Friction and Wear of Materials: Principles and Case Studies

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Lecture – 1
Tribology: Introduction

Welcome to this course on tribology of materials principles and applications. So, what we are going to do is that, we will have 40 lectures in this particular NPTEL course. We will start with an introduction of the tribology and also, we will cover various tribological materials or whatever materials they are used for tribological applications. So, let me begin with the statement that tribology is truly an interdisciplinary field because it integrates the concepts of mechanical engineering, lubrication science as well as material science.

What we are planning to do in this specific NPTEL course that, firstly we will go through the basics of the tribology, particularly the friction, wear and lubrication and that will be followed by several case studies primarily from my research group as well as the research group of professor B. V. Manoj Kumar from Indian Institute of Technology Roorkee where we are going to illustrate how to develop new materials for better wear resistance applications.

So, all in all, this course will be suitable for undergraduate students, senior undergraduate students and graduate students pursuing the field of tribology. I am a material scientist by training, so therefore many of the lectures I am going to cover as in my part will also focus largely on the principles of tribology as relevant to material science because this specific subject of tribology can be taught from mechanical engineering point of view as well as from material science point of view.

I think it is quite relevant to state that tribology as a field is widely being pursued in various mechanical engineering departments in the world, but it is not being pursued to that significant extent in the material science departments in different universities of the world. So therefore, it is very important for the students from material science point of view to understand the fundamentals of the field of tribology.

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Tribology: Introduction; Overview of tribological materials

In this first lecture, I will be covering some definitions of tribology as well as I will give an overview of the tribological materials.

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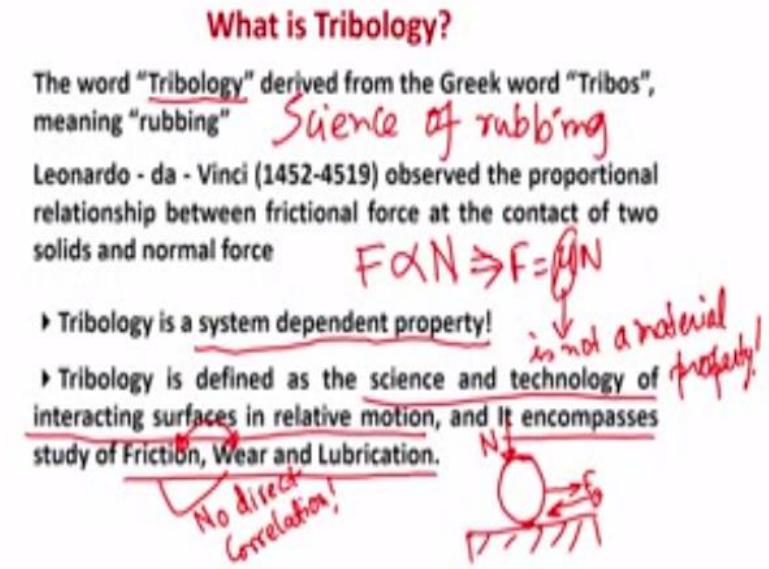

The first is that what is the meaning of the word tribology? Tribology is derived from the Greek word Tribos means rubbing and essentially tribology means the science of rubbing. So, tribos means rubbing and logus means science. If you combine these 2 things, essentially it is known as science of rubbing. Science of rubbing means it essentially means that what is the interaction when two solids are being rubbed against each other.

Little bit of historical perspective Leonardo-da-Vinci observed for the first-time couple of centuries back that, frictional force at the contact of two solids is proportional to the normal force. If the frictional force is F then it is proportional to N, N is a normal force which gives

rise to this equation F = μN. We will come back to these equations later when I teach about the friction or the theory of friction. But at this point of time, it is just important to know that μ is the coefficient of friction, F is the frictional force and N is a normal load.

One of the main things in tribology that, all the researchers should always remember tribology is a system dependent property. So, what it means that friction of steel or friction of stainless steel does not mean anything unless one would ask you that what is the friction coefficient of stainless steel against alumina? or what is the friction coefficient of stainless steel against aluminum alloys? for example. So, it is simply because of the fact that friction is not a friction coefficient that is μ is not a material property.

