Friction and Wear of Materials: Principles and Case Studies
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Lecture – 07
Wear Mechanisms: Abrasive Wear

Hello, welcome back to this NPTEL course. In continuation with the wear mechanisms today, we learn about the other wear mechanism abrasive wear mechanism. Abrasion is generally defined as a mode of material removal that is caused by hard asperities or hard particles sliding over a relatively softer surface, so that causes damage at the interface. So, such an abrasion is very important in several engineering applications.

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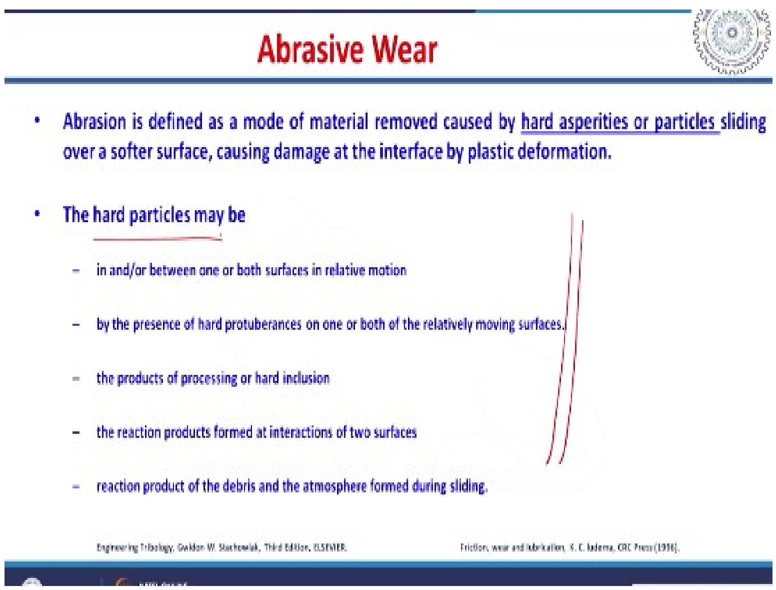

The hard particles or the asperities which are in contact with the asperities of other surface or probably they are in the surfaces or between the surfaces in relative movement or they are formed by the presence of hard protuberances on one or both of the relatively moving surfaces or the products that are formed because of the processing or the hard inclusion or such reaction products that formed at the interactions of two surfaces or the reaction products formed at the interactions of two surfaces or the hard particles may be the reaction products of the debris and the atmosphere formed during sliding. So, any of these result into hard particles. These hard particles during the sliding movement removes material, such a removal of material by the hard particles at the contact is defined as an abrasion. So, the material removal is called abrasive wear. There are several engineering applications where the abrasive wear is predominant.

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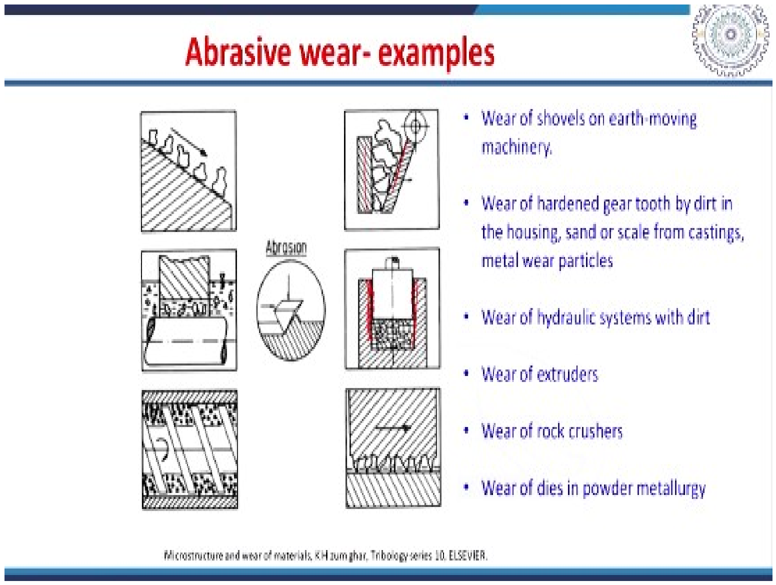

For example, the wear of shovels on earth moving machinery or certain jaw crushers, where there are certain hammers and they are damaged because of the abrasive wear or there are certain wear of hydraulic systems with dirt or wear of the rock crushers or metal forming devices where there is a chance for the abrasive wear. There are so many instances where the abrasive wear is predominant.

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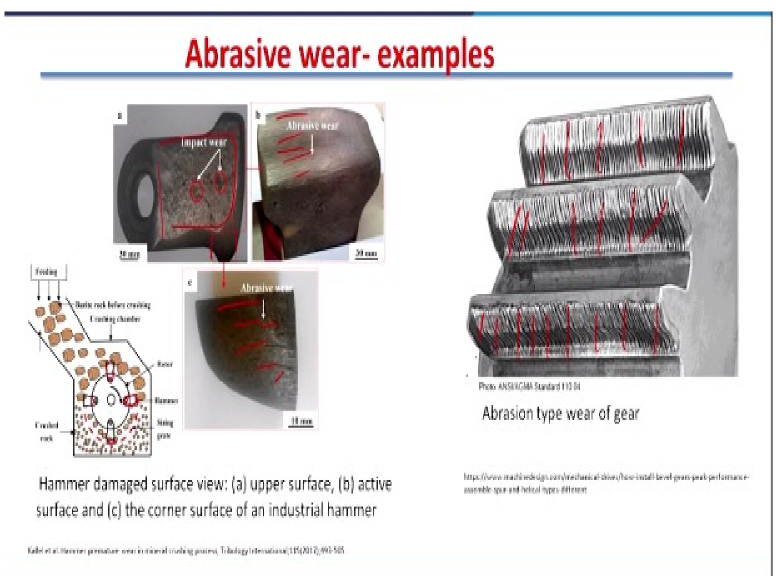

So, these are real life photographs of abrasive wear. Then you can see the jaw crusher, where you have several hammers. These hammers are actually worn out by the impact where are certain abrasive wear, you can see such a rough surface. These grooves are instances of this abrasive wear or you can also see the excessive wear happen because of the abrasion on these gears. So, there are several grooves formed because of this abrasive wear. There are so many certain examples of abrasive wear in engineering applications.

