Friction and Wear of Materials: Principles and Case Studies
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Lecture – 06
Wear
Wear Mechanisms: Adhesive Wear

Hello, welcome to this NPTEL course on friction and wear of materials: principles and case studies. I am B. Venkata Manoj Kumar from IIT Roorkee. So far Professor. Bikramjit Basu of IISC Bangalore has given lectures on fundamentals of the friction, lubrication and overall tribology of engineering materials. So, continuing this; So today, I would like to give a lecture on the wear and then we will also describe the adhesive wear mechanism in this lecture.

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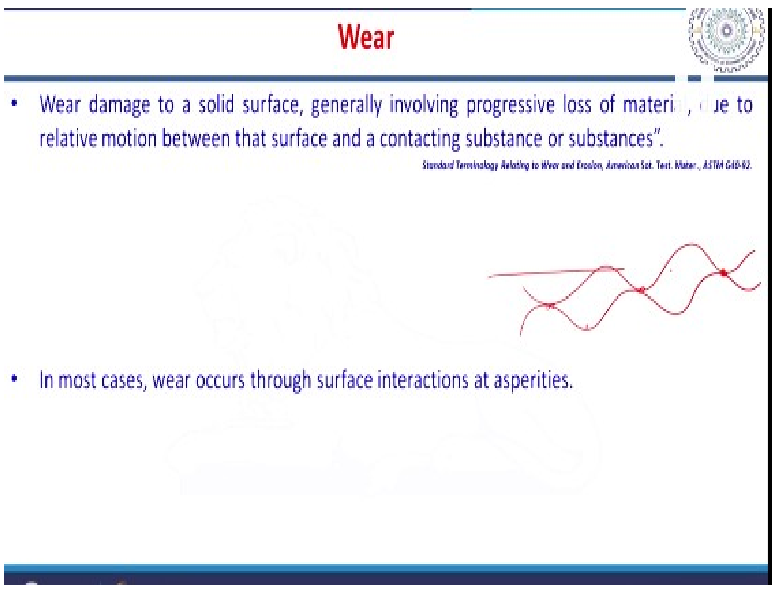

So, wear is a material loss to a solid surface. When two materials are in contact at their surfaces and they are in relative movement, the material removal because of this movement is called the wear or the material loss because of this movement is called wear. So as per the American Society for testing and materials (ASTM), the definition of the wear is; wear is a damage to a solid surface generally involving progressive loss of material due to relative motion between that surface and a contact in substance or substances.

In most cases wear occurs through the surface interactions at the asperities. So, every material has a surface which is not actually a flat surface. Whereas microscopically this surface has certain peaks and valleys and we call them as asperities. So, one surface with a different asperity levels will be interacting with the other surface asperities and then the material removed at the asperity levels is actually we call it as a material loss that is termed as a wear.

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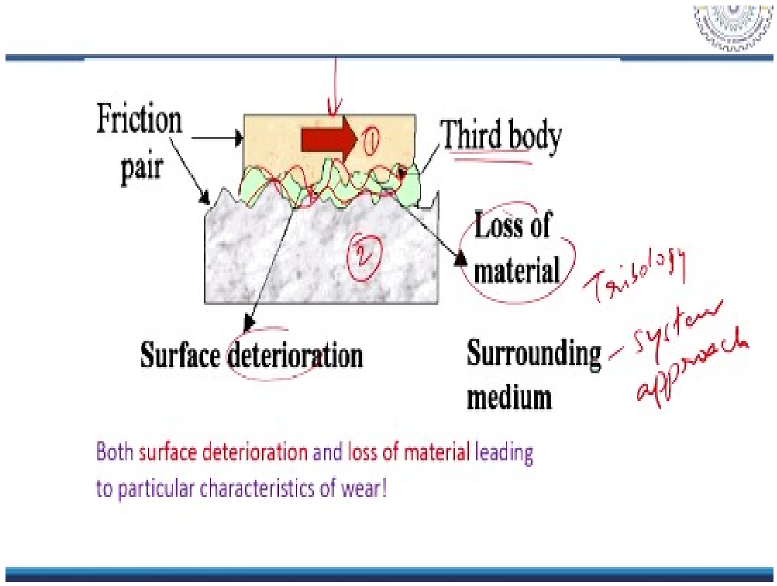

So, if you have a body and a second body and they are in relative movement and the asperities they come in contact of these two surfaces, right. And then under this loading conditions, the sliding movement. So, you have a friction generated at these asperities. And these asperities, the friction induced material loss is called wear. So, you have a deterioration even at the surface or inside the material. The loss of material or the surface deterioration both are called wear.

So, for the wear to happen, there has to be a friction, right and this friction generates wear and this wear generates certain material called third body. This is first body, second body which are in relative movement and the material removed is actual becomes a third body, right. So, both these surface deterioration and loss of material lead to the particular characteristics of wear and this wear is not a material property. It is actually a system property.

So, wear is actually dependent on the materials which are involved and also the conditions in which this such a wear is happening and also the environment in which this wear is happening.

so, all these account for the wear behaviour of a material. So, we called a wear or the tribology is a system approach, right.

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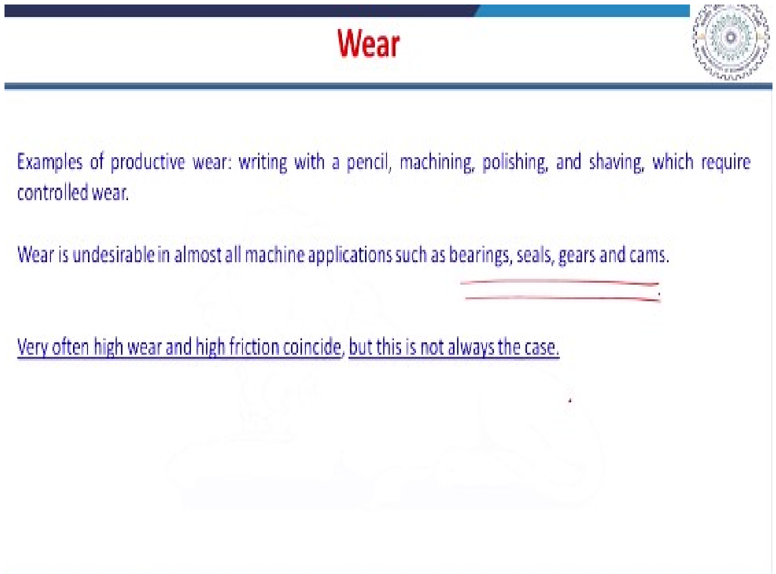

So, examples of wear: you know writing with a pencil or I am writing with this pen on this board. So, at the tip of this pen there is certain friction and that is generates a very minute amounts of the material loss. May be over a long period of time, the material removal may be considerable, right. So, writing with a pencil or writing with the chalk on a board is itself wear. The material that leads to the material loss that we called wear of this pencil or a pen or this chalk.

Machining; right. Every engineering material has to be given a shape through a machining process. what do you do? A material will be worn out by a controlled process that we called machining. A polishing; a surface homogeneity can be obtained by polishing a material on certain other time material. So that, polishing is itself a wear. A progressive loss of material that leads to polishing off a certain material surface. Even shaving which required all.

