Video Course on Tribology

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Lecture No. # 03

Friction

Welcome to the third lecture of video course on Tribology. Topic of this lecture is friction. It is interesting. We experience friction in day to day life when you walk we experience friction, when we cycle we experience friction, when we drive we experience friction. This is very common mode which we experience every day.

TRIBOLOGY

Lecture 3:

FRICTION



And often when you go to mall, we find this kind of signal or warning that slippery when the floor is wet. So, you need to be careful when you walk resending the water place as lubricant layer.

Some Typical Values of Coefficient of Friction for Metals sliding on themselves

Metals Sliding on themselves	**μ**
Aluminum	1.5
Copper	1.5
Copper((oxide film not penetrated)	0.5
Gold	2.5
Iron	1.2
Platinum	3
Silver	1.5
Steel(mild steel)	0.8
Steel(tool steel)	0.4

Observations:

1. $\mu > 1.0$
2. Mild steel vs Tool steel
3. μ depends on environment.

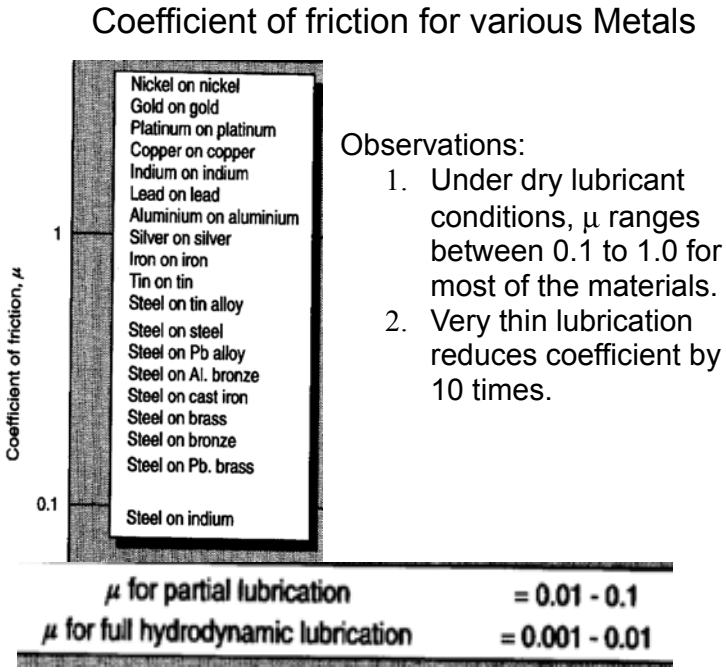
And it reduces the friction. So, we need to walk with more force. So, the overall the friction force turn out to be same. I have gone through number of books and found number of variation in coefficient of friction. So, I am just showing on the first slide of this course that typical value of coefficient friction which is often quoted in books. We say these values are static coefficient of friction or this value belongs to static coefficient of friction. there is some difference; static coefficient of friction and kinetic coefficient of friction. We will come to that topic later, but, see what is mentioned in this table. It says aluminum verses aluminum when aluminum roughs over aluminum under pressure of force having relative velocity, it shows coefficient of friction 1.5; amazing!

We normally believe that coefficient of friction will not go beyond 1.0 and here we are showing the coefficient of friction as 1.5. Similarly, when copper roughs over copper it gives coefficient of friction 1.5. Interestingly this value cannot be repeated again and again This is just a mean value. to get some variation in coefficient of friction; Now, let us see another example when copper is oxidised; that means, when we are allowing to contaminate coefficient of friction decreases 2.5 is one third that is amazing thing.

Coming to the coefficient of friction of very high values, the gold over gold is soft material. Coefficient of friction is 2.5 Look on the platinum over platinum coefficient of friction is 3. Well we have two examples of the steel also. See mild steel over wild steel shows the

coefficient of friction .8 while tool steel over tool steel gives the coefficient of friction .4. That means, same material of same composition but some change in hardness gives variation in coefficient of friction. It is not only the material property. It is a property of a system. Coefficient of friction will vary if you change any one parameter of the system. You change temperature, coefficient of friction will vary. You change the material composition, coefficient of friction vary, if you change the surface roughness, it will vary, if you change hardness it will vary. So, you can say observation from this slides are mu, coefficient of friction is greater than 1.0. Mild steel verses tool steel shows different coefficient of friction. I say that mild steel or wild steel shows coefficient of friction .8 tool steel verses tool steel shows coefficient of friction .4 if I do intermediate it with somewhere in between.

May be mild steel verses tool steel is somewhere .6. And another interesting thing which we observe is when copper is getting oxidiyed coefficient of friction reduces to one third. That means, mu depends on the environment. Let us take another example or other published data here the coefficient of friction is given to us and it shows that steel is getting rubbed on indium steel or lead brass, the steel on bronze, steel in brass cast iron, aluminum bronze.



Observations:

1. Under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials.
2. Very thin lubrication reduces coefficient by 10 times.

So, on and finally, come as a steel on steel; that means, similar kind of material will go high coefficient of friction compared to two different pair of materials. You say that tribe-pair made of two different material will show lesser coefficient of friction compare to tribe-pair made of the same material.

And another interesting thing we can observe from this data is that when there is thin lubrication, partial lubrication some sort of lubrication is provided at interface between the two materials. Then coefficient of friction reduces by one tenth and if we can completely separate two surfaces no asperity contact. That is why we are saying, a hydrodynamic lubrication thin thick film lubrication then coefficient of friction reduces to one hundred. That means, one percent of coefficient of friction which we can experience in dry condition. So, here it is indicated that lubrication is very important to reduce the coefficient of friction, to reduce energy loss.

