Friction and Wear of Materials: Principles and Case Studies
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Lecture – 09
Wear Mechanisms: Fatigue Wear and Fretting Wear

Hello, welcome back. Today we will like to see two different mechanisms of wear; the fatigue wear and the fretting wear. These two wear mechanisms are generally considered to give a relatively mild wear compared to abrasive wear or adhesive wear. Let us see the principles of this wear fatigue.

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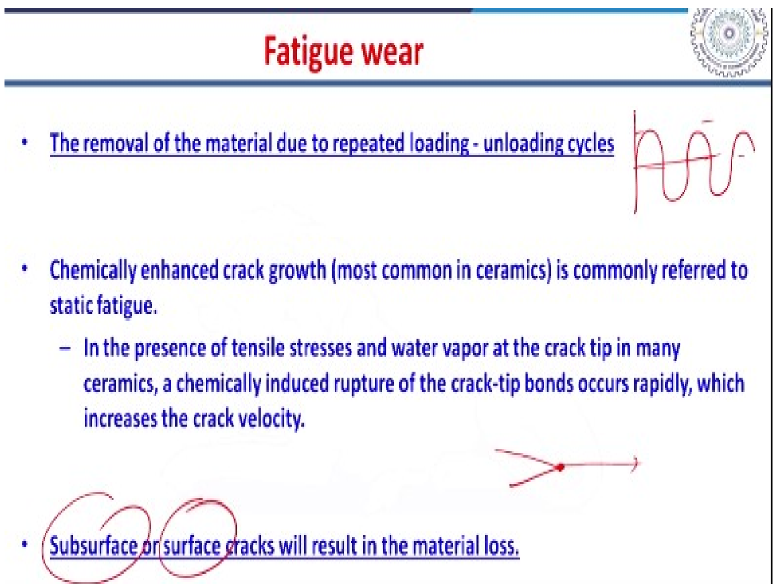

Generally, when any material is subjected to repeated loading and unloading, based on the stress amplitude and the numbers of cycles, you will have a removal of material. That removal of material is due to the repeated loading and unloading cycles, we called fatigue. So, the removal of material due to fatigue is generally termed as a fatigue wear, and you know engineering applications, fatigue wear is almost always present because of the relative movement between the engineering components.

In case of ceramics, chemically enhanced crack growth is commonly referred as static fatigue. So, if you have certain chemically induced rupture of the bond at the crack tip, this crack will be propagating very easily. The materials which are prone to chemical reaction and the wear conditions generally give accelerated wear because of this fatigue.

In the presence of the tensile stresses and water vapour at the cracked tip in many ceramics, a chemically induce rupture of the crack-tip bonds occurs rapidly, which actually gives increase in the crack velocity. Basically, the fatigue and the fatigue induced wear that we call fatigue wear is mainly by the formation of the surface cracks or the sub surface cracks. These surface cracks or subsurface cracks once they are initiated, they propagate and then they coalesce each other and then lead to material removal as a fracture.

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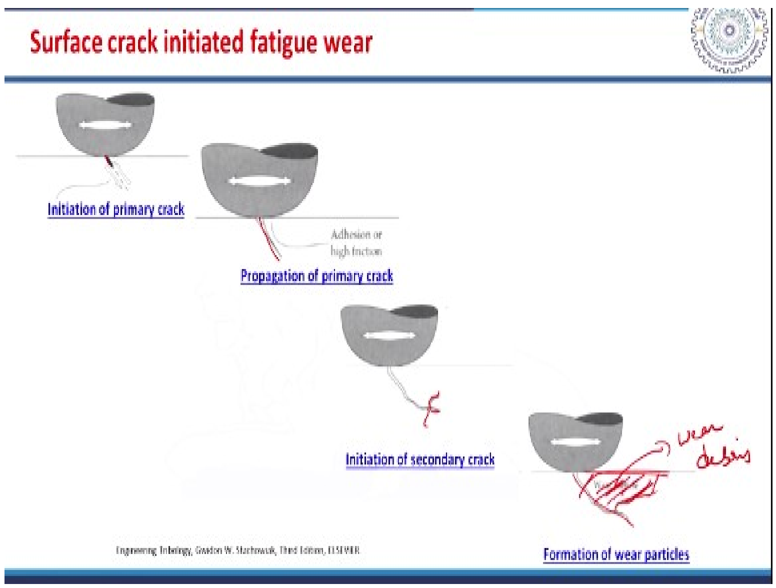

If you see the first one, surface cracked initiated fatigue wear. Under the stress conditions, there is an initiation of the primary crack just beneath the contact. Because of the internal stresses, there will be certain location where the energy will be dissipated by creating a crack and the crack will be propagated further in continuation of these wear movement.

So, this primary crack itself may lead to wear, that is material removal or there maybe certain initiation of secondary cracks from this primary crack or there may be a wear particle formation. Because of this primary crack or the second crack going and intersecting the free surface, then this material removal is the wear particle or we can say the wear debris. So, initially the surface is subjected to high stresses.

So, because of these high stresses at the contacts, there will be certain location at the surface where the energy will be dissipated by forming a crack. The crack may lead to intersection at the free surface or it may lead to the initiation of the secondary crack. The secondary crack will meet the free surface and then you will have a fatigue wear.

