Video Course on Tribology
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Lecture No. # 01
Introduction

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What is Tribology ?

- TRIBOS (Greek word) = RUBBING (English word)
- triboLOGY (term coined in 1966) = Science of Rubbing
- A science that deals with friction, lubrication and wear in all contacting pairs.
- Tribological knowledge helps to Improve service life, safety and reliability of interacting machine components; and yields substantial economic benefits.

Welcome to the course on Tribology. This is the first lecture, introduction to Tribology. First question comes in mind to what is the meaning of Tribology. Is it related to travels? Is related to anyway some village related thing? In real fact it is not. It is been derived or this word has been derived from Greek word TRIBOS meaning rubbing. So, you can say Tribology is the science of rubbing. This is one of the easiest meaning or easiest definition of Tribology. However, slightly difficult definition of Tribology is the science that deals with friction, lubrication and wear of all contacting surfaces.

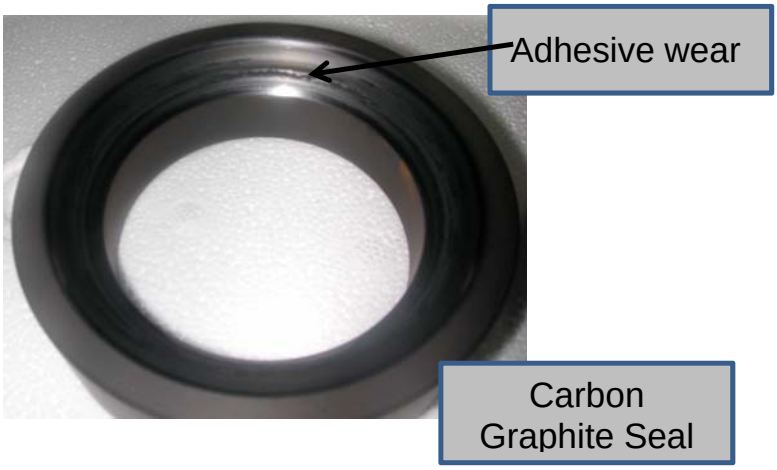
Here, meaning of the contacting surface is that two surfaces which are an intimate contact and subjected to load have some relative speed. So, contacting pairs having relative speed subjected to load comes under the tribological field. We need to understand that subject using tribological knowledge. As I mentioned, this is slightly difficult definition reason behind is that friction itself is a

statistical parameter. It can never get constant value of even though if you repeat experiment again and again. You can get some mean value and some misunderstand variation.
And ratio of mean to extended deviation will always vary depending on whether is the direct contact, mix lubrication or full film lubrication. In case of better the lubrication, mean to standard deviation value will increase. Another point is that we have too many mechanism may be more than thirty two mechanisms. So, understanding all those mechanisms is slightly difficult. That is why we say that this is difficult definition and lubrication science itself is a complete subject. However, if we understand friction, wear and lubrication; gets some knowledge and apply that knowledge to the real machine components.

It will lead to improve service life, improve safety of the components, and increase the reliability of the system. So, if you are able to achieve all this naturally then there will be substantial economic benefits.

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Few Examples requiring tribological knowledge



So, you can say this tribology is most important for all machine elements. We need to understand this machine elements is science related to friction, wear and lubrication of these mechanical elements. To get a better feeling let us start with few examples.

First example which I am showing in this is carbon graphite seal. This carbon graphite seal is made from powder by competing and centering that powder and when it comes into contact with is stainless steel shaft or some other material; there is the possibility of intimate contact, relatives large sliding and applied load. So, it makes a tribo pair. You can see there is some mark some destruction on the surface. It appears some material is removed from this surface and transfer to some other material this is known as adhesive wear occurs because of tribological phenomena, but, it can be delete it can be restarted it can be reduced, by proper knowledge of the tribology.