However, when we are talking about the reduction of coefficient of friction I believe there are a couple of examples where we really require coefficient of friction or high coefficient of friction or high frictional force. I gave one example initially there when we walk; we require some coefficient of friction at our shoes level or we say that we require coefficient of friction at between shoe and the road is a needed. If you are providing a lubricant layer there the coefficient of friction reduces and our efforts towards walking.

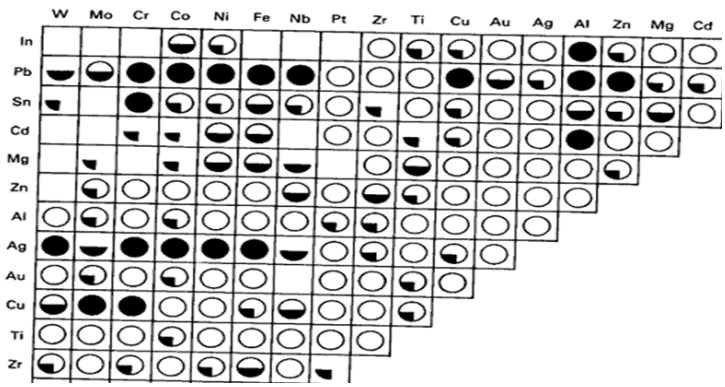
So, that way we can say friction is important. We have another example of a break. When we want to stop automobile, we apply a break there is coefficient of friction works where we are trying to enhance or increase coefficient of friction. This is not only that we always target lesser coefficient of friction we can target high coefficient of friction also. So, in tribology we can say that we work more towards a controlling friction compared to the lesser friction or higher friction. You want to make coefficient of friction at the desirable level.

May be ninety percent cases we try to reduce coefficient of friction in almost all our machine wherever there is a interface and friction. That requires power or energy loss. We want to reduce it because energy loss will, will increase the temperature and we do not want that. So, by and large we want to reduce, but, we have examples where the coefficient of friction also can be increased, So, in short we can see tribology as means of controlling friction. What are the observations from this slide? See that under dry lubrication condition mu ranges between .1 to 1.0 by and large.

The few examples like nickel on nickel, gold on gold, platinum on platinum, copper on copper and on. Again this will not be repetitive results. These are the mean

values may be in one lab. This kind of coefficient of friction have been experienced in one lab.

Comparison among various Material Pairs



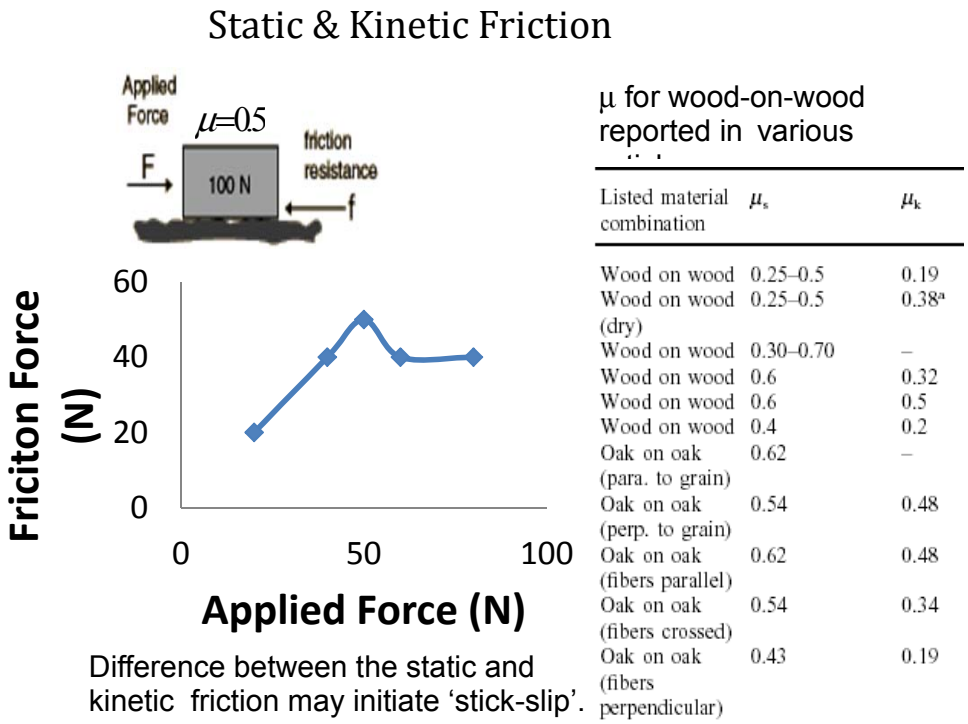
Observation: Similar materials have higher tendency of adhesion.

But, if you do similar experiment in another lab in other environment there is a possibility of change in coefficient of friction and another observation from this slide is that very thin lubrication reduces coefficient of friction by ten times. You invest delta money and you get ten times profit. That is encouraging to learn the tribology. It is another chemical related to it shows that we should choose proper material pair for tribological application. Let us take an example.

You see lead can be selected with the chromium. Lead can be selected with cobalt, lead can be selected with nickel, lead can be selected with the iron and lead can be selected with a niobium. Why we say this to be selected, because this circle is filled with a black circle and this table indicates a fully occupied or complete black circle means a low adhesion force. If the adhesion force is very high; adhesion will increase a friction force. So, if you want to really target for low coefficient of friction, we choose that kind of material pair. Similarly, we can choose a silver verses chromium, silver verses cobalt provided we have enough money because silver is one of the costlier material compare to lead. That is why we in most of the application we use a lead compare to silver. From this table also, we can see that aluminum should not be used against tungsten, and aluminum should not be used against the chromium, iron should not be use against the nickel. So, it has some restriction. Partly it can be used with zirconium and cobalt.