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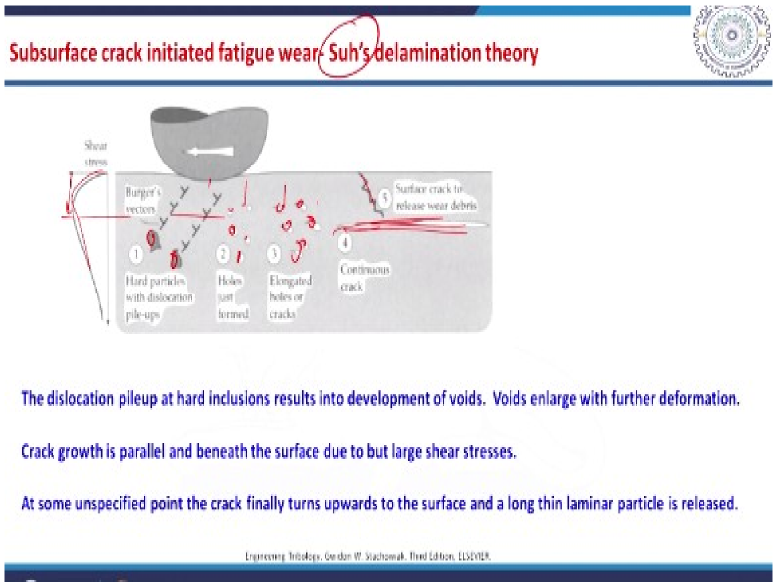

Or there may be a subsurface crack induced fatigue wear. Generally, this subsurface crack-initiated fatigue wear is because of the dislocation activity or that will lead to delamination of this material. This was proposed by the Professor Suh. So, this is usually called Prof Suh's delamination theory. So, mainly for the ductile materials there will be dislocation pileups at the very hard inclusions or some certain particles inside the material underneath the surface of contact.

So, generally the shear stress will be maximum underneath the surface, it is generally half; 1 / 2 to 1/3 from a distance from this. The dislocation pileup at the hard inclusions results into development of voids, these voids coalesce and then then they form large elongated voids or we can call them as a crack, right.

So, these enlarged voids become a crack front and the crack will be propagating. The crack will be propagating continuously underneath the surface of contact just almost parallel to the surface because of the large shear stresses. At certain unspecified point, the crack finally turns up to the surface and then the very long thin or sheet like material will be removed that we called a delamination.

So, this theory is more or less valid for most of the materials particularly, ductile materials. You can see certain spalling of this ball bearing race, which leads to delamination, and then delamination leads to the pits on the surface when it is a dry contact.

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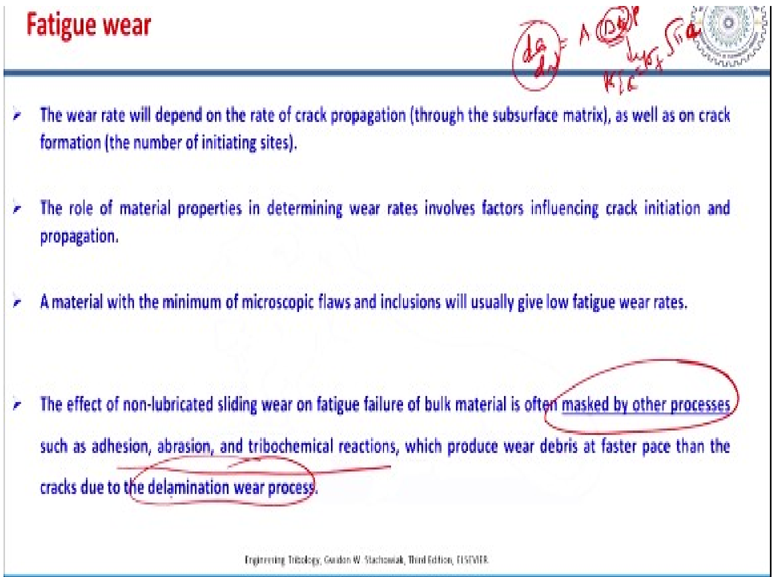

The wear rate will depend on the rate of crack propagation as well as on the crack formation. If you know the Paris law for the fatigue,

$$\frac{da}{dN} = A \Delta KP$$

K, which is a stress intensity factor, P is a Paris constant. So, it depends on the stress intensity factor, which is the stress intensity factor is nothing but it is proportional to the fracture toughness.

$$K_{IC} = \sigma_f \sqrt{\pi C}$$

Again, the fracture toughness depends on the σ_f and C. So, you can actually determine the stress intensity factor raise it to P, which is a Paris constant and then see the crack growth rate. N is the numbers of cycles, a is the crack size, the role of material parameters in determining such wear rate involves factors influencing the crack initiation and propagation.

So, always fatigue is considered as a sequence of the crack initiation and propagation. A material with minimum defects or inclusions will usually give low fatigue rates and long life. The effect of non-lubricated sliding wear on fatigue failure of bulk materials is often masked by other processes such as adhesion, abrasion, tribochemical reactions, which produce wear debris at a faster pace than the cracks due to delamination wear process.

So, as I told this fatigue wear can be considered as a hidden by these dominant adhesion, abrasion or tribochemical reactions. But one should note that even these tribochemical wear or the abrasive wear or adhesive wear are also influenced by this fatigue.