So, it is a system property. It is not a material property. So therefore, always one is to find out that what is a mating solid? Having said that the text book type of definition of tribology is that it is the science and technology of interacting surfaces in relative motion and it encompasses Friction, Wear and Lubrications. Let me spent some time in explaining you the significance of this specific statement. What it means that when two solids are in motion?

For example, if you take a simple sphere and a flat surface. This simple sphere is pressed against the flat by normal force N. Now if you keep some sliding motion to this particular contact, what it will have? you will have in essentially the friction force that will be acting here. The friction force will always be acting opposite to that of the motion or the sliding motion. Because, the friction force is the force which will oppose the motion of one solid over another.

Now this friction force, if there is so essentially what you can consider that one solid is stationary and another solid is in relative motion. Essentially there is relative motion between 2 solids that is one is the sphere and one is the flat body. So, if there is no relative motion absolutely, then there is no friction and no wear. Now in the field of lubrication, often people develop certain commercial lubricants which are used at two surfaces in motion, then what will happen is that these two surfaces? Often their interaction or their relative motion is inhibited.

If this relative motion is inhibited that means that lubricant is not allowing the two solids to come in close contact with each other, and if it happens, then coefficient of friction can be

extremely small and it can be going to 0.001 or something like that. So that means, essentially the surfaces become frictionless. Some of these are coatings. For example, self-lubricated coatings. The motivation for the development of self-lubrication coatings is to provide the surfaces frictionless.

So, friction and/or wear as well as lubrication are system dependent properties. But friction and wear do not have direct correlation. What it means that, a tribological system can experience low friction but high wear or at the same time a particular tribological systems may experience high friction with low wear. So, what it means is that they have no direct correlation. As I have explained that a same system can have high wear but low friction.

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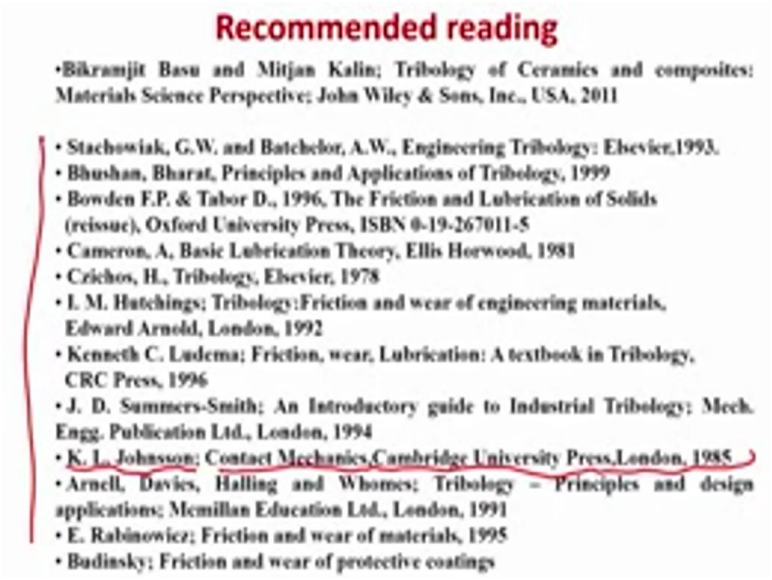

Way back in 2011, we have written a book, myself and my colleague Mitjan Kalin from University of Ljubljana, Slovenia. We have written a book which is published by John Wiley & Sons and American Ceramic Society, the name of the book is Tribology of Ceramics and Composites: A Materials Science Perspective. A few minutes ago, I mentioned that tribology as a field is much more significantly pursued in the mechanical engineering community but to a much lesser extent in the material science.

The major motivation of this book is to provide material science perspective to the tribology of ceramics. But there are of host of other books which are written by Stachowiak and Batchelor. Bharat Bhushan has written books on Principles and Applications of Tribology. Bowden and Tabor, they have also written another book called Friction and Lubrication of Solids; Cameron, Basic Lubrication Theory; I. M. Hutchings from Cambridge University

written a book on Tribology, Friction and Wear of Engineering Materials; Kenneth Ludema, Friction, Wear and Lubrication, a text book in Tribology.

