Friction and Wear of Materials: Principles and Case Studies

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Lecture - 10
Wear Mechanisms: Erosive Wear

Hello, welcome back to this NPTEL course. Today, we will learn about the erosive wear mechanism. Erosive wear is mainly caused by the impact of solid particles or liquid against the surface of an object.

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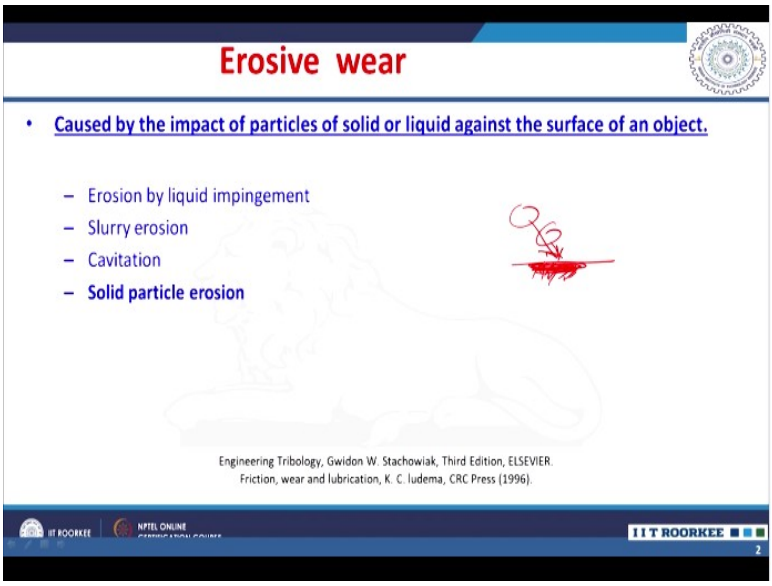

If you have certain solid particles impinging on a surface, you will have the material is removed from this surface or the underneath the surface. That material removal is called erosion or the erosive wear. So, the erosive wear can happen in many numbers of ways. For example, erosion can happen by liquid impingement. The liquid can strike the surface and then lead to material removal, or mixture of particles and the fluid then you will have a slurry erosion.

Or a cavitation erosion, certain mechanism where the cavities are formed. So, you will have a cavitation erosion. Or a solid particle erosion, where the several particles will be impinging on the surface that leads to material removal.

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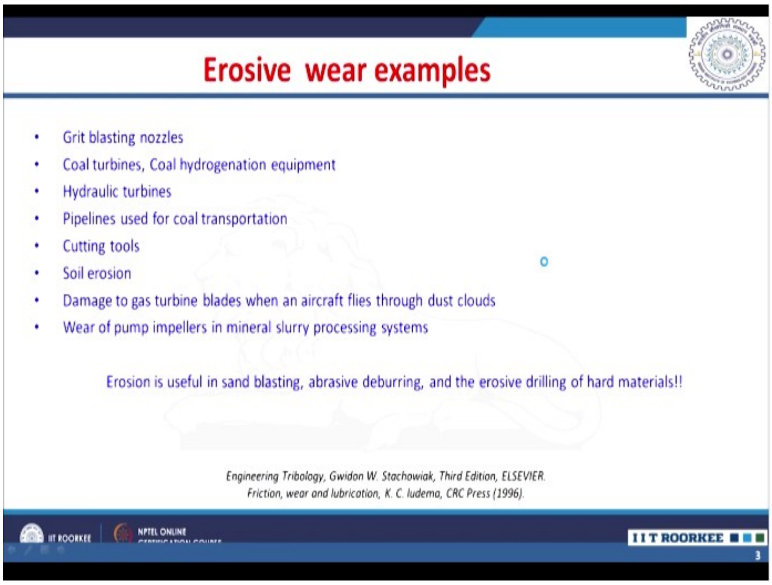

Listing down the examples of erosive wear, we will confine the erosive wear dominating in grid blasting nozzles or coal-turbines or coal hydrogenation equipment, where the coal particles will be impinging and then leading to the equipment’s material removal. The hydraulic turbines, where you will have a stream of liquid as well as the mixture of the liquid or the particles will impinge on the material, that leads to material removal. Or pipelines used for coal transportation same; coal particles in hot air.

Cutting tools, where you will find lot of particles being removed from the edge of these cutting in the contact with the workpiece. These particles will be impinging on the surface of this cutting tool material and the material is removed by the erosion. Or the erosion of the soil itself we can find.

A damage to gas turbine blades; when an aircraft flies through a dust clouds; or wear of pump impellers mainly in the mineral slurry processing systems. There are several examples like this, where erosive wear is dominant. Erosion in some cases is useful for example, sandblasting; you want erosion to happen by this sandblasting, right but in a controlled way, or abrasive deburring or erosive drilling of the hard materials, you need a controlled erosive wear.

So, erosive wear shall be understood thoroughly. First we will see erosion by a liquid. So, erosion by a liquid is as dangerous as by the soil particles provided the impact velocities are sufficiently high.

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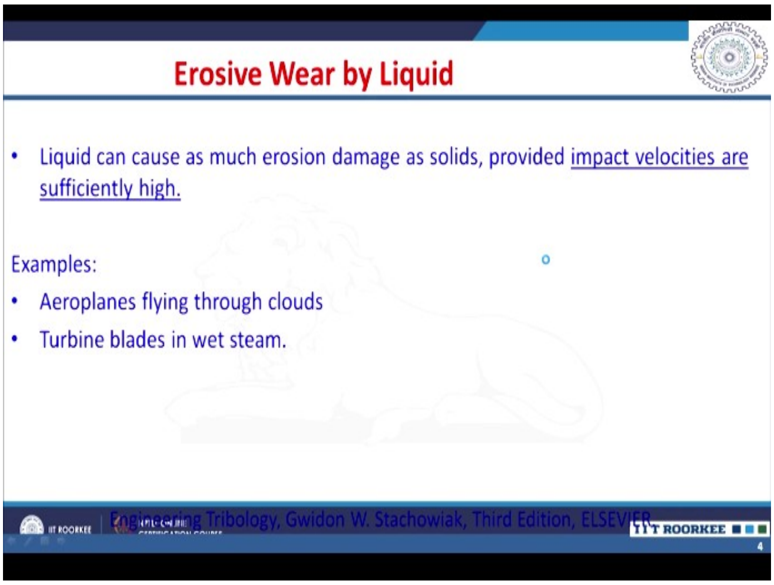

For example, aeroplane flying through clouds, or a turbine blades in wet steam conditions, where you can find this erosive wear by the liquid.