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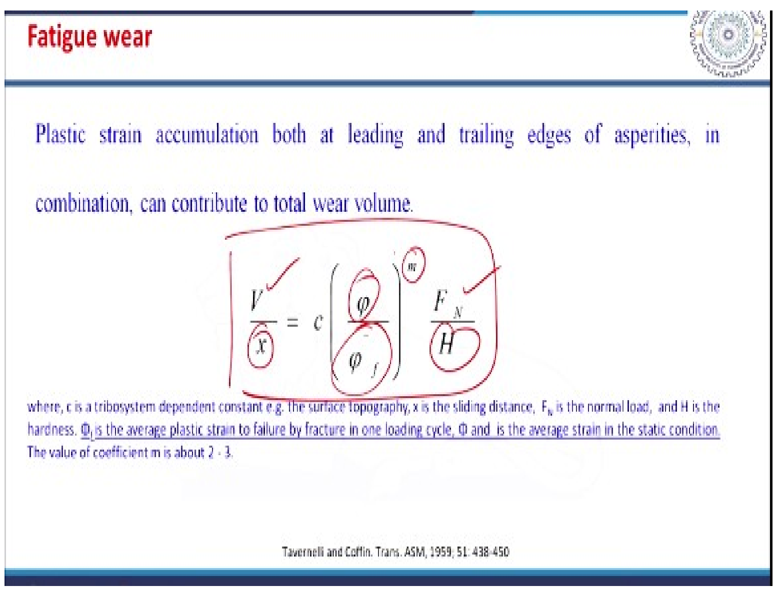

So, the plastic strain accumulation both at the leading as well as the trailing edges of these hard asperities in combination can contribute to the total wear volume. So, if you know what is the distance travelled, the wear volume per unit distance can be found out by a parameter; Total wear volume can be described with this equation,

$$\frac{V}{x} = c\left[\frac{\phi}{\phi_f}\right]^m \frac{F_N}{H}$$

where the F_N is the normal load and H is the hardness, and this φ_f is the average plastic strain to the failure by fracture in one loadings cycle condition.

Whereas, this φ is the average strain in the static condition and C is generally a constant, which is dependent on the system. Whereas, this coefficient m is a constant, which is generally 2 to 3. So, you can actually assess the wear due to fatigue by knowing these parameters, the plastic strain accumulation in the given tribo system conditions.

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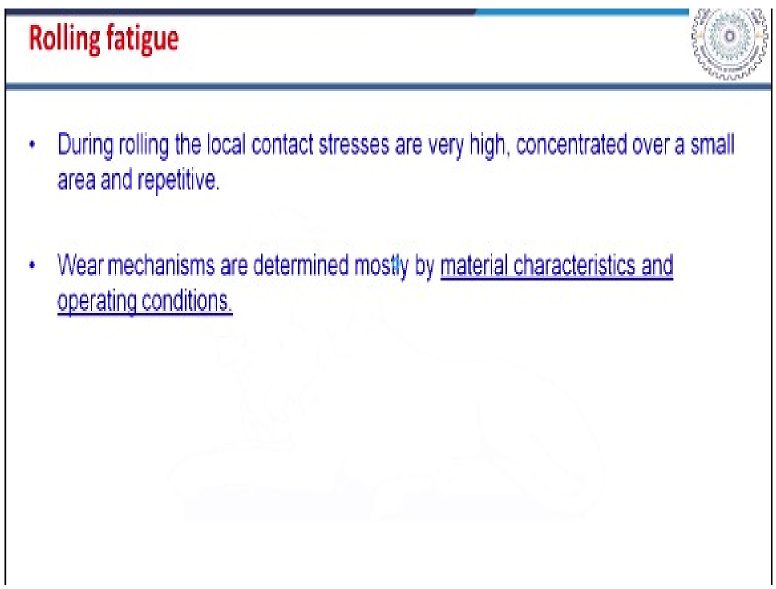

Fatigue can be found even in the rolling conditions. Fatigue can be in the sliding conditions or can be a rolling condition. So, in the rolling fatigue the local contact stresses are very high during rolling. They are concentrated over a small area and they are repeated. So, the wear mechanisms in this rolling condition are determined mainly by the material characteristics and operating conditions as we have seen in other wear mechanisms.

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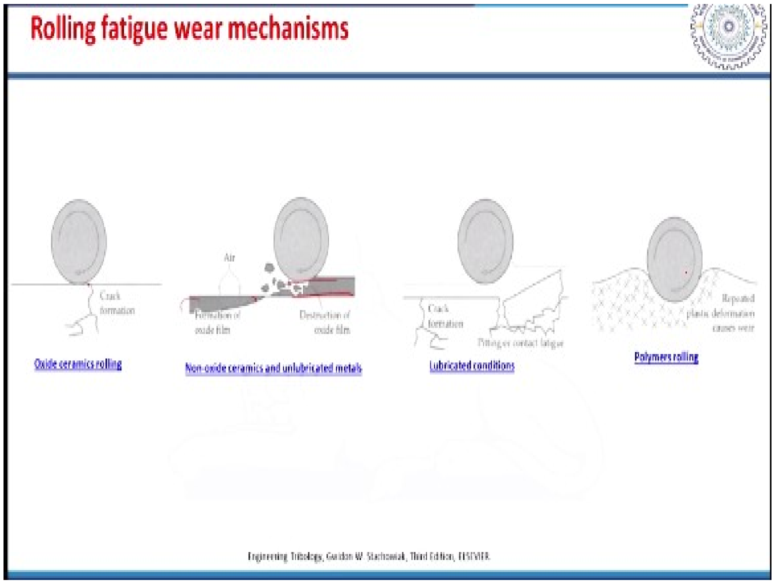