If you can reduced that; this kind of irregular surface can be reduced. That will reduced smooth or roughness increase smoothness and if there is smooth the surface more and more contact then there is a possibility of lesser stress. It as a lesser stress serviceability will service life of the component will increase. Another view, if I make extra smooth its absolute nanoscale smooth surface that will also cause some problem. So, we can say there is always a trade off between roughness and smoothness and understanding that trade off we require good tribological knowledge. So, we require this course.

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Example 2: Cam



Pitting wear of cam surface

This is what I have shown earlier that there is adhesive wear. We call as adhesive wear because occurs because some intimate contact occurs between new surfaces and then removed from one surface to other surface or transfer from one surface to other surface. Let us

take another example. There is cam, you know cam is used to impact rotary motion and cam follower appear, can be used to change rotary motion to the sliding motion when cam failure occurs or occurred in one tooth paste company. One tooth paste factory where this kind of the pitting failure occur this pits was generated because of the fatigue wear.

You know very well if we drive car on irregular surface there will be lot of noise, vibration that will cause fatigue. Same thing happens in this case. Due to irregular surface or we say that number of pits noise generation increased. That caused machine failure. That can be avoided if you have proper knowledge related to tribology and this can be named as this figure or can be named as pitting wear of cam surface.

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Ex: Journal Bearings



Abrasive Wear



Rubbing Wear

Let us take another example related to journal bearings. We know journal bearings are used to support radial load. Generally they have infinite life if they are properly designed.

I have shown the two figures left hand side figure is bearing of an Ice engine or it is called as a crane shaft bearing. You can see the number of scratches on this bearings surface, it is know as abrasive wear. Well, right hand side this figure is an another aluminum bearing is also known an general bearing, you can see there is more amount of the wear. What we call as rubbing wear where the sharp touches to the bearing surface and runs along with that. Try to scratch the surface with more contact. You can say this kind of wear

occurs when there is a heavy load on a bearing or relative speed is low. Sliding a speed is lesser than desirable.

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Ex: Magnetic Bearing



This kind of failures can be avoided by enhancing the relative speed, reducing load or filtering the lubricant, but, we require proper knowledge to target those ends, that is why we require tribology course. Let us take an another example of magnetic bearing. you see magnetic bearings are known for non-contact levitation, zero wear. We did this experiment in our lab assuming that magnetic bearing under repulsion levitates shaft without any contact, but, it did not happen. Shaft was tilted and started loading the bearing surface. Due to that edge loading, you can see there is enormous wear. It is not only levitation failure it caused wear much more as compare to an ordinary nonmagnetic bearing.

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Ex: Multi-row Roller Bearing