So, all these wear processes that we need or sometimes when we walk on the floor, you have certain friction. Right. So, the friction is a desirable or the wear is not desirable. Right. So, for certain instance we require wear. So, wear is undesirable in almost all machining applications such as bearings, seals, gears, cams, piston and cylinder linings. All these things we do not require the material loss.

So, our approach is to reduce the material loss. When I tell about a relative movement that leads to wear. So, very often high wear and high friction coincide. But actually, this is not the case always. Right. For example, if you take a ceramic material, wear is very less whereas the friction is high. Right. So, you cannot say if high friction always leads to high wear. In general, it is not always the case that always high wear is a resultant of a high friction, right.

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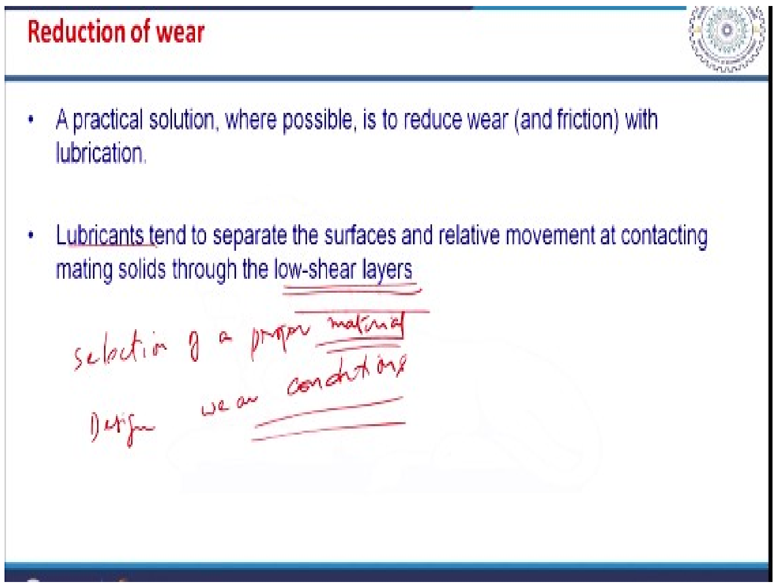

So, how to reduce the undesirable material loss? The undesirable material loss can be reduced by applying certain lubrication between the two surfaces where they have a contact. That means, you have to give certain lubricant material and that tends to separate the surfaces and relative movement at the contacting mating solids through forming a low shear layer. So, that leads to lubrication.

Professor Basu has already explained to you about the lubrication and the fundamentals of the lubrication, regimes and mechanism so far, right. So, one way of reducing the wear is by applying a lubrication. Then what are the other ways to reduce the wear? You select a proper material, right. Selection of a proper material for the given application; So that you get a better wear resistance, right.

So, you design the parameters or the wear conditions. You design the conditions of the wear or you can say you use the component in such a condition where you get a less wear, right.

So, how to reduce a wear? By proper selection of a material or proper condition of the wear either by operating parameters or by certain environmental parameters. So, you can reduce the wear.

The best way is to apply certain lubricant, right. So that lubricant forms a low shear layers at the contacts. So, the wear becomes less right.

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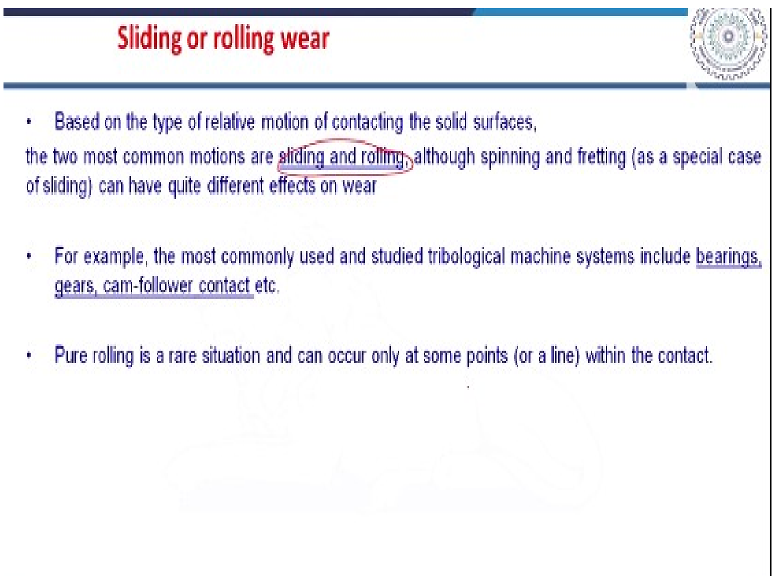

So, when we say the wear? The wear in engineering applications generally happen in sliding conditions or in a rolling condition although, spinning and fretting can have a quite different effects of wear. But generally, based on the type of relative movement of contacting solid surfaces, most common movements are sliding and rolling. Among the sliding and rolling, you have sliding more dominant than the rolling in most of the engineering applications.

In other way, pure rolling is a rare situation and can occur only at certain points or lines within the contacts. So, you have actually the micro sliding rather than rolling. Sliding wear: how to study such as sliding wear behaviour of a given engineering material? The major aspects of the sliding wear test methods include the materials of which each of the two bodies in the couple are made.

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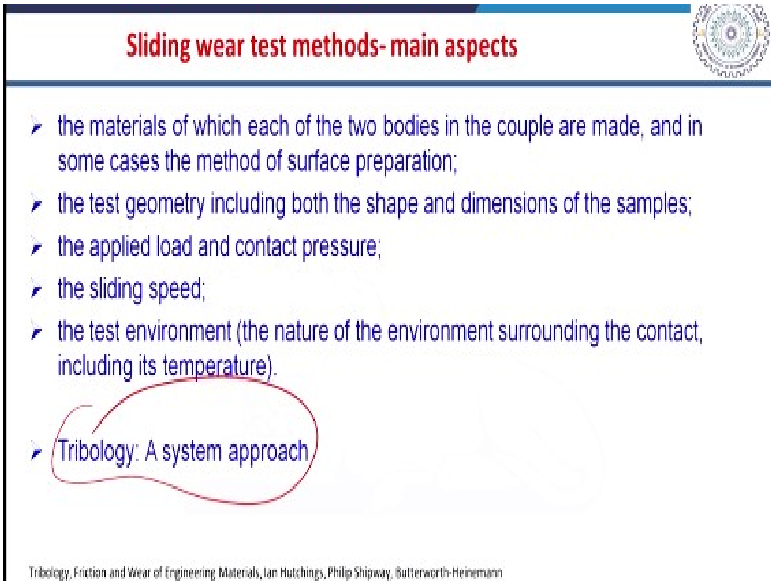

And in some cases, the method of surface preparation or the test geometry including both the shape and dimensions of the samples; the applied load and contact pressure; the sliding speed; the test environment that means the nature of the environment surrounding the contact including its temperature. So, if you look at that all these aspects that we consider for understanding the behaviour of engineering materials in sliding wear conditions, you can say this behaviour of the wear is a system approach or you can say the tribology is a system approach rather than a material specific rather than operating condition specific rather than an environment specific. It is actually a combination of all these operating conditions, environmental parameters and the material parameters altogether gives a property called tribology or you can say the wear. So, the wear behaviour is a system dependent behaviour, right.

So, it is very interesting to see several geometries are available for the sliding wear testing or we can say the apparatus with which we study the wear behaviour in sliding conditions are called tribo testers or sometimes it is called friction and wear testers. Right.