But if we treat this nickel metal properties will change, surface properties will change and we can utilize against another material pair. So, this is just a guideline for us, but, it is not uniform and have a cheap material like aluminum it is available in abundance; we can use that material with modification to reduce coefficient of friction as per our desire. So, we can say that observation from this slide, similar materials have high tenancy of adhesion. I skip that this in this case particularly whenever materials in this case zirconium verses zirconium,

we have left anti cycle empty place. That is always known zirconium verses zirconium will have more and more molecular attraction. We say that similar material have more attractive force.



And then they will try to increase adhesion force or we say that they have coefficient force and coefficient force will be by and large more than adhesion force. So, that should be avoided. Initially. I mentioned about static and kinetic coefficients of friction. We are going to explore that. What is really static and kinetic coefficient of friction? To explain this let us take this figure. We are applying 20 Newton load to move this block, 100 Newton block. 20 Newton load is applied to 100 Newton block which as a coefficient of friction .5 and we find that block is at the same place. We are not able to move this block.

Now, if we increase this force to 40 Newton, apply some additional load on that, the block remains in the same position. It does not move. Reason being opposing force, friction force is higher than applied force. However, when we applied 50 Newton load there is a possibility of sliding of block if coefficient of friction which is estimated is accurate. In that case block will start sliding as it gets movement then opposing force or friction force reduces and this is reduced to the 40 Newton; that means, we get some sort of movements, some sort of acceleration on this block and after that this friction force is steady. It remains as the same

forty level or 40 Newton level. However, friction force, its starts from 0 increases to the value mu into whatever the normal force.

After that there is a possibility of decrease in that magnitude and what we say this points belong to the static friction force and this line belongs to the kinetic friction force. Kinetic friction force in this case is shown to be lesser than a static friction force, but, it is not always the case. Most of this kind of a metal it is. But, prepolymers have shown a different behavior variation in that. Now, this table is shown to indicate that there is huge variation in static and kinetic coefficient of friction mu as here represents as static coefficient of friction and mu k is kinetic coefficient of friction. So, this literature table has been picked up from one of the books. See here wood on wood, coefficient of friction varies from .25 to .5 almost 50 percent variation.

And kinetic coefficient of friction which is having steady value that is .19 which is much lower than .5 we say intermediate value .4 is almost half of that. However, in other case, wood on wood with already given as a dry condition and in coefficient of friction was this. But, kinetic coefficient of friction is towards higher in different literatures. That means, first data is from one literature second data is from other literature. Almost similar kind of wood material have been used in third case is a wood on wood. Coefficient of friction is varying from .3 to .7. Similarly, we have number of examples. We say that just slight change in there fiber orientation, coefficient of friction is varying.

An interesting thing is that kinetic coefficient of friction is shown always lesser than static coefficient of friction. Is there any problem if there is a difference in a static coefficient of friction and kinetic coefficient of friction? Will there be any problem? Yes there is a problem. We say in hydrodynamic bearing, when we start rotating the shaft, coefficient of friction may be around .3 and after development of hydrodynamic film, coefficient of friction may reduce to .01 or .001. The huge difference if I want to run the shaft for longer duration, I have to keep some power source to start the shaft. That requires high friction force or that requires to overcome high coefficient of friction force.

Well, for running condition I do not require that much power. So, there is unnecessary problem. Initially we have to spend too much money on the power source if coefficient of friction is higher. If it is on same level whatever running coefficient of friction is there then will be requiring same power source we do not have to put additional equipment in machine. So, by and large we try, we should aim to keep same coefficient of friction throughout from its start to end. That will help us. There is another problem also what we call as stick lift phenomena.

Let us say we want to run one component or other component at the micro motion device may be like, we want only very low velocity. What will happen in that case? We supply high force, it starts sliding it will come down because of the very low velocity motion it will again come to the stationary, again we have to push it. That means, we need to shafted high force to low force and that will be a stick slip phenomena which is often experienced in the micro machine devices. It is a important topic and it introduces a vibration which will be dealing with friction topic may be in fourth or fifth lecture.

Observations

1. $\mu > 1.0$.
2. μ depends on environment, hardness, and chemical composition.
3. Very thin and thick lubrications reduce μ by 10 and 100 times, respectively.
4. Tribo-pair consisting of similar materials have higher tendency of μ.
5. Difference between μ may initiate friction instability.

There is a need to understand science of friction.

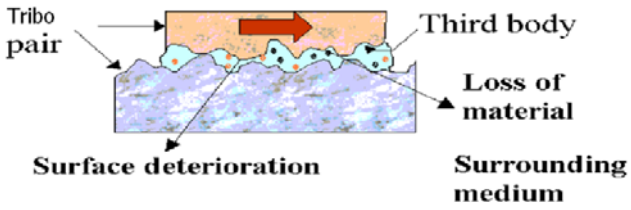
So, what are the observations? You really say the coefficient of friction is greater than 1.0 which is generally not written in number of books. Then we say the mu depends on

environment which does not come in ordinary friction loss. It depends on hardness also, it depends on chemical composition. So, coefficient of friction from one lab to other lab can vary easily because of these reasons. Then we can say third point is very thin and thick lubrications reduce mu the coefficient of friction by ten to hundred times respectively.

That means if you are providing thick lubrication there is always a reduction in friction, but, controllability will reduce. See if you want more and more controllability naturally we have to compromise between thin and thick lubrication as zero to thin lubrication. Another interesting point which we observe is that tribo pair which having a similar materials have a high tendency to stick and have high coefficient of friction. It should be avoided as for as possible. Interesting thing is that when we use ball bearing example, we use in both the cases the same chromium steel say 52 100 as I grade reason being that we are keeping very high hardness with a plastic deformation or any additional friction devices cannot take place.