If you look at the material parameters, you see the ceramics; oxide ceramics, they are generally under rolling conditions and fatigue, the crack is propagated because of the high stress concentrations at the contact and then they propagate easily then they give to fatigue wear. And for non-oxide ceramics in an oxidising environment or in an ambient environment they easily tend to form a surface oxide film, and the surface oxide film is destructed because of the fatigue action in the for the non-oxide ceramics.

This is also valid for the lubricated metals and at a ambient conditions because of the high stress concentrations at the contact, there happens a tribo oxidation reaction triggering that leads to the oxidation of the surface. On the surface oxidation, the surface oxide film is destructed because of the fatigue, and then the material is removed. Or in lubricated conditions, the material is damaged mainly by the pitting or the contact fatigue or the crack formation.

In case of polymers, repeated plastic deformation causes the material removal. So, material characteristics as well as the operating conditions both contribute such a fatigue wear. This is the brief description of the fatigue wear. We will also see in certain case studies, the presence of such fatigue wear or the contribution of the such fatigue to the overall wear of the materials in several case study classes later.

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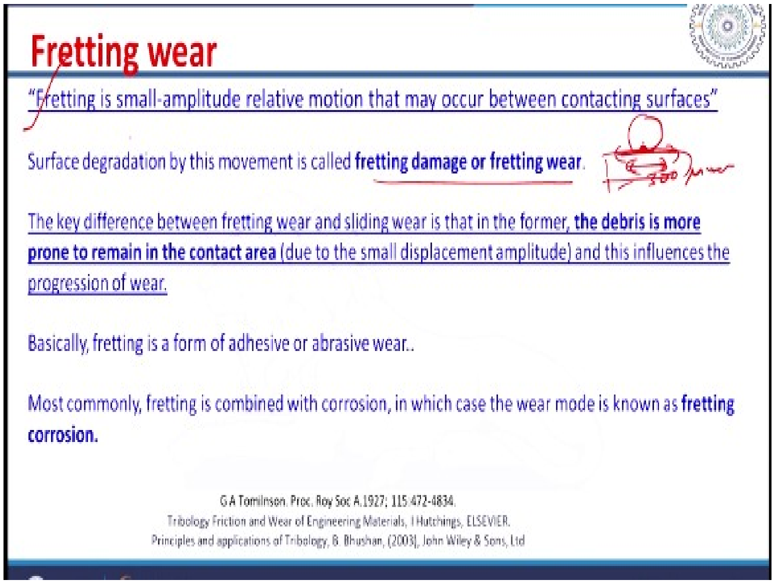

Then, comes the next wear mechanism fretting; Fretting is also similar to sliding. Fretting is a small amplitude relative movement generally oscillatory relative movement that may occur between contacting surfaces. And how much is the small amplitude? This is generally up to 300 micron metres. So, 1 to 300 micron metres such an oscillation at the contact that will lead to a material removal is called fretting.

So, generally surface degradation by this movement is called as a fretting damage or a fretting wear. The only difference between the fretting and sliding is, because of the very small amplitude of movement. For example, if you have certain ball and a disc here and the disk is oscillating at a very small oscillation movement amplitude of around 50 to 100 micron. Then what happens? The debris which is formed because of the wear at the contact is not able to come out of it.

That means, the debris is more prone to remind inside the contact area. So, if the debris is a hard enough or if you have severe mechanical properties than the either of these surfaces, what happens? This will actually lead to enhanced wear. So, sometimes we feel in certain cases fretting wear is more severe based on the debris formed because the debris are prone to remind inside the contact area.

Fretting is another form of an adhesion, abrasive wear. Most commonly fretting is combined with corrosion. So, we usually see literature with fretting corrosion as well.

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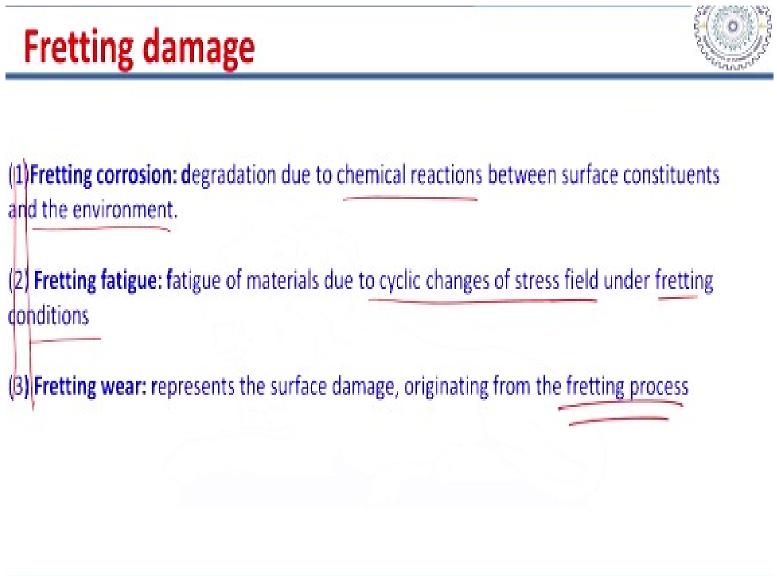

Or you can say the total damage can be described in terms of fretting corrosion, fretting fatigue or fretting wear. The fretting corrosion means the degradation due to chemical reaction between surface constituents and the environment. Fretting fatigue is the material is removed due to cyclic change of stress field under fretting conditions, the fatigue as well as fretting. The fretting wear is simply representing the surface damage originating from the fretting process itself.

