Friction and Wear of Materials: Principles and Case Studies
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Lecture – 3
Friction: Laws and Mechanisms

This is the third lecture in this NPTEL course on tribology of materials. In the first two lectures, I have covered the fundamentals of tribology and its impact on the nation's economy as well as industry. In the second lecture, I have covered that how to characterize the tribological surfaces, in terms of the surface roughness, R_a values and R_z values, and what are the different parameters on the basis of which that one can distinguish the various engineering surfaces, what is the rationale of using different parameters?

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In this particular lecture, I will be covering mostly on the friction laws and mechanisms.

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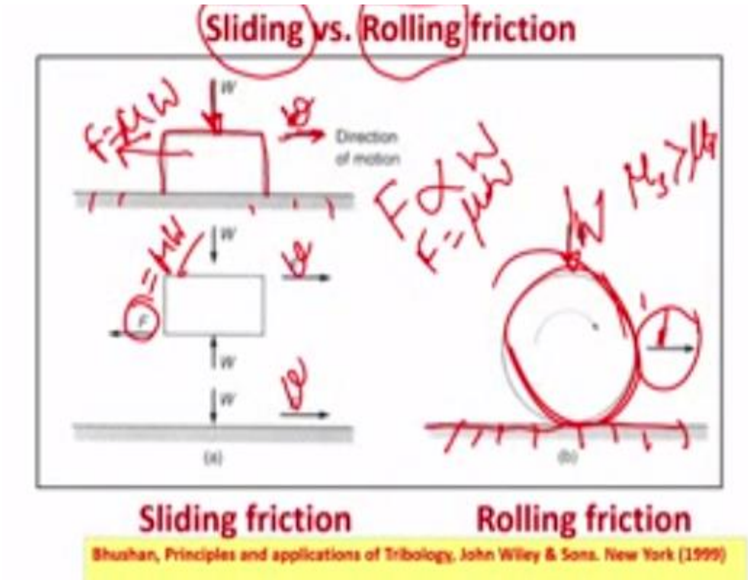

Let me start with this particular slide where I have shown very clearly the two major types of friction, one is the sliding friction and another is the rolling friction. What is the sliding friction? Sliding friction is that you have a one solid here and this is the nominally flat solid. So, this particular rectangular solid is being slid against the nominally flat surfaces. Once you pull it, the frictional force $F = \mu W$ would be acting on the opposite side.

This is the v that is the sliding direction of motion. Now, what you see from the sliding friction that F is proportional to W and that coefficient proportionality is called as coefficient of friction, that is μ. So, $F = \mu W$. For rolling friction, here again you apply the load W and your motion is this ball would be rolling, not sliding in contact with the flat surfaces and there will be frictional force that will be acting. So, rolling friction is much less.

So, if you say sliding friction is μ_s, μ_s is much larger than the rolling friction. Typically rolling friction is fairly less compared to that of the sliding friction.

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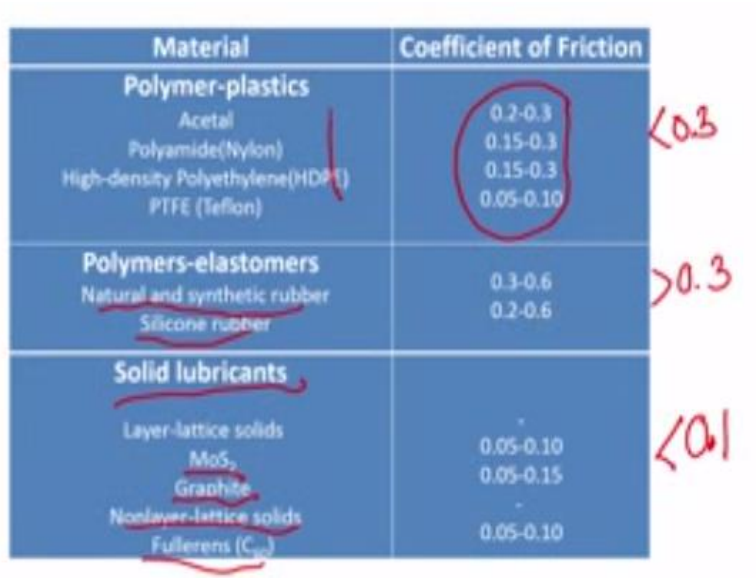