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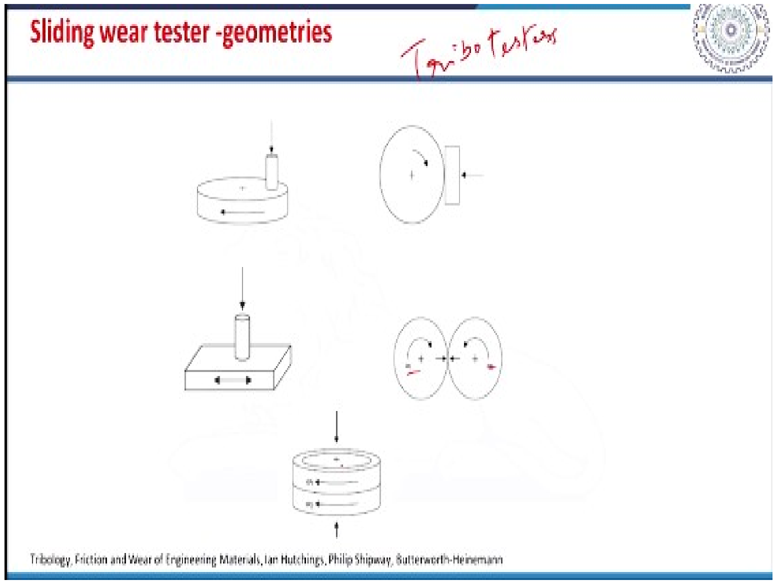

So, these are certain important geometries of the sliding wear testing apparatus. For example, here you can see a pin and a rotating disc, right. Here you can see a block on a ring or you can see a reciprocating movement of a disk in which the pin is with the contact under the loading conditions.

Or you can see two discs is rotating at certain speeds and two flat discs in contact, right. These are all important geometries of the sliding wear testing apparatus.

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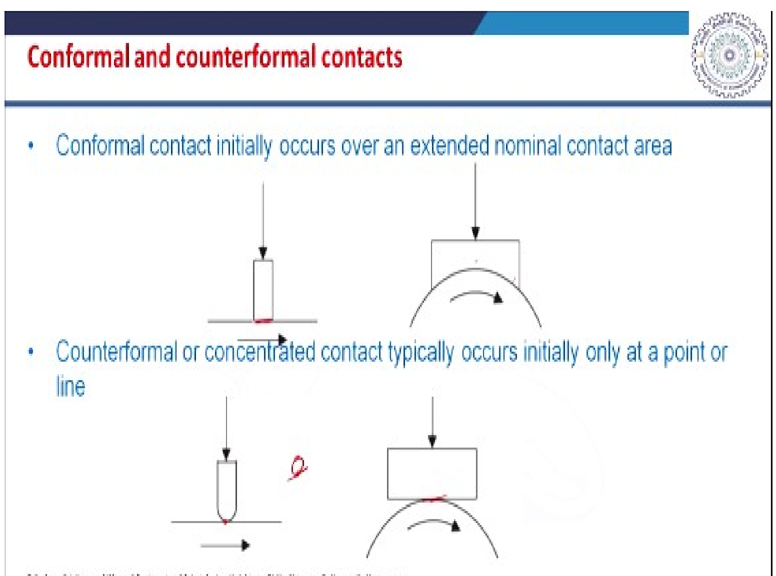

If you look at the contacts where the sliding wear is can occur, there are actually conformal and the counter formal contacts. Conformal contact initially occurs over an extended nominal contact area. For example, you have a pin which is having a large area of contact with the other surface, flat surface or you have the block on a ring. So, you can see the large nominal contact area. Whereas, in case of a counter formal or concentrated contact this typically occurs initially only at a point.

You can say the pin with a rounded bottom, right. So, sometimes you can also say a ball on a disc or a ball on a flat where you have a point contact or you can see this for a line of this block on a ring. So, you have two types of contacts. The conformal contact and a counter formal contact. Generally speaking, Counter formal contact is present where you have certain point contact or line contact, rather than an extended nominal contact area.

So, these cases you have higher stresses generated, right. Under the given loading conditions, the stresses are few magnitudes higher than this stresses at these contacts of conformal.

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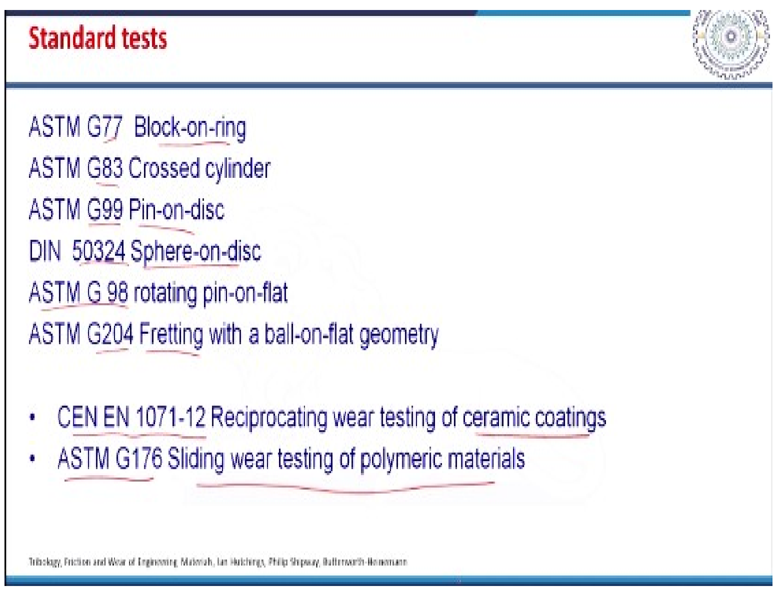

There are several tests nationally or internationally standardised to understand the behaviour of these engineering applications in sliding wear contacts. For example, block on ring we have an ASTM standard of G77, crossed cylinder we have ASTM G83, pin on disc we have ASTM G99 or sphere on disc we have DIN 50324 or a fretting with the ball on flat geometry ASTM G204 or rotating pin on a flat ASTM G98.

And with respect to the material also, there are a couple of standards available. For ceramic coatings the reciprocating wear testing, we have the CEN EN 107112 standard test or for the sliding wear testing of polymeric materials, we have ASTM G176. So, there evolved certain standardised test methods for understanding the behaviour of materials in the sliding wear conditions.

An improved understanding of wear mechanisms and material properties together with technological parameters can lead to substantial improvements and tailoring of such material damage processes. So generally, what we do? After the wear has happened, that means material loss occurred.