So many of these previous books if you look at, often authors of these books are traditionally from the mechanical engineering backgrounds. The same is true for Mitjan Kalin who is currently dean of Mechanical Engineering at University of Ljubljana, but there are few people who are from material science background who has written text books in the field of tribology.

One of the major books which have much more relevant to tribology and that is Kane Johnson's book that is on Contact Mechanics and that is published by Cambridge University press at least 30 years ago. This book is kind of bible in the field of contact mechanics and many theories of contact mechanics which are directly applied in the field of tribology. So, the young researchers or students who are going to pursue the field of tribology, they can make a note of the different text books which are particularly available in the market.

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Many of the research results that I am going to show you in my following lectures are the outcome of several R & D projects which are sponsored by Department of Science and Technology, Government of India; Department of Atomic Energy, Government of India; Defence Research and Development Organization, Government of India; Indian Space Research Organization, ISRO, Government of India; and BrahMos Aerospace, New Delhi, a joint Indo-Soviet venture in the field of aerospace.

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Also, a large number of students from ceramics background and from materials science background have also contributed to the field of tribology in my lab and many of them are currently faculty members. In those with Manoj Kumar, I have formulated this particular NPTEL course. Debasish Sarkar does ceramic engineering at NIT Rourkela who is currently professor. Ashutosh Dubey is currently assistant professor at BHU Varanasi. Suresh Babu is currently scientist at ARCI. Brahma Raju is currently assistant professor at NIT, Warangal.

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These are like recent group alumni and some of them also have done quite a bit of tribology work in my group in recent past.

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So, these are the most recent people who have pursued in last two to three years in the field of erosion wear, arc jet wear, sliding wear in my group. First few of them, they are from BrahMos Aerospace. I had a long project with BrahMos Aerospace. Then there is this particular guy Arharan, he was a Ph.D. scholar at IIT, Kanpur. Tarak is doing lot of tribology work, particularly high temperature erosion on a new class of ceramics that is niobium boride and he is currently registered as a Ph.D. scholar at IIT, Kanpur.

Ravi finished his Ph.D. and now currently Post Doc. at IISc and he does lot of sliding wear studies at IISc Bangalore.

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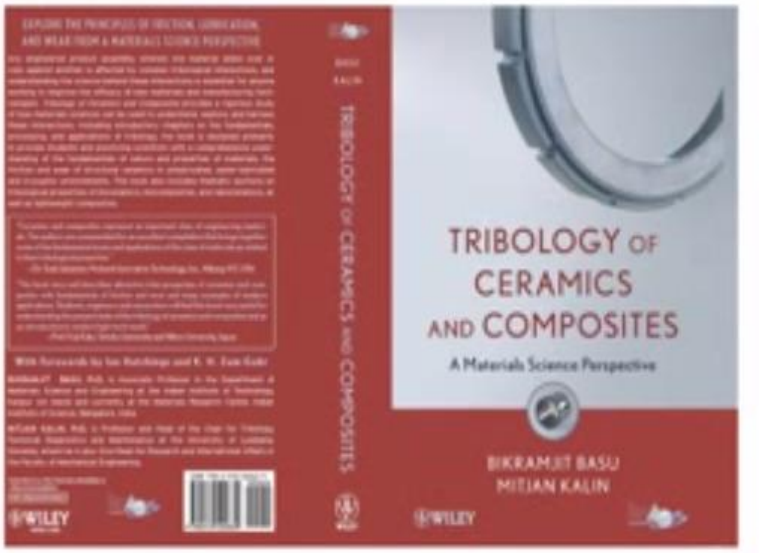

So, this is the book on Tribology of Ceramics and Composites, and this book is become quite popular in the community. We are coming up with another version of the book with myself, Mitjan Kalin and Manoj Kumar. We will have lot of assignment problems and questions and answers for the benefit of the students.