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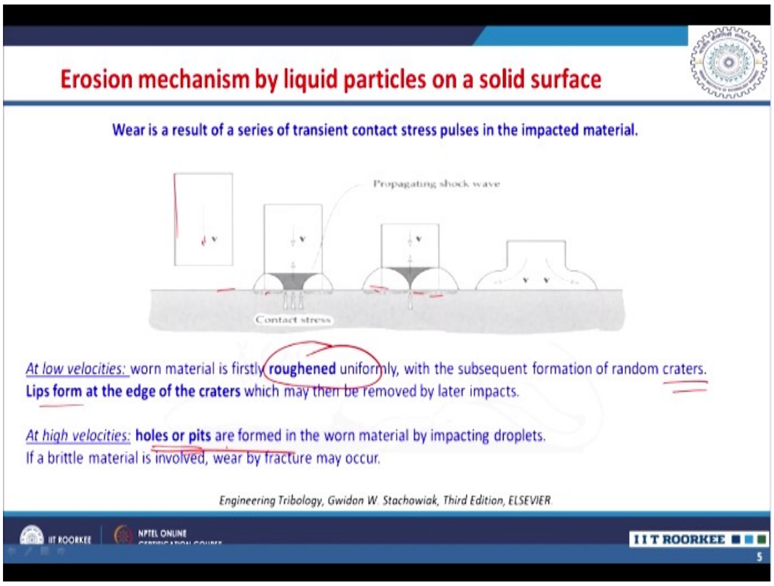

If you have certain water droplet coming onto the surface at high velocity, there happens certain shock waves at the contact, and these are relieved by forming a crack and then material is removed. So, this is one example where the water coming onto the surface that lead to fracture of the surface. Wear is a result of a series of such transient contact stress pulses in the impacted material.

With respect to velocities; At lower velocities, worn material is firstly roughened uniformly and then subsequent formation of the craters. These craters will lead to the material removal.

At high velocities, holes or pits in the worn material by impacting droplets. So, if at all the material is brittle material which is impacted, then you will have the fracture dominant.

So, at low velocities and high velocities, the material is removed in the form of a crater and then forming lips or by forming holes and pits with respect to the velocities of the liquid.

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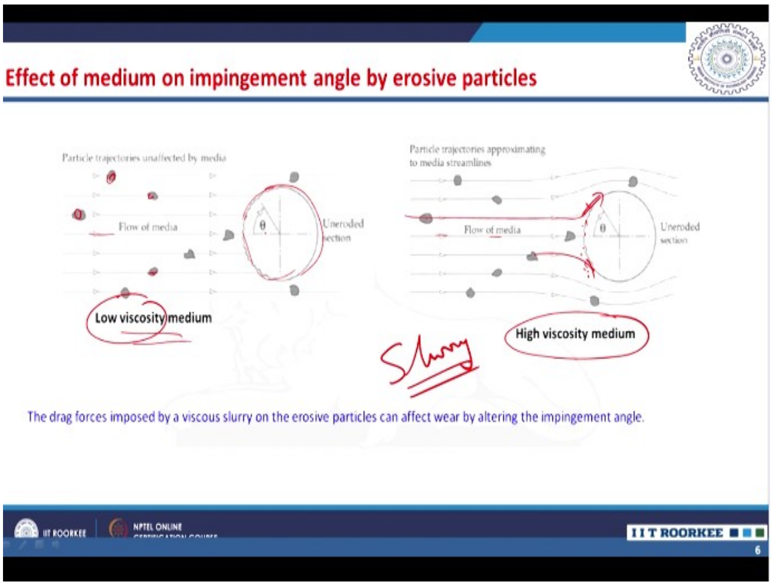

In a particle plus the fluid mixture, generally you can say the slurry erosion. Slurry that is formed by a mixture of a particle and the fluid. If you have a difference in the viscosity of the medium in which these particles are flowing, there will be difference in the overall material removal.

The particle trajectories are unaffected by the media, when you have the low viscosity. If the medium is of high viscosity, then what happens? The flow of the particle is actually deviated. So, the flow of these particles in this medium is changed because of the viscosity of the medium.

So, the drag forces imposed by this viscous slurry on the erosive particles can affect in altering the impingement angles. So, you will have a difference in the material removal. So, in a slurry erosion generally the fluid viscosity or the medium viscosity plays a major role.

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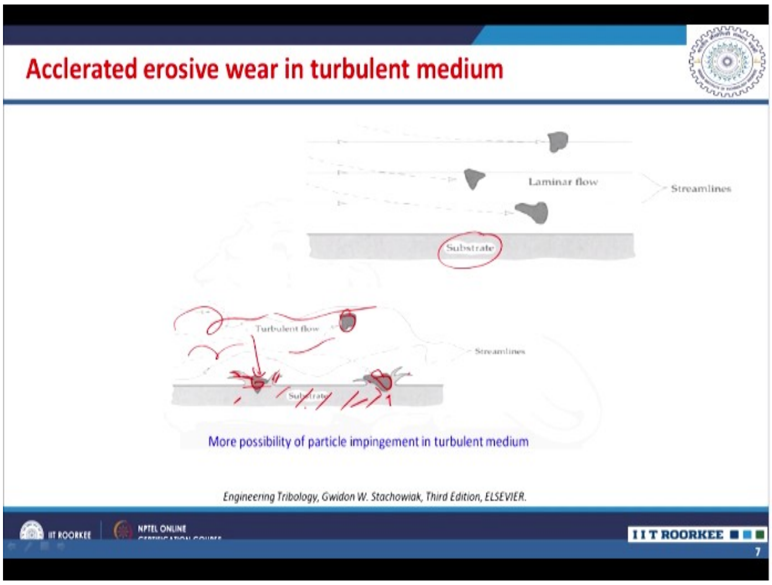

Or you can also see the turbulence of this flow is also making a difference in the erosive wear. If you have the laminar flow, the particles will be moving in a stream lines without impinging on the surface. So, the material is still not removed substantially or not fractured substantially. But if you have the turbulent flow of this medium, the particles are more likely to come and then impinge on the surface.

So, that will lead to more plowing or cracking that leads to more wear. Compared to the laminar flow, if you have the turbulent flow of this medium, the particles are more impinging on the surface, and that leads to accelerated erosive wear.

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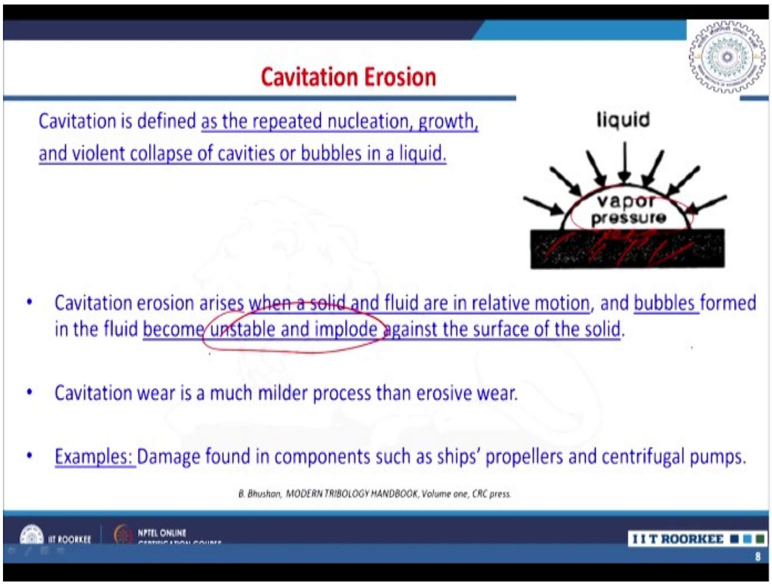

Cavitation is defined generally as the repeated nucleation, growth and then violent collapse of these bubbles or cavities in a liquid, that leads to material removal. So, where these bubbles are impinging or collapsing on the surface that material is removed. So, we called this as cavitation erosion. Cavitation is defined as the repeated nucleation, growth and violent collapse of cavities or bubbles in a fluid in a liquid that leads to the material removal.