That means we make component in such manner, surface that chemical composition of surface material not going to play much role. In that case we can use similar material similar hardness. But, otherwise for common application we should avoid similar material pair and last point which is written here that difference between the mu or static coefficient of friction and kinematic coefficient of friction in stability, which will be covered in subsequent lectures. But, all these were shown as only data, no science was explained as such, no quantification was given to. No explanation in mathematical term was given to us how we have understood we have not explained that.

Dry FRICTION



- Leonardo da vinci(Earliest experimenter, 1452-1519):
- "Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length". $F \neq A$
- "Friction produces the double the amount of effort if weight be doubled". $F \alpha W$

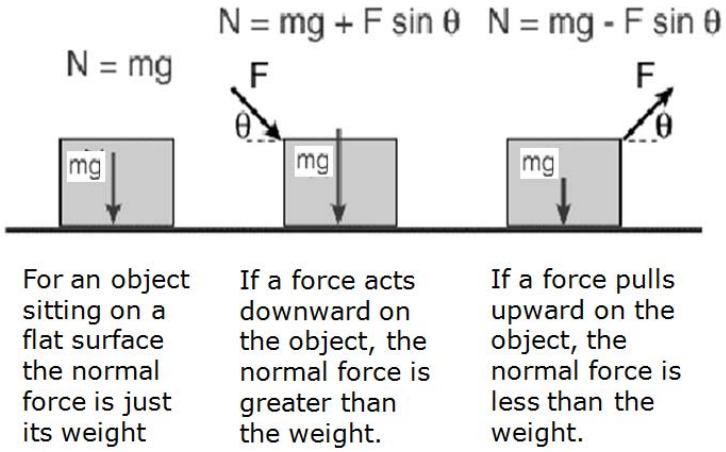
So, there is a need to understand science behind this friction. Start see let us start with dry friction. We are assuming this third substance will not be available, the lubricant is not available in a dry friction or we say the fluid in form of liquid, in form of the powder or in form of the gas is not available over here and there is possibility of aspartic contacts coming and interfering with motion of other components. And there is a possibility of loss of wear, loss of materials wear. There will be some effect of surrounding medium, there will be surface deterioration and that is why there will be particle generation on debris.

Now, to give a complete view, let us start with the history of how friction was evolved or how friction was expressed generally gives in common text books. You say that Leonardo ad Vince was the first person who did an extensive experiment and based on this experiment some results could be concluded. What were those results? He said that friction made of same weight; that means, you are emphasizing on a weight. It will be of equal resistance at the

beginning of movement; that means, if there is some weight w, friction force will be decided based on that.

Whatever the area you choose which is ten by ten or you choose 5 by 20 any multiplication which gives a same area. Or it may be say any weight any dimension which gives a same weight that will give us same friction force that was the interpretation by Da Vince. And second interpretation what he mentioned is that if I double the weight friction force will double. That means, first law when he says the friction force does not depend on area of contact, second friction force depends on applied load or weight of the component.

- G.Amontons, 1699:
  - Rediscovered Leonardo da vinci laws. $F \neq A$; $F\alpha N$
  - $\mu = 0.3$ for most of materials.



These laws were rediscovered by and he purposed few laws in 1699. First he also showed that friction force does not depend on area of contact. However, he changed the second law, a friction force is prepositional to normal weight or normal force. He removed the word weight or applied force directly. He said the use of the word to be normal then only we can say friction force is propositional to that. He give some example something like this; let us check if there are first block second block and third block.

In first block weight is downward direction. So, here a normal force will be unchanged. If I push this block in horizontal direction naturally friction force which will be a maximum resistance force will be equivalent to mj. Now, if I apply or pushing force is to some angle theta what will happen? In that case there will be one component coming vertically down and

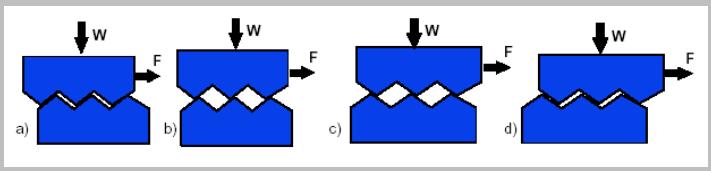
other component will be going horizontal and friction force will be based only on horizontal component.

What is the drawback on this side? He said that whatever weight was there in addition to that friction force is the tensile force is creating a component to resist. That means, this f sign theta is additional component it is increasing the friction force. In third case it is subtracting. We are trying to pull up where the one component is vertical which is acting against the gravity force. That means, this is helping us and friction force will be reduced in this case.

So, what we say is that Da Vinci allowed the friction force proportional to the weight is not a real case and has modified. He said that friction force should be stated as a proportional to normal force. It is not directly proportional to weight. Now, how we are applying or how we are pushing that block or pulling that block that is going to be decided, what will be the friction force? And that is real case and that is why it has been again and again repeated in number of books.

Another interesting thing from was that he did a number of experiments and by and large if you found that coefficient of friction is equal to .3 from most of the materials. That means, if I do not have any knowledge any time or maybe say are doing design of the start and I have not selected material pair, and going to be selected material pair based on the same criteria or shiftiness criteria that will come much later in that case. I can choose a coefficient of friction under dry condition equal to .3 at this start.

- C.A.Coulomb 1781 (1736-1806):
  1) Clearly distinguished between static & kinetic friction
  2) Contact at discrete points.
  3) Friction due to interlocking of rough surfaces



  4) $f \neq$ func(A)
  5) $f \neq$ func(v)

So, these results were encouraging and we account these results. Later coulomb purposed a few additional points in 1781. The first thing and more important thing is, it could identify difference between static friction force and kinetic coefficient friction force that was the one

of the best achievement from the Coulomb. Another thing he came with micro models he said that aspartic contact will happen. That means, there is a discrete point of contacts when there are two materials coming into contact. Before that nobody else pointed out that there is a discrete point of contacts and that because of this there will be some interlocking and he mentioned that friction force will be induced because of the interlocking.

