Video Course on Tribology

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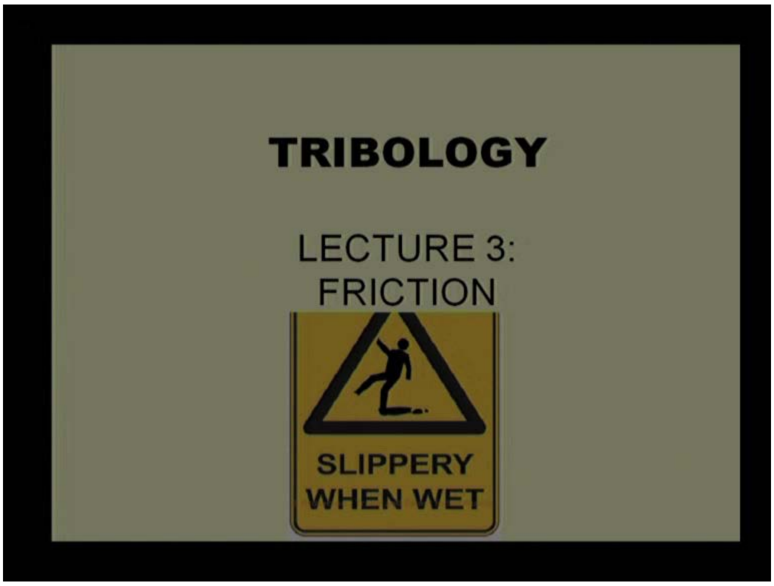
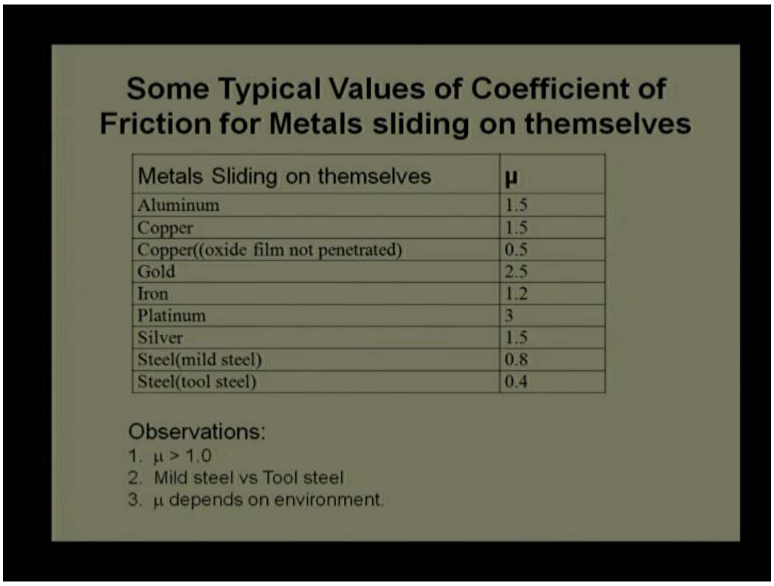
Lecture No. # 03
Friction

Welcome to third lecture on video course 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.



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

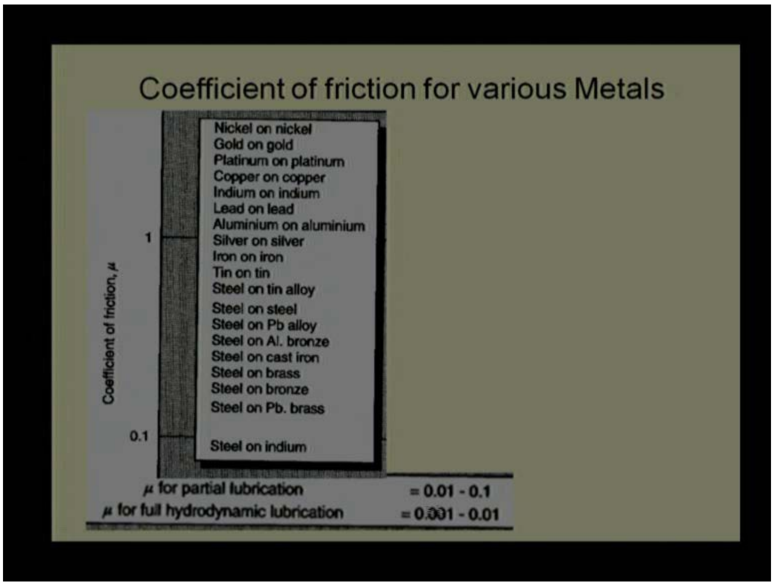


And it reduces the friction. So, we need to walk with more force. So, the overall the friction force turn out to be same. I have gone through number of books and found number of variation in coefficient of friction. So, I am just showing on the first slide of this course that typical value of coefficient 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. This 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 was gives coefficient of friction 1.5. Interestingly this value cannot be repeated again and again this is just a mean value get some variation in coefficient of friction. Now, I see another example when copper is oxidised; that means, when we are allowing a to contaminate coefficient of friction decreases 2.5 is one third that is amazing thing.