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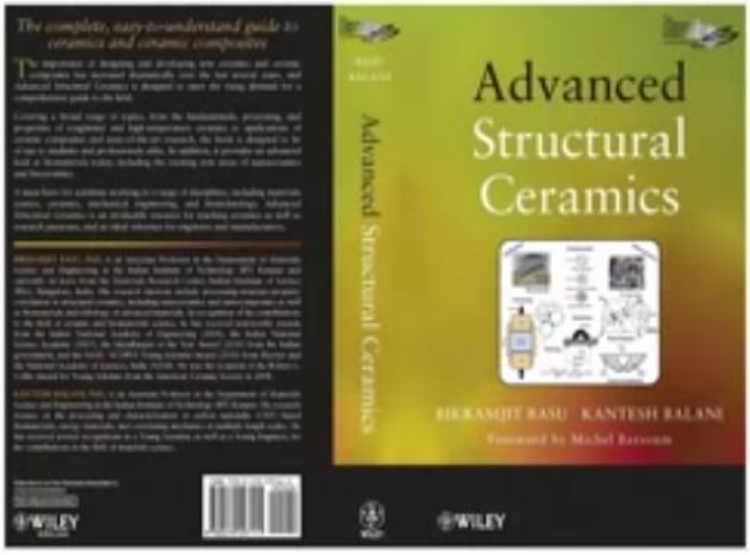

This is another book which is Advanced Structural Ceramics where I have also covered many of the things on structural ceramics and this is published by John Wiley & Sons Incorporated.

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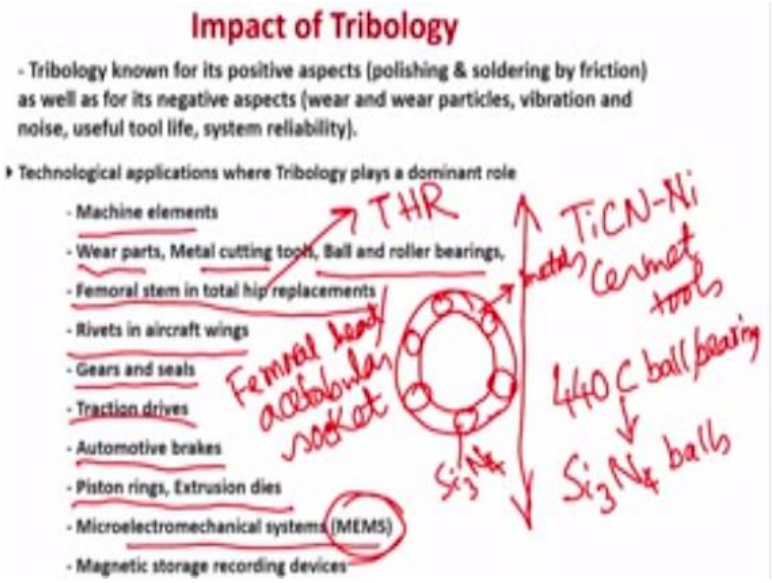

Now why tribology is so important? or in other words what is the impact of tribology in industry to start with? Tribology actually plays a very important role in several technological applications and some of them are listed here. If you can see, mostly these are used as different components in either large machines or some of the engineering structures. For example, the first one is of machine elements.

Second one is wearing part or metal cutting tool like you know some of these are cermets. I think in some of the lectures, we will be using like titanium carbonitride-nickel based cermet tools which are used for the metal cutting. Now ball and roller bearings. Ball bearings, it is certainly 440C martensitic stainless steel, they are used as ball bearings in space shuttles. But we have also done lot of investigations just to show that 440C ball bearings can perhaps be replaced by some of the ceramic bearings like silicon nitride balls.

There is a most recent innovation in the field of bearings. They call hybrid bearings like silicon carbide balls but raceway would be metals. So, these would be metals and then there are balls which will be placed which are fixed between the two raceways and these balls can be silicon nitride balls or sialon balls. This is the concept of the hybrid ball bearings.

Now femoral stem in hip replacements, more than femoral stem it is essentially femoral head and acetabular socket. These femoral head and acetabular socket combination that experiences wear depending on what is the type of the materials that are used in the total hip joint replacement. These are normally people call THR. THR stands for total hip joint

replacement. So, in this total hip joint replacement, what is the femoral head and acetabular socket combination they are used? and that would be very important.