He gave couple of examples that this roughness profile of one surface, roughness profile of other surface is more like sutured profile when the normal load is applied and friction force is trying to push it up. What coulomb thought that may be without any deformation starts sliding up as it requires a force to move component out of pit. That is the friction force. However, later it was realized that when it is going down same energy will be gained back.

So, there should not be any friction force. Some explanation was given that there is always a hysterical loss. Materials when it moved from one place to other not necessary we will get hundred percent energy back. Some energy will be lost and that is going to give us coefficient of friction or is going to give a friction loss. Coulomb also mentioned that friction force does not depend on area of contact and another interesting point which was pointed out by Coulomb that whether coefficient of friction will depend on velocity, relative velocity because this model was given by him..

It is clear when you are pushing over the rough surface it takes slightly more time from this stationary position. But, on running condition naturally this component will not fall back to the complete depth. It will be in partial lapel. That is why the kinetic coefficient of friction was lesser what was suggested by coulomb. But, this depends also in velocity. If you see that speed up velocity of this component it push hard and hard, coefficient of friction should be reduced. But, Coulomb did some experiment and based on that he concluded that coefficient of friction does not depend on velocity is only initial velocity, static coefficient of friction.

TOMLINSON's Theory of Molecular attraction: 1929

- Relation between friction coefficient & elastic properties of material involved.

$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

E is young modulus, Mpsi

$$\theta = \frac{3.E + 4.G}{G(3.* E + G)}$$

G is modulus in shear, Mpsi

- Clean Steel E=30 Mpsi, G=12 Mpsi → 0.6558
- Aluminum E=10 Mpsi, G=3.6 Mpsi → 0.742
- Titanium E=15.5 Mpsi G=6.5 Mpsi → 0.5039

- Due to molecular attraction between metal, cold weld junctions are formed.

And once it start moving then there will be only kinetic coefficient of friction it is not going to continuously reduce with the velocity. Then an interesting thing came in a 1929. Tomlinson gave a theory related to molecular attraction. He said that one component or one element is captures another element then there is a possibility of molecular attraction. We know atomic forces. We know some material have more tendencies to attract compared to the other materials. Take an example of ceramics. They will be having lesser tendency for molecular attraction. But, for metals they will be having high tendency to attract other material. So, based on his experiment, he did an extensive experiment and then came up with some comfort equations.

What are those comfort equations? It is something like f is friction force is equal to 1.07 theta one, theta two where theta can be given for individual material and he also thought that two materials in one tribo pair applying a role. Theta one is this theta for surface one, this theta for surface two, and he mentioned that this depends on material proprieties. It depends on e and g, young modulus and shear modules. If there is a high shear modules the theta will be lesser, coefficient of friction will be lesser.

He directly mentioned that the material which have a high strength that will have a lesser coefficient of friction and it was also known soft material will show a loss, a higher coefficient of friction because deformation will be more, energy loss will be more, coefficient of friction will be more for hydro material, deformation will be lesser and that is how the coefficient of friction will be lesser. So, this theory was justified to some extent and just to get flavor of this theory I took three material of the clean steel, aluminum and titanium.

And this formula was based on unit in MPsi and mega psi and that is why we are sticking to the same unit. We are not changing si units in this case. Let us take a clean steel verses titanium if I use formula if I substituted thirty twelve in theta one to find out theta one. Similarly, if I substitute 15.5 and 6.5 in this theta value to find out the theta two; I will be able to get, theta one and theta two substitute this value and I will find out friction force. And that turns out to be .5039 roughly .5 coefficient of friction. That is again static coefficient of friction. If I use other material pairs, the clean steel and aluminium.

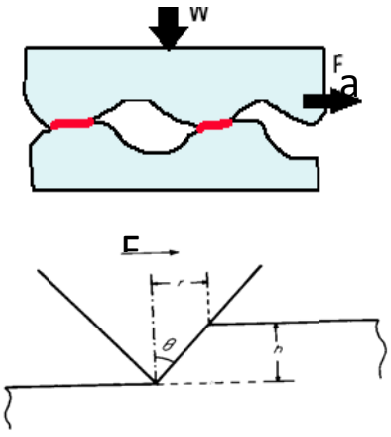
coefficient of friction is increasing. That is, experimentally observed results say here reason being that g is reduced from 6.5 it is coming to 3.6, from 15.5 e is coming to the ten. Naturally, e and g are reduced. That is going to give us higher coefficient of friction. Take a third example, we say the aluminum verses titanium here these are two week material there was two soft material and coefficient of friction turn out to be .7.

This experimentally observed results to some extent this comfort equations are valid, but, it does not give complete science. It gives the result based on the experiment. It is the only imperial relation still need of science is required to explain this and as I mention that metal have high molecular attraction. So, they will show high coefficient friction. Ceramics will be having lesser molecular attraction. So, we will show lesser coefficient of friction. Polymers will also show lesser coefficient of friction because they have lesser tendency to attract molecularly or experience molecular force.