Coming the coefficient of friction is very high values is the gold over gold is soft material coefficient of friction is 2.5look on the platinum platinum over platinum coefficient of friction is 3. Well we have two examples of the steel also. See mild steel over wild a steel is shows the coefficient of friction .8 while tool steel over tool steel gives the coefficient of friction .4. That means, same material same composition ban large 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 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 variable. So, you can say observation from this slides are mu coefficient of friction is greater than 1.0. Mild steel verses tool steel it 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 will somewhere in between.

May be mild steel verses tool steel is somewhere .6 something in that and another interesting thing which we observe is when copper is getting oxides 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.



So, on and finally, come as a steel on steel; that means, similar kind of material will go will give high coefficient of friction compared to two different pair of materials have. 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.

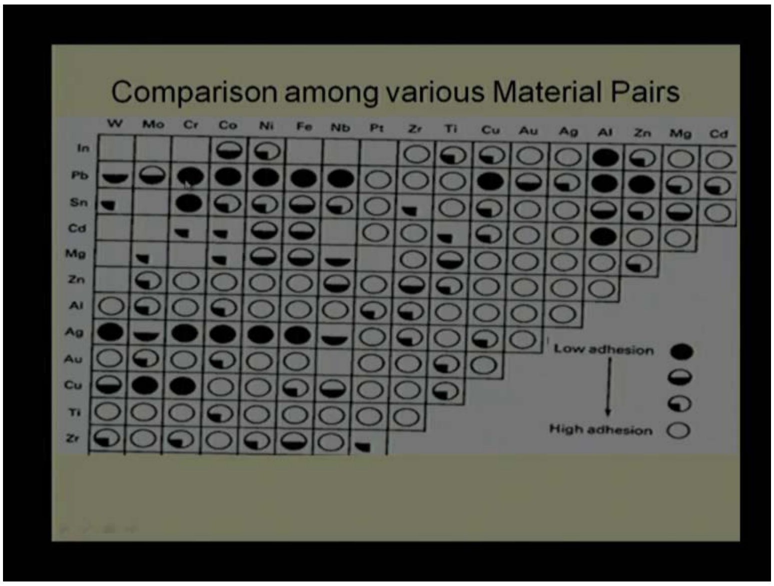
And another interesting thing we can observe from here in this from this data is that when there is thin lubrication partial lubrication some sort of lubrication is provided at interface between the two materials. Then coefficient of friction reduces by one tenth and if we can completely separate two surfaces no asperity contact. Take that is why we are saying is 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 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 effects towards walking or increasing.

So, that way we can say friction is important. We have another example also take 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, when tribology we can say that we work more towards a controlling friction compared to talking the lesser friction or higher friction. You want to make coefficient of friction at the desirable level.

And may be ninety percent cases we try to reduce coefficient of friction in almost all our machine wherever there is a interface and friction is appearance and that requires power or energy loss. We want to reduce it because energy loss will enhance a temperature will increase the temperature and we do not want that. So, by and large we want to reduce, but, we have examples where we coefficient of friction also can be increase, we want to increase it. So, in short we can see tribology in means 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.

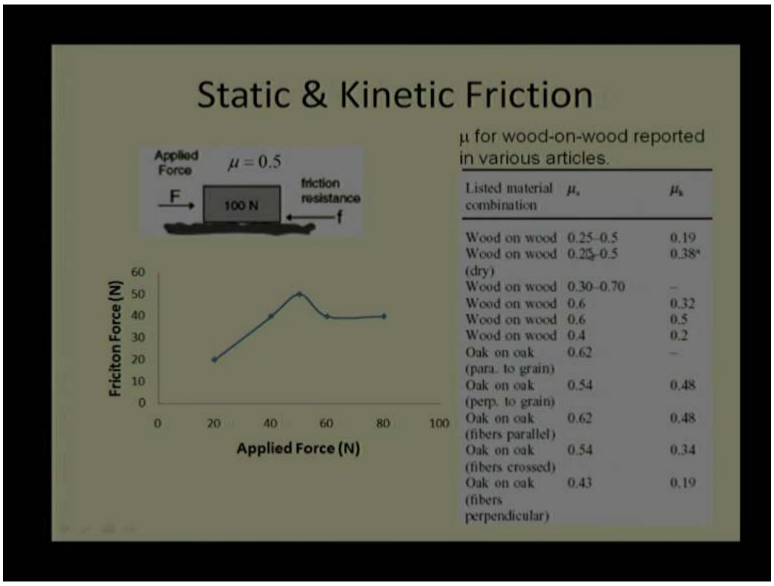
Excess the few examples like nickel on nickel, gold on gold, platinum on platinum, copper on copper. So, on again this will not be repetitive results. These are the mean values may be one lab. It is as been experience this kind of coefficient of friction have been experienced in one lab.