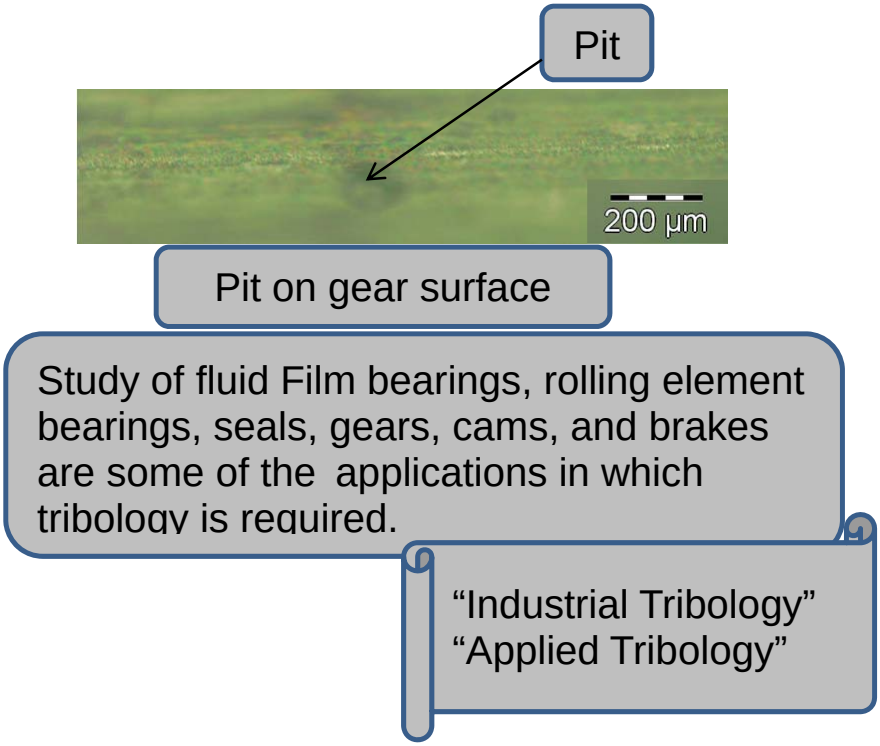


Failure of large size roller bearing

So, we require good tribological knowledge to design this kind of components. We can name this figures as wear scars due to edge loading as I mentioned shaft tilted is shown under operating conditions and cause edge load. We did not impose any side load it happened due to unnecessarily operating conditions. Let us take another example; this multi row roller bearing is four row roller bearing and I am showing only the figure of outer ring wear cracking happen under savere operating conditions you can see there are deep cracks through and through cracks.

Now, these cracks happen if we do not mount bearing properly. So, these bearings fail because of improper mounting. That can be avoided if we go through tribology course understand physics of tribo-pairs and we can really avoid the failure of this big roller bearing which cost huge amount. It is not only initial cost, but, spot edge of cool rolling may cost much more production loss.

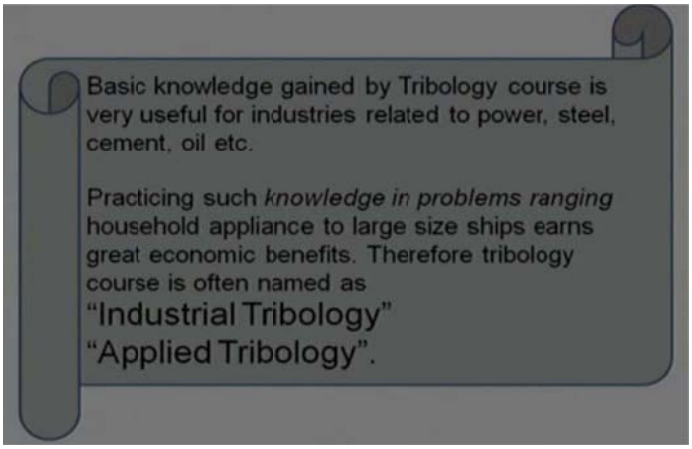
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So, here over all much higher loss compare to bearing costs of this. This is another figure you are seeing the gear failure. This is a picture of gear tooth. You can see there are one pit, second pit, third pit. So, this happens near the pit circle damager, just below the pit circle damager. Due to this kind of pit during operation lot of noise is generated and which is generally not acceptable by customers. So, we need to open assembly gear box and replace this gear. That means, this pit is causing production in service life of gears. That can be avoided by proper lubrication if you understand lubrication properly we can avoid this kind of failure or we can reduce this kind of failure or we can say enhance life of the components.

As pit is show in figure, we can label this figure as pitting failure of gear surface. Apart from this examples there are number of other examples, number of other kind of fluid film bearings. There are more than 20,000 rolling element bearings. Number of seals elastomeric polymer, ceramic scenes, cams various kind of cams in the break materials, every one of this component involve some tribology and we need to understand tribology to do a better design of this machine elements.

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So, we can say if we understand the basic knowledge; we gain basic knowledge of tribology that will be helpful in a industries like power generation industry, steel, cement, oil industries. Apart from these major industries even we can use the tribological knowledge in household appliance as well as very big machine component or big machine assemblies like ships, aircrafts. As this course is highly related to the practice industry; that is why many a time this course is known as industrial tribology, applied tribology.