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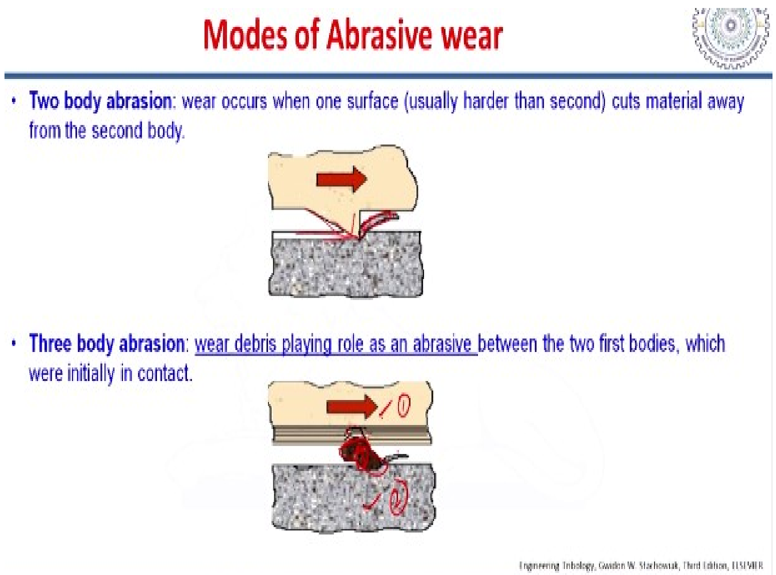

There are two modes of abrasion; one is the two-body abrasion, another one is the three-body abrasion. Two body abrasion is the general abrasion that occurs when one surface cuts the material away from the second material. So, this is a harder body, this is a relatively softer body. This cuts the surface and the material is removed as a chip or if you have the particles removed from the softer surface, those we call wear debris.

These wear debris are retained in the contact and these wear debris particles play a major role, how? This wear debris may be different from the physical or chemical or mechanical characteristics of either of these surfaces or both of the surfaces. Then what happens? These retained wear debris between these two first bodies play a very important role either by damaging either of the surfaces or by both or both the surfaces.

So, this abrasion is because of this third body. This is first body, second body and the third body which is completely different in physical, chemical or mechanical characteristics. So, that will actually abrade the relatively softer surfaces of either of these body or both bodies. So, this abrasion the material removal because of the third bodies called 3 body abrasion and the material removal is called 3 body abrasive wear.

If you look at the mechanism of wear macroscopically, it is because of the cutting of the harder asperities on the softer surface. Actually, in a microscopically there are several mechanisms which you can account for the material removal in the abrasive wear conditions.

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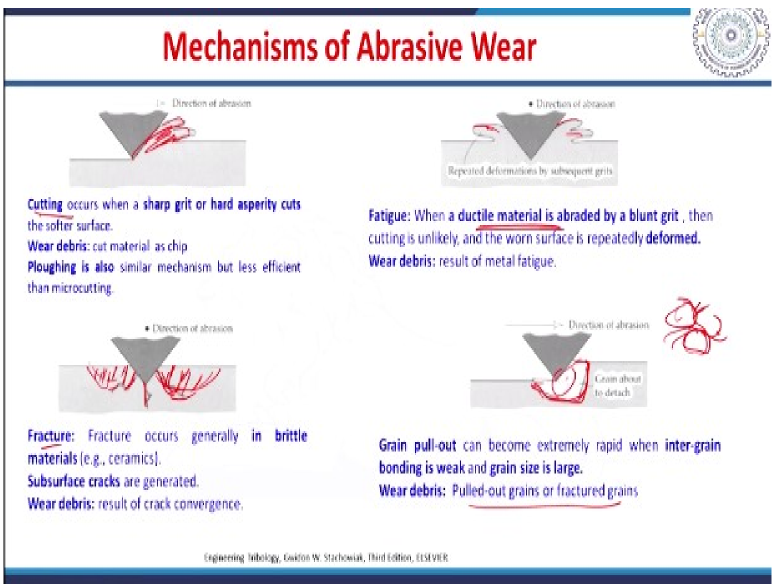

For example, as I told this is the cutting. So, this cutting generally happens when a sharp asperity cuts the softer surfaces. So, you have got usually a chip, the wear debris is in the form of the chip. Ploughing is also similar mechanism but only difference is ploughing is less efficient than the micro cutting or there can be a fracture. You know because only by the crack propagation.

So, when the harder asperity in contact with the softer material in abrasive conditions, there happens certain cracks. These cracks generally are dominant in brittle materials. For example, ceramic materials. So, these cracks by virtue of their lateral movement or radial median movement. They actually propagate and then they actually come on to the surface and the material is removed.

Generally, in a brittle material it is thought that the material is removed by the lateral cracking meeting the free surface. So, the material is completely removed. So, the fracture generally occurs in a brittle material and subsurface cracks are generated when they are parallel to the surface and they meet the free surface then the material removal, then you can get an abrasive wear.

So, the debris is the result of such a crack convergence with the free surface or there can be a fatigue. Particularly, when a ductile material is abraded by a blunt asperity then the cutting is unlikely, but the worn surface is mainly deformed repeatedly. Because of the repeated deformation, there happens certain cracks and the material removes because of this fatigue action.

So, the wear debris is the result of such metal fatigue. Generally, it happens in a ductile material or there will be another mechanism which is generally dominant is a grain pull out. Grain pull out you know grains are pulled out when you have the weaker surface being the grain boundary. So, the crack propagates through this grain boundary and then complete the materials from the grain is removed.