So, generally in literature we find these three types of fretting; a fretting corrosion, fretting fatigue or fretting wear.

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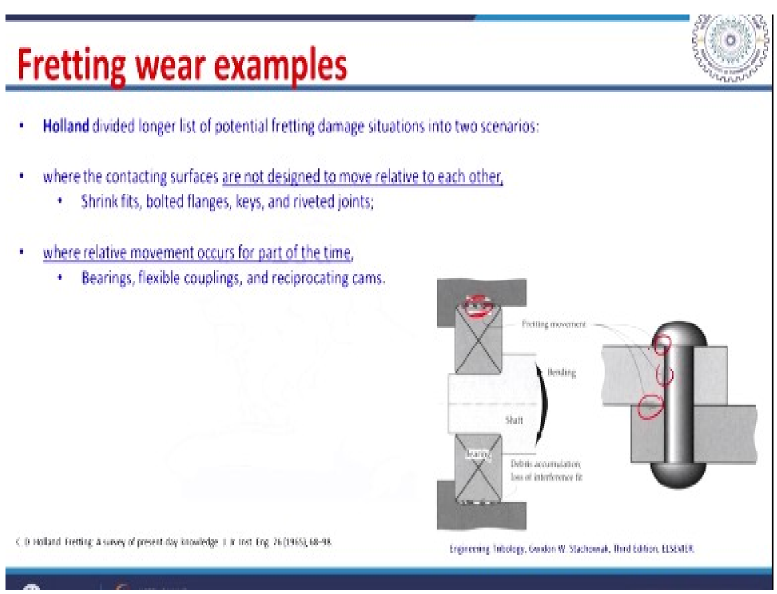

We can actually summarise these fretting only by considering the fretting wear as a fretting damage. There are certain examples of engineering applications, where you will have fretting contribute into the total wear of the material component. Holland divided the list of such fretting damage into mainly two categories, where the contacting surfaces are not at all designed to move relative to each other.

For example, riveted joints in aeroplane wing; you will have many riveted joints of those aluminium sheets and those riveted joints are not supposed to be moving. But there will be very small movement because of the flying action and all this aerodynamics, and you will have certain very small amplitude of movement that will result into the wear. Similarly shrink fits, bolted flanges, keys, etc.

And the other case, where relative movement occurs for part of the time. For example, flexible couplings or reciprocating cams, where the movement is only for a very small in time but actually that will lead to wear, and that will deteriorate the integrity of the component system. So, these are actually shown here that there is very small relative movement that will lead to the wear.

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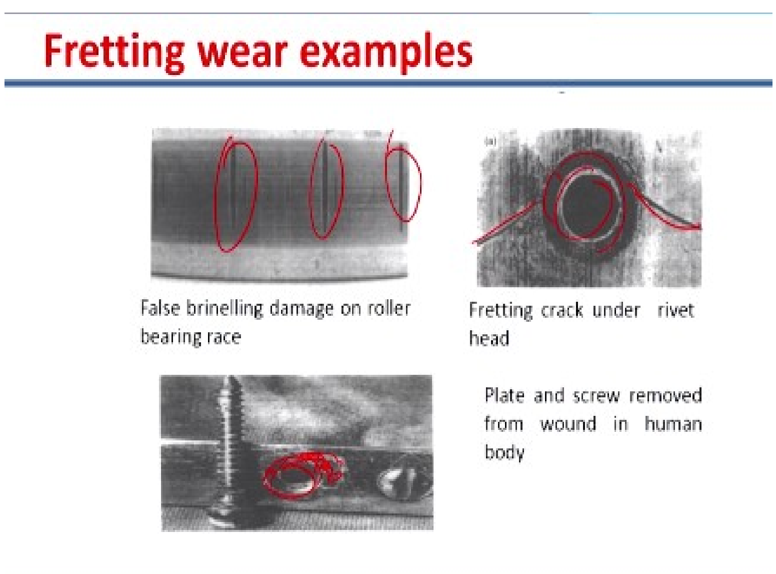

There are so many instances where the fretting is noteworthy. For example, false brinelling damage on the roller bearing race surface or fretting crack, you see this is rivet and then you see these cracks. Or you see the plate and screw removed from the wound in the human body, you can see so much of wear happened here.