Cavitation erosion generally arises, when a solid and fluid are in relative movement and bubbles are formed in the fluid that become very unstable and implode against the surface of the solid. So, you have to maintain the stable bubbles then you have a lesser cavitation erosion. If you have unstable bubbles, that will lead to more possible impingement on the solid surface or the more collapse on the solid surface that leads to material removal from the solid.

So, the cavitation wear is much milder process than erosive wear. Damage in components such as ships, propellers, or centrifugal pumps, you will find all this cavitation erosion. Or bubbles collapsing on these pumps' surfaces or the ship propeller surface that leads to erosion, that is cavitation erosion.

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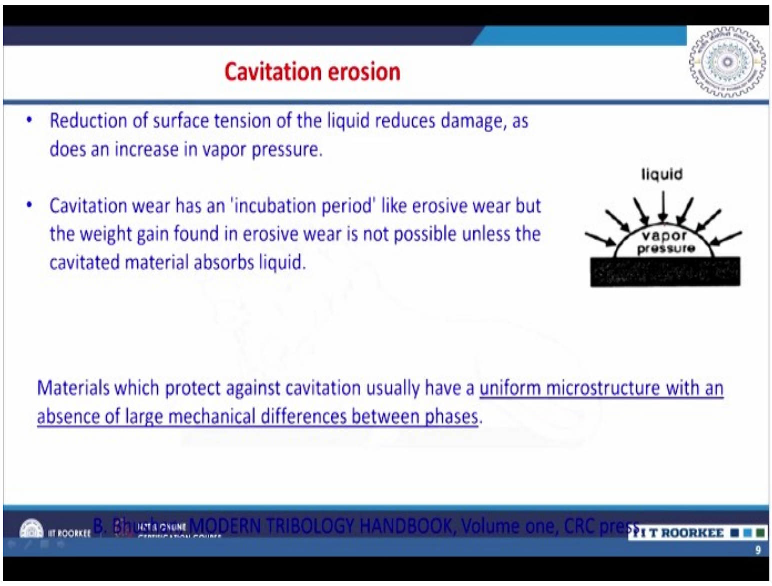

The reduction of the surface tension of the liquid reduces damage as does in the increase in the vapour pressure. So, cavitation erosion has an incubation period like that we found in erosive wear but the weight gain found in erosive wear is not possible unless the cavitated material absorbs liquid. So, weight measurement is not a prominent technique to assess the cavitation erosion.

The materials which protect against the cavitation usually have a uniform microstructure without having any difference in the mechanical properties between the phases. So, you will have minimum cavitation erosion.

Solid particle erosive wear is the dominant erosive wear found in several engineering applications. In coming classes, we will also see several case studies on the solid particle erosion of several ceramics and ceramic composites. So, we shall study the solid particle erosion thoroughly.

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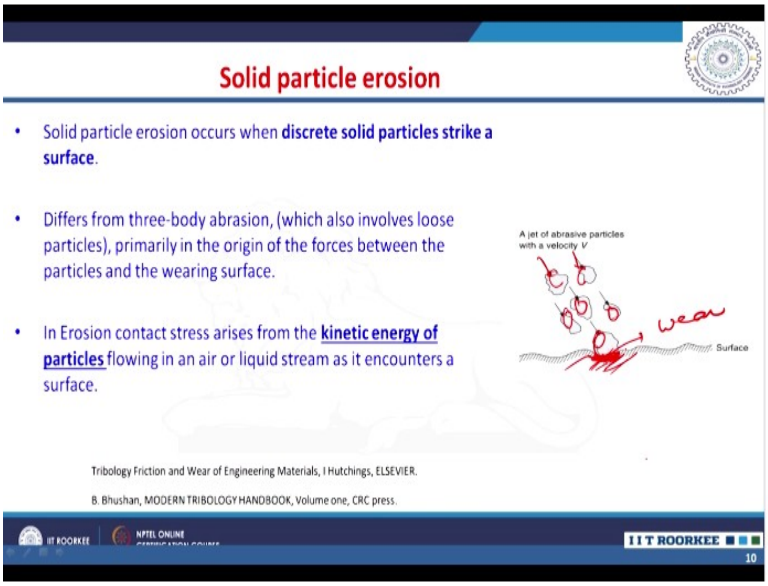

Solid particle erosion occurs when discrete solid particles strikes the surface with a high velocity. So, they come and then impinge on the surface. So, the energy has to be transferred onto the surface of this material. If this material is not able to absorb such energy, then what it will do? It will actually fracture.

So, when the energy is not absorbed by this material, then that leads to material removal. But you can see here also there are particles, which are causing the material removal like that we found in the abrasion. Abrasion also we have certain particles causing the material removal but it differs from the three-body abrasion, primarily in the origin of forces between the particles on the wearing surface.

Basically in erosion, contact stresses arises mainly from the kinetic energy of the particles because they are coming with high velocity and they have certain mass. So, this kinetic energy of particles flowing in air or liquid stream as it encounters the surface. So, you will have a material removal. This material removal is the erosive wear. So, basically the kinetic energy of the particles contributes to the wear.

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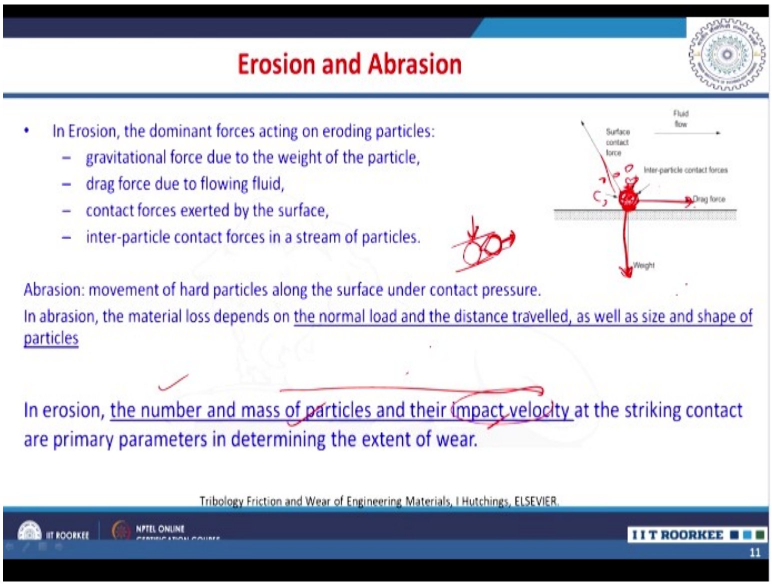

If you look at the forces acting on the eroding particles, in a fluid flow there is a drag force and the particle itself has a gravitational force due to weight or the drag force in the fluid, contact stresses exerted by the surface or inter-particle by the surface or the inter-particle contact in surfaces in a stream of particles. You will have several particles. So, inter-particle surfaces also.