Scientific Explanation of Dry Friction

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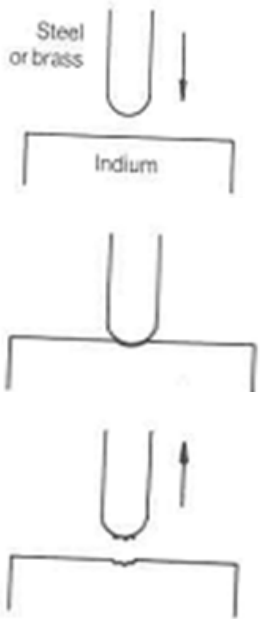
Now, we want to start with scientific explanation of dry friction. We believe there are two modes of friction or two sources of friction which are called as adhesion molecular attraction, other one is called deformation. One surface is trying to deform the other surface. So, that you have two friction sources; one is adhesion, and deformation. The resultant friction will be summation. It will be more like super position friction force contributed due to the adhesion and friction force contributed due to deformation. It will be just summation of these two.

Now, just to make a variation; if I want to lubricate this tribe pairs; what will happen? Lubricant is going to reduce adhesion reduce molecular attraction between components between tribo-pair. If it is reducing molecular attraction naturally adhesion force will be negligible. That means, only there will be one source of friction that is deformation. Now, if I come to the other end we say we want to make extra smooth surface. No asperities at all. Almost perfectly smooth surface mica over mica then what will happen? There will be negligible deformation. It will be only adhesion force. So, there twist strings; we can lubricate surface partially or we say that mix lubrication in the case the adhesion force turn out to be 0 or negligible.

And when we use extra smooth surface then we have only adhesive force and the deformation force will be negligible. We will try to explore about the options and develop individual expression one for adhesive force, other will be for deformation force.

ADHESION



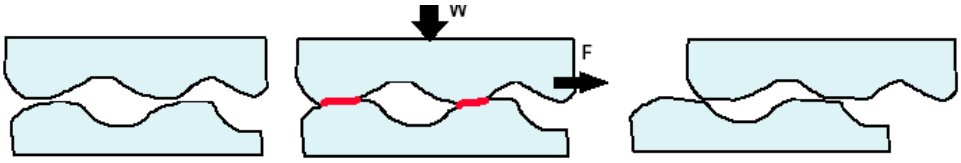


Just before developing some experiment expression or mathematical relation let us see the example of this carbon graphite seal verses stainless steel. This carbon graphite seal is having some attractions through was aluminum. That is the strength strain because this is made of powder form and when it is rubbed what will happen? It will leave its prints on a shaft. That means, one layer will be transferred.

So, this surface is transferring this carbon layer graphite layer on the surface. It is an interesting thing people have experienced that adhesion to some extent can play as a good lubricant role. What is happening in this case? We are utilizing adhesion after understanding, we are transferring a carbon graphite layer on other surface and that carbon graphite surface will subsequently act as lubricant. It will be more like powder lubrication. So, it is important or it has come after understanding how adhesion can be utilized to better side.

Let us take another example it is a steel pin is pushed in some block of indium. When you push it what will happen there is a possibility the indium is soft material steel will penetrate in that material to some depth. And if I remove push it back or you say the lift this rod back or pin back, we will find some material attached to this a rod. You can see there are some particles attached to this rod and that is the material transfer. Indium is transferring the material now when we are pushing it, indium is having some attraction towards steel surface. It gets deposited on the steel surface.

When we are removing it, It is not getting friction or the interface or we say that interface between steel and indium is a stronger than indium itself or in other words indium as a lesser strength compare to the strength of interface made by steel and indium. So, when we understand this, we should design interface in such a manner. That interface need to have a lower strength compare to any of material. Whether the material two or material one or whether steel or indium. If I provide a lubricant at the interface, that will have some strength.



$$\mu_a = \frac{F_a}{W} = \frac{s}{H}$$

And that strength need to be lower than indium material then only we will be getting clean surface we will not get any material transfer in that case. Now, let us develop a theory. We are facing that when we are applying two applying force on one irregular surface against other irregular surface; they are going to undergo the plastic deformation and due to that plastic deformation there is a possibility of cool junction formation. This cool junction formation, is a cool wilding. Under pressure you are applying a force and that is why this kind of wilding is happening.

Now, if I apply a tangential force I push this component throughout the right side, those junction will be shear. Now, depends on how this components are, this interface is sheared. If interface is sheared then there is no problem, but, if the interface is getting higher strength compared to the one of the material then there is a problem. That means, higher coefficient of friction will be there at this. Now, if you develop mathematical relation, we can say simply that we know what is the hardness of the soft material. If I am using material one and material two and material two is softer than material one and it has and hardness H. If I know H; and w normal load which is being applied on this component, then I can find what will be the area of contact.

Because a plastic deformation is considered that is what hardness is accounted. If you considered only elastic deformation then I can think about that yield is strength of propositional limits. But, we are considering the plastic deformation that is why hardness is

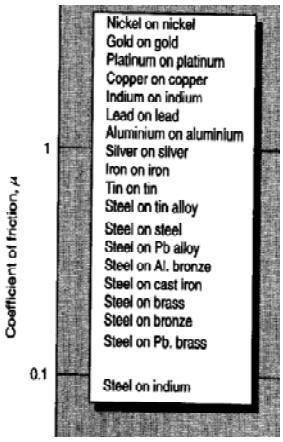
accounted in this case. So, area of contact or we say that contact can be figured out using this relation w divided by h and this area need to be sheared whatever the junction was made. That needs to be sheared. So, to shear this we need to apply some force in tangential direction.

And I can represent this as $F_{adhesion}$. which is given as real area of contact together shear strength of junction. May be variable, may be constant. We can take a mean value of that. So, if I know the friction force, If I know the normal load I can find out the coefficient of friction that will be symbol relation μ_a is equal to $F_{adhesion}$ by w. Substitute the value. of F_a and W; the real area of contact will be canceled out; that means, we really do not have to find out what is the real area of contact which is very difficult parameter estimating theoretically.