Material	Coefficient of Friction
Polymer-plastics	
Acetal	0.2-0.3
Polyamide(Nylon)	0.15-0.3
High-density Polyethylene(HDPE)	0.15-0.3
PTFE (Teflon)	0.05-0.10
Polymers-elastomers	
Natural and synthetic rubber	0.3-0.6
Silicone rubber	0.2-0.6
Solid lubricants	
Layer-lattice solids	-
MoS_2	0.05-0.10
Graphite	0.05-0.15
Nonlayer-lattice solids	-
Fullerens (C_{60})	0.05-0.10

Now this particular slide if you see, I have shown the different classes of materials. Now, if you know that there are 3 different classes of materials are there and these 3 classes of materials those were from nonmaterial background.

You know that there are 3 classes of materials and these classes of materials are as follows.

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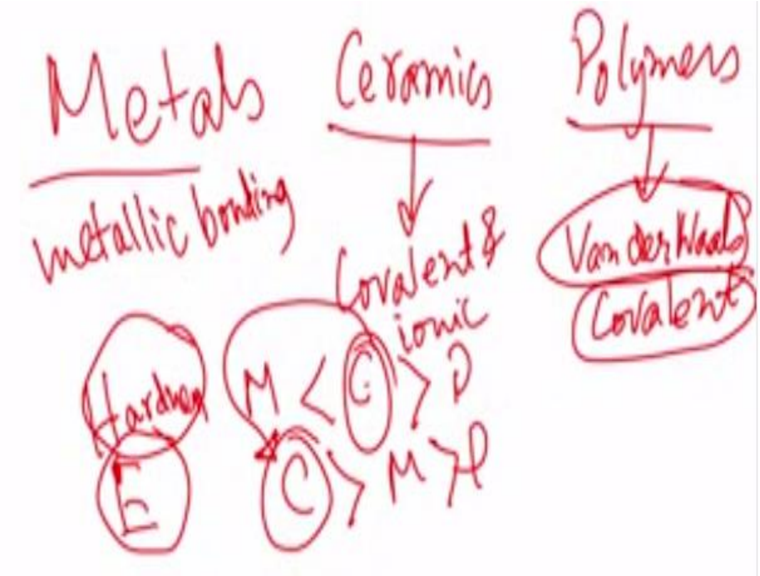

These materials are essentially metals, ceramics and polymers. So, all these 3 classes of materials are widely used in the tribological applications. But these metals, ceramics and polymers they are distinguished from each other by different properties. Metals typically have metallic bonding. So, this bonding wise these metals have different bonding compared to ceramics.

Ceramics are essentially covalent and ionic bounding and polymers across the chain they have a covalent bonds and Van der Waals bond. So, these metals, ceramics and polymers they are really distinguished from each other in terms of bonding. Now, if you look at this other parameter like hardness wise. Hardness wise metals are actually less than ceramics and ceramics is much greater than polymers. So, ceramics by far the harder material.

Now in terms of this elastic modulus, ceramics is greater than metals and metals is much greater than polymers. So elastic modulus wise ceramic by far has much higher elastic modulus. Hardness wise also ceramic has much higher hardness than metals and polymers. These are the some of the reasons that's why ceramics had attracted wider attention in the tribology community. Simply because, they have much better material properties than other counterparts, that is metals and polymers.

Now, the friction and wear does not depend only on hardness or elastic modulus, that also depends on the chemistry of the surfaces or chemical composition of the surfaces. So therefore, hardness or elastic modulus cannot be considered as the sole parameters for determining that what would be friction and wear of a particular mating couple. Now, coming back to this particular slide where I have shown the polymers like plastic like Acetal, polyamide nylon, high-density polyethylene, PTFE polytetrafluoroethylene.

If you see that these particular materials, they have a fairly low coefficient of friction and mostly it is less than 0.3. If you go to some of the elastomers like natural or synthetic rubber or silicone rubber, mostly it is greater than 0.3. If you go to solid lubricants like MoS_2 moly disulfide, graphite, fullerenes C_{60} and all, it is less than 0.1 mostly. On the top of it if you use lubricants together with solid lubricants, then even the friction coefficient would be much less. It would be less than even 0.1or something.