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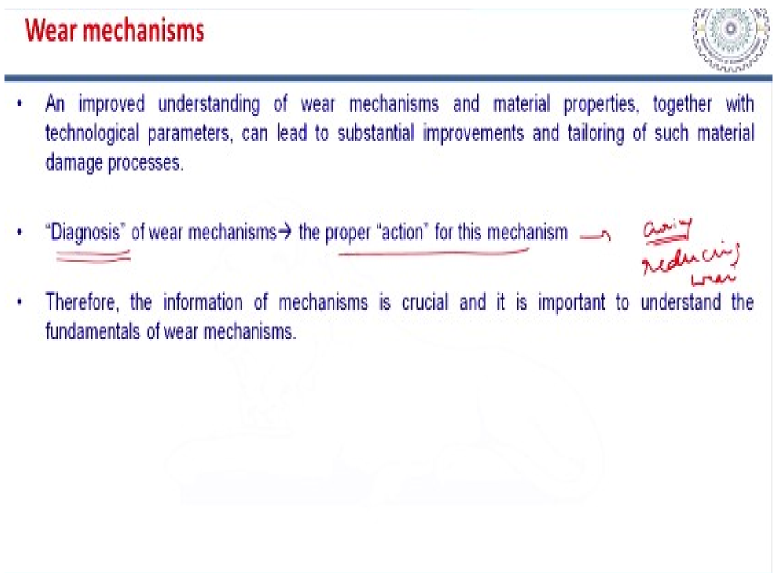

Then we go for you know post-mortem analysis or we can say a diagnosis of wear mechanisms. That will be helpful to take a proper action for this mechanism. So that further wear can be reduced or you can say, that can be used for curing of this wear or reducing this wear, right. This understanding is useful for reducing the wear. So, first to diagnosis of the wear mechanisms. This will be helpful to take a proper action. So that the wear can be reduced. Therefore, the information of different mechanisms is very important and it is very important to understand such fundamentals of those wear mechanisms, right. So, the mechanisms through which the material loss is happening, the mechanisms through which the material removal is happening is called the material removal mechanism or we called wear mechanism.

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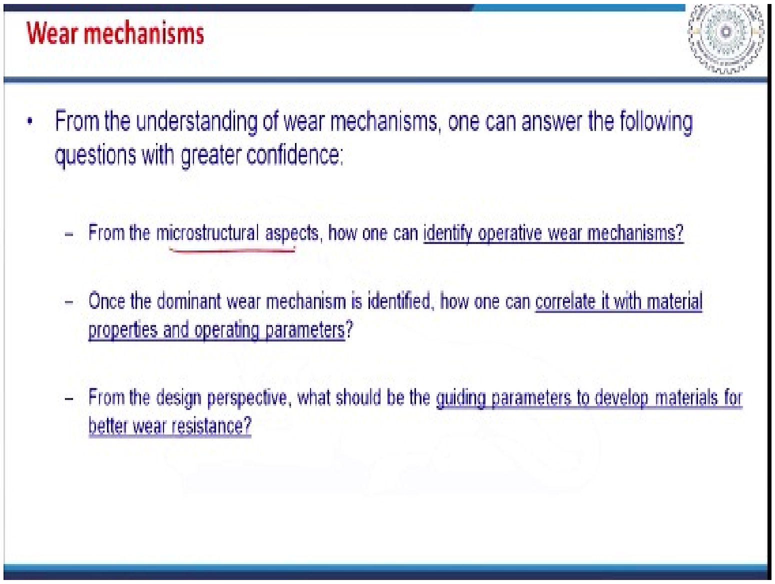

So, from the understanding of wear mechanisms, one can answer the following questions with the greater confidence. From the microstructural aspects, how one can identify operative wear mechanisms? There can be multiple wear mechanisms happening but you have to identify what are the multiple operative mechanisms? Out of them which is dominant in a given conditions of wear for a given material system.

So, once the dominant wear mechanism is identified, one can correlate with the material properties and the operating parameters, whether you have a hardness influence on the wear resistance or a toughness or any elastic models or you have a load influence on the wear or the temperature. So, you can actually correlate, if you know the wear mechanism. You can correlate it with the material properties and operating parameters.

And from the design perspective what should be the guiding parameters to develop materials for better wear resistance? So, for a given application the material system was selected and the material system selected in a given applications whether it is giving a better wear resistance or is there any window of the parameters in which the wear resistance is superior? So, you have to select such parameters. For that you have to know the wear mechanisms.

So, wear mechanisms can be useful to identify or to guide the parameters in developing materials for better wear resistance. In general you know sliding of metallic materials you have plastic deformation at the asperity levels or you may have an oxidative wear in an ambient condition. So, you have a plastic deformation oxidative wear are dominant for the sliding of metallic materials.

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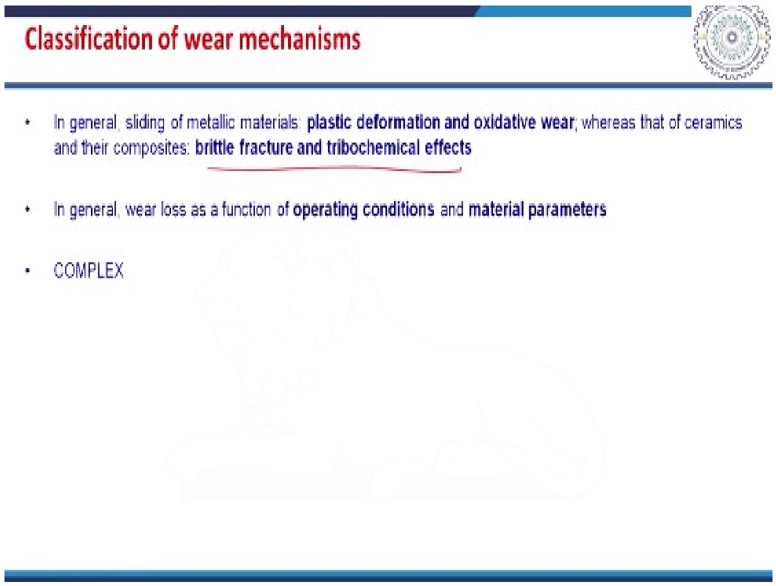

Whereas that of ceramics and their composites, you generally find the brittle fracture and tribo chemical effects, right. In general, wear loss has a function of operating parameters and material parameters. So, operating conditions include the environmental as well. So, it is a very complex phenomenon that progress of the wear is a complex phenomenon to understand that you have to understand it with a system approach.

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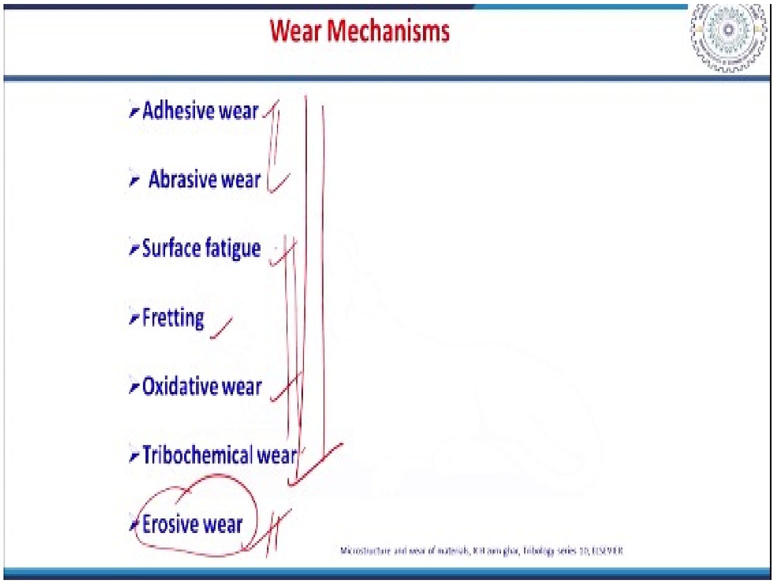

So, there may be multiple mechanisms of material removal. For example, adhesive wear, abrasive wear, surface fatigue, fretting, oxidative wear, tribo chemical wear, erosive wear. If you look at the identified wear mechanisms, there are at least you know many numbers of wear mechanisms identified. One can say there are more than 30 wear mechanisms identified.