You have certain grains and then the crack generally propagates through the weaker region. So, the weaker region being grain boundary. This grain boundary weaker region facilitates easy propagation of this crack and then this material from this grain is removed. So, you will have a wear debris as a result of this pulled out grains or the grains fractured. Pulled out grains or fractured grains are the wear debris by this mechanism of grain pull out.

So, there are mainly 4 different micro mechanisms responsible for the abrasive wear. The cutting or the fracture, fatigue and the grain pull out.

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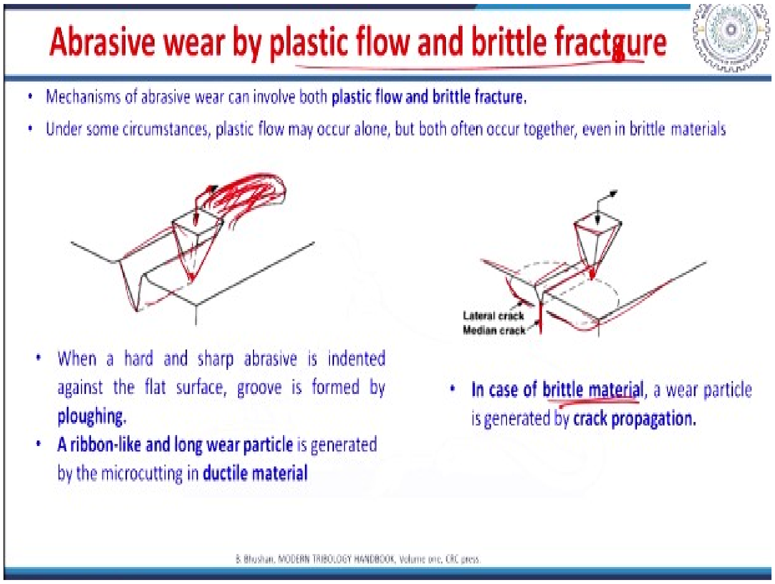

Abrasive wear by virtue of the material being abraded, you can actually have 2 different types of material removal. The abrasive wear by plastic flow or abrasive wear by plastic flow or abrasive wear by brittle fracture. Brittle fracture: The mechanisms of abrasive wear can involve both plastic flow and brittle fracture based on the material which is being abraded.

So, under certain circumstances the plastic flow may be occurring alone. But generally, these 2 occur often together even in the brittle materials. That means, even in ceramic materials you will also find certain plastic flow and then the brittle fracture. For example, when a hard and sharp abrasive is indented against the flat surface; you have certain hard material and the very sharp material indented against the softer surface and being slide, and being moved in a sliding condition.

Then what happens? There forms a certain groove and this groove is nothing but as a result of a ploughing. So, the resultant is like a ribbon like material or you can say long wear particle. This long wear particle is generated mainly by the ploughing or by the micro cutting in a ductile material. As I told, the cutting is more severe than the ploughing. But the mechanism reminds almost the same. So, it happens in a ductile material, a very long ribbony kind of wear particle is a resultant of such a ploughing. But in case of brittle material because of the inherent brittleness, the propagation of a crack will result into the material removal. So, we will see the sharp and hard asperity.

If the material slides over the relatively softer material. What happens? There is a groove but at the same time, this material cannot accommodate large amount of elastic strain energy. So, what happens? Their forms certain cracks. The cracks can be a radial median crack or then can be a lateral crack. And the material is removed by the propagation of such cracks. So, the material removes in abrasive wear conditions by plastic flow or the brittle fracture or a combination of a plastic flow and brittle fracture.

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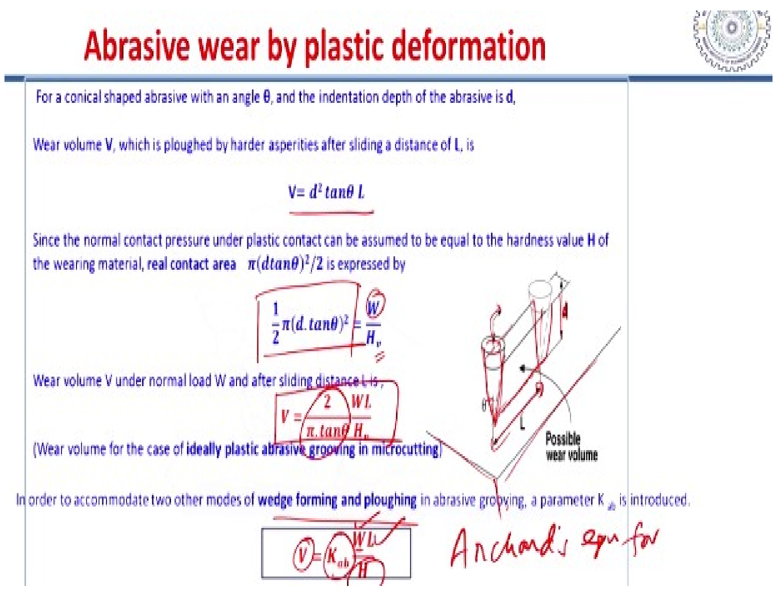

Let us understand these more clearly. Abrasive wear by the plastic deformation: You consider a conical shape abrasive with an angle theta. So that you can accommodate the shape factor as well and this indents to a depth of d. Depth of the abrasive is d. So, the material is removed because of the sliding over this distance of L.

The sharp indent is moved on this surface up to this position. So, the sliding distance is L. The wear material or wear volume which is ploughed by this harder asperity after a sliding distance of L,

$$V = d^2 \tan\theta\, L$$

Since the normal contact pressure under plastic contact can be generally equal to the hardness value of the wearing material.

Then the real area of contact that becomes

$$\frac{1}{2}\pi\left(d\tan\theta\right)^2=\frac{W}{H_v}$$

Where, W is the load applied, Hv is the hardness; Vicker's intendation hardness.

So, wear volume V under normal load W and after the sliding distance of L. So, you can consider

$$V=\frac{2}{\pi\tan\theta}\frac{WL}{H_v}$$

So, this is the wear volume in generally for the ideally plastic abrasive grooving in micro cutting.