But, if you do similar experiment experiment in another lab 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 a in that is encouraging to learn the tribology. It is another chemical related chat with us it shows that we should choose proper material pair for tribological application. Let us take an example.

You are seeing 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 saying this to be selected because this circle is filled is a black circle and this table indicates a fully occupied or black 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. In this, from this table also we can see that aluminum should not be use against tungsten, angle aluminum should not be use against the chromium, iron should not be use again 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 right. So, this is a just a guideline for us, but, it is not from uniform have a cheap material like aluminum is a it available in abandon; we can use that material with modification two reduce coefficient of friction as per our desire. So, we can say that observation from this slide is 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. Now, initially our first second slide I mentioned about static and kinetic coefficient of friction. We are going to explore that. What is really static and kinetic coefficient of friction? To explain the lets take this figure. It is a first point we are applying 20 Newton load to move this block, 100 Newton block. 20 Newton load is applied 100 Newton block which as a coefficient of friction .5 and we find that block is at 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, it is in the block remains 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 starts 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 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 a 0 increases to the value mu into whatever the normal force.

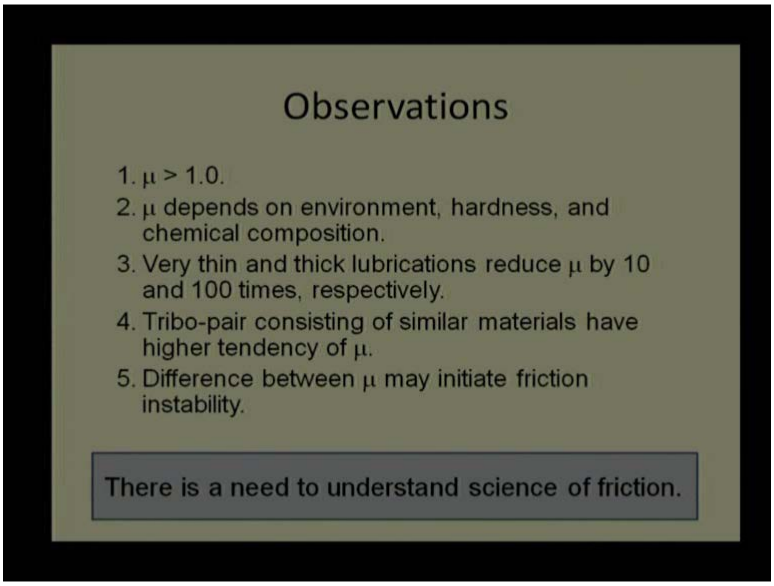
After that there is a possibility of decrease in that magnitude and what we say this is a this points belong to the static friction force and this line belongs to the kinetic friction force. Kinetic friction force in this case is shown to be lesser then a static friction force, but, it is not always the case. Most of the kinds of a metals it is, but, prepolymers it as shown a different behavior variation in that. Now, this table is shown to indicate that there is huge variation in static and kinetic of coefficient of friction mu as here represents as static coefficient of friction and mu k is kinetic coefficient of friction. So, this literature this table as been picked up from one of the books. See here the 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 a .19 which is much lower than .5 have 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.

And interesting thing is that kinetic coefficient of friction is shown always in this case, 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 of rotation of 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 been a high friction force or that request to overcome high coefficient high friction force.

Well, for running condition I do not require that much power. So, there is a problem. Unnecessary 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 if it is start to end. That will help us. There is another problem I talked about power source there is in this case, but, there is another problem also what we call as stick lift phenomena.

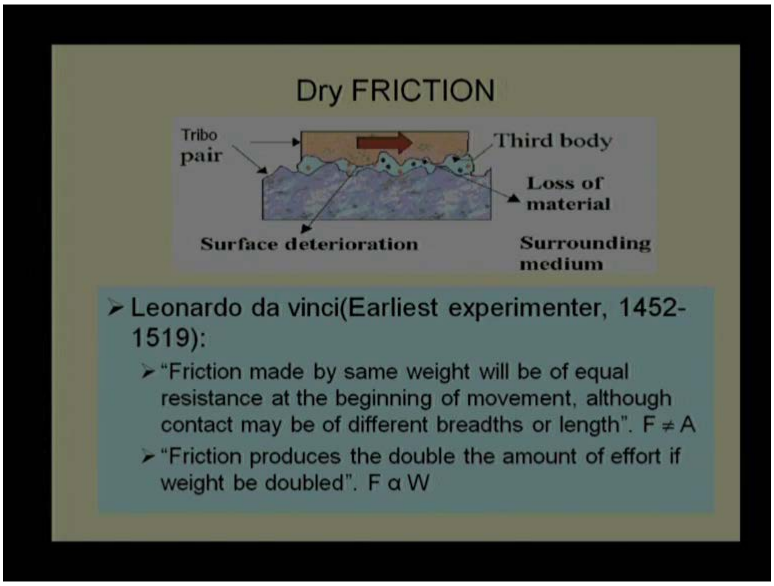
Let us say we want to run some one component or other component at the micro motion device may be like, we want only very low velocity. What will happen in that case? We supply high force, it starts sliding it will come down because of the very low velocity motion it will again come to the stationary,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