So, there are several forces acting at the contact where this particle impinging onto the surface. Whereas, in abrasion involves movement of hard particles. We will have two surfaces in which we will have hard particles along the surface under contact pressure conditions. In abrasion, material loss depends mainly on the normal load and the distance travelled as well as the size and shape of these particles.

Whereas in erosion, it is the number of these particles and their impact velocity at the striking contact that actually determines the extent of the erosion wear. So, mass and impact velocity that leads to kinetic energy. Number and the kinetic energy of the particles striking on the surface leads to the wear.

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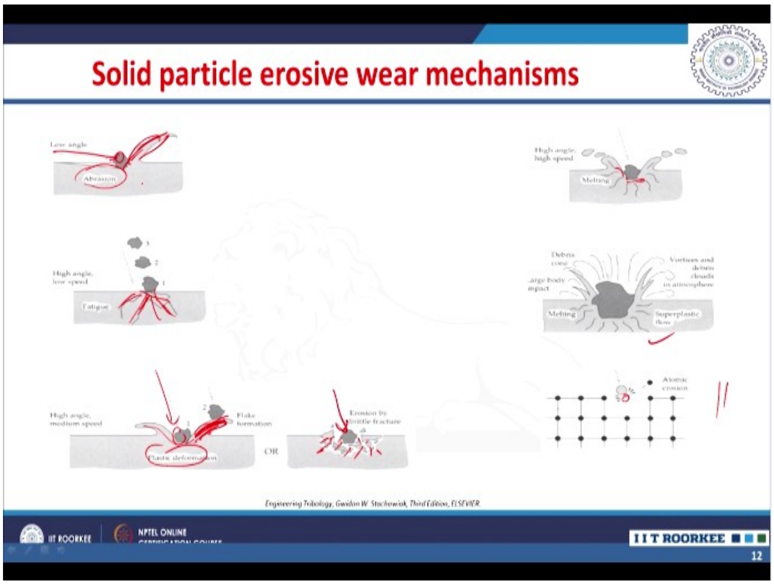

If you look at the overall wear mechanisms in a solid particle erosive conditions, the wear can occur by simply abrasion or fatigue or plastic deformation or fracture or by melting or by secondary effects of superplastic flow or such things or even the atomic erosion. So, generally abrasion is found in erosive conditions when the erodent particle comes and strikes at lower angles.

So, you will have this material removed as chips. Or the fatigue at higher angles and lower speeds. You will have this surface or subsurface cracks propagating that leads to material removal. So, fatigue actually contributes to the erosive wear, or the solid particles impinging at very high angles, right 90 degrees. But with a medium speed then you will have the plastic deformation of the surface and leads to the flake formation or thin sheet-like material removal.

Or if the material is not plastically deformable that means it is brittle material like ceramics, whenever these particle strikes at a higher angles with a medium speed, then there is a lot of fracture nearer to the contacts, so that will lead to the brittle failure by the propagation of such cracks, or at higher angles and high speeds, there will be a possibility even for the melting in addition to this cracking.

Or there may be certain secondary effects like superplastic flow or melting or the deformation of the debris so on and so forth. So, these are also possible. Or there can be at atomistic level also, an atom can be eroded from the crystalline arrangement by this. But these are less likely to happen. But most of the engineering components they wear in erosive conditions, when solid particle impacts on the surface by mechanisms of abrasion, fatigue or deformation, fracture, melting on some certain superplastic flow.

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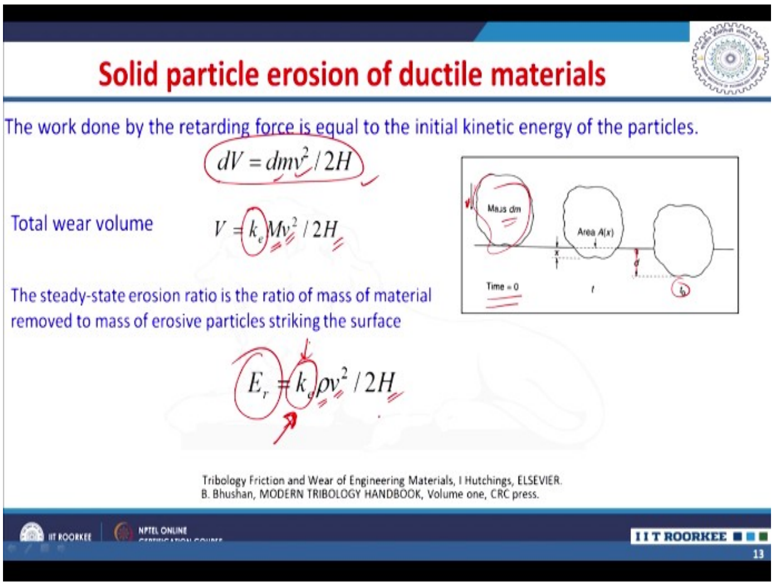

Let us understand this solid particle erosion of a ductile material.

$$dv = dm v^2/2H$$

You can consider a particle of mass dm impinging at a velocity v and travels a certain distance, and by travelling actually it erodes the material or by the depth of the d. So, actually the work done by retarding force is actually equal to the initial kinetic energy of the particles. So, you can actually determine the work done by taking the velocity and the mass for the given eroded material's hardness.

So, from time t0 to time t there is certain material removed. The total wear volume because of this erosion for certain exposure time t can be understood.

$$V = K_e M v^2/2H$$

V is equal to this steady-state erosion. This m is the total mass of these particles impinged, velocity of the such particles v, H is the hardness of this eroded material. So, steady-state erosion ratio is the ratio of mass of material removed by the mass of erosive particles.

$$E_r = K_e \rho v^2/2H$$

So, the mass of material removed to the mass of erosive particles. So, the steady-state erosive ratio is equal to the ke. ke is the erosive wear parameter that actually accounts for the shape and size of these particles, right and rho is the density of this material, v is velocity of this particle, H is the hardness of this material.

Now just you can remember that we will have an adhesive wear conditions or abrasive wear conditions also, the wear rate can be related to the hardness in a similar way. So, higher is the hardness of the material being eroded lesser is the erosion. It is almost similar to the abrasive wear or adhesive wear equation but only difference is you will have the term involved with the kinetic energy at the velocity, whereas in abrasive and erosion you do not have such kinetic energy related parameter.