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HISTORY of TRIBOLOGY

- September 1964 -- Conference on Lubrication in Iron and Steel Works in Cardiff (UK) : Realization of considerable losses due to lack of knowledge related friction and wear of machine components.
- Formation of committee by UK Minister of State for science to investigate the questions of lubrication education, research and need of industry.
- Conclusions of Committee: Interdisciplinary approach embracing solid & fluid mechanics, chemistry, and material science is essential to address lubrication related problems. New name "Tribology" was coined in 1966.

So, once again welcome to this course. I believe I have conveyed the meaning of this course and the importance of this course. Let us just go back how this course is started. How this topic was coined. somewhere in 1964, there was one conference in UK Cardiff; where most of the service engineers from an iron and steel industry participated, they issued, they expressed failures which happened in their industry and surprised this kind of failure happened because a lack of knowledge related to the lubrication, related to the friction and wear. These points were conveyed to UK minister of science and he wanted to reduce this kind of losses. He formed a committee to look into those matters related to friction and wear of those industries.

This committee took almost two years and gave final conclusion that reduction and friction and wear of iron and steel industry machine components is not an easy task. It requires inter disciplinary approach. It requires knowledge related to solid and fluid mechanics, chemistry of lubricant, material science of surfaces, bulk material also. So, that inter disciplinary approach was essential to address problem raised in conference 1964. And there was no common word available the committee chairman Peter Josh contacted oxford dictionary people and then came up with a word tribology. As I earlier mentioned the tribology is derived from the word tribos which means rubbing.

So, this is the easiest definition science related to rubbing is tribology. But, this topic is related to friction and wear of contacting surfaces which involve number of difficult topics.

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HISTORY of TRIBOLOGY

- After 1966, the word “Tribology” has been used for
  - Basic mechanisms governing interfacial behavior.
  - Basic theories quantifying interfacial mechanisms.
  - Solutions to important friction and wear problems.
- 1981: Development of “Scanning tunneling microscope” and systematic theory based on “Contact mechanics”.
- 1985: Development of Atomic Force Microscope
  - Measurement of surface topography & friction force of all engineering surfaces.
  - Studies of adhesion, scratching, wear, lubrication, surface temperatures and measurements of elastic/plastic mechanical properties.

To continue this course after 1966 when that term was coined; wherever people have given mechanisms governing interfacial behavior that mechanism must be termed as tribological mechanism.

Wherever the theories were used to quantify interfacial mechanism; theories were related to tribology. Wherever solution were given to reduced friction and wear problem; solution will be termed as tribological solutions. Major development happened somewhere in 1980's due to development of scanning, tunneling microscope that provides good surface reference profile in non-contact surface profile without damaging to the surface.

However, one major drawback of this esteem was the conductivity it require material to be conductive. So, it could not be enhanced, it could not be use for almost every material. However, that was satisfied in 1985 due to the development of AFM. (Atomic Force Microscope). Major purpose major aim of AFM is to measure surface topography with some additions it can used can be use for the friction force measurement requiring number of tools. This kind of instrument can be used to study adhesion which causes adhesive wear, adhesive friction, scratching. It causes abrasive wear, some other wear mechanism like fatigue wear, corrosive wear, lubrication thin or thick lubrication. It can be used for finding elastic and plastic mechanical properties of the surfaces.

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Need of TRIBOLOGY

- Friction, wear and lubrication have been taught in science and engineering classes, but at a rudimentary level.
- Inherently complicated and interconnected origins of most tribological phenomena.
- Integration of knowledge from multifaceted disciplines.

So, after 1985, we can say that big knowledge came in tribological field and this component were used extensively to study almost all tribo-pairs. to understand this tribo-pairs enhance sufficiency of more machine elements and get overall economic benefits. Interesting! This course has been taught in number of engineering colleges and science colleges at elementary level. Only problem is that this course has been taught at very basic level. The meaning of the

basic level is that most of the, these laws which are given or written in books are based on experimental results.