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 show have high tendency of coefficient of friction are should be avoided as per as possible. Interesting thing is that when we use ball bearing example, we there we use both in both the cases the same chromium steel say 52 100 as I grade reason being that we are keeping very very high hardness with a plastic deformation or any additional friction devices cannot take place.

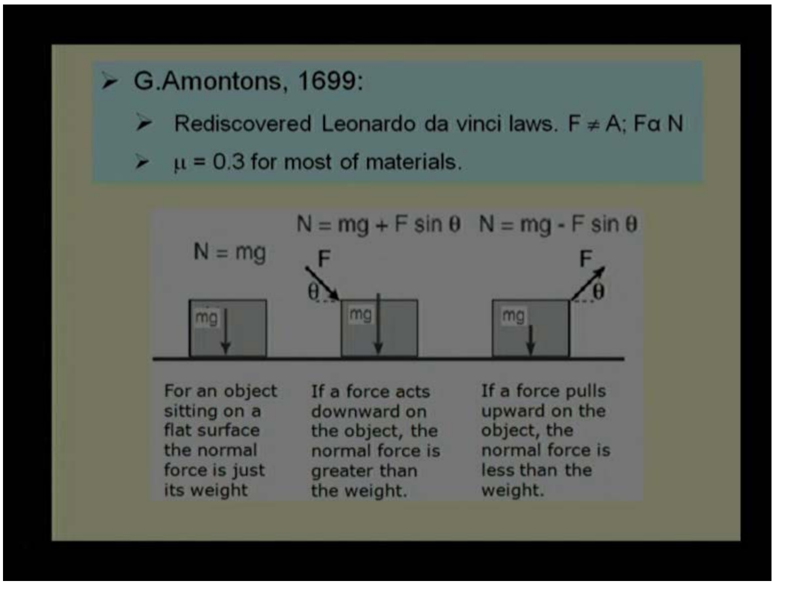
That means we make component in such manner, make surface surface of the material in such manner chemical composition is not going to play much role in that case we can use similar material similar hardness. But, otherwise for common application we should avoid similar material pair and last point which is written here that difference between the mu or static coefficient of friction and kinematic coefficient of friction named use friction in stability which will be curved 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.



So, there is need to understand science behind this friction. It is a start see that we can start with dry friction. We are assuming this this third substance will not available, the lubricant is not available is 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 motion of other components. And there is a possibility of loss of wear, loss of materials wear. There is a there will be a some effect of surrounding medium, there will be surface deterioration and that is why there will be generation of particle generation on debris.

Now, to give complete view let us start with history how friction was evolved or how friction was expressed in some of loss which are generally give in common text books. You say that Leonardo ad Vince was a first person who did an extensive experiments and based on this experiments it could conclude some results. Whatever 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 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 say the friction force does not depend on area of contact, second friction force depends on applied load or weight of the component.



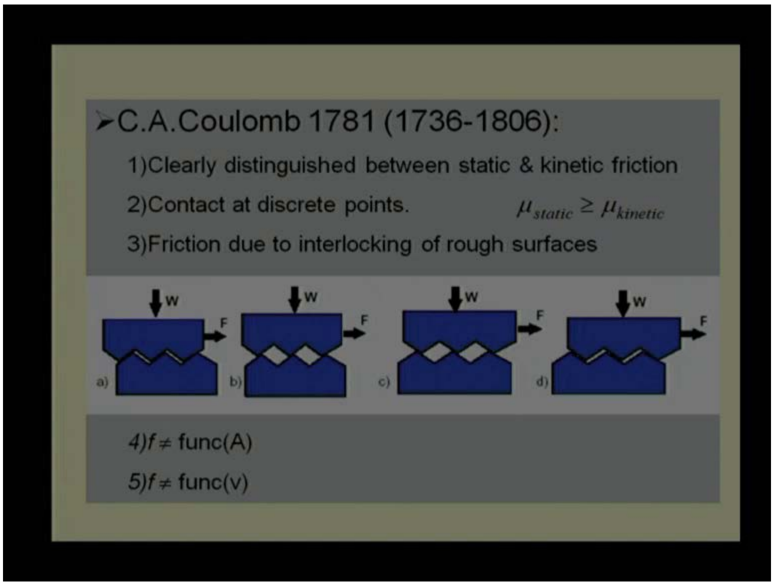
These laws were rediscovered by (( )) and he purposed few laws in 1699. First he also showed that friction force does not depend on area of contact. However, he changed the second law is a friction force is prepositional to normal weight or normal force. He removed the word weight or applied force directly.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