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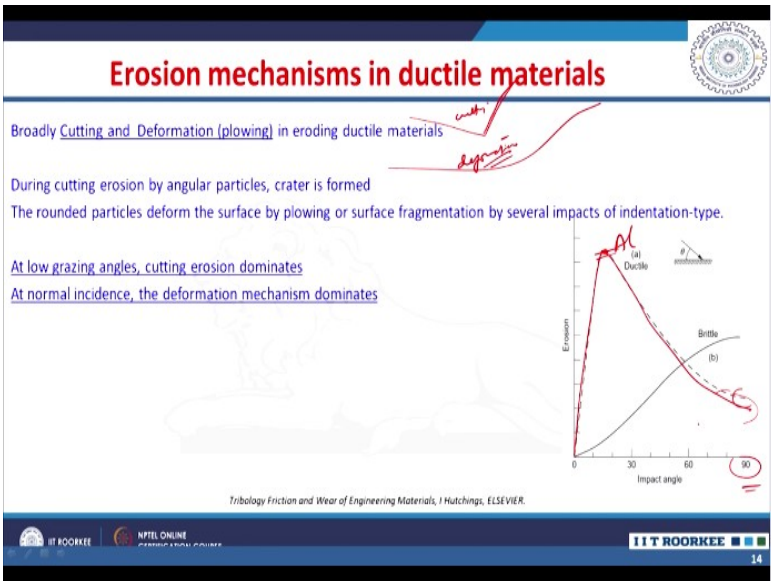

If you look at these ductile materials, mainly they are damaged in erosive conditions by cutting or by plowing. So, during cutting by angular particles mainly a crater is formed, and in repeated conditions the crater leads to the lip formation and the material is removed. So, you will have the lip removal or you have this cutting or by simply deformation which we call plowing.

During cutting erosion by angular particles, crater is formed. The rounded particles deform the surface by plowing or surface fragmentation by several impact of indentation type. So, if you have this particle after cutting go in a forward direction, generally material is removed as a chip. Whereas, if you have certain material particle in cutting conditions and then they rollback, then they lead to again the lip formation.

But with respect to the angle of this impingement at low grazing angle, cutting erosion is dominated. So, you will have at lower angles maximum erosion occurring for a ductile material. For example, aluminium; and then after that it reduces with increase in the impact angle almost one third or half of this peak of the angle, you will find it high at this condition. So, erosion is reduced after this peak angle.

But at normal incidence, deformation mechanism is dominating. So, here it is the cutting and here it is the deformation. So, the deformation mechanism dominates in ductile materials that leads to less erosive wear, whereas cutting is dominated then lead to higher erosion wear. So, at lower angles cutting is more dominant, at normal incidence or higher angles the deformation mechanism is dominant.

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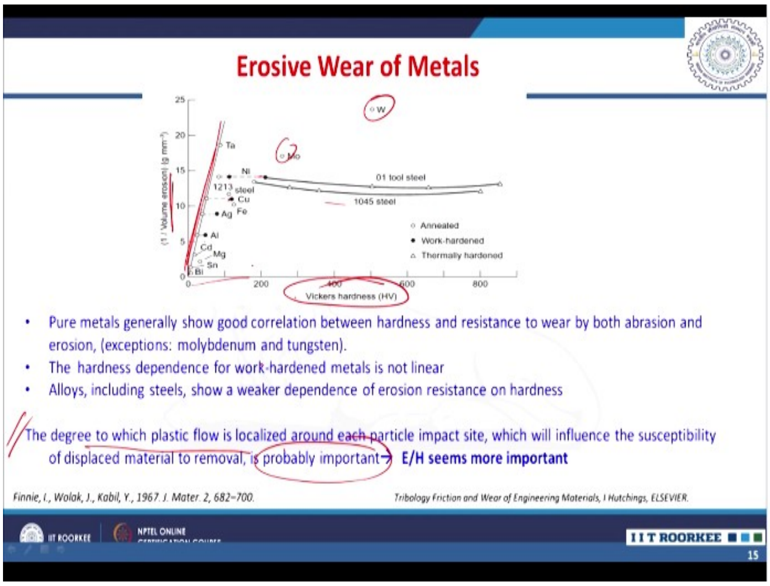

If you look at the erosive wear of several metals, pure metals generally show good relation with the hardness and resistance to wear by both abrasion and erosion. Of course, there are certain exceptions of tungsten or molybdenum. But you can see the resistance, it is inverse of the volumetric erosion versus the Vickers hardness. You can see the pure metals always show with increase in the hardness you will have increase in the erosion resistance.

But hardness dependence for work-hardened material is not linear, and alloys including steels show a weaker dependence of erosion resistance on hardness. That means this gives a very important observation that it is not only the hardness that leads to the erosion or if you want to select a material with a higher erosion resistance, you have to not only see the hardness but all you have to see even the elastic modulus of that material.

If you remember our discussion in the abrasive wear, the degree to which the plastic flow is localized around each particle impact site, which will influence the susceptibility of the displaced material to the removal. So, this degree to which the plastic flow is more important, or in other words the ratio of elastic modulus to hardness is more important than simply hardness.

But if you see erosion of a brittle material, brittle material they tend to fracture easily by the propagation of a crack.

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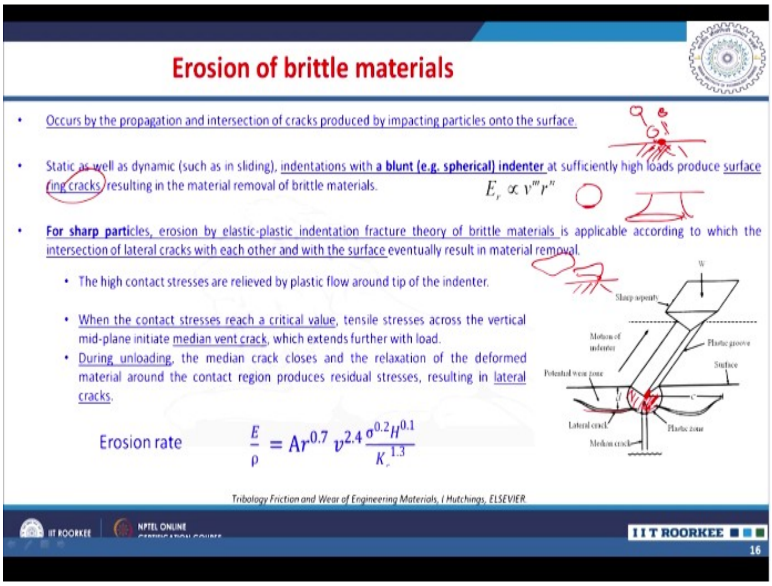

So, this erosion of the brittle materials occurs by the propagation and intersection of the cracks produced by impacting particles onto the surface. You will have several particles and then they actually create lot of cracks at the impacting contact. With blunt indenter for example, spherical indenter. If you consider this particle having a blunt indenter, a spherical indenter at sufficiently high loads that produce surface ring cracks.

In other classes, we will also understand there are mainly two types of cracking developed in brittle materials. One is the ring cracks or the conical crack, second is the lateral fracture or radial median lateral fracture. So, radial median lateral fracture generally developed by the sharp indenters whereas, the surface ring cracks or conical cracks are developed by the blunt indenter.

So, we will have less concentration of loads, actually that will lead to a conical cracking or will have conical cracking. Whereas, in a sharp crack that means a particle with sharp edges that will lead to a cracking and this cracking is generally radial median or the sharp cracking. For sharp particles, erosion by elastic plastic indentation fracture, theory of brittle materials is applicable. So, the high contact stresses are relieved by the plastic flow just around the tip of this indenter. When the contact stresses reach a critical value, tensile stresses across this vertical mid plane initiate these radial median cracks.