So, what you see that depending on the different composition of the polymers although their elastic modulus properties may be comparable in some cases, the coefficient of friction varies. But overall the coefficient of friction for polymers are certainly lower.

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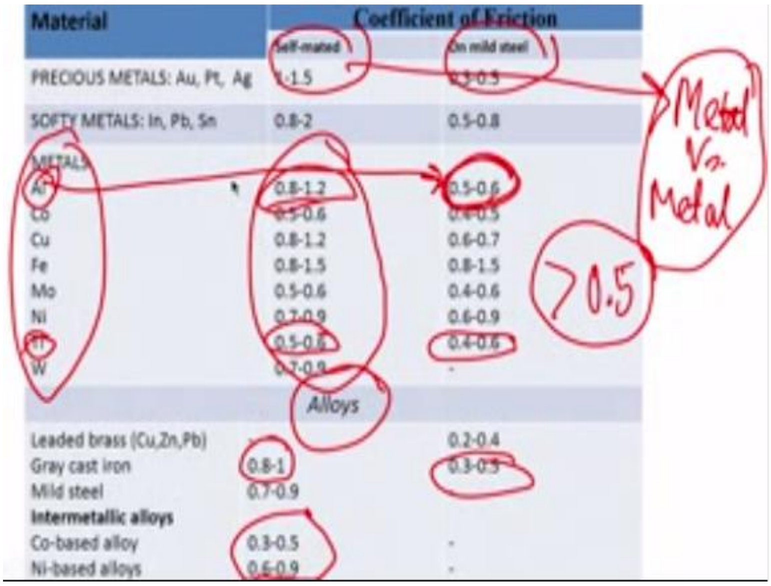

Material	Coefficient of Friction	
	Self-mated	On mild steel
PRECIOUS METALS: Au, Pt, Ag	1-1.5	0.3-0.5
SOFTY METALS: In, Pb, Sn	0.8-2	0.5-0.8
METALS		
Al	0.8-1.2	0.5-0.6
Co	0.5-0.6	0.4-0.5
Cu	0.8-1.2	0.6-0.7
Fe	0.8-1.5	0.8-1.5
Mo	0.5-0.6	0.4-0.6
Ni	0.7-0.9	0.6-0.9
Ti	0.5-0.6	0.4-0.6
W	0.7-0.9	-
Alloys		
Leaded brass (Cu,Zn,Pb)	-	0.2-0.4
Gray cast iron	0.8-1	0.3-0.5
Mild steel	0.7-0.9	
Intermetallic alloys		
Co-based alloy	0.3-0.5	-
Ni-based alloys	0.6-0.9	-

Now, if you look at the materials like metals like aluminum, cobalt, copper and all the metals typically in the self-mated condition, self-mated means the identical metal versus identical metal. So, two mating solids when they are identical in terms of composition and grades and so on, then we call it self-mated. On mild steel means for example aluminum against mild steel is 0.5 to 0.6. I mentioned in the very beginning or even in the first lecture that friction coefficient of stainless steel does not mean much unless you mention friction coefficient of stainless steel against what?

So, unless one mentions what is the mating solid, one cannot say what is the friction coefficient. So, from this particular table, 2 things that emerge. That for a same material coefficient of friction certainly varies when you change the other mating solids. For example, let us take the example of aluminum. In the self-mated conditions, aluminum's coefficient of friction is 0.8 to 1.2, but on mild steel - aluminum's coefficient of friction is 0.5 to 0.6.

Let us take the example of titanium. Why aluminum? Why titanium? Because aluminum and titanium, these are the alloys they are mostly used in various engineering applications from aerospace, defense and so on and so forth. Titanium, self-mated titanium is 0.5 to 0.6 whereas on mild steel it can be little lower it can go to 0.4. So overall if you compare the slide that I have shown the earlier and the slide I am showing with this present table, it is very clear to you that metals typically have more frictional coefficient or coefficient of friction is much more compared to polymers.