So, in addition to accommodate other two modes of wedge forming and ploughing in abrasive grooving generally, an abrasion parameter called K_{ab} is introduced. So, it becomes volume of the material removed. Abrasion is equal to a parameter called abrasive wear parameter which is again a dimensional less parameter into the load applied into the distance moved divided by the hardness of the softer surface.

$$V=K_{ab}\frac{WL}{H_v}$$

If you can remember, this is actually similar to what we understood in the Archard's equation. Archard's equation for the adhesive wear. So, adhesive wear also has similar equation. So, it again indicates for a plastically deformable material that means, for a ductile material in abrasive conditions. The wear volume is proportional to the load applied; is proportional to the sliding distance; is inversely proportional to the hardness;

So, if you have a hardness more, then you will have material removal less. If you have a loading conditions high, then you have material removal high. If you slide for a longer distance, you have material removal high. In case of the abrasive wear similar to that what we found in the adhesive wear conditions, right.

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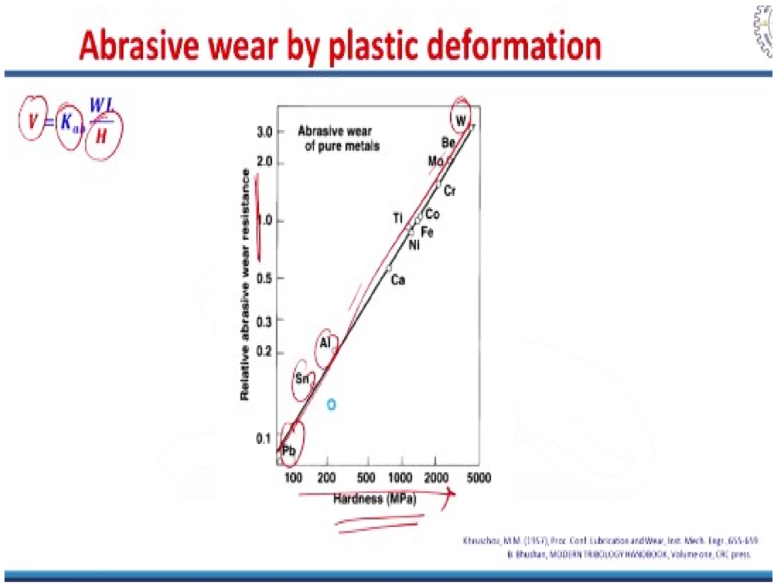

So, this is what it is represented. This is represented wear volume is inversely proportional to the hardness. You can see several metallic materials with the hardness ranging from you know 100 to typically 5000 MPa. This is relative abrasive wear resistance. The wear resistance increases, wear resistance is nothing but the inverse of the wear volume. So, the wear resistance increases with the increase in the hardness value.

You can see the tungsten being a very harder material, the resistance is also high. Whereas, aluminium, tin, lead being softer materials, they have very less wear resistance in abrasive wear conditions. And if you look at these intermediate values of hardness, the calcium, titanium, nickel, cobalt all these have intermediate wear resistance in abrasive wear conditions. So, this parameter includes the size and the shape factors.

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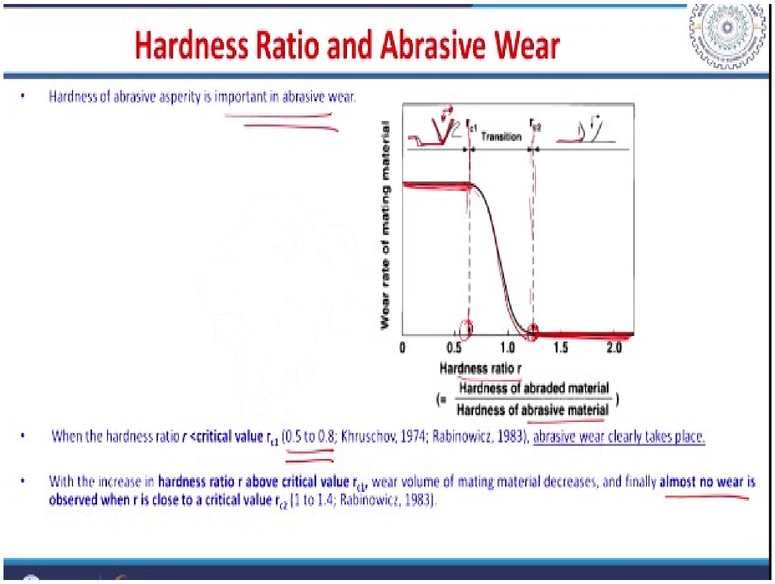

In addition to the size and shape factors of the abrasive indent, the hardness plays a major role in abrasive wear. So, if you can take a hardness ratio as a hardness of abraded material to the hardness of abrasive material, this is the abrasive and this is the abraded material. So, the wear rate of this mating material actually is influenced by this ratio.

So, rather than just a making a hardness of the abraded material, you can actually take a ratio of this hardness of abraded material to the hardness of abrasive material. So, you see here up to a critical hardness ratio usually < 0.5 to 0.8, the abrasive wear is predominant. Whereas, when the hardness ratio decreases above this critical value, then the wear of the material removal actually decreases.

And finally, almost no wear is absorbed when this ratio is close to the second critical value of $r_{c2,}$ generally more than 1. So, 1 to 1.4 if it reaches, then what happens? You have mostly the wear of the material removed mainly by the plastic deformation not by the abrasive wear. So, when it reaches more than 1 or 1.4, then you have almost no wear in the abrasive wear conditions. So, it depends on the critical ratios of this hardness.

When the hardness ratio is less than the critical value of r_{c1}, it is generally 0.5 to 0.8, abrasive wear is dominant and the abrasive wear decreases when the hardness ratio is above this r_{c1}. So, wear volume of the material removal decreases and finally, almost no wear is absorbed. When this ratio is close to the second critical hardness ratio, you have always an important influence of hardness ratio on the abrasive wear of this material.