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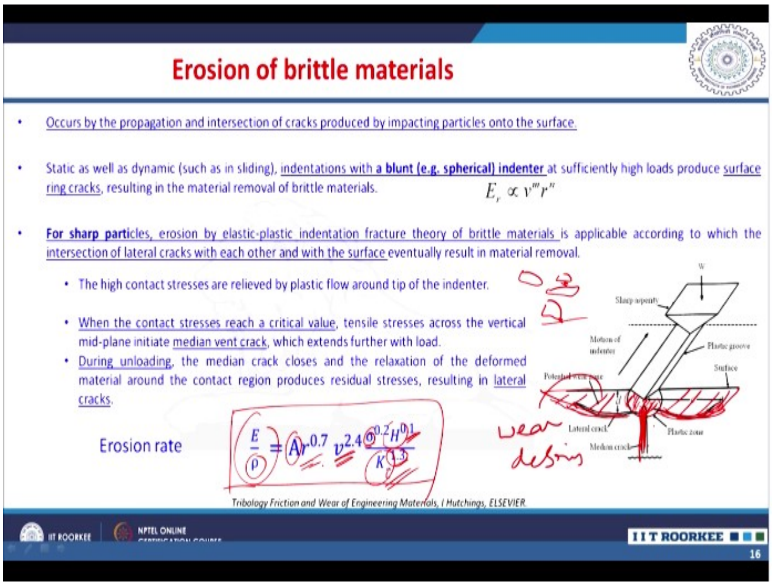

So, when high contact stresses are relieved by the plastic flow around the tip of this indenter, I mean the particle with a sharp edge. When the contact stresses reach a critical value, tensile stresses across the vertical mid plane initiate this median vent crack, which extends further with the load. So, while rolling of this erodent particle or while going away from the contacts of this erodent particle, what happens? That is unloading happens.

So, during this unloading the median crack is closed and the relaxation of the deformed material around the contact region produces residual stresses. The residual stresses result in a lateral crack. When this lateral crack propagates further and then they reach the free surface, this material is removed, and this material is nothing but the wear particle or wear debris.

So, erosion of brittle materials can be estimated by knowing the size of the particle, velocity of the particle coming, and this is the density of the erosive particle and then hardness and fracture toughness of the eroded material. You can see the fracture toughness exponent is much more than the hardness exponent. So, we can also say the erosion is more dominant by the fracture toughness than the hardness for a brittle material.

This ρ is the density of the material being eroded. So, the erosion rate can be;

$$\frac{E}{\rho} = A\, r^{0.7}\, v^{2.4}\, \frac{\sigma^{0.2} H^{0.1}}{K_{IC}^{\;1.3}}$$

A is a constant, the erosion rate can be estimated by this formula. There are certain similar formulae actually developed based on the experimental results but what we can note down here is the erosion rate is dependent on the particle size, particle velocity, the particle density, the hardness of the material being eroded and fracture toughness of the material being eroded.

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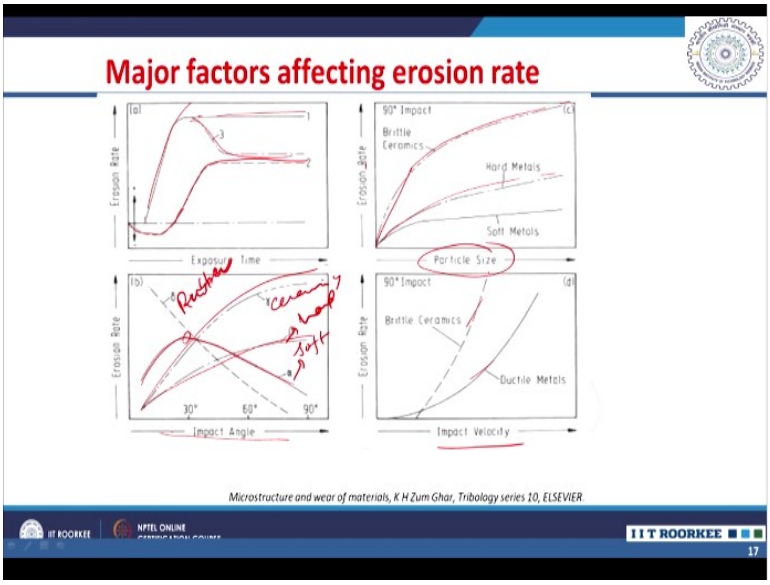

If you look at the major factors affecting such erosion rate you will see with increasing the exposure time erosion actually increases, and after that it may lead to steady-state or it may decrease. Or in other case there will be initially negative erosion wear to accommodate all the plastic strains inside the material and then it reaches a steady-state. With respect to this particle size, you can see the erosion rate.

So, as the particle size is increasing, erosion rate also increasing. But the rate of increase is different from one material to another material. The hard material has higher rate of erosion with increase in the particle size than the softer material. So, you can see even harder ceramic materials have a very sharp increase after certain particle size. With respect to impact angle, as we discussed. So, for softer materials the peak is in the shallow angles.

For relatively hard materials, it goes to the 90 degrees angle or normal incidence. Similarly, for a brittle material like ceramics, you will have always erosion rate higher, at the same time erosion rate leading to maximum at the normal incidence. But for a rubber like materials, This you can see as the impact angle is increasing, erosion rate is decreasing.

So, these are the metallic materials which are soft material. At the hard material, this is hard metallic material. For hard ceramic material, much more erosion rate and increases to maximum at 90 degrees angle. With respect to impact velocities, as the impact velocity is increasing, erosion rate increases for both brittle and ductile materials but with a different rate of increase. So, all these factors affect the erosion rate.

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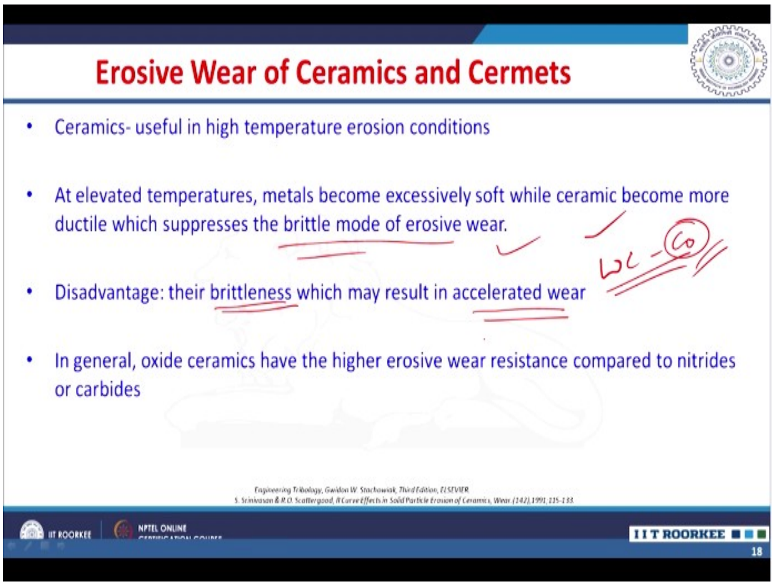

If you look at the ceramics and cermet materials, these materials are useful mainly in high temperature erosion conditions. Why? At elevated temperatures metals become excessively soft whereas ceramic become more ductile which suppress the brittle mode of erosive wear. So, you can have an advantage if you use the ceramic or cermet material in high temperature erosive conditions.