Polymers you can go down to even 0.1 or less than 0.1 where the metals are largely above 0.5. If you see the COF of the metals, it is mostly greater than 0.5. Some of the other things, the alloys. So again, those who are not coming from the metallurgy background.

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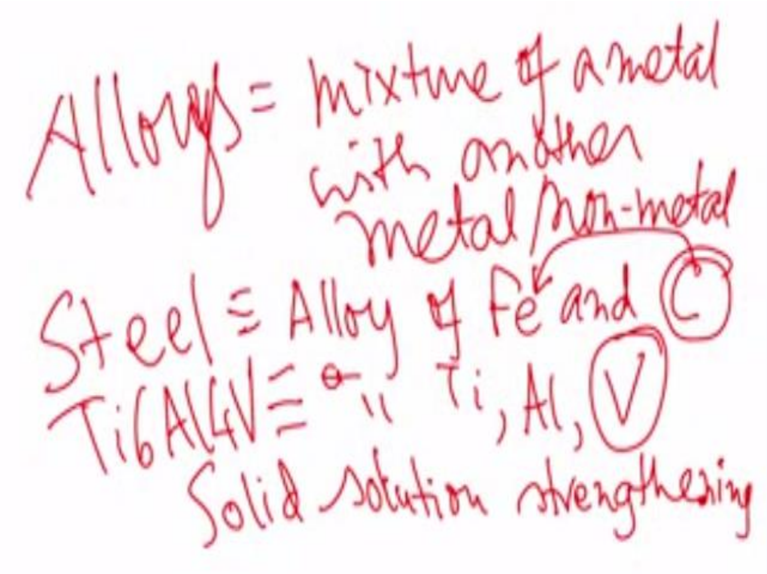

Alloys essentially means that mixture of two metals or mixture of a metal with another metal or a nonmetal. For example, steel. It is an alloy of iron (Fe) and carbon. So Ti6Al4V another material which is widely used in engineering applications. It is an alloy of titanium, aluminum and vanadium. So, alloy does not always mean that it is a mixture of two alloys. Alloy can be a metal and can be nonmetal. In this particular case nonmetal is carbon. So, all these alloying elements essentially serve certain purposes.

For example, in some of the metallic alloys, these alloying elements increase the strength of the materials. And this increase in strength is particularly due to the mechanism called solid solution strengthening. What is solid solution strengthening? Solid solution strengthening means that carbon goes into solid solution in the iron lattice, and therefore when it goes to such an iron lattice, it essentially restricts the dislocation motion and this dislocation motion essentially gives rise to ductility in the metal.

The moment the dislocation motion is restricted in any material, the strength of that particular material will go up or will increase. So that is the underlying mechanism as how solid solution strengthening increases the strength of any metal. Now let me go back to these alloys like you have leaded brass, copper zinc plate, or gray cast iron where coefficient of friction is 0.8 to 1 for the self-mated, but on mild steel it is less 0.3-0.5. Cobalt-based alloys, nickelbased alloys they are also very useful for various engineering applications. Here in the self-mated conditions, this coefficient of friction is 0.3 to 0.5 or 0.6 to 0.9.

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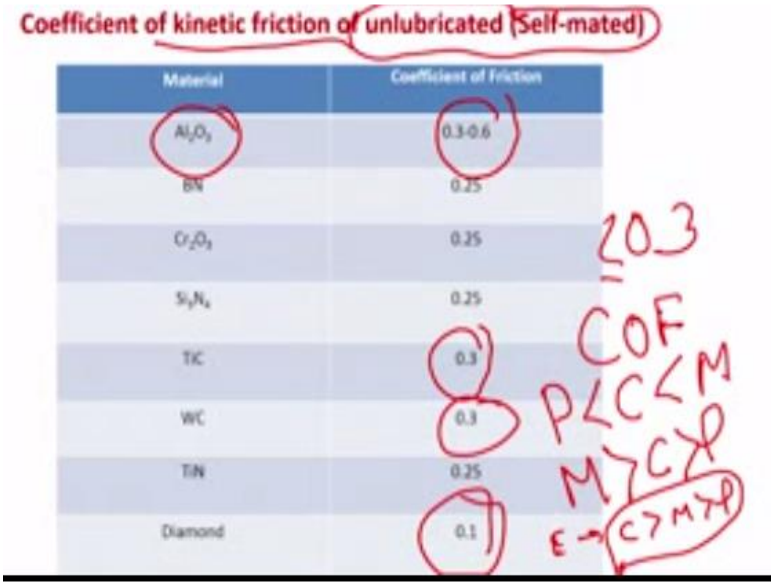