But out of them, these are very important wear mechanisms and the remaining may come as a sub division of or a subsection of these major mechanisms. Again, out of which you can see the tribo chemical wear, oxidative wear, fretting and fatigue that leads to a bit mild wear. Adhesive and abrasive lead to severe wear. Erosive wear is a different wear where this is not actually the sliding, there is an impingement of a particles or fluid that leads to the material removal, right.

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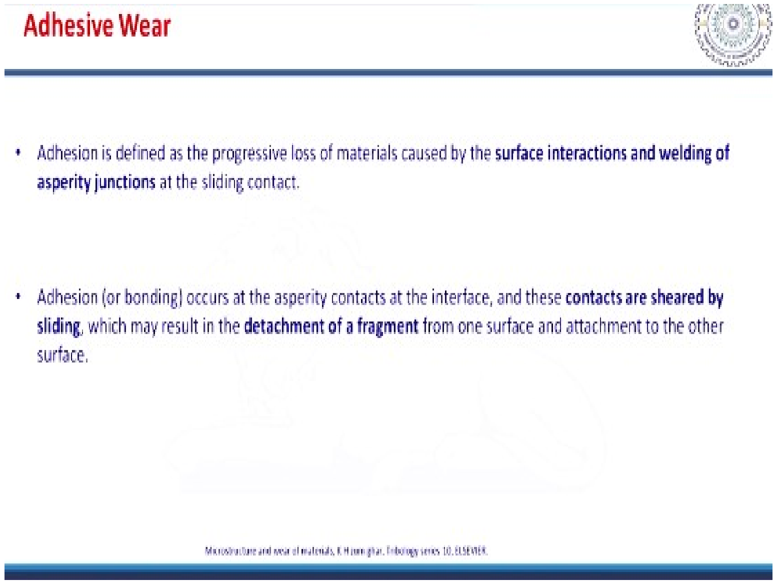

We will deal this later. So, first let us understand this adhesive wear. Adhesion generally defined as the progressive loss of material caused by the surface interactions and welding of asperity junctions at the sliding contact. So, adhesion or in general we can say bonding occurs at the asperity contacts at the surface and these contacts are sheared by the sliding which result into the detachment of fragments from one surface and that may even attach to the other surface.

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So, you have one surface and another surface which are attached and these bonding leads to the adhesion and the material can be removed from these junctions. This material removed can be attached to either of these surface, right. So, you will find several applications of this where you can find adhesive wear. For example, cutting tools. you have a cutting tool nose in contact with the work piece where you can find certain adhesive wear or wire drawing or gears or bearings.

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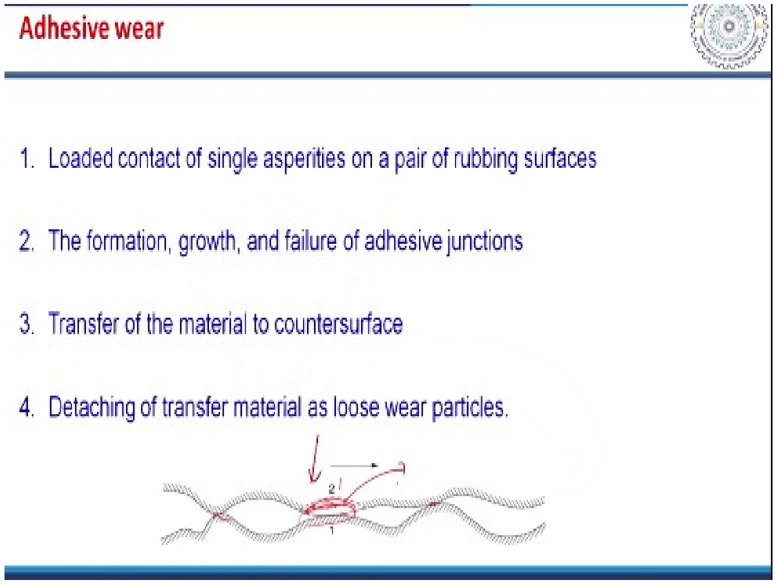

You will find number of such engineering applications where adhesive wear is dominant. So, generally the sequence of adhesive wear is like this. First the loaded contact of the single asperities on a pair of rubbing surfaces, right. So, under this loading conditions one asperity is with contact with the other asperity, right. Then the formation, growth and failure as adhesive junctions; transfer of this material; So, whatever material is removed that transfer of the material to the counter surface. Detaching of transfer material as loose wear particles.

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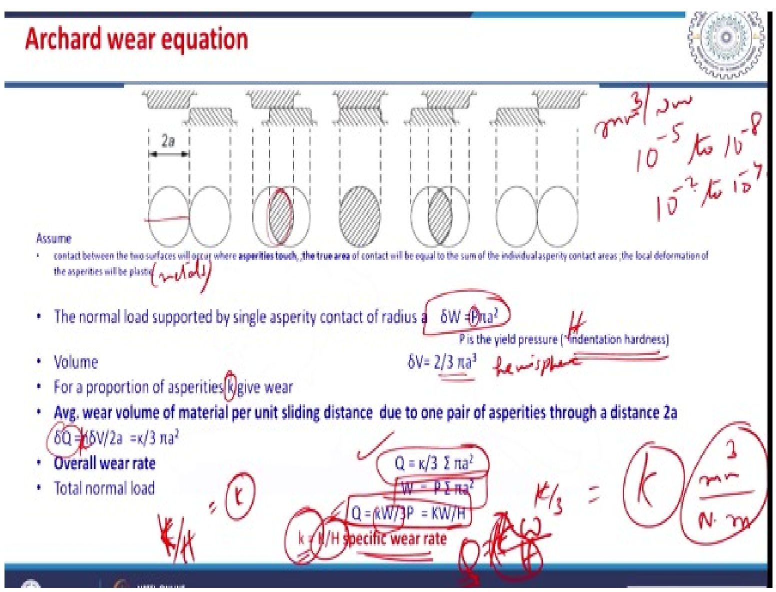

Let us understand it more clearly. There is a fundamental theory proposed by Archard to understand such a mechanism of adhesive wear. For example, you assume two surfaces are in contact and they are in a relative movement under a loading condition. First of all, assume these contacts between the two surfaces occur where asperity is touch, right. The true area of the contact will be equal to the sum of the individual asperity contact areas.

And the local deformation of the asperities will be plastic. That means, I am talking about mostly for the metals. So, for the simplicity we talk about this deformation; local deformation as a plastic. Assuming these conditions when you have two bodies in contact, the asperities you have certain contacts, right. So, if you consider the asperity is of a circular cross-section with the diameter of 2a.

You can see the sequence while the sliding is going on. you have overlapping of these and then you have detachment and then that leads to the material removal. Now, let us actually understand how to quantify such wear? For example, you take this single asperity. The normal load supported by a single asperity of a circular contact of radius a, then you have this δW; W is a load.

$$\delta W = P \pi a^2$$

So, P is the yield pressure that can be safely taken as an indentation hardness and the volume of the material removed at this single asperity. You can consider as material removed from these asperity interactions as a hemisphere. That volume is 4/3rd πa^3 divided by 2.

$$\delta V = \frac{2}{3} \pi a^3$$

So, you know every asperity is not in contact with the other asperity that leads to wear of this material. So, only a fraction of asperities is in contact that leads to wear particle. For example, if you consider a proportion or the fraction of asperity as k, the average volume of the material per unit sliding distance because of the one pair of asperities sliding through a distance of 2a.