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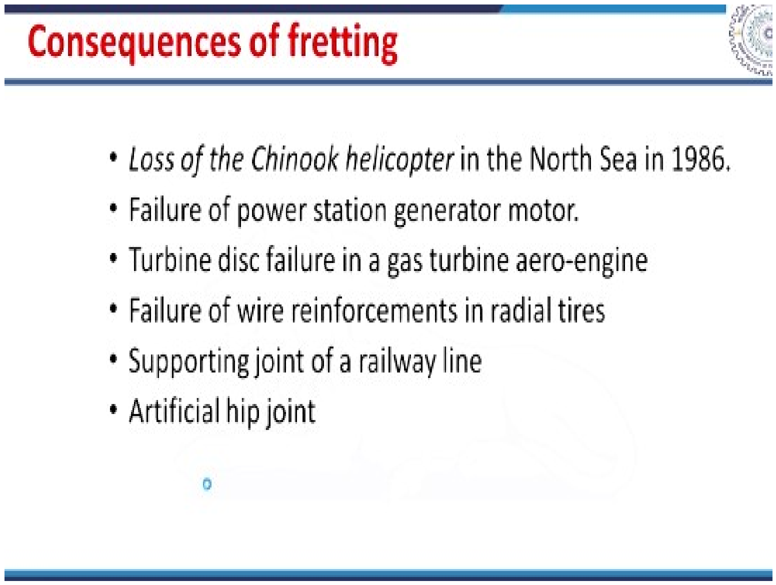

There are so many consequences of fretting like loss of Chinook helicopter; the failure of power station generator motor; turbine disc failure in a gas turbine aero engine; failure of wire reinforcement in radial tires; supporting joint of a railway line; artificial hip joint failure; These are happened because of the fretting only. So, we have to understand the fretting wear thoroughly.

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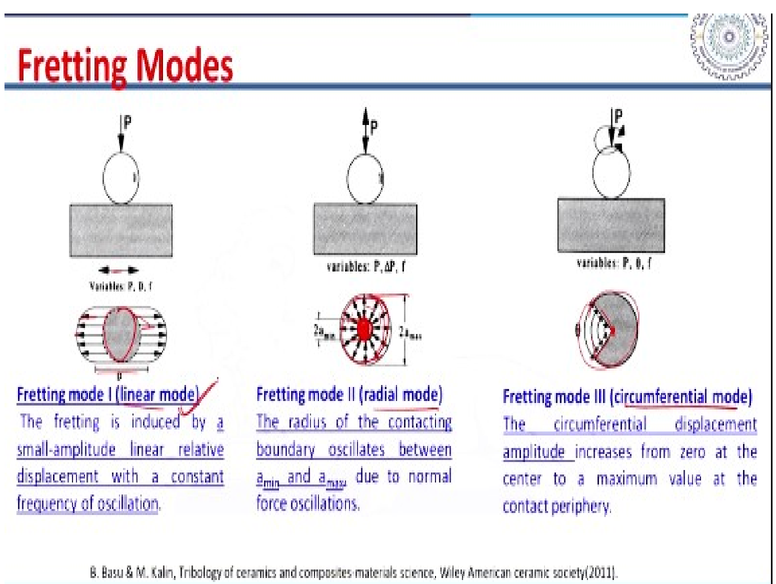

In understanding this fretting wear, we can see there are actually three modes of such fretting wear. One is the linear mode or the radial mode or the circumferential mode. So, linear mode you see this is represented by a simple ball on flat geometry. This fretting is induced by a small amplitude linear relative displacement with a constant frequency of oscillation.

So, you have only this area, where the fretting is dominant, and then you can see with the frequency of oscillation, the fretting is only in the linear. Whereas, the radial mode, radius of the contacting boundary oscillates between this minimum as well as the maximum. Because of the normal force oscillations, you will have a variation from this minimum to maximum. So, you will have this fretting mode as a radial mode.

Or another mode called fretting mode III, which is a circumferential mode. You can see the circumferential displacement amplitude increases from 0 at the centre to a maximum at the periphery of this contact. You will have the maximum at the contact periphery or the minimum 0 at the centre of this contact.

So, you will have this load as well as this oscillatory; the circumferential mode that leads to the fretting. Out of all these three modes, fretting mode I is generally considered as important mode because that leads to maximum wear. In literature generally we can see the linear mode or fretting mode I. Fretting mode II and mode III are still found in several engineering applications. For example, electrical contact wires; Several bearings, where you can see the fretting mode II.

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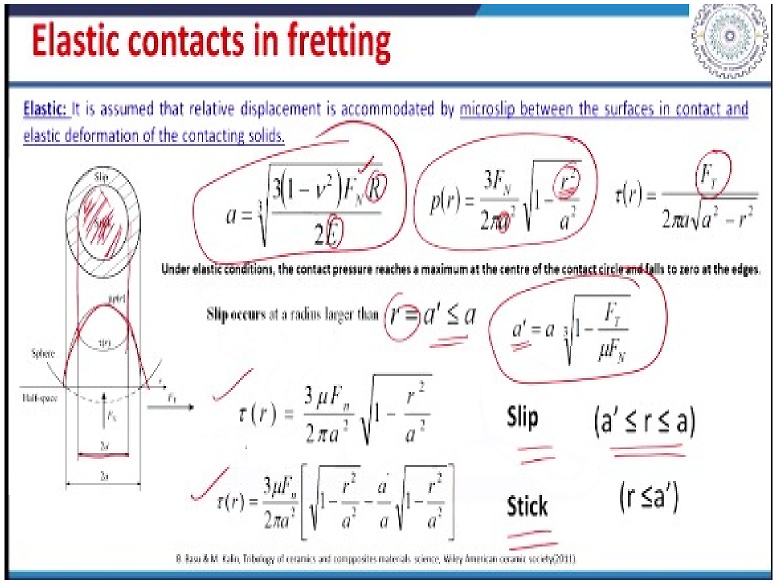

But this is generally referred as a representative mode for the fretting. With respect to the mechanisms in the fretting, elastic contacts can be considered or elastic plastic contacts can be considered to understand the wear mechanism. First of all, in the elastic contacts, it is assumed that the relative displacement is accommodated mainly by the micro-slip between the surfaces in contact and the elastic deformation of the contacting solids.