In first block weight is to as gravity downward direction. So, here a normal force will be unchanged. If I push this block and 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 a sort 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 base 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 a 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 that ad ad Da Vinci is allowed the friction force a propositional to the weight is not a real case and (( )) has modified. He said that friction force should be stated as a prepositional to normal force. It is not directly prepositional to weight. Now, how we are applying or how we are pushing that block or pulling that block that is going to 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 a (( )) was that he did a number of experiments and by ban 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 are going to 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.

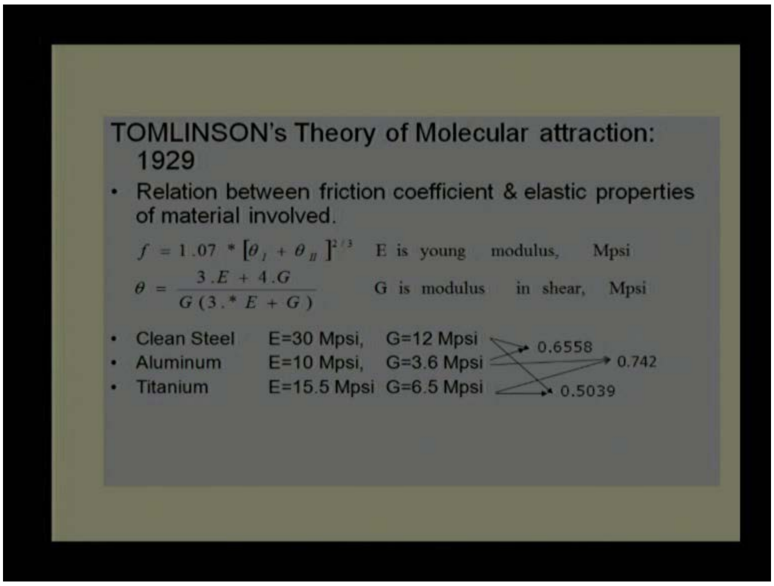


So, these results were encouraging and we account these results. Later coulomb purposed a few additional points in 1781. The first thing first more important thing is it could identify there is a difference between static friction force and kinetic coefficient friction force that was the one of the best achievement very good achievement from the Coulomb. Another thing he could came with micro models he said that aspartic contact will happen. That means, there is a discrete point contacts when there two materials coming into contact. Before that nobody else could pointed out that there is a discrete point 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 something like 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 he taught coulomb thought that may be without any deformation is 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 places 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 there 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 to Coulomb that whether coefficient of friction will depend on velocity, relative velocity because this model was given by him..

It is clearly 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 we 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.



And once is start sliding is 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 is Tomlinson gave a theory related to molecular attraction. He said that one one component or one element is capture 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.

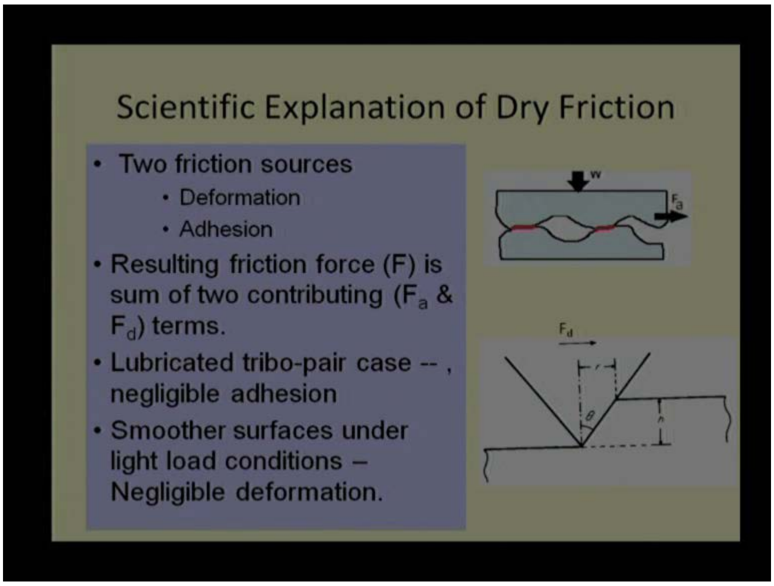
What are those comfort equations? It is something like f is friction force is equal to 1.07 theta one theta two where theta can be given for individual material and he also thought that two two material in one tribo pair applying a role. Theta one is this theta for surface one this theta for surface 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 mention that the material which have a high strength that will have a lesser coefficient of friction and it was also known as after soft a 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 what the coefficient of friction will be lesser. So, this this theory was justified to some extent and just get flavor of theory I took at 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 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 out theta one and theta two substitute this value and I will be to 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 if the clean steel and aluminum, clean steel and aluminum.