Then rivets in aircraft wings. That is also a place where a tribology plays an important role. Gears and seals that is important, traction drivers, automotive breaks, piston rings, extrusion dies. Extrusion dies, they are used for the metal extrusion and those dies depending on what is the frictional force and these frictional forces play an important role there. Microelectromechanical systems that is also important and magnetic storage recording devices. So, these are MEMS and NEMS, they call micro and nanoelectromechanical system, MEMS or NEMS, though they also play an important role in the field of tribological applications.

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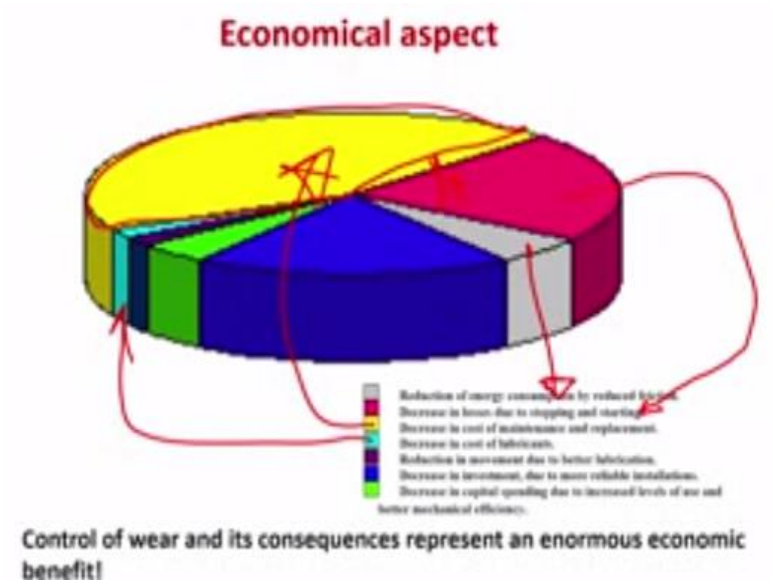

Now, if you look at the economical aspect. It has an impact on the industry, definitely it will have an impact on the national economy. So, this is the kind of a qualitative, not a pie chart. Qualitative chart where you know different color sincerely represents different aspects. For example, this red essentially shows decrease in losses due to stopping and starting of the machine. This one is directly related to reduction in energy consumption by reduced friction.

Then there is something other things are there, this one is related to the decrease in the cost of lubricants. From this particular angle suppose if it is θ, θ/360 will determine what is the total fraction? That is very important. Now cost of maintenance and cost of replacement that is by far the larger fraction which impacts the nation's economy and the industry as well. I have

mentioned here the bottom line is that control of wear and its consequences essentially represent an enormous amount of economic benefit.

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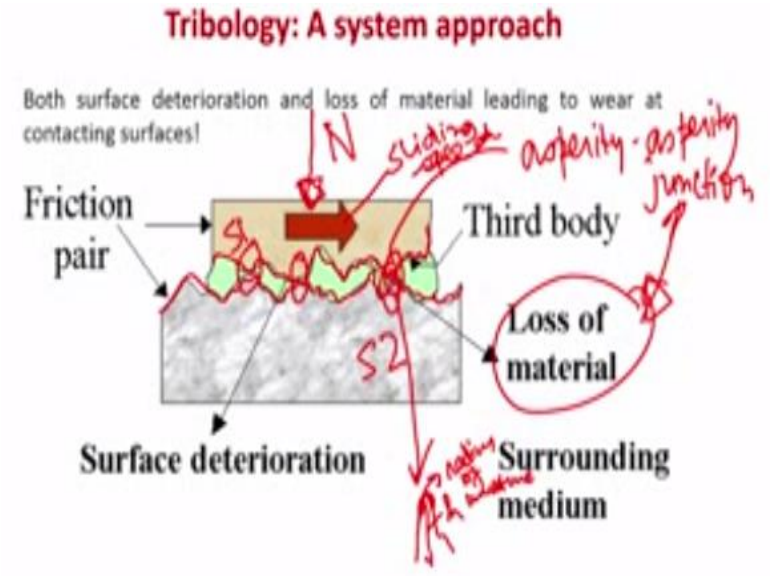

So again, let me reiterate here that the tribology is a system dependent property. What you see here that there are two solids. Let me spent some time here to explain. There are two solids and I have shown you the top solid is being placed against the bottom solid. So, let if you take this is the S1, solid 1 and this is the S2, solid 2. The top solid is being placed against the bottom solid and what you see here is the projection of this asperity from the top solid and from the bottom solid you see that there is a projection of the asperity.