Now, other things that I have mentioned that there are three types of materials. one is metals, one is ceramics and one is polymers. So, you have already seen in last two slides how the polymers and metals, their coefficient of friction in the self-mated or against some mild steel varies. In this particular slide, what you are seeing is the unlubricated self-mated ceramic couples. what is the coefficient of kinetic friction? In case of alumina, it is point 0.3 to 0.6. In case of titanium carbide, it is 0.3. For diamond, it is 0.1.

So, diamond as you know it is one of the polymorphs of carbon. So, diamond and graphite are there. For Tungsten carbide, it is 0.3. So roughly, it is again less or equal to 0.3, that is a typical coefficient of friction of most of the ceramic materials. So again, if you rank in terms of the coefficient of friction, I think polymers is much less than ceramic and ceramic is less than metals or in other words metals coefficient of friction is much higher than ceramics than polymers.

So, it definitely does not have any correlation with the elastic modulus. Because if you go by elastic modulus, elastic modulus wise ceramic is higher than metal higher than polymer. So, it does not follow the same trend as elastic modulus. Although elastic modulus influences the contact pressure and other things as you have seen in the last lecture, but it does not have any direct correlation with that of the coefficient of friction.

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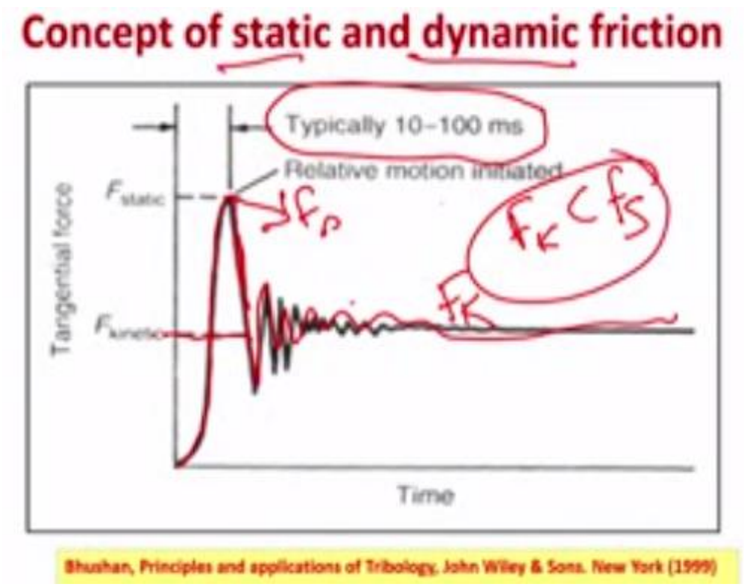

Here I am introducing two different terms, one is called static and another is called kinetic friction. What is static friction? Like you know if you start any sliding experiments, initially the friction force goes very high up and then it goes down, then it goes to steady state friction. So, this is your steady state friction and this is called kinetic frictional force F_k and this is called static frictional force F_s.

Now typically, the static frictional force is limited to 10 to 100 milliseconds and here relative motion is initiated and this kinetic friction that goes down, so typically kinetic friction is less than that of the static friction.