Now, higher on coefficient of friction is increasing. That is, there is experimentally observe 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 as higher coefficient of friction. Take a third example we are 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 where experimentally observe results and to some extent and this comfort equation are valid, but, it does not give complete science. It gives the result based on the experiment results is the only imperial relation still science need 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 tendency to attract molecularly or experience molecular force.



Now, we want to start with scientific explanation with dry friction we believe there are two modes of friction or two sources of friction which are called as a adhesion molecular attraction, other one is called deformation. One one surface is trying to deform other surface. So, that you have two friction sources; one is adhesion, where here deformation this one and resultant the 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 lubricant 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 and only adhesion force right. So, there twist strings; we can lubricant surface partially or we say that mix lubrication in case were the adhesion force turn out to be 0 or negligible.

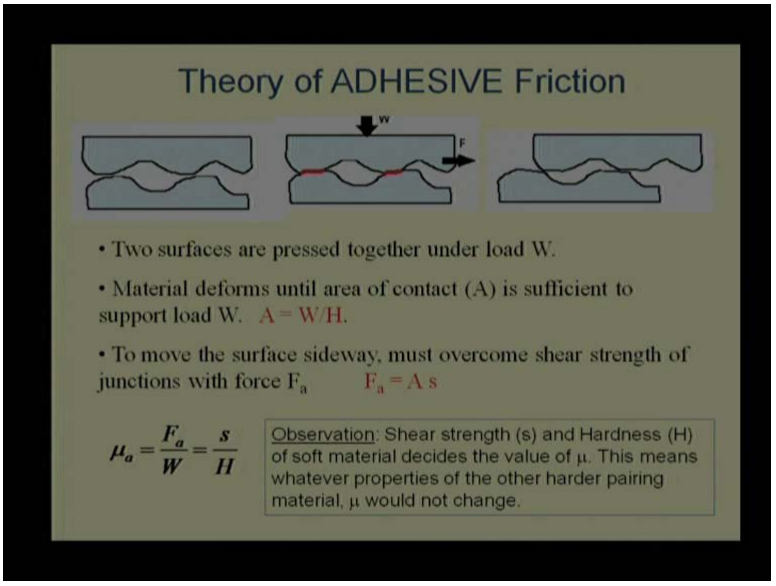
And when we use extra smooth surface then we have a only adhesive force and the deformation force with negligible. We will try to explore about the options and develop individual expression one for adhesive force, other will be for deformation force.

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 experience that adhesion to some extent can play as a good lubricant role. What 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 taken another example is a steel pin is a 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 attach to this rod and that is the material transfer. Indium is transferring the material now this is going to 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 right. So, when we understand this we can say that we can differ, we should design interface in such manner 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.



And that will the strength you need to be lower than indium material than 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 may be say on the plastic deformation and due to that plastic deformation there is a possibility of coal junction formation. This is the cool wilding cool junction formation, is a cool wilding. Under pressure you are applying a force and that is what the this kind of wilding is happening.

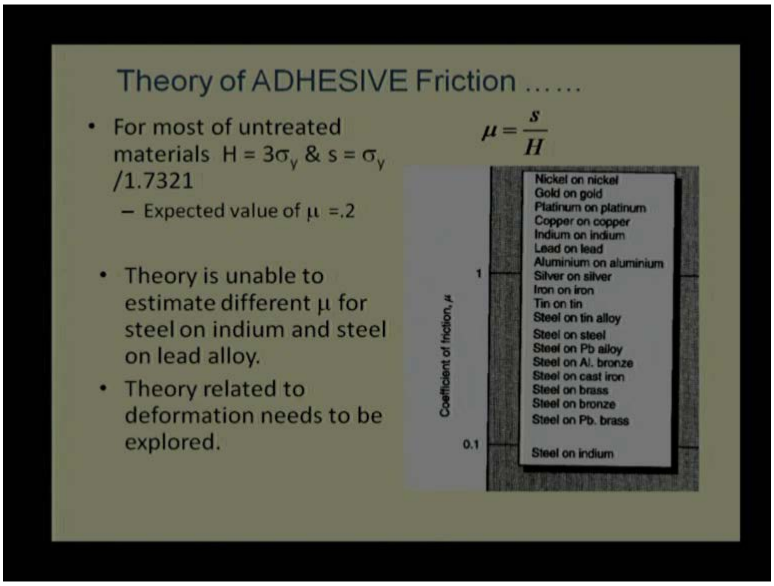
Now, if I apply a tangential force I push on see the push this is component throughout the right side those junction will be shear. Now, depends on how this this components are this interface is sheared. If interface is sheared then there is no problem, but, if the interface is kind getting higher strength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