We will also see certain case studies where this point will be highlighted. Disadvantage in using the ceramics or cermet materials of course with the brittleness which may result in accelerated wear. Cermet materials for example, a ceramic material of tungsten carbide with a cobalt binder. This cobalt being a metallic, it increases the toughness. So, there happens a balance between the toughness and the hardness.

So, the brittleness actually is reduced by an optimum content of this cobalt. So that this wear can be produced to acceptable levels in erosive wear conditions, when you use the cermet material. So, this tungsten carbide cobalt being a very popular hard material used as cutting tool, where you can find less erosive wear. In general, oxide ceramics have higher erosive wear resistance compared to carbides or nitrides.

For example, aluminium oxide, zirconium oxide or zirconia toughened alumina ceramic materials have higher erosive wear resistance compared to silicon nitride or silicon carbides. Coming to the next category of material polymers, polymers show good wear resistance mainly because of the low elastic modulus or you can say the polymers generally show a good erosive wear resistance.

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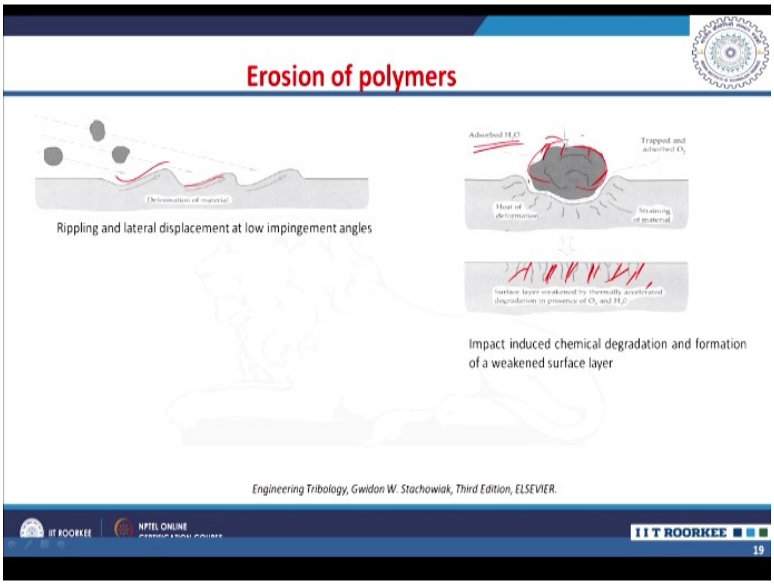

When particles are impinged on a polymeric material, there can be a rippling on lateral displacement at low impingement angles, or the impact induced chemical degradation. For example, adsorbed H2O and that lead to material removal. So, impact induced chemical degradation and formation of a weakened surface that leads to cracking and then the surface layer is weakened by the thermally accelerator degradation in presence of oxygen or water. So, erosion of polymer generally is lesser than the ceramics or metals.

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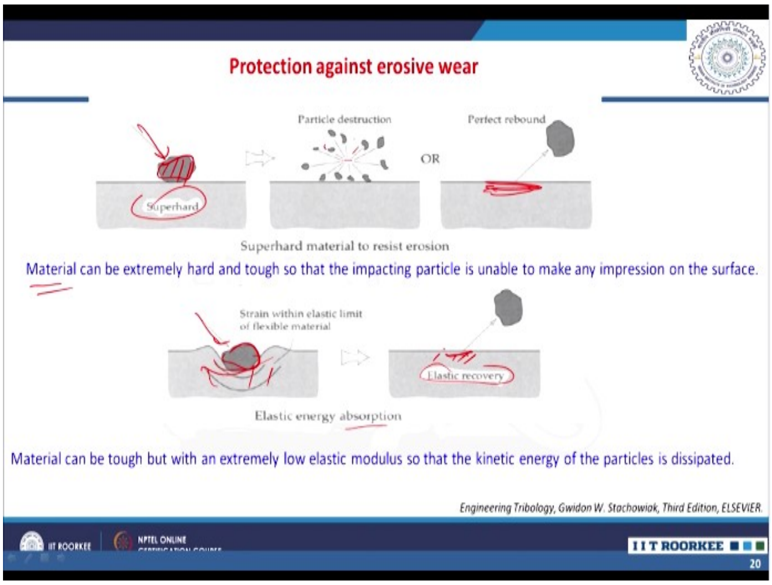

Finally, how to protect the material against an erosive wear? There are two ways to protect. One way is you can actually have a material, which can be having extremely high hardness but at the same time tough, so that the impacting particle is unable to make any impression on the surface after erosion. So, a material particle actually impinges on the super hard material, which is also tough, so that this particle is itself damaged.

After erosion, you do not find any damage on the surface of this material, or you can also have a material which can be tough at the same time extremely low in elastic modulus, so that all the kinetic energy of the particles is harmlessly dissipated. So, you see the particle is impinged on this material, the strain within the elastic limit of the plastic with the flexible material, so the energy is absorbed.

Because of this energy absorption you do not find any permanent damage on the material surface. So, the erosive wear can be protected by choosing a material which is extremely hard and tough or a material which can be tough with an extremely low elastic modulus. In both conditions, you can have a protection against the erosive wear.

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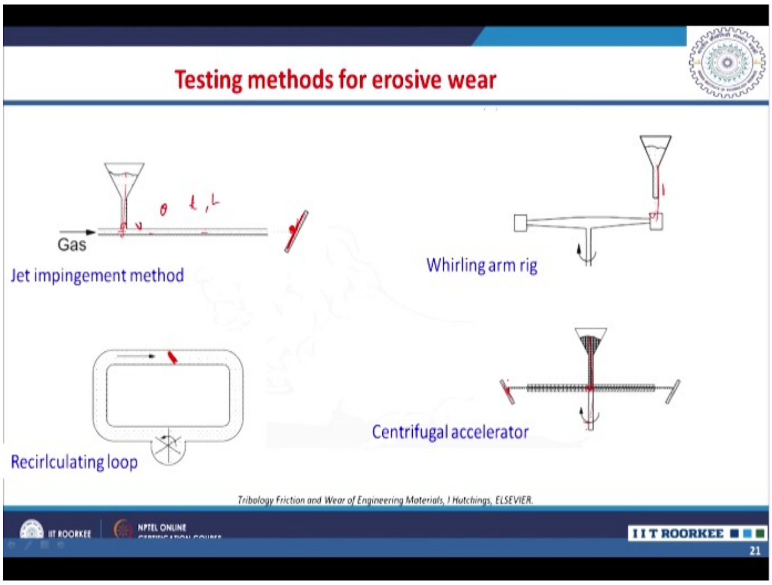

You have several testing methods to assess the erosive wear. By jet impinging method; A gas and the particles total mixture is impinged. This mixture of this particle and gas is impinged on the surface and the material is damaged. So, at a particular velocity and the angle of impingement at a particular temperature conditions and humidity conditions, you can have this material removal assessment.