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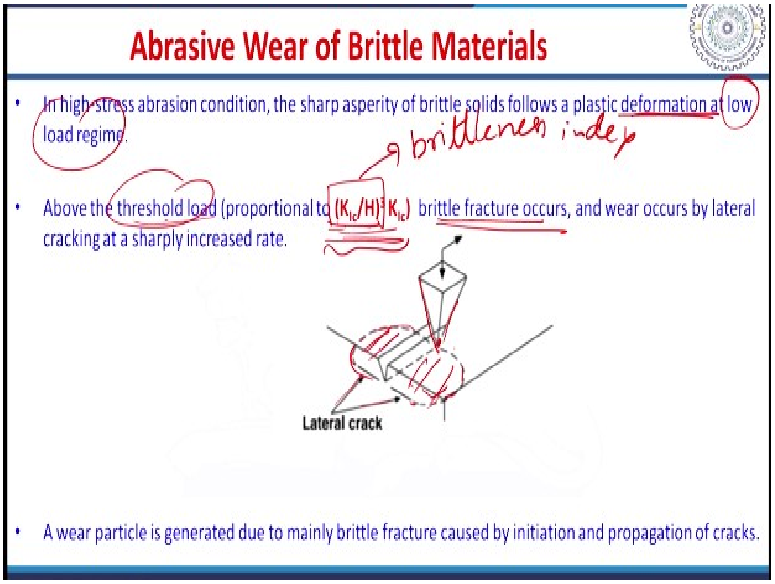

Let us understand the abrasive wear in an ideally brittle material. In high stress abrasion conditions, if you have the sharp asperity of the brittle solid follows a plastic deformation at a low load regime but above certain threshold load generally, proportional to a parameter which is

$\left(\frac{K_{1C}}{H}\right)^3 K_{1C}$. So, if the load is above this threshold value, then brittle fracture is dominant and wear occurs mainly by the lateral cracking at the sharply increasing rate.

So, generally this $(K_{1C}/H)^3$ is actually called brittleness index. There you can see the brittleness index is represented by this ratio of this fracture toughness to hardness rather than only fractured toughness. So, this brittleness index * K_{1C} is actually proportional to the load applied. When the load is above the threshold load, which is proportional to this total parameter, then the brittle fracture is dominant.

Below this, the plastic deformation is dominant. That means, based on the applied load you will have a plastic deformation or a brittle fracture dominant. So, the wear particle is generally due to the brittle fracture caused by the indentation and propagation of such lateral cracks. So, the total material here is removed as a wear.

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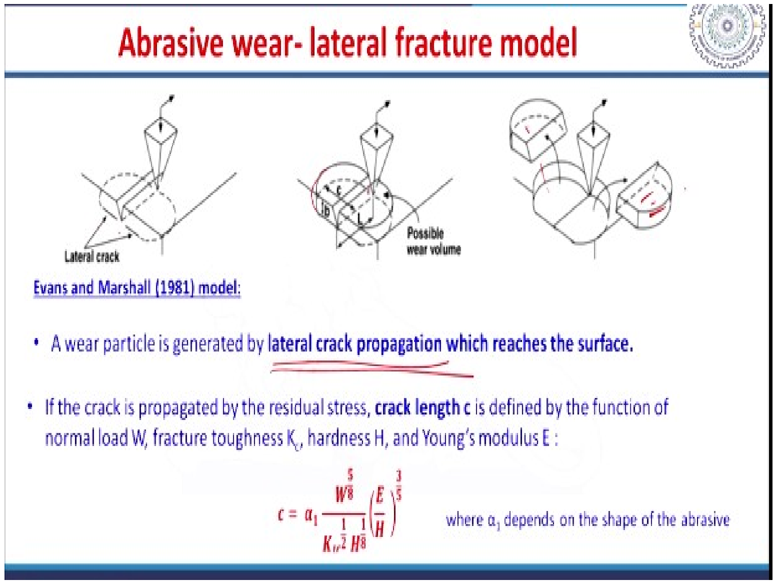

So, for this lateral fracture induced wear, Evans and Marshall as actually proposed a model which shows that wear particle is generated by the lateral crack propagation which reaches the free surface. So, when the lateral crack is propagating, it reaches the free surface. When it reaches the free surface, the material is removed as wear.

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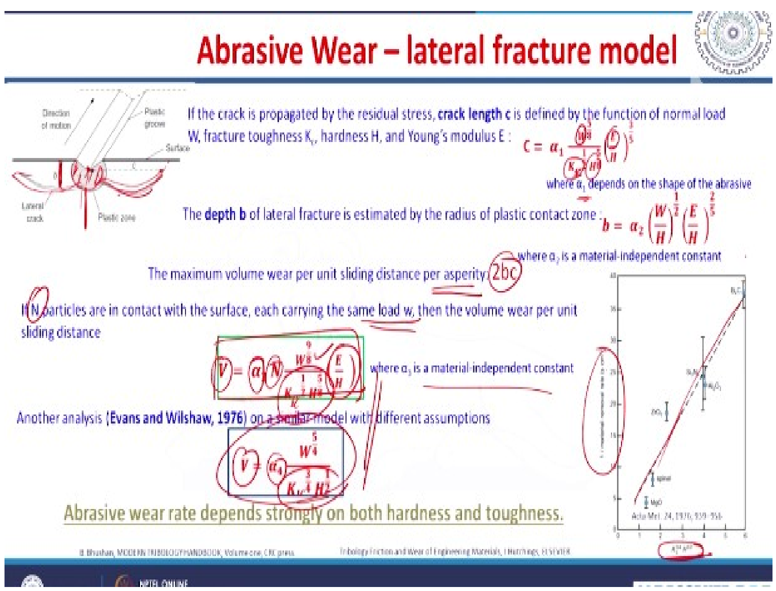

If the crack is propagated by the residual stresses, this is the contact initially and just underneath the contact. There happens certain zone where this energy is stored. As the load is increased what happens? There will be a radian median crack. When the load is removed, you will have this radial median crack closing but you will have a lateral crack generating.