Because is a plastic deformation is considered that is what hardness is accounted. If you considered only elastic deformation that 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 we using this relation w divided by h and this area need to be sheared whatever the junction has made and 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. F adhesion can be given as a area or real area of contact together this kind of bonds are made into shear strength into the shear a strength of junction. May be variable, may be constant. We can take a mean value of that. So, if I know the the friction force. If I know the normal load I can find out the coefficient of friction that will be symbol relation mu a is equal to f a divided by w. Substitute the value. We say that a into sorry s into a and here it will be a into h; a a 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.

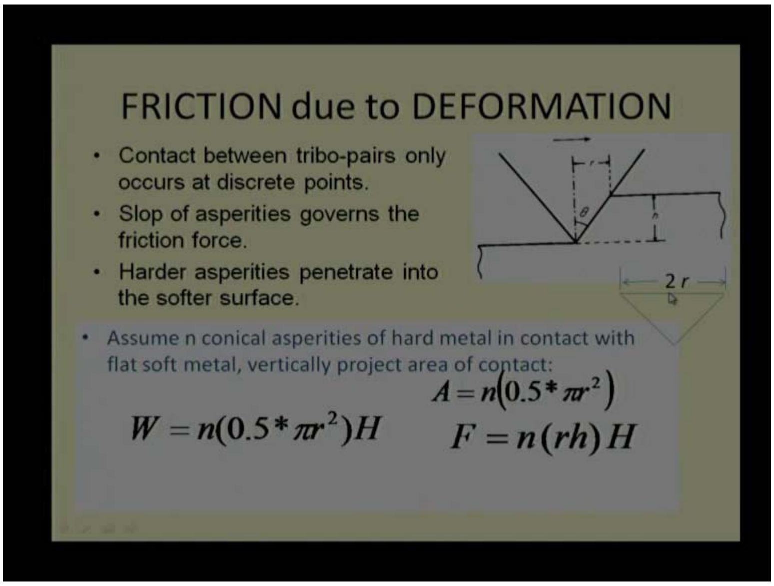
We can find out experimentally, but, estimation using theory is slightly difficult. So, in this case we we are not getting area of contact at all, we are getting s divided by h and both are the material and surface properties and both belong to same material though belong to the soft a material in this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

What is interesting in observation from this 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. It have It needs to some additional theories to explain it. This is what we mentioned over here.



For most of the materials if I if I assume this is not happening now will come to other argument. We say the for most of the material hardness can be given at three times of the Young's three times of yield is strength and shear strength can be given as yield strength divide by root three. That is would not much stress theory here. 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.

Right and this is what is showed initially this stable. 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 a material which is a shear strength is accounted and hardness of a soft a material is accounted. So, this theory is insufficient or unable to estimate different value different value of mu coefficient of friction and there is a possibility that theory of deformation or we say that other source friction source may give some good results as we are not happy with results obtained by this adhesion theory.

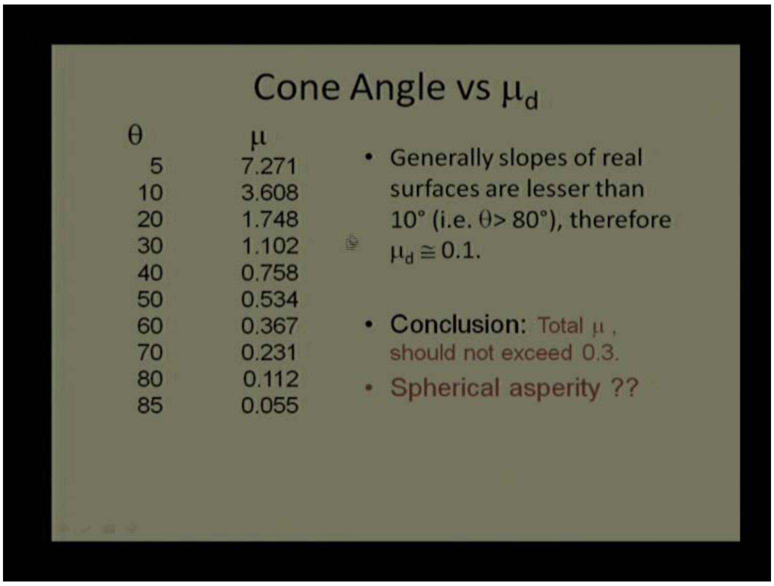


So, let us explore what is the what deformation theory says. The deformation we can assume different kind of asperities because de deformation surface softness playing a important role in deformation.