Then the average volume of this material per unit sliding distance

$$\delta Q = \frac{n\delta V}{2a} = \frac{k\pi a^2}{3}$$

k is this proportion of the asperities that leads to actual wear.

So, overall wear rate becomes

$$Q = \frac{k}{3}\sum \pi a^2$$

You have so many such asperities that leads to overall wear rate. So, if you look at the normal load, the total normal load

$$W = P\sum \pi a^2$$

Then Q becomes

$$Q = \frac{kW}{3P} = \frac{KW}{H}$$

So, this k and this k/3 can be considered as a capital k. So, you can see the KW/P and as I told the P is the yield pressure that can be safely considered as indentation hardness. So, and then becomes KW/ H that is actually the wear rate. This is the wear equation proposed by this Archard. So, actually this K is a dimensionless constant and that actually gives the probability of producing the wear.

In general, we consider this K divided by H as a one constant and then the constant can be a small k and this is called specific wear rate and you can say the K divided by H is a small k. So, what you are actually doing is the volume of the material removed per unit load per unit sliding distance. So, if you say the volume of the material removed is in mm cube. mm cube divided by this load in Newton and a sliding distance in meter.

So, generally the specific wear rate is a dimensional coefficient. That has a units of mm cube per Newton per meter. For the comparison purpose the specific wear rate is more important.

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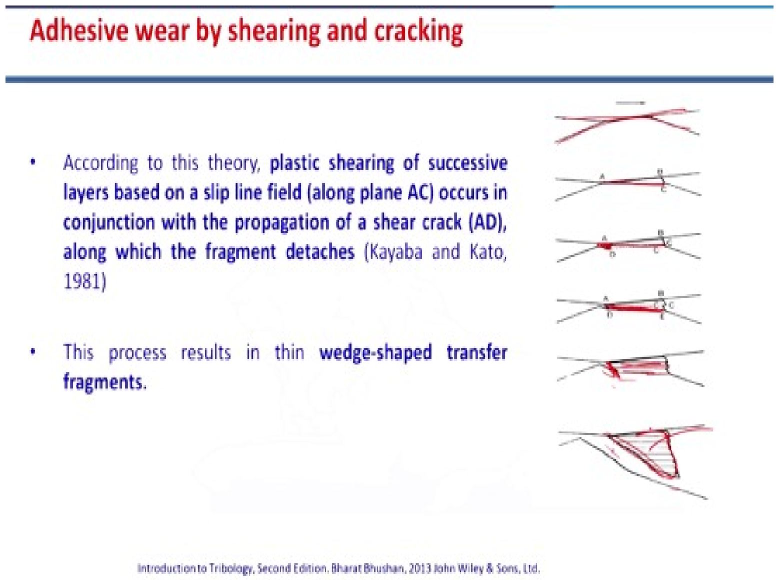

In later sessions, in case studies we will also see several examples, where the specific wear rate is used to understand the behaviour. And generally, the specific wear rate is less for the ceramics, right. For example, that may be from 10^{-5} to 10^{-8} mm^3 / Newton meter or for metallic materials it is 10^{-2} to 10^{-4} generally. For polymeric materials, it is even more, right.

So, for understanding this adhesive wear, there are certain mechanisms proposed. one mechanism says the adhesive wear occurs by plastic shearing and then cracking. So, the plastics shearing of successive layers; For example, this one layer is in contact with other layer in the sliding conditions, right. So, the plastic shearing of the successive layers based on the slip line field along this AC.

So, you have certain slip line field as the sliding proceeds. You have a crack generated it is called AD along which the fragment detaches. So, you have the shear off these layers and then the removal by the cracking. So, you have shear and cracking, when this cracking achieves a certain size. So, this material is removed. This material is actually called the wear debris or you can say this is the wear particle, right.

So, generally this type of plastic shearing of successive layers and then the propagation of a shear crack that leads to the material removal is in the shape of a wedge. So, this wedge-shaped fragment is actually transferred. So, it may attach it to the other surface; either of these surfaces.

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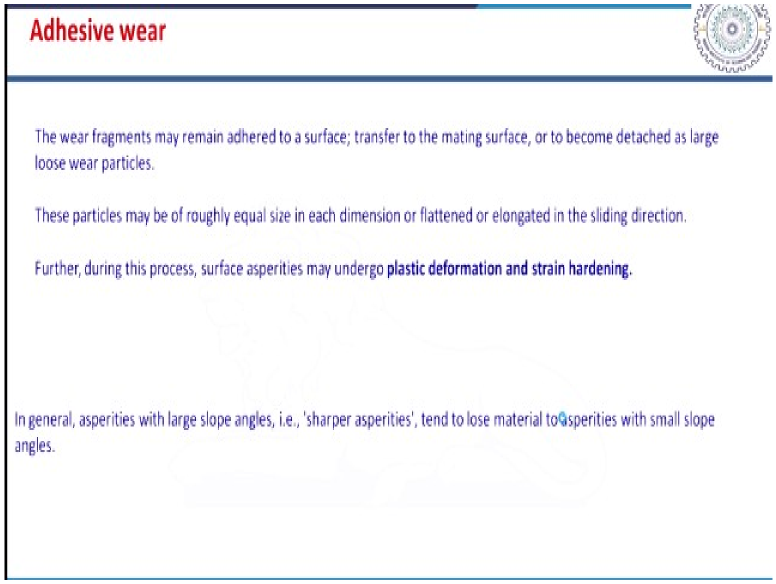

So, these wear fragments may remain adhere to a surface or transferred to a mating surface or to become detached as a large and loose wear particle. So, these particles may be of roughly equal size in each dimension or flattened or even elongated in the direction of a sliding. So, further during this sliding process, the surface asperities may even undergo plastic deformation and strain hardening.

That means, the wear particle which is coming out as a result of adhesive wear is a strain hardened. So, this is strain hardened material may even produce more wear on the either of these surfaces which ever has the lesser hardness. So, in general asperities with largest slope angles that means, the sharper asperities tend to lose material to asperities with a small slope angle.

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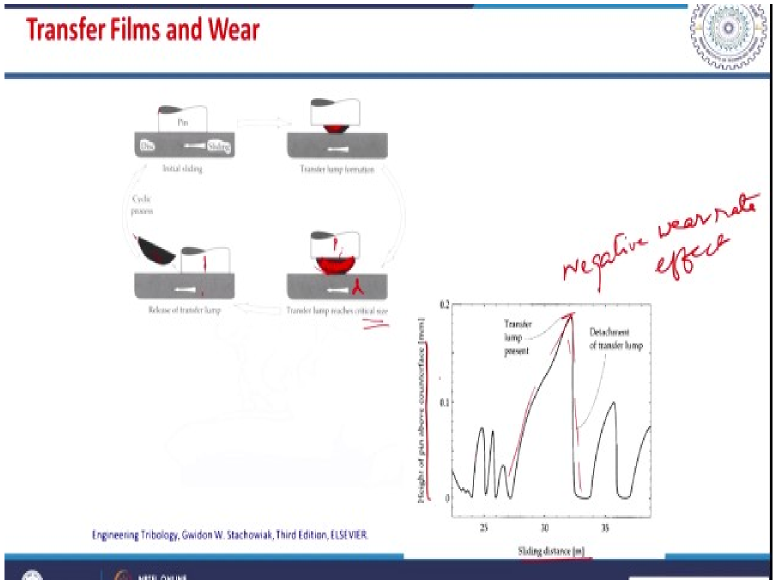

As I told there may be a transfer film happening. For example, if you consider a pin on a disc in a sliding condition there happens certain material. It becomes critical in size and then after that it is removed from the contact and then the process continues. So, you can see the height of the pin above the counter surface versus the sliding distance, when this transfer lump reaches a critical size, you can see a negative wear rate effect, right.