We can find out experimentally, but, estimation using theory is slightly difficult. So, in this case we are not getting area of contact at all, we are getting s divided by h and both are the material and surface properties and both belong to same material though belong to the soft material in this case. Only point variation will be that quite possible as for a softer material is higher and interface as lesser. In that case s will be slightly lesser. However, we are assuming as per the proper material property of a soft of material, h is a hardness of softer material.

What is interesting in observation from this we see that shear as strength and hardness related to material. That means, if I choose one material if I choose indium now choose any other material pair which as a high shear strength and high hardness I should get same coefficient of friction because indium is going to decide what will be a coefficient of friction. Now, if I choose steel as I choose chromium and I choose nickel I choose any other material indium is one of the soft material it should show the same coefficient of friction through any material pair which is not that case. That means, something else is required to explain that phenomena. This is not complete. It needs some additional theories to explain it. This is what we have mentioned over here.

$$\mu = \frac{s}{H}$$

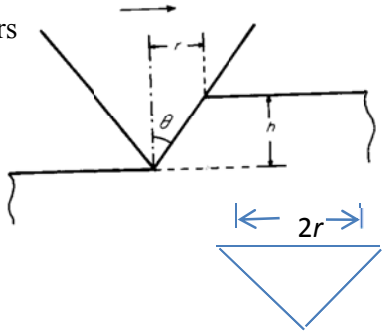


For most of the materials if I assume this is not happening now will come to other argument. We say for most of the material hardness can be given as three times of yield is strength and shear strength can be given as yield strength divide by square root of three. I am trying to utilize solid mechanics to interpret what will be the coefficient of friction? If I want to use based on adhesion theory, if I substitute this as s equal to sigma divided by root three and h is three sigma what I will be getting? Roughly this coefficient of friction equal to .2. That means, whatever the material pair I choose, coefficient of friction should be .2. It does not depend on the material pair. That means, this theory is insufficient to explain what coefficient of friction is and how coefficient of friction will vary with material properties.

This is what shown in this table. So, that coefficient of friction will be different. It depends on the material pair if the material pair is same then coefficient of friction will be high which not the case in this is. It says that one of the materials as a shear strength which is soft material which is a shear strength is accounted and hardness of a soft material is accounted. So, this theory is insufficient or unable to estimate different value of mu coefficient of friction and there is a possibility that theory of deformation or we say that other source of friction may give some good results as we are not happy with the results obtained by this adhesion theory.

FRICTION due to DEFORMATION

- Contact between tribo-pairs only occurs at discrete points.
- Slop of asperities governs the friction force.



$$* \pi r^2 \Big)$$

$$\mu_d = \frac{2}{\pi} \cot\theta \qquad F = n(rh)H$$

So, let us explore what deformation theory says. The deformation we can assume different kind of asperities because deformation surface, softness playing a important role in deformation.

Let us take first example there was conical asperity and we assuming same cone radius for all asperities. There may be n asperities on a desirable or a surface area which we are defining. It is trying push conical cavity at some depth in a soft material; the depth is h and we are trying to push this asperity. So, that sliding occurs. In that case what we can say the expression can be given in or we need to find out what is the area, projected area on which the load is applied and what is the area on which the force is tensile force. Then we can calculate what will be the friction force what will be the normal force and based on that we can find a coefficient of friction. For doing that let us start with area. We say that this is conical area and we have to find only this much because even though cone as a higher position or dimensions are more than this.

But contact is happening at this radius only. So, area pi r square is a area plus half because this is an zero over here it is a average area and n is a number of asperities total area of contact can be estimated. I am not saying that this is accurate. It is estimated probably and into .5 into pi r square and r is cone radius. Now, we know the area of the contact.

If I multiply with a hardness I will be able to find out what is w what is the normal force applied on this aspirates. All aspirates are complete area which as n asperities and n asperities

in contact. To find out friction force; we need to find out the projected area on the other side. That means, I want to project this cone on normal plane perpendicular to that. We say that tilt this figure by ninety degree. So, that line appears in the slide and that will give me area of contact.

So, this is having a two r as a dimension, perpendicular not depth we known as h. So, half of the area will be counted because half surface it will be r into h. So, friction force can be given as n, number of asperities into radius of the cone into h the depth in a soft material into hardness. Now, if I take expression mu I assume the mu is equal to f by w;; that means, friction force divided by w and r h into capital h divided by n into .5 into pi r square into h right.

Cone Angle vs μ_d

q	μ
5	7.271
10	3.608
20	1.748
30	1.102
40	0.758
50	0.534
60	0.367
70	0.231
80	0.112
85	0.055

- Generally slopes of real surfaces are lesser than 10° (i.e. θ> 80°), therefore $\mu_d \cong$ 0.1.
- Conclusion: Total μ , should not exceed 0.3.
- Spherical asperity ??

So, what will happen? Some terms will be canceled out and we know expression of the cot theta will come and this theta is known to depth we know r they can find out cot in terms of h and r. So, coefficient of friction can be expressed as two divided by pi. So, pi is roughly 3. Something. So, it will be .5 and in the cot theta based on cone angle based on this theta angle we can find out what will be the coefficient of friction. I did some calculation and given in

tabular form you say when theta is fine; that means, asperities is very sharp. Asperities is very sharp in that case it will penetrate immediately. It is more like needle.

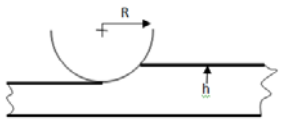
It will penetrate immediately; however, if the theta is increase to 85 degree is almost a flat surface then coefficient of friction reduces to very low value almost negligible say .055. However, intermediate value may be 80's 70 60 some coefficient of friction is stable. What was an interesting point is that there is a high sensitivity. This expression very sensitive throughout theta changing by few degree coefficient of friction is changing drastically taken example from five and ten.