As the load is removed, the contact is not in the loading conditions and this lateral crack propagates up to the free surface and the material is removed.

The crack length C is defined by the function of normal load W and the fracture toughness K_{1C}, the hardness and elastic modulus.

$$C = \alpha_1 \frac{W^{\frac{5}{8}}}{K_{1C}^{1/2} H^{5/8}} \left(\frac{E}{H}\right)^{\frac{3}{5}}$$

Where alpha 1 depends on the shape of the abrasive. Whereas, the depth b of the lateral fracture is again estimated by the radius of the plastic contact zone.

$$b = \alpha_2 \left(\frac{W}{H}\right)^{\frac{1}{2}} \left(\frac{E}{H}\right)^{\frac{2}{5}}$$

The maximum wear volume per unit sliding distance per asperity is 2bc. So, this depth * 2c.

So, if there are such N number of particles in contact with the surface each carrying the same load W, then the wear volume per unit sliding distance becomes

$$V = \alpha_3 \frac{W^{\frac{9}{8}}}{K_{1C}^{1/2} H^{5/8}} \left(\frac{E}{H}\right)$$

So, this is the wear volume per unit sliding distance, right.

So, this indicates V is inversely proportional to the product of this $K_{1C}^{1/2}$ and $H^{5/8}$. Generally speaking, the E/H for a brittle material is constant. So, it happens wear is proportional to the $load^{9/8}$ and inversely proportional to the product of this fracture toughness and hardness values. So, where α_3 is a material independent constant. Another analysis by Evans and Wilshaw on a similar model with the different assumptions also lead to similar wear volume quantification.

$$V = \alpha_4 \frac{W^{\frac{5}{4}}}{K_{1C}^{3/4} H^{1/2}}$$

So, these semi empirical equations are more or less valid for brittle materials wear in abrasive wear conditions. You can see here this parameter $K_{1C}^{3/4}$ * $H^{1/2}$, this is reciprocal of the material removal rate. You can see as this parameter is increased; you will have material removal also increases.

For a brittle material like magnesium oxide, zirconium oxide, silicon nitrate and boron carbide, the parameter is increasing, the wear resistance is also increasing. So, the wear volume is inversely proportional to this parameter. So, very important point we need to note here is abrasive wear rate depends strongly on the both hardness and fracture toughness.

It is not independently influenced by hardness or independent influenced by the toughness, it is actually a combination of hardness and fracture toughness that actually influences the wear volume in abrasive wear conditions for a brittle material. So, as I told you that there is a fracture happening in a brittle material when the load is above the threshold load which is proportional to this parameter.

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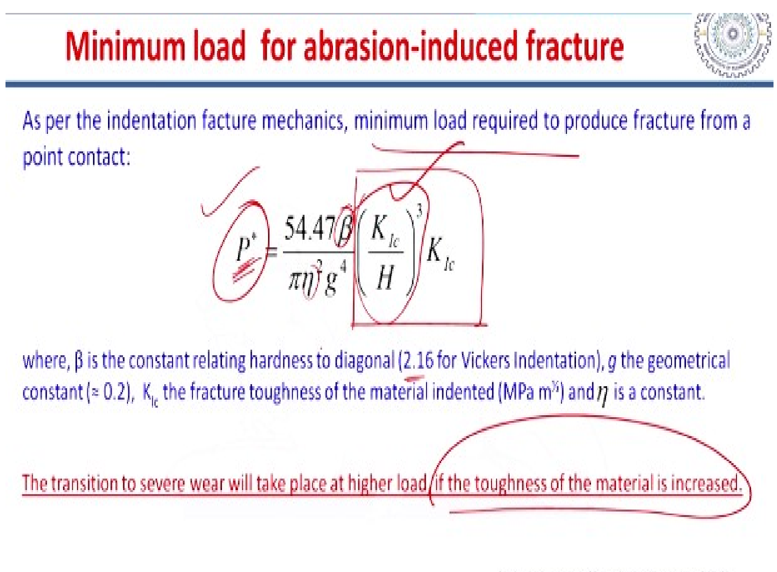

The minimum load as per the indentation fracture mechanics, the minimum load required to produce fracture from a point contact which is a sharp contact,

$$P^{¿} = \frac{54.47\,\beta}{\pi\,\eta^{2}\,g^{4}}\left(\frac{K_{1C}}{H}\right)^{3} K_{1C}$$

you can see this β is a constant relating to the hardness to diagonal generally, in a Vickers indentation becomes 2.16. So, g is a geometrical constant generally taken as point as 0.2, K_{1C} is the fracture toughness of the material indented and then η is a constant.

So, you can have this minimum load required to fracture in a brittle fashion is proportional to this parameter. If the load is above this load then the fracture happens by the brittle fashion. So, it is proportional to this parameter and as I told this particular $(K_{1C}/ H)^3$ is generally referred as a brittleness index of this material. So, the point here is if the load is increasing, there happens a plastic deformation induced abrasive wear changing to brittle fracture induced abrasive wear.

As we know, for a brittle material as the fracture is initiated that means the crack is initiated, the propagation becomes spontaneous. If the crack length is more than the critical length, then the propagation is instantaneous and then leading to brittle fracture which is a catastrophic. So that means the wear becomes severe, as the load is increased from lower load to higher load. That means, from the plastically deformed region that means the plastic deformation induced wear to brittle fracture induced wear.

So, we have a wear is also increasing in its magnitude but the transition to that such severe wear will take place at higher load, if this fracture toughness of the material is increased. You can see this is actually proportional to K power 4, right. So, these minimum load required will be increasing if the fracture toughness is increasing.