It is something like friction force is proportional to normal load. In other words if friction force is constant normal load is constant, coefficient of friction will remain constant irrespective of temperature condition, irrespective of lubrication conditions which is absolutely wrong. This kind of sentences or these kinds of laws are applicable in very narrow domain. Let us take an example we say static coefficient of friction is always greater than kinetic coefficient of friction right. It is only used for the metals. The most of the polymers static coefficient of friction is lesser than kinetic coefficient of friction. And have velocity higher coefficient of friction occurs.

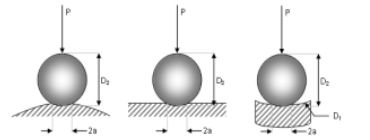
So, this loss which we studied in earlier classes we are restricted to very narrow domain. It cannot be applied in general. We require a course where we can understand this loss and we can utilize for almost all machine components. Another problem is that why this course has not been taught in earlier engineering colleges and science colleges.

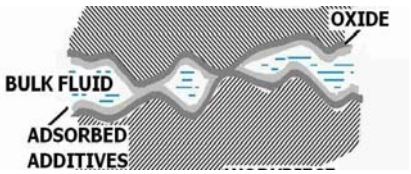
The reason I can say is that this course is a slightly complicated and it interconnects a number of subjects, getting mastery in number of subjects and teaching that course is slightly difficult. That is why it has been always avoided. But, we require two integrate knowledge come from solid mechanics, fluid mechanics, chemistry, material science etc etc. in one course and that is why we are proposing this course.

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Various disciplines in Tribology

- Solid Mechanics: Focus is on expressions of contact stresses and surface temperatures due to sliding.
- Fluid Mechanics: Study of lubricant film formed between various geometric shapes of sliding surfaces.
- Material Science: Focus is on atomic and micro scales mechanisms whereby solid surface degradation or alteration occurs during relative motion.
- Chemistry: Deals with reactivity between lubricants and solid surfaces.





So, that overall economic benefit can be achieved, is through learning and then applying on machine element components. As I mentioned that we want to integrate number of subjects in one subject. Naturally, we need to think what are those subjects? I can broadly see there are four subjects which we need to be integrated into one subject; one is the solid mechanics, fluid mechanics, material science and chemistry.

Solid mechanics is generally related to the forces, stresses strains will be interested to find out what are the contact stresses as a function of surface temperature during sliding. Now, this can be contact, can be between two convex surfaces, flat surface, convex and concave surface. Interesting thing about this subject is that what we generally treat it as point contact or line contact. It never happens. It is always the surface area contact which need to be examined properly to get overall good results. When you think about the fluid mechanics they are more interested to find out whether there will be any fluid film between contacting pair? If there is a fluid film we know contacting surface can be avoided or contributing two surfaces can be avoided.

That will help minimizing wear, reducing the friction and bringing more and more stability in friction experiments. In other words if the surface is lubricated; friction behavior will remain by and large at the same level . But, if the surfaces are under dry contact then, there is more chance of friction, variation or extended deviation. The values of friction will be higher. Similarly, material science deals with atomic and micro scaling, micro scale mechanisms. We understand how surface is degraded. If we understand the surface degradation then we can modify our fluid mechanics and solid mechanics Related theories and get better and better results. Final subject which we are planning to integrate is chemistry. We know the lubricants have some chemical form. You want to know whether those chemicals will spread uniformly on the surface, will attach two surfaces strongly. If it is possible then, requirement of the lubrication or wheel lubrication will reduce. That will help us in reducing overall cost required for lubrication of wheel, lubrication of the surfaces.

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Solid Mechanics → TRIBOLOGY

- Response of solid material to applied force.
  - Elastic, Viscoelastic and Plastic materials.
    - Storage & Loss modulus
  - Hertzian contact pressure.
  - Surface roughness and Real area of contact between surfaces.
  - Behavior modeling of thin layer coatings having different elastic properties than the substrate.
  - Heat source and heat conduction equations.

