in the rolling elements where does only elastic deformation and pure rolling will cause more problem compared to providing no lubricant or under deforming them under no lubrication conditions. So, we can say in short; whenever we are choosing lubricant we choose we need to see what kind of deformation mechanisms or whether the rolling or sliding is happening. If we are able to quantify sliding ratio if your able to say yeah sliding is thirty percent or sliding is fifty percent; then there is a meaning to provide lubricant otherwise not. So, is generally stated because otherwise when we see the definition or the friction we say that we require third substance to reduce coefficient of friction. While in this case third substance will create a more coefficient of friction.

So, providing more lubricant in that situation will be more problematic. So, we need to avoid that kind of situations. So, when we compare rolling element, rolling friction and sliding friction again I can say that we should always vote for the rolling friction as far as possible. However, there is a possibility of high stress concentration due to the rolling action which requires the special treatment of the material may be many times it turns out to be the costly compared to the simple sliding pair. Sliding pair will be economy economic and we required a short life or we required we are not caring about the friction loss or gear loss, we can go ahead the sliding pair. But, if we require d very high reliability definite life, definite fatigue life with high reliability that in that case we should prefer the rolling element or we should prefer the rolling friction compared to sliding friction.

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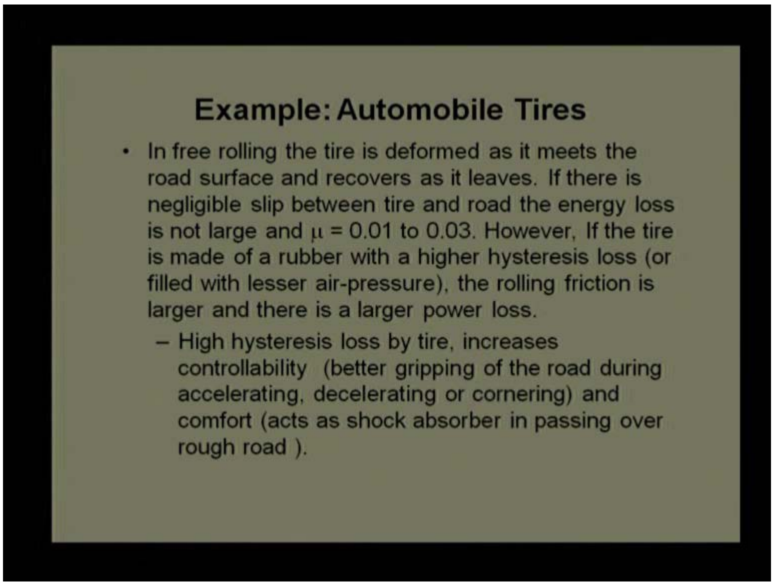

Example: Automobile Tires

- In free rolling the tire is deformed as it meets the road surface and recovers as it leaves. If there is negligible slip between tire and road the energy loss is not large and $\mu = 0.01$ to 0.03. However, If the tire is made of a rubber with a higher hysteresis loss (or filled with lesser air-pressure), the rolling friction is larger and there is a larger power loss.
  - High hysteresis loss by tire, increases controllability (better gripping of the road during accelerating, decelerating or cornering) and comfort (acts as shock absorber in passing over rough road).

In when we discuss the rolling friction; we are adding one more thing that when we take an example of tire. Then we need to see whether the tire is completely filled with air or not. When we drive car many times due to the lesser filling in filling of the tire, deformation of the tire will be excessive and that will cause high coefficient of friction, will lose will be losing that the petrol consumption or we say that when we travelling some kilometres per unit litre that will be lesser than tire having completely filled air or we say is completely filled air. That is why it is this slide show that in free rolling the tire is deformed or it meets the road surface. But, it recovers as it leaves it is deformed because of the nature of surface it is a rubber material and is filled with the air. So, it will deform to some extent, but, it will recover.

If we use a good tire material which has a low stresses analysis, low stresses then energy saving will be very high. We say that if there is a negligible slip between the tire and the road then energy loss will not be very large. That is roughly the estimation is given as the coefficient of friction of .01 to .03. However, if the rubber material is made or we say that tire is made of a rubber material having high stresses losses what will happen in that case? Elastic deformation will be very high. More than what we understand when the coefficient of friction was .01 to .03. Then in that case the rolling friction will be larger and power losses will be higher side.

So, even when we choose next time that tire for our car we should choose rubber tire which has lesser stresses. However, choosing that kind of a tire may create some problem what we say when hysteresis losses are lower is a perfect rolling then there will be some problem related to the steering of the vehicle. We say that high stress loss per tire increase the controllability. Slight deformation of the tire will help in controllability, will provide the right direction. But, if it is a perfect rolling then in that case we face some steering related problem or direction related problem. So, there should be a trade off. We should not have perfect rolling; there should be some deformation of the surface. So, that we have a good control on our vehicle

So, this is what we say that controllability means a better griping of the road during acceleration, deceleration or when we are taking any turn. That is required and in addition to that this deformation provides some sort of comfort. It acts like a spring action or maybe say that the part of a shock absorber. It is in does not transmit the odd all road unevenness to the passengers. So, from that angle, from comfort point of view we can that some elastic deformation needs to be there or rubber material need to have that kind of a deformation. It should not be very rigid it should not very solid otherwise the whole vibration of road whatever the road condition will directly get transmitted to the passenger who is sitting inside and it will not be very good option.

So, a balance to keep a low coefficient of friction there should be perfect rolling. To give good controllability good comfort there should be some good elastic deformation and whenever there is some elastic deformation, surely there will be some additional sliding or micro slip will be there and coefficient of friction even under rolling due to deformation will be high compared to perfect shape will be non deformation or we say rigid tire coefficient of friction.

With this I am closing today’s lecture and will be starting with related to friction instability, friction causes on instability in number of machines. We will be discussing in our next lecture. Thank you.