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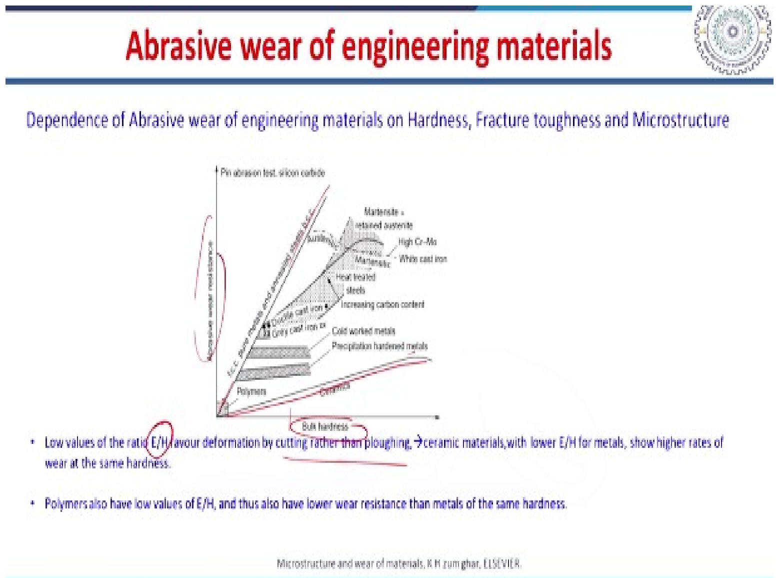

So, let us understand abrasive wear of engineering materials in general. So, the abrasive wear resistance generally depends on the material parameters like hardness, fracture toughness as well as the microstructure. So, you can see this is abrasive wear resistance plotted against the bulk hardness of several materials. So, you can see the ceramics, right. As the hardness is increasing the resistance is actually increasing.

Similarly, for the metals and steels also, it is increasing. So, but you can see that you cannot actually differentiate how this hardness and fracture toughness influence for different classes of materials, right. So, but actually it depends on the hardening and the brittle fracture, right. So, the low values of the plastically deformed groove region, so it depends on how much is the groove fraction that lead to abrasive wear.

So, that can be represented by a ratio called elastic modulus to hardness. So, low values of the ratio of E to H favour deformation by cutting rather than ploughing. So, ceramic materials having lower E/H values compared to metallic material. So, higher rates of wear at the same hardness, right. Higher rates of wear at the same hardness. But polymers also have low values of E/H and thus also have the lower wear resistance than the metals of the same hardness.

So, if you have the same hardness materials of different classes then the abrasive wear is also different. So, it actually depends on the material or it actually depends on the bonding or the microstructure right.

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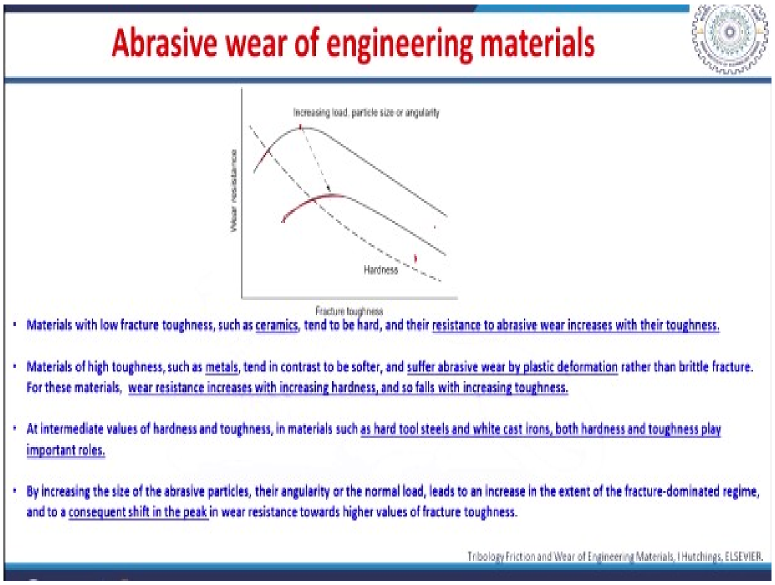

So, if you look at the wear resistance versus the fracture toughness, materials with low fracture toughness for example, ceramic materials they are tend to be hard but their resistance abrasive wear increases with the toughness, right. But materials of high toughness for example, metals they tend to contrast to be softer and the soft and they suffer abrasive wear by plastic deformation, right rather than the brittle fracture.

So, for these metallic materials, wear resistance increases with increase in hardness. So, falls with the increasing toughness but those materials having an intermediate values of hardness and toughness such as the hard tool steels or white cast irons, both hardness and toughness play important roles in resisting such an abrasive wear. So, by increasing the size of the abrasive particles, their angularity or the normal load actually that leads to an increase in extent of fracture dominate regime.

And to a consequent shift in the peak, right. Consequent shift in the peak in the wear resistance toward the higher values of the fracture toughness. So, it depends on the material right.

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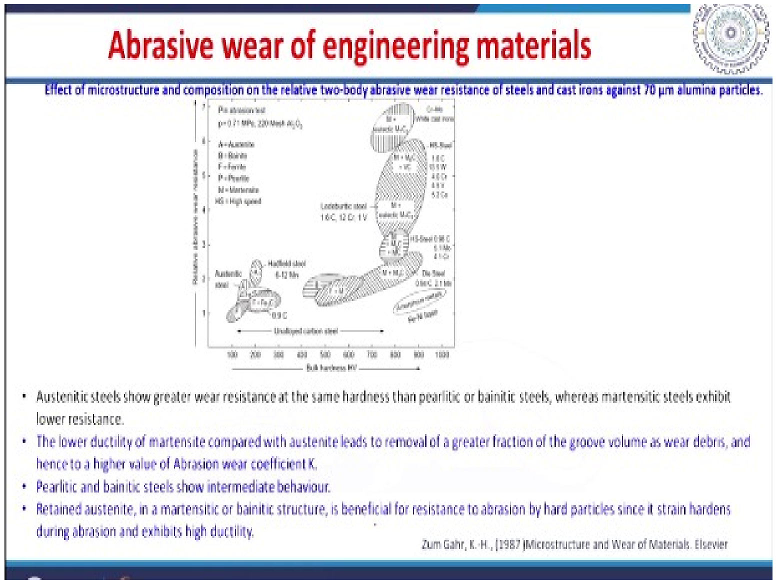

So, more clearly if you see the effect of microstructure and also the composition, relatively abrasive wear resistance of steels and cast irons, you can see the austenitic steels show greater wear resistance at the same hardness than the pearlitic or bainitic steels. Whereas martensitic steels exhibit lower wear resistance, right. So, the lower ductility of the martensite compared with the austenite that leads to removal of a material to a larger extent, right.