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 to it as pushed it this conical cavity is at some depth in a soft material; the depth is h and we are trying to push this asperity. So, that sliding occurs right. 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 is applied. 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 to 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 right. 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 I can.

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.

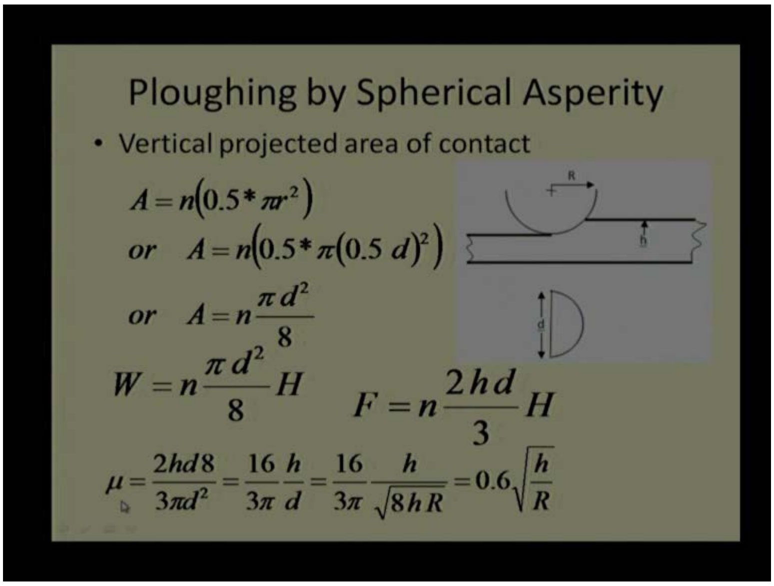


So, what will happen? Some terms will be canceled out and we know expression of the cot theta will come and this theta is known we know this depth we know r they can find out cot in terms of h and r. So, coefficient of friction can be expressed as two divided by pi. So, pi is roughly 3. Something. So, 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 very sharp. Asperities is very sharp in that case what was happen 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 thought the form is that there is a highly sensitivity. This expression very sensitive throughout theta changing by few degree coefficient of friction is changing rustically taken example from five and ten.

The theta is only five did 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 result 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.



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 is the 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 as 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, some radius d by two and depth will also be d in this case. Because is a whatever the cross section I take that will be circle right.

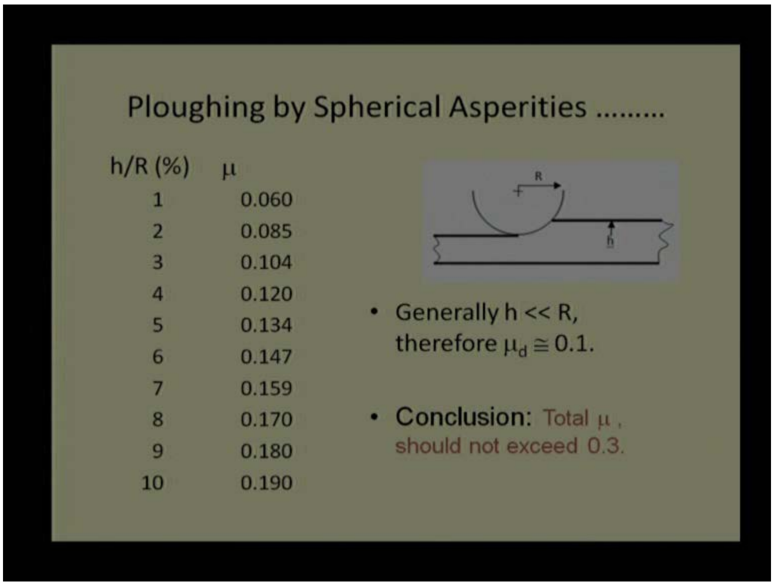
So, whatever I get over here the d by two same radius; I will be getting d by two; however, if I project and perpendicular direction again the depth will be h and other dimension will be 2. So, using this dimension I can find out what will be the area of contact. I can find out the normal force and I 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 turn 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 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 the dimension d. So, we can express d if 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 of particularly to the due to spherical asperities; I can simple say f divided by h expression will be something like this. Rearrange this expression one ten 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 compare to capital r;

that means, depth of penetration is much lower compare to the as 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 is the result 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 can you going to get very high or different results. So, I did that this was 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 valid we have to change expression if you are going beyond that.



Now, coefficient of friction is not very very sensitive as what shown as shown in conical cavity or conical asperities. So, in form 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 even in this case if add or we say that few asperities are conical few asperities are spherical and I will get some intermediate value and, but, after running in time I all conical asperities will be damaged; will be turn out to be some sort of spherical asperities and I may get results somewhere intermediate results. But that is still it is not going to give us satisfactory results which we obtain earlier or we showed in as 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 is how some short coming these are classical theories. We need to expose 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. Thanks for your attention.