This material pin and the disc are not in contact actually. This is in between. So, the wear is happening here, not between these two actual bodies. So, you may also have certain negative wear. Once this transfer film is removed, again this is contact with the actual body.

So, again knew there is a decrease in the height of the pin above the counter phase. So, you have ups and downs like this in the height of the pin. So, sometimes you may also get this negative wear effect because of the transfer lump with a considerable thickness.

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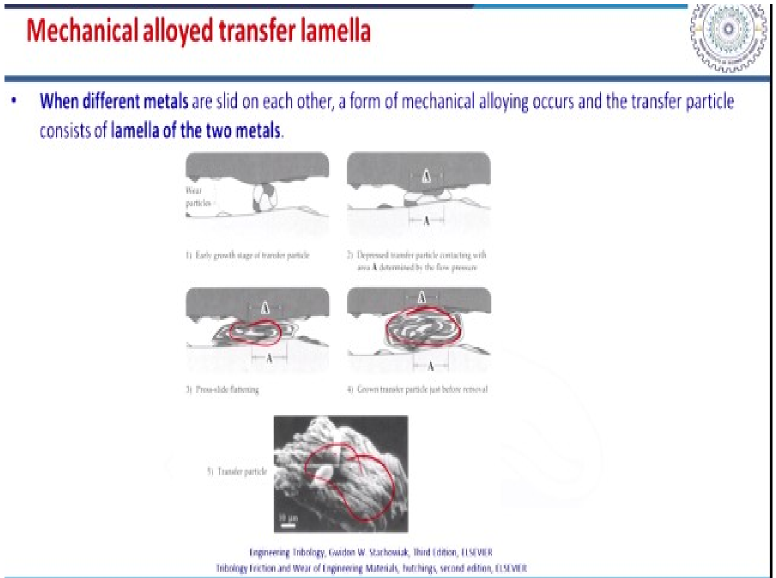

When different metals are slid on each other and they form a mechanical alloy, right and the transfer particle consists of lamella of two metals. So, you can see the transfer particle that may consists of a mechanical alloy. So, you can see this kind of transfer particles even. So, early growth of the stage of transfer particle, then depressive transfer particle contacting with the area A determined by flow pressure, press slide flattening and grain grown transfer particle just before removal and after removal, you can see this transfer particle.

So, when different metals are slid on each other, a form of mechanical alloying occurs and the transfer particle consists of lamella of two metals.

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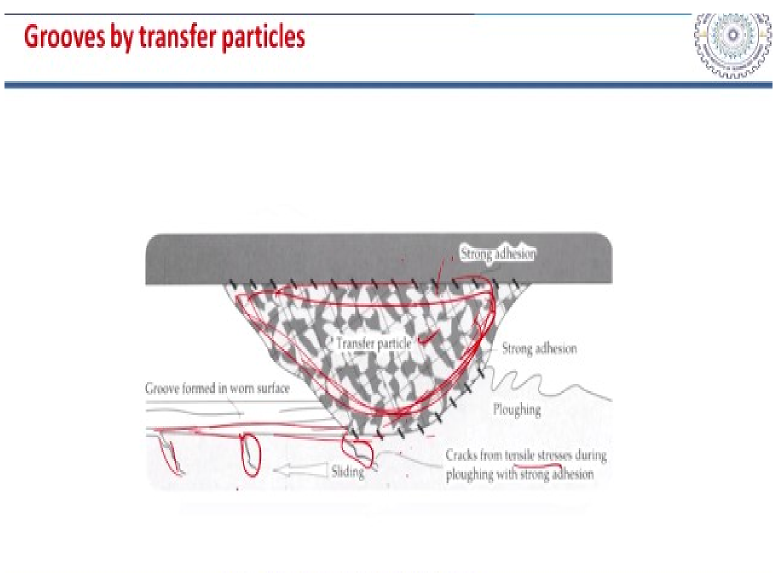

As I told, this transfer particle is heavily strain hardened, right. If you have a strong adhesion between this material transfer particle and this body and then you have a strong adhesion between this body and this body. So, what happens? This actually remains in the contacts and this is subjected to strain hardening. Particularly these metallic materials, you have a very strain hardened transfer particle.

Now, hardness of this one may become even twice or thrice than the hardness of this metal or this metal. Then what happens? These transferred particles will try to groove on the surface of whichever is having a softer material, whichever is having a lesser hardness that material surface will be grooved because of these transfer particles which are strain hardened. So, the strain hardened transfer particles forms a groove on the softer surface, right.

So that even generates a certain tensile stress during this ploughing and with strong adhesion. So, because of the tensile stresses, there may be certain cracks and the material is fractured. So, the strain hardened material ploughs the relatively softer material and even leads to cracking because of the tensile stresses. So, you have a grooving and then fracture because of the strain hardened transfer particle in contact, right.

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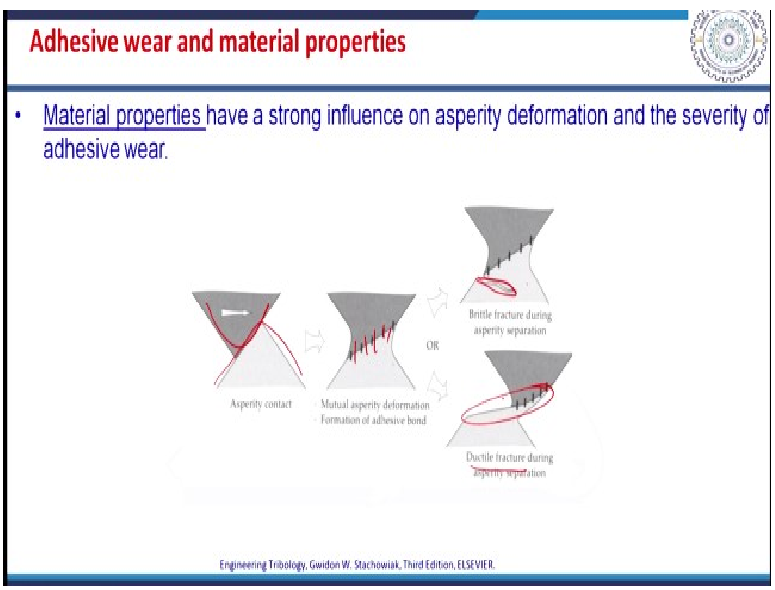

So, material properties have a strong influence on the asperity deformation and the severity of adhesive wear. For example, you have one asperity in contact with other asperity, there is a mutual asperity deformation and then formation of adhesive bond. There is a strong adhesive bond. So, there may be two cases in extreme conditions that material may be a brittle and you have a brittle fracture during asperities separation or that maybe ductile fractured during asperity separation. So, there is a ductile fracture or a brittle fracture based on the material property. So, the material properties have a strong influence on these deformations or the fracture of this asperity or the asperity junctions.