So, hence to a high value of abrasion wear coefficient, pearlitic and bainitic stainless steels show intermediate values, whereas retained austenite in martensitic or bainitic structure is beneficial in resistance to abrasion by hard particles since this strain harden during abrasion and exhibits high ductility. So, it is the play of ductility and strain hardening, right. So, whichever is dominant, you will have a reflection on the abrasive wear resistance, right.

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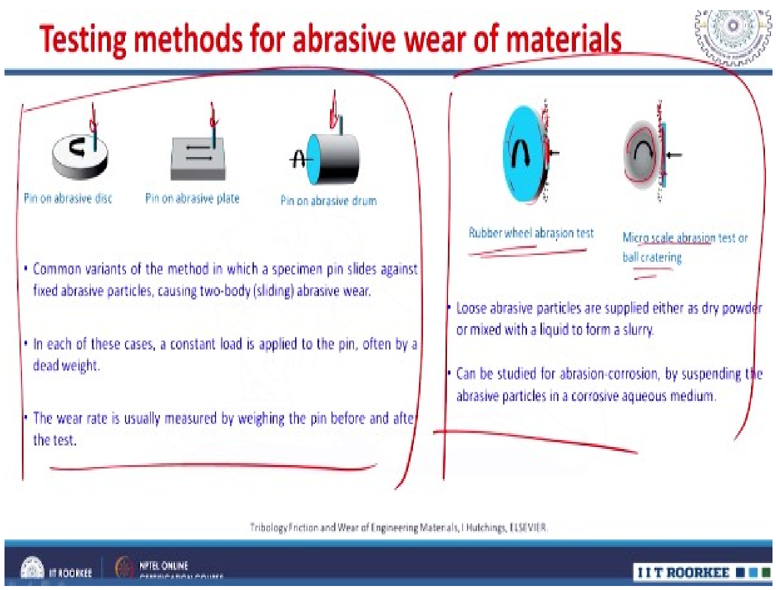

So, there are few testing methods for the abrasive wear materials, testing methods for abrasive wear of different materials. So, they can be categorised into two groups. The first group is like pin on abrasive disc or pin on abrasive plate or pin on abrasive drum. The common variance of this method in which a specimen which is specimen pins slides against a fixed abrasive particles that cause 2 body abrasive wear.

So, but in each of these cases, a constant load is applied, right. Constant load is applied to the pin generally by a dead weight. The wear rate is usually measured by weight loss that is weighing the pin before and after the test. So, you will have the wear rate. Whereas, in other category loose abrasive particles are supplied either as a dry powder or those mixed with the liquid that forms a slurry.

So, you have a rotating disc and then you have a specimen fixed and then this can be a rubber wheel or a disc or a micro scale abrasion test all. The ball rotating at a particular speed in contact with this specimen, right. The abrasive particles are supplied. So generally, either by rubber wheel abrasion test on a micro scale abrasion or you call ball cratering, the loose abrasive particles are supplied either as dry powder or mixed with the liquid to form a slurry.

So, these can be studied even for abrasion corrosion study by suspending the abrasive particles in a corrosive aqueous medium. So, you will have two categories of testing methods for abrasive wear of different materials.

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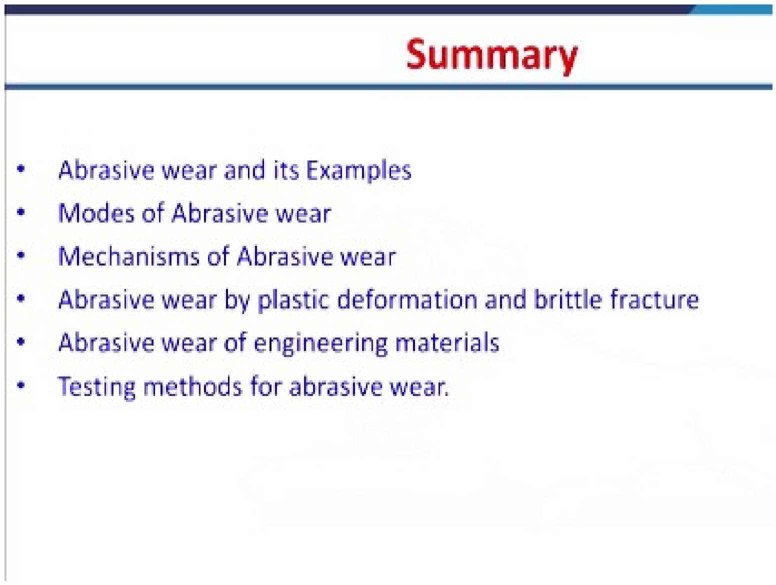

So finally, summarising we understood what is abrasive wear? and also, we have seen several examples. We also understood there are two modes of abrasive wear; 2 body and 3 body abrasion wear. They depends on the wear debris particles. If they also contribute to the wear, then we call 3 body abrasion. or the mechanisms of abrasive wear: the micro cutting, ploughing or the fracture, fatigue or the grain pull out, right.

So, abrasive wear may occur by plastic deformation and brittle fracture even in case of ideally brittle materials. There will be a plastic deformation and brittle fracture depending on the load you apply. So, abrasive wear in a brittle material or plastic deformation can be quantified by generally by Archard’s equation or similar type of equation. So, abrasive wear of engineering materials though depends on the microstructure and as well as the properties and composition.

There are several testing methods for the abrasive wear. In coming classes, we will also see several classes of materials worn out by abrasive wear. So, several case studies will be provided to understand this abrasive wear in more detail in coming classes, thank you.