    Theories related to crack nucleation, crack propagation, and delamination

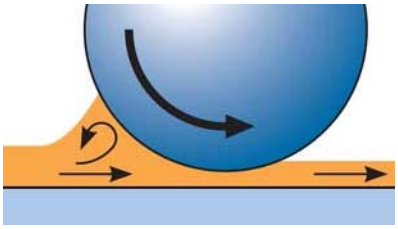
So, we are planning to integrate these courses in one course named as Tribology. Some more detail about the subjects, the solid mechanics you say is related to the applied force. Under application of force; material may behave as elastic material, may behave as visco elastic material or may behave as plastic material. Generally we distinguish between this material based on storage and loss modules. If very high storage modules we can say the material is elastic, very high loss modules we can say material is visco elastic or viscose nature. What are the important topic in this subject is something like a word hertzian a contact we need to find out what is the hertzian is contact pressure.

What kind of stress it will develop? But, this is also related to the surface softness by changing the surface roughness as in contact facial can be changed as we know changing surface roughness will change real area of contact. So, that will change contact pressure. Sometimes we require thin layer modeling of the solid surface if the top layer is behaving is different manner compared to the bulk material. Solid mechanics to some extent will be related to the heat source because of the heat generation due to friction and heat getting conducting away from the surfaces. So, we are involving heat equation to get overall good results. In addition to that, we will be using some sort of friction mechanics where we need to understand how crack is nucleated. and the loading condition of how that crack propagated and finally, delaminated from the surface. So, you relate friction mechanics with solid mechanics. So, that we can utilize this subject for Tribology courses.

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Fluid Mechanics → TRIBOLOGY

- Hydrodynamic, aerodynamic, hydrostatic, and aerostatic theories of fluid film lubrication.
- Theories related to convective heat transfer.
- Rheological behavior of liquid to semi-solids.
- Boundary, mixed and Elastohydrodynamic lubrication mechanisms.
- Viscosity thinning and thickening effects.
- Mathematical modeling of thin lubricant film.



Coming to the fluid mechanics there are two major type of the fluid mechanics; topics in this one is that pressurized, one self pressurization or external pressurization. This kind of fluid which we are using, we can name this topic as hydrodynamic, aerodynamic, hydrostatic, and aerostatic lubrication. By and large hydrodynamic and aerodynamic mechanisms will remain same only fluid and fluid property will change.

In aerodynamic, we need to account compressibility of the air. So, governing equation will involve density term. Well, in hydrodynamic case, density term can be avoided because under pressure liquid is generally non-compressible and that will simplify to some extent, solution, in other word aerodynamic solutions will be slightly difficult compared to hydrodynamic solutions. Similar case is with hydrostatic and aerostatic. Aerostatic means we are using some compressible gas in hydrostatic we are using liquid, but, under external pressure.

We are pressurizing from outside as well in case of hydrodynamic aerodynamic pressure is generated because of the related velocity in self pumping action. Apart from these theories, will be trying to relate the convective heat transfer, coefficient in solid mechanics is generally in connection is treated well in fluid mechanics. Convective heat transfer can be treated properly will be studying some rheological behavior of liquid. We know viscosity will vary under temperature under velocity of sliding conditions.

We will be studying the liquids along with semi-liquid. have taken a typical example of the grease. Grease is a semi solid substance. If you want lubricate bearings with grease; we need to have rheological model and two use that rheological model we need to understand in fluid mechanics. We will be studying something like boundary lubrication, mix lubrication and

elasto hydrodynamic lubrication. Typical example given for the elasto hydro lubrication is rolling element bearings, gears and easiest way to study the elasto hydrodynamic lubrication is that this the roller of slander sliding against a surface. It may be convex surface, concave surface of flat phase that for mathematical treatment we can always make up here with one convex surface and another flat surface.