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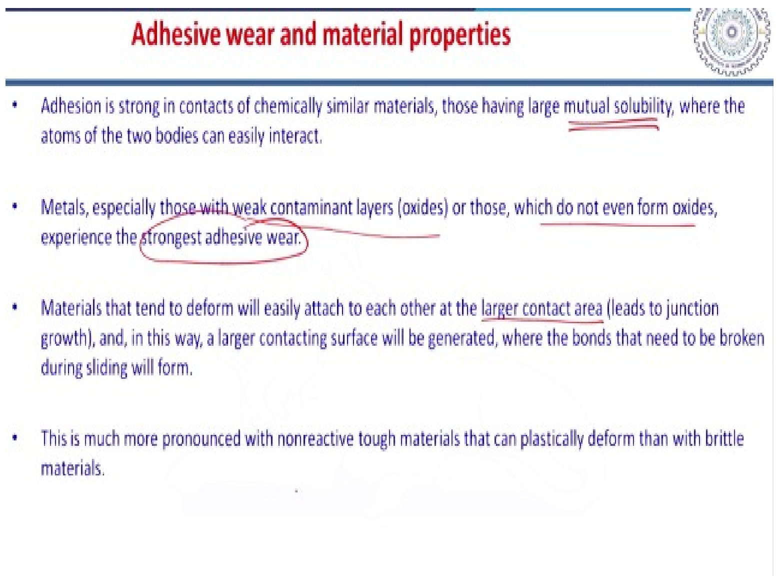

So, adhesion if you say is a strong in contacts of chemically similar materials, those having large mutual solubility. So, where the one type atoms of the two bodies can easily interact. So, there you have a very strong adhesion. So, metals particularly those with weak contaminant layers, generally oxide layers are those which do not form even oxides. Weak oxide layers are which do not form oxides experienced the strongest adhesive wear.

We have a very strong adhesive bond and material is removed as a junction in a large amount. Materials that tend deform will easily attach to each other at the larger contact area that leads what we call junction growth and in this way, a larger contacting surface will be generated where the bonds that need to be broken during sliding will be formed. This is much pronounced with non-reactive tough materials that can easily deform than with brittle materials.

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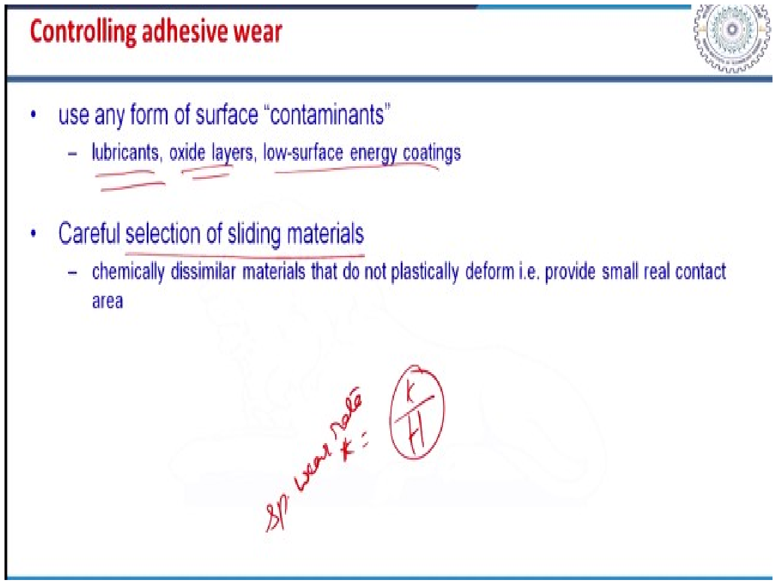

In brittle materials, the fracture is dominant, right. So, how to control such an adhesive wear? You can actually control by using any form of surface contaminants; contaminants may be in the form of lubricants, right. So, we have a lubricant in applied in the contact, so this lubricant having a low shear strength will be facilitating such a sliding, right. So, you do not have such an adhesive wear dominant or oxide layers.

You have certain oxide layer is generated at the contact or you may also have a certain low surface energy coating. So, you can use any form of this surface contaminants, so that the adhesive wear can be reduced. The severity of the adhesive wear can be reduced or overall adhesive wear can be controlled. Another form, another method to control the adhesive wear is by careful selection of the sliding material.

As it was told earlier chemically dissimilar material that do not plastically deform that is provide small real contact area can be preferred, right. So, in other classes we will see several examples of metal matrix composites, ceramic composites and polymeric composites where you can see such a domination of adhesive wear and the severity of adhesive wear is generally studied in terms of the specific wear rate, right.

As I like told the adhesive wear coefficient divided by the hardness. Particularly, if you see the polymeric materials, the hardness is not well defined, right. So, this parameter called the specific wear rate that we call small k. The specific wear rate is very much useful to understand the wear behaviour of different classes of materials and also to compare this specific wear rate of different materials or materials done it with a different condition of the sliding.

So, summarising today's class, today we understood what is wear? It is a material loss, right. When two bodies on relative movement, the loss of the material either from the surface or bulk of this material. This material loss is called the wear. So, there happen certain physical material removal mechanism through which the material is dominantly removed such mechanisms are called wear mechanisms.

And there are several mechanisms which play an important role in material removal. This material removal can be a summation of all these mechanisms but a one or two mechanisms will be dominant in the given conditions of the sliding wear for a given material system. So, those mechanisms are called dominant wear mechanisms.

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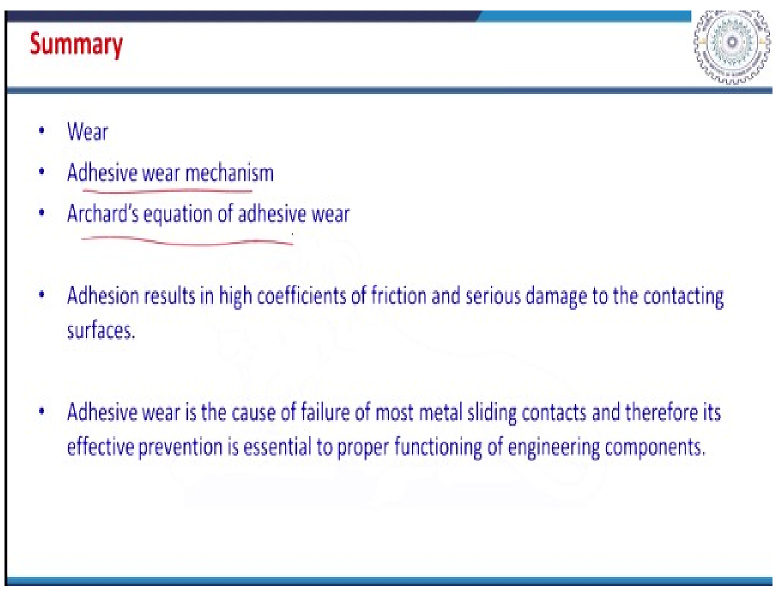

So, today in this class we understood what is adhesive wear mechanisms? And also, we understood what is the quantification method for the adhesive wear that is by Archard's equation. So, adhesion results in high coefficients of friction and serious damage to the contacting surfaces. Adhesive wear is the cause of failure of most of the material sliding contacts and therefore its effect to prevention is essential to proper functioning of engineering components. So, in other class, we will see other important wear mechanisms, thank you.