So, if you take one example of ball on a flat; You will have a contact at the centre; You can have this contact represented by a circle with a radius of a, this contact radius can be estimated by the loading conditions as well as the material parameters. So, the pressure is distributed and have a maximum at the centre of this contact, and you can see the pressure distribution again can be understood by the contact radius, and the pressure at a distance of R from the centre and under a loading conditions of F_N.

Or the shear stress traction can be represented by the tangential force. The tangential force which is actually maximum at the edges of the stick region, stick region is where you do not find any deformation or the slip region where you find mostly deformation or the fracture.

So, at the edges of this stick, you will find maximum shear stress. Under elastic conditions the contact pressure reaches a maximum at the centre of the contact circle and falls to 0 at the edges. So, the slip actually occurs at a radius is larger than the radius R which can represented

$$R = a' \leq a$$

then you can actually have what is the slip occurring with respect to this a'. So, you can actually modify the shear stress in the slip region and the stick region.

As I told the slip is a region where you will find maximum deformation occurring, stick is a region where you do not find such deformation. With respect to the radial distance, you can actually see the shear stress that leads to such a stick or a slip.

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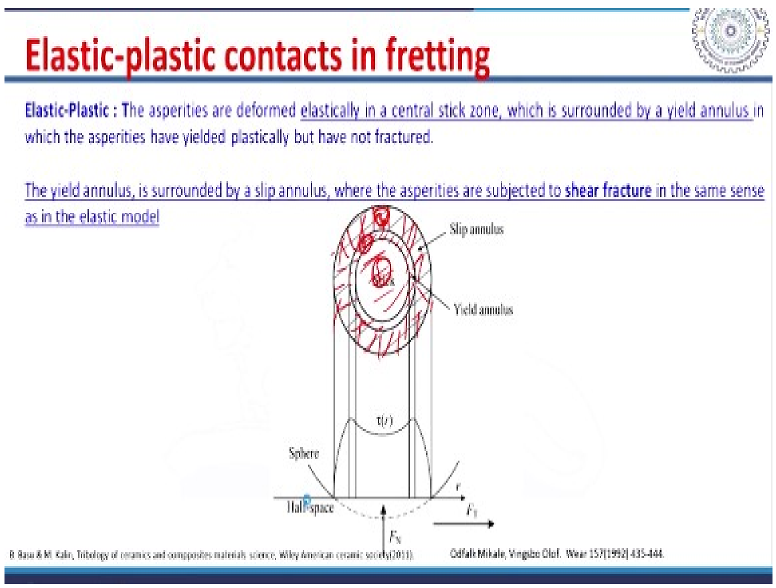

So, you can actually assess what is the material deformed in the slip region?

In another concept elastic plastic contacts in fretting, the asperities are deformed by elastically in a central stick region which is surrounded by a yield annulus. There is a yield annulus, in which the asperities have yielded plastically but have not fractured, but you will always find a slip region where you will find more fracture, right.

The yield analysis surrounded by a slip annulus, where the asperities are subjected to shear fracture in the same sense as in the elastic modulus. So, you will have actually three regions; one is the stick region, second is the yield annulus and third is the slip annulus. As I told in a stick, you will have elastic deformation, no permanent deformation possible, and yield annulus, where you will have a permanent deformation but you do not have any fracture.

But a slip region, where you will have fracture also occurring. So, you can actually define this elastic plastic contacts conditions in fretting leading to three different regions.

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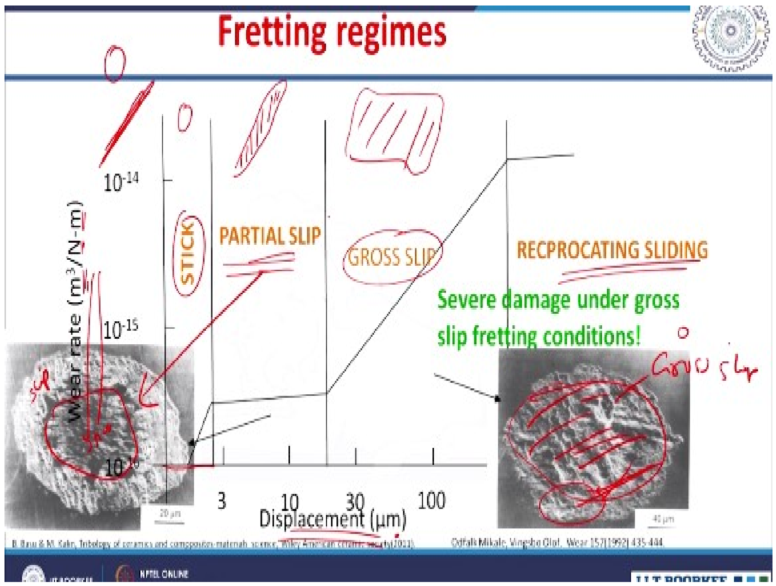

So, you can actually understand these mechanisms of the fretting by regimes. You can actually see the wear rate versus the displacement, this wear rate is nothing but the amount of material removal divided by the product of load and the sliding distance. Over a displacement in the fretting conditions, you can see in a very small displacement, you will have a stick region, and a very large displacement, you will have reciprocated a sliding.