Same theory can be utilized irrespective of whether flat surface, convex surface or concave surface by changing the factor reduce and if we understand a factor reduce model we can utilize or we can analyze all kinds of machine elements under elasto hydrodynamic lubrication. As I earlier mentioned; viscosity is a function of temperature. Increase in a temperature, viscosity will decrease, but, it is only for the liquids it is not for the gases. In gases under high temperature condition more and more molecular activity will occur. That will create more and more disturbance in fluid parts. That will enhance viscosity.

So, there is a basic difference within viscosity of gases and viscosity of liquids. When we pressurize lubricant oil it gets treated there is possibility of viscosity increase under pressure and we need to do a mathematical modeling of this viscosity behavior. Apart from that will be doing some mathematical modeling related to thin film lubrication, may involve liquid, may involve gas, may involve solids, but, if you want quantification we need do mathematical modeling.

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Material Science → Tribology

- Surface hardening/treatment.
- Development of high/low temperature coatings to provide non-stick surfaces in molds and dies, gears, bearings and military weapons.
- Manufacturing processes to apply nanometer to micrometer thick coating on various materials (material compatibility).
- Modeling of thin and thick coatings.



Coming to the material science; I can see material science has changed tribology significantly. matching the surface properties we can change wear behavior many times, by just coating few micro level coating on the surface life can be enhanced significantly. Take an

example of simple needle which is used to stitch the clothes. If I do not quote with common steel it may get corroded, it may get blunt, it will not be useful. But, just lengthen coating on that needle, enhances the life, may be say ten years twenty years under coating thickness will not be more than ten microns. By changing the material of the surface, you just change material properties of the surface.

We can increase the service life significantly. Similarly, we have seen cars. All cars are quoted may be the toughen coating that will provide better look, better appearance of that car. So, its coating changes drastically service life of the component. Coating can be thin coating or thick coating or it can be just a surface treatment, surface hardening like shot-peeing.

shot-peeing increase the hardness of surface, causes the lesser processing

deformation under subsequent loads. So, that enhances its properties to sustain wear or to torrid wear, it may substance or component much more wear resistant.

We can go ahead with a number of high temperature coatings also. Some time we can use simple solid materials or say solid lubricant and we can rub on the surface get overall good results. Take an example of cam surface if we rub cam surface with molybdenum disulfide powder; it will show much lower friction for at least couple of hours before that layers is delaminated. To form or attach it either we can use the carrier fluid along with molybdenum disulfide or we can use some manufacturing process deposit the particles on the surface.

So, that it can be easily removed from the surface. So, it is important for us to understand what are the manufacturing processes behind these coating technologies or what are the different coating technologies. And again if you want to quantify the tribological behavior of coating then we need to model thin and thick coatings. Mathematic treatment is essential for that. Coming to chemistry that plays a major role and in fact, many chemistry background people are good tribologists. Taken an example of anti wear additives developed by, take an example of surface tense developed by the cams.

Example of extreme pressure additives developed by the cams, but, we can utilize this additives to enhance service life, to increase load carrying capacity of machine components. However, we need to understand what is the compatibility of these lubricants with process fluids. If we understand chemistry of process fluids we can be utilizing this processes fluid as lubricant itself by using adding some additives in those processes fluids we can avoid extra lubrication requirement.

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Chemistry → TRIBOLOGY

- Synthesis of additives:
  - Antiwear additives
  - Extreme Pressure additives
- Compatibility of lubricants with process fluids and contacting surfaces.
- Shelf life of lubricant and its additives.
- Performance of lubricant layer as a function of temperature, sliding, etc.
- Optimizing concentration of lubricant additives
  - Covalent, metallic and Van der Waal bonds.

So, we need to understand the chemistry of lubricant to do that. Understanding chemistry of the lubricant will give some knowledge related to shelf life of lubricants and its additives we know very well all additives have some shelf life.