From these two asperities, they meet at certain points and this is the particular spot, asperity-asperity junction. This asperity-asperity junction will experience a friction depending on the load and the sliding speed. These particular asperity-asperity junctions can get knocked off, can get knocked off and then that can lead to the wear.

So essentially these are the potential asperity-asperity junctions, so essentially the arrow should be this way, that leads to loss of material in the surrounding medium. So, what it means is that a material based on the whatever surface finish or the polishing. The material may appear to you as extremely flat. But in reality, it is not extremely flat. In many literatures, they are mentioned as the material is nominally flat. But nominally flat materials also have a finite number of asperities and these asperities have certain radius of curvature and surface height.

So, if you blow up these particular asperities here, these will be having like this, so this is your height h and there is also radius of curvature here. So, this radius of curvature is very important and this height is also very important. Depending on the radius of curvature and sharpness of the asperity, the coefficient of friction that will generate. So, what you can see as a complete total frictional force? This total frictional force essentially is the summation of local frictional forces here at different asperity-asperity junctions.

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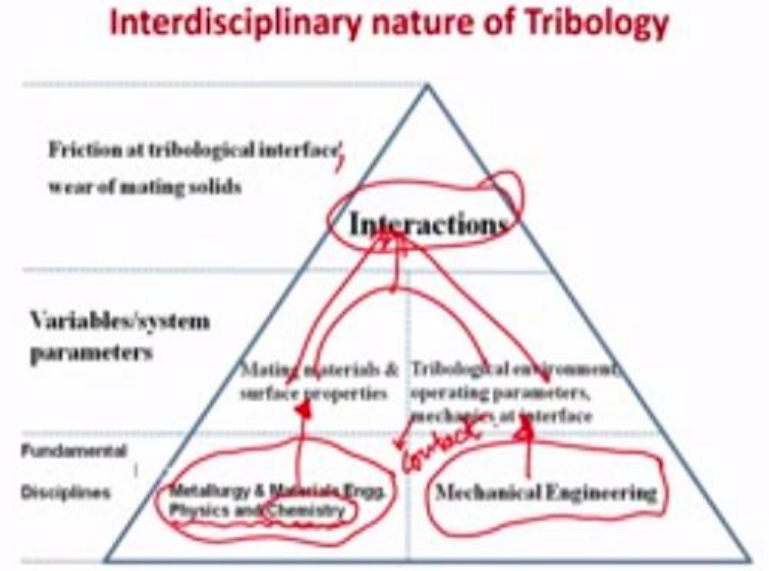

As I said before, the tribology is an interdisciplinary field and its interdisciplinary nature can be attributed to the fact that the fundamental disciplines of this tribology are Metallurgy, Material Science Engineering, Physics and Chemistry and also on the other hand Mechanical Engineering. Why physics and chemistry? Because many tribological interactions like frictional force that will be generated, what is the physics of the mechanism? you need to bring lot of physics-based concepts.

Why chemistry is important? Many lubrication designs or the fluid lubrication, what is the lubricant additives that you use? what is the EP additives (extreme pressure additives)? So those things require lot of knowledge from the chemistry. Now Metallurgy and Materials Engineering, from there you can develop mating materials and that will have surface properties. Mechanical engineering that will lead to the tribological environment, mechanics of the interface, contact mechanics of the interface. So, this is the contact mechanics of the interface and operating parameters.

Now these two interactions essentially lead to the friction at tribological interface and wear of mating solids. So, essentially the interactions between mating solids and interactions between tribological environment that will result in the friction and wear.