Similarly, whirling arm rig; you will have this material rotated and then you will have this particle impinging on the component, or reciprocating loop you will have the material is placed here and then these particles are rotated in a fluid, or a centrifugal accelerated particles are dropped at the same time there is a mechanism for the centrifugal force and then with the centrifugal force material is damaged. So, you can assess the erosive wear.

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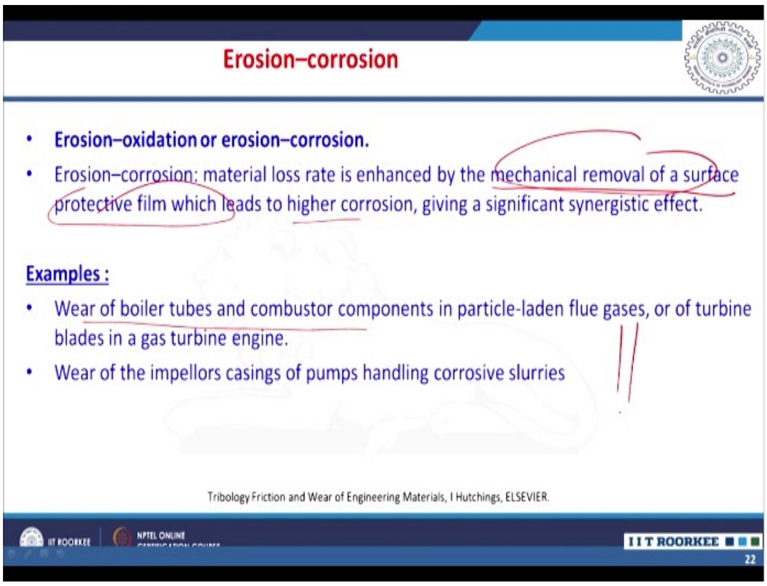

So, last one; There is a synergetic effect of a corrosion and erosion in certain conditions. In high temperature conditions, oxidation or aqueous corrosion conditions, corrosion dominates. So, there is always erosion oxidation or erosion corrosion in certain engineering applications. For example, wear of boiler tubes and combustor components in particle-laden flue gases, or of turbine blades in gas turbine engines, wear of the impellors castings of pumps handling corrosive slurries.

In all these conditions, you have a synergistic effect of corrosion and erosion. So, erosion corrosion material loss rate is mainly enhanced by the mechanical removal of a surface protective film which leads to higher corrosion giving a significant synergistic effect. You have a mechanical removal of this protective film. There is a corrosion, which forms a passive layer.

Because of the mechanical removal of this passive layer, the corrosion even increases and corrosion rate also increases. So, material is removed by both erosion and corrosion, or in other way a synergistic effect acts on the material removal in erosion condition which also to be controlled for the use of several engineering components.

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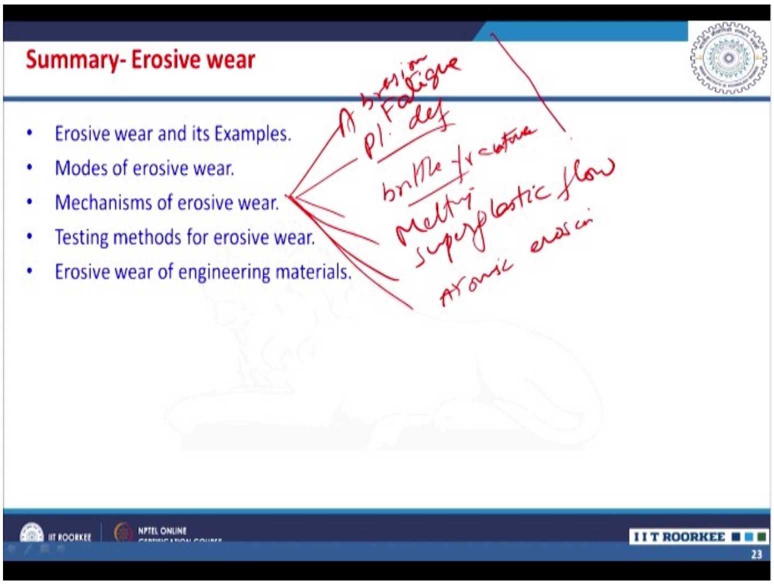

Summarizing this erosive wear; we understood what is erosive wear? Particles impinging or a fluid impinging on the material, so that the material is removed. That material removal is called erosive wear. You will have slurry erosion, cavitation erosion and the solid particle erosion. In slurry erosion, the slurry is a mixture of particles and the fluid. So, you will have erosion by the slurry.

Or you have by simply a liquid impingement; a cavitation erosion, bubbles forming and their collapsing on the surface. So, you will have a material damage. Or a solid particle erosion you will have solid particles impinging at a certain velocity, the kinetic energy is transformed onto the material. So, if the material is not able to absorb such an energy, so that dissipates on the material by a fracture. So, will have a material removal as erosion.

Mechanisms of erosive wear by plastic deformation or erosive wear by brittle fracture. So, under these categories again you will have a cutting and the plowing. You will have inherent internal mechanism like abrasion, fatigue or the melting or secondary effects followed by this deformation or the brittle fracture.

So, listing down all these mechanisms, you will have this abrasion, fatigue, plastic deformation, brittle fracture and you can have melting or superplastic flow, or even you will have a crystalline arrangement in which atoms are atomic erosion. So, all these erosions are more dominant for overall material removal. With the help of all these mechanisms, Erosive wear can be understood for the deformable material and brittle material.

In both cases, the erosive wear rate increases with increase in particle size or the velocity of the particles, or the impact angle for the deformable material or a ductile material, you will have a maximum erosive wear occurring at the lower angles. Whereas, a brittle material or a harder material you will have maximum erosion occurring at the higher angles at normal incidence.

We have also seen several examples of engineering materials; metals, ceramics and polymeric materials. So, in all these conditions, we find for ductile materials it is the E/H more important parameter than simply H. Or for a brittle material you have more domination of the fracture toughness than the hardness. So, brittleness has to be controlled by such certain material processing techniques, so that the erosive wear can be controlled.

Mainly the protection against the erosive wear can be obtained by materials having super high hardness and at the same time tough, or the materials tough at the same time low elastic modulus.

If you use these materials, then the erosive wear can be restricted. In coming classes, we will see several examples of these erosive wear, where we found systematically how this erosive wear can be understood by material parameters as well as the operating parameters? Finally, closing this wear mechanisms part of this lecture, under a given combination of operating parameters there may be number of competing wear mechanisms; Adhesive, abrasive, fatigue, fretting, oxidative wear, tribochemical wear or erosive wear based on the operating parameters. So, you will have a number of competing such wear mechanisms that leads to actual material removal. So, one has to find out, out of them what is the dominant wear mechanism? It is also important to investigate the role of various material parameters.

For example, hardness, elastic modulus and