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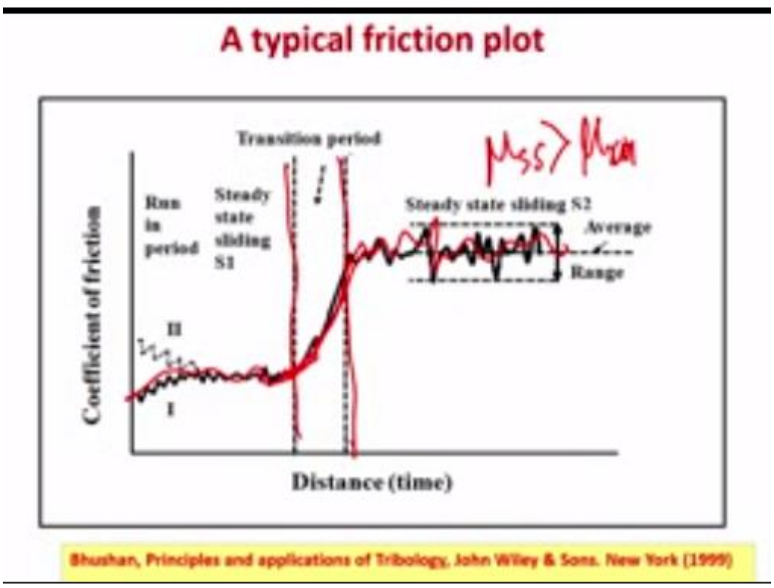

Now a typical frictional force to frictional plot, I will show you at least 3 to 4 different frictional forces and I will try to explain that how this frictional force varies? Now initially this frictional force here it is typically low, then it goes up, then it goes to steady state sliding conditions. And if you see this steady state sliding condition, there is a transition. So, transition is that it goes from low to high frictional force. Here steady state coefficient of friction μ_{ss} is greater than that is the μ running in period.

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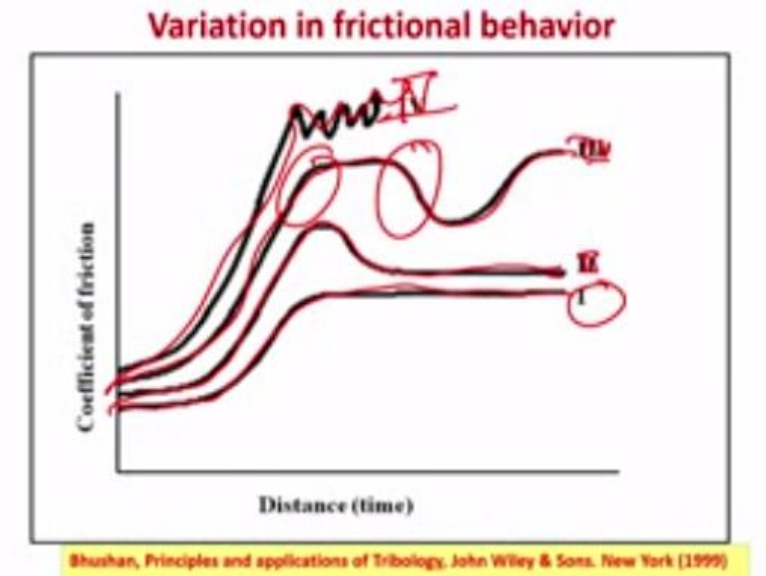

These are the 4 different types of frictional properties. So first one, it goes from very low to very high that is the type I; then second one, it goes to low coefficient of friction, goes to little high, then goes down, it is type II; then third one, it goes to low, then high, and then it goes to, this is type III; and fourth one, it goes to very high, then it goes to extremely high, coefficient of friction is retained.

So, all these different frictional forces, one of the things that you must remember whenever frictional force goes to high from the low values, it goes through a transition and therefore the mechanism of friction and wear must be changing when it goes through transition, at this point and also at this point. In any curve which goes up and down, then there must be limited to or must be related to certain changing mechanisms.

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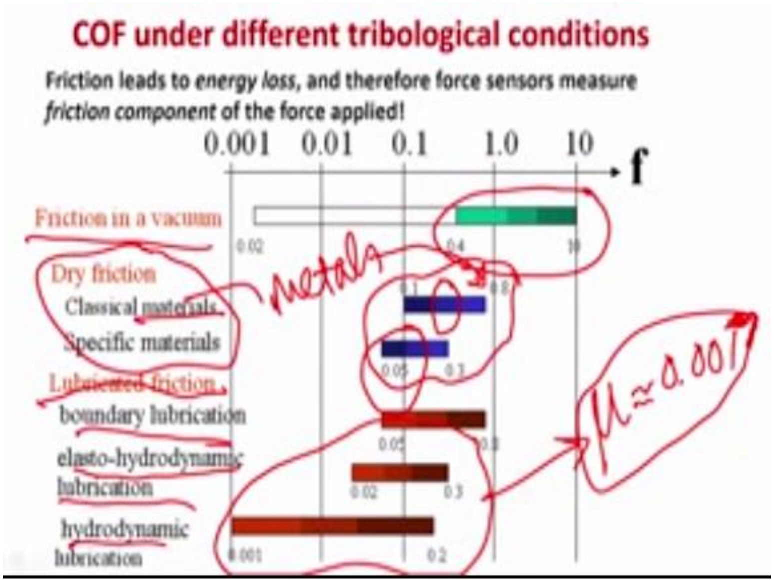