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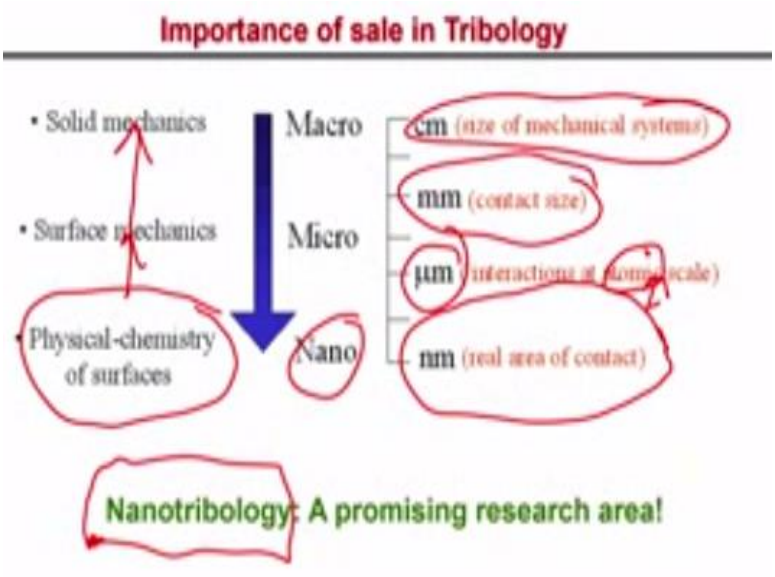

What is the importance of scale in tribology? If you start with the physics and chemistry of the surfaces with nano scale, you have the real area of contacts. So, if you go back to the previous slides where I have shown. This is that actually nano scale introduction, so this is the place and this is called nano scale interaction. Then if you go to the interactions of the atomic scale, then it will go even larger.

Interactions in the atomic scale are of micrometers, then contact size is in millimeter scale and the mechanical systems that we will have centimeter scale. You go from physics and chemistry of surfaces to surface mechanics to solid mechanics. So, nanotribology essentially means friction and wear of surfaces in relative motion but at the nano scale. Whenever that mechanism operates at the nano scale, we call it is a Nanotribology.

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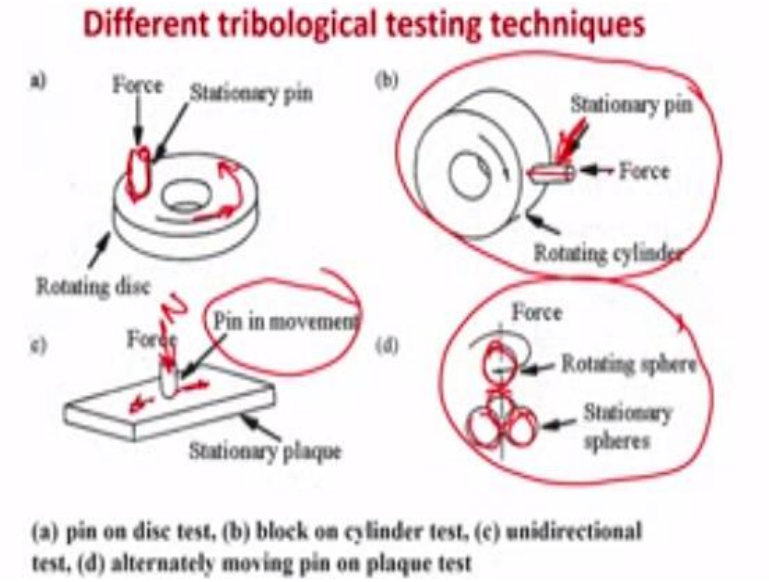

(a) pin on disc test, (b) block on cylinder test, (c) unidirectional test, (d) alternately moving pin on plaque test

What are different tribological testing machines? This is more from experimental research point of view. You have a pin on disc which is by far most commonly used machine in the laboratory. So, this is your pin and this is the unidirectional motion. Stationary pin and this is the rotating disc, so this is a pin on disc. So, this is the pin on cylinder, so you have a pin here and this pin is pressed against the drum or rotating cylinder by force, this is a pin on cylinder.

This is called pin on plate. Essentially this is a reciprocated motion sliding motion, this is your force N, so this pin is placed against that. This is your 4-ball tester and 1 ball is here and these are 3 balls, so this 4-ball tester, widely used for the lubrication testing.

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This is the commercial machine. This ball is placed against the flat and one of this mating solids is rotating here and here in this particular case disc is rotating at certain rotational

speed like rpm and then as a result ball and flat; this particular system experiences friction and wear. We will come back to the next lecture after some time. Thank you.