But in between you can see there is a gross slip region generally happening between 20 to 300 micron, and from 3 to 10 or 20 micron, there is a mixed partial slip. So, you will find a tangential friction force versus the displacement curve in the stick region almost as a linear. So, you do not have any energy dissipated to give such a deformation, elastic deformation of the asperities only possible.

Whereas in plastic deformation, you will find certain area hysteresis loop. That actually indicates there is a slip started but it goes to gross slip only, when it goes to displacement larger. In a partial slip plastic deformation of asperities in the yield zone and fracture in the slip zone occurring. So, you will have a plastic partial slip. In a gross slip, where the displacement is much larger, then you will find such a large area of this tangential friction force versus the displacement that gives to large amount of energy that leads to the maximum fracture.

So, where you can find the severe fracture here a displacement more than 300. Generally, we call this is a sliding. So, if you see the severe damage undergoes in the slip fretting conditions here, gross slip conditions; so, if you look at this steel surface worn in a fretting conditions against steel, so this stick region gives, this is the partial slip one, right; you see this is stick region, where you do not find considerable deformation or the fracture.

Whereas, this is a slip region; this is a stick; this is slip; both are happening in the partial slip. Whereas, at a longer displacement conditions, you will find the contact surface is completely worn out. So, this is actually gross slip; This is called gross slip.

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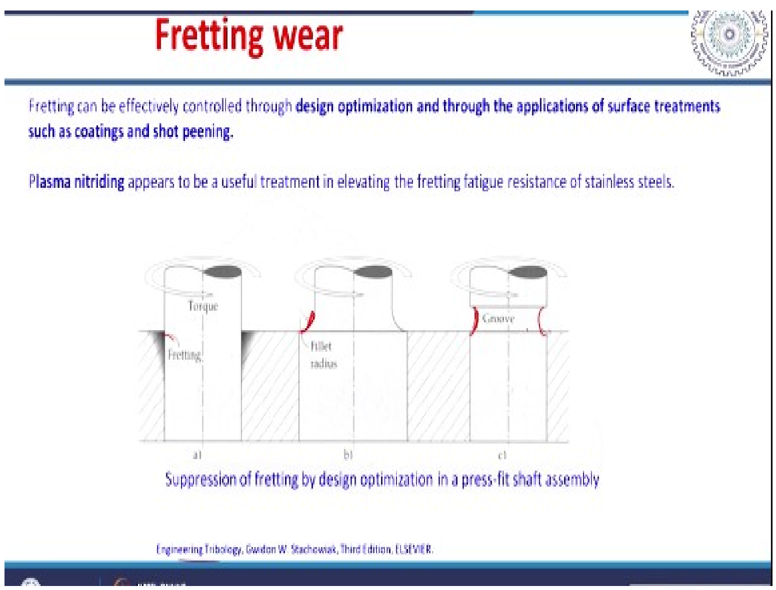

The fretting can be effectively controlled through design optimisation and through the application of surface treatment such as coatings or shot peening. By shot peening, we aim to develop compressive residual stresses; We aim to develop compressive stresses at the surfaces. So, the cracks will be delayed in their propagation. So, the wear can be reduced.

Or coatings that will also cover the material and then lead to delayed fracture, or plasma nitriding appears to be more useful treatment in elevating fretting fatigue resistance of stainless steels. So, you can see one example from this book, suppression of fretting by design optimisation in a press fit shaft assembly. You can see this fillet radius, if you design such a thing, the fretting can be reduced. not a sharp one; if you give a groove with the radius, then you can actually reduce the fretting wear.

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In this class we understood what is the fatigue wear? or the material removed because of the repeated loading and unloading conditions. So, the fatigue wear is mainly by the formation and propagation of surface cracks or the subsurface cracks. Subsurface crack propagation is proposed by the Professor Suh, it is actually called professor Suh's delamination theory. So, generally subsurface crack propagated fatigue wear gives the delaminated sheets. Fatigue wear can be assessed by the plastic strain accumulated.

Coming to the fretting wear, it is the small amplitude relative movement mainly in the oscillatory fashion, that will lead to the material damages that we call fretting wear. Fretting damage is called fretting wear or fretting corrosion or fretting fatigue, but mostly it is represented by fretting wear. Fretting wear can be understood by elastic contacts or elastic plastic contacts.

In most of the engineering applications, we will find elastic plastic contacts and where you will have mixed regimes of the partial slip or gross slip to give a major contribution towards the fretting wear towards the material removal. So, it is basically a mixture of all these regimes that will lead to the material removal. Generally, a mixed regime or reciprocated sliding conditions regime that leads to maximum wear.

And the slip or the partial slip or the stick regimes always gives a mild wear. So, fretting can be reduced by design approach or by giving certain surface treatments like coating, nitriding or short peening.

We will see in certain case studies, where this fretting wear is dominant and then that lead to material removal in coming classes, thank you.