If oil is kept it will get oxidized if not treated properly and performance of lubricant is generally function of temperature and sliding speeds. If there is a very high relatives sliding speed; naturally there will be possibility of shearing of additives which are mixed with lubricant. So, you know if you are going for very high relative velocity application will be requiring quite different additives compared to additives require for the low speed operations. Further understanding chemistry will help what percentage will suit overall requirement of lubricants.

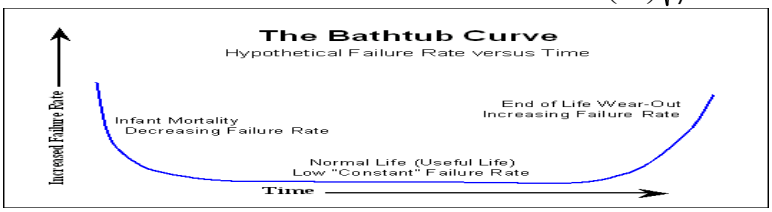
Many a times we use just few percent of additives in lubricant which may not be right. Sometimes .1 percent, .2 percent because additives conflict each other. Let consider an example of detergent. It will try to remove the layer from surface while extreme pressure additives get attached on the surface. If I mix these two without proper understanding one additive will remove the layer and other additive will get attached with surface and overall result will turn out to be 0, no use. We need to have proper understanding between these two kind of additives. Once we have proper understanding that will help us. Sometime understanding of this additives requires whether these are getting attached to the surface due to covalent bonds, metallic bond or weld bond pounds.

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Example to demonstrate the role of
various disciplines in TRIBOLOGY



$$\psi = 0.6\left(\frac{E'}{H}\right)\sqrt{\frac{\sigma}{\beta}}$$



So, modeling of these bonds, modeling of this force is important for us. Let us take one of the very simple example and try to relate these subjects. I am just showing in this figure, component one, component two. Now we try to push component with some tangential force. What will happen? Due to irregular surfaces in contact there will be number of barriers. Either this barriers need to be elastically deformed or ruptured. Then only this top component can move related to this component or else it will not build to more. If it ruptured and there is a possibility of further generation of irregular surface and if this happens continuously machine component will loose its thickness in no time.

However, we if we use this properly then there is a possibility that there is a low contact and lubricant layer is playing intermediate role or lubricants they are getting load. They are supporting load from component one and transferring to other one. So, they are using as a cushion between two surfaces or they are able to express stresses more uniformly. A more area comes into picture comparative low or lesser area due to irregular surface and if I try to project this on one curve, I say that in trying to relate wear rate with a time, sliding time what we get?

Initially there is a irregular surface. It will wear out it will give more and more derby, but, due to lack of further asperities and possibility that no uneven surface is generated or

other surface; there is a possibility of lesser wear and reaching to one steady state after sometime. That is why we call this time 0 to this time as a bedding time. It may take few hours, it may take more number of hours or may cause catastrophic failure depending how we are treating these two surfaces, how are we designing this two surfaces. You know very well after long time again surface will wear out.

If wear is consistent; that may wear occur due to increase in clearance between two surfaces, lesser thickness remain after sometime or may be some other reason. So, generally this part of curve is plotted or used to find out what will be overall overall life of the component. We need to do detailed understanding about these two components how they will come in a contact, whether they are making any adhesive bond or not. If there is a adhesive bond between component one and component two then there will be excessive wear. Even if the one surface is very hard compare to other surface what will happen in that case? Hardest surface will scratch rough soft a surface. However, with hardness of the two components is same.

And they have some sort of toughness and ductility then this surface, asperities will simply tear away without generating additional surface problem on this other component and this behavior will occur. But, we if are using some ceramic components and there is a possibility of fracture of the asperities; very high rough surface will be generated after tearing those asperities. Then there is a possibility that these two curves match this line and removing this intermediate path. So, there is a possibility of failure in this situation. We will continue with this topic in our next lecture. Thank you for your attention.