The theta is only five is only half cone angle over a cone angle is ten between and here from five to ten. That means, overall cone angle is twenty degree and ten to twenty cone angle what we find coefficient of friction .73 and 3.6 almost half. That means, this back expression is very sensitive towards theta I am getting any reliable theta will be difficult for us. However, experience says that most of the time after initial running in time or running in period this theta turns out to be greater than 80 degree. By and large coefficient of friction will turn out to be .1 or say .01 in this case. So, if I add coefficient of friction due to adhesion coefficient of friction due to deformation I should not get coefficient of friction more than .3.

However, in first slide which I had shown experimental results coefficient of friction was estimated also as equal to 3.0, very high coefficient of friction is ten times somewhere what we are able to product through theory. Interesting thing is that when we are saying this cone when is coming almost to the flat level or theta is on a higher side; 80 degree do I need to use this conical theory? Instead of that I will prefer to use asperity as a spherical shape, as a cone particular in this case shown as cone angle is increasing.

$$A = n\left(0.5 * \pi r^2\right)$$

$$or \quad A = n\left(0.5 * \pi (0.5\, d)^2\right)$$



$$or \quad A = n\frac{\pi d^2}{8}$$



$$W = n\frac{\pi d^2}{8}H \qquad F = n\frac{2hd}{3}H$$

$$\mu_d = \frac{2hd\,8}{3\pi d^2} = \frac{16}{3\pi}\frac{h}{d} = \frac{16}{3\pi}\frac{h}{\sqrt{8hR}} = 0.6\sqrt{\frac{h}{R}}$$

It will turn out to be more and more uniform or flat surface theta in 90 degree, but, lesser than that it will be some sort of cone some sort of spherical shape which some round ages generally happens during the process. So, let us explore what kind of expression I can get when I assume there is asperity, spherical asperity. In this case we are saying that this is a hard material having spherical asperity and radius of sphere is given as half. It has to penetrate to some depth that the depth is h in a surface. When I project on as top view of this contact what I find some radius d, by two and depth will also be d in this case. Because whatever is the cross section I take that will be circle.

So, whatever I get over here the d by two same radius; I will be getting d by two; however, if I project and perpendicular direction again the depth will be h and other dimension will be 2. So, using this dimension I can find out what will be the area of contact. I can find out the normal force and I can find out tangential force. So, area of contact will be pi r square, in this case r is a .5 d half of the area in a projected direction or the half which is getting pushing asperities towards a soft material and when we express in terms of d it turns out to be n pi d square divided by eight. That is the expression.

So, if I multiply with the hardness what I will get? I will get normal load as a number of asperities, contact area with to one asperity into hardness. What I will be getting f friction force it will be tangential as I say that if I move vertically by 90 degree as in the side view, I will be getting depth h and d will be other dimension. So, in that case area of contact or tangential direction will turn out to be with some simplification two h d divided by three.

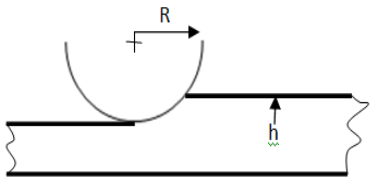
We do not know the dimension d. So, we can express d if I express d in terms of capital r or express h in come turns of capital r, the radius of the shear then you can get good results. However, in this case we will try to express h d in terms of capital r. So, we can play with h by r and find out what will be the results and all how results will vary. So, in that case if I want to find other coefficient of friction due to the deformation particularly due to spherical asperities; I can simple say f divided by h expression will be something like this. Rearrange this expression one 10 out to be 16 divided by 3 into pi h pi d. Here d can be given with assumption that h is very very low compared to capital r; that means, depth of penetration is much lower compared to the spherical radius or with radius of the spherical asperity.

In that case, I can give expression eight into h into r; that means, this overall expression can be given in terms of h depth of penetration dived by radius of sphere. Now, with this expression I can play and I can find out what results I can get if I change h in terms of

percentage whether one percent two percent three percent four percent ten percent will I mean to go to get very high or different results. So, I did that this is we are taking an example as a h divided by r in percentage assuming depth of penetration will not be significant. That means, I can go maximum to ten value. Beyond that this expression will not be valid we have to change expression if you are going beyond that.

Ploughing by Spherical Asperities .....

h/R (%)	μ
1	0.060
2	0.085
3	0.104
4	0.120
5	0.134
6	0.147
7	0.159
8	0.170
9	0.180
10	0.190



- Generally h << R, therefore $\mu_d \cong 0.1$.
- Conclusion: Total μ , should not exceed 0.3.

Now, coefficient of friction is not very sensitive as shown in conical cavity or conical asperities. So, in that point of view you say that this expression is slightly better. It is not very sensitive and it may give very good results also. Here the coefficient of friction when h is almost a negligible, depth of penetration almost negligible here almost one percent; coefficient of friction can normally .06. As we are increasing depth of penetration coefficient of friction is increasing, but, maximum value is turning out to be .2.

That means coefficient of friction is not very high in this case we say that few asperities are conical few asperities are spherical and I will get some intermediate value and, but, after running in time all conical asperities will be damaged; will turn out to be some sort of spherical asperities and I may get results somewhere intermediate results. But that is still is

not going to give us satisfactory results which we obtain earlier or we showed in a experimental result. Coefficient of friction is very high say one two and three that is not been explained with this theories. That means, this theory has some short coming these are classical theories. We need to some new theory will try to explore that theory in our next lecture which will be mostly on the friction due to junction growth where the motor cycle stress relation will be shown and we say that we can find out reasonably good expression to estimate coefficient of friction in this. Thank you.