Now, here you will see that what I have mentioned in the very beginning that how coefficient of friction varies under different tribological conditions. So, let us say if you consider the friction in vacuum about the two mating solids, the coefficient of friction can go up to very high, up to 10, 0.4 to 10. If you go to dry friction like classical material and specialty materials, then it goes to 0.05 to 0.8. I have shown the classical materials means metals and alloys, then it goes to up to 0.5-0.6, some of the ceramics they will follow at the 0.3-0.4 and 0.05 it is more in the domain of polymers.

Then if you go to lubricated friction like boundary lubrication, electrohydrodynamic and hydrodynamic lubrication and so on, these kinds of lubrication I will explain later. But it is possible to achieve coefficient of friction μ value as low as 0.001. I have mentioned it to you earlier that with the help of some of the commercial lubricants and certain additives, even one can reach the coefficient of friction as small as 0.001. So, this is extremely a good value of the coefficient of friction.

So, when the coefficient of friction is 0.001, essentially the asperities of the two mating solids they are not coming in physical contact with each other. So, they are kind of physically more or less separated. So that, these two solids they behave more or less like frictionless surfaces. So, I will stop now.

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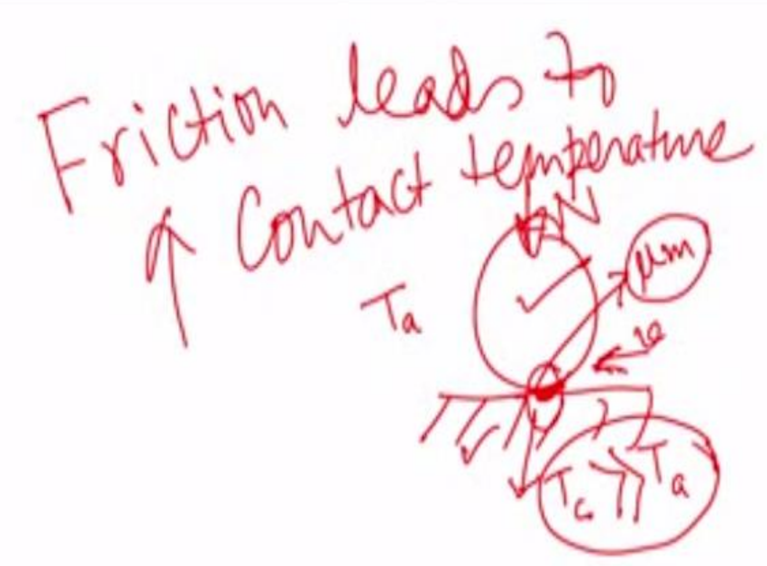

One of the things that I will carry forward in the next lecture that because of the continuous rubbing, the friction leads to increase in the contact temperature. So, this contact temperature is very important. Because contact temperature means that although you are doing these experiments at room temperature.

This is a ball and flat, I will use this kind of model multiple times in this course. This ball is placed against the flat by normal force N and then there is a sliding motion between these 2 is v. Although this temperature is ambient temperature T_a, this entire test is conducted at ambient temperature. But temperature which is generated here at the contact temperature T_c, it is much higher than the ambient temperature and how much high it would be depends on the physical properties of the two solids like thermal conductivity of the solids.

What is the mechanism of heat dissipation like by conduction and so on? But then the point is particularly this contact dimension is of the order of micrometer. At this small region, it is very difficult to precisely measure the contact temperature. So therefore, certain theoretical models are there which is very useful to predict that what is the magnitude of this contact temperature at the ball and flat interfaces and those will be the subject of discussion in the next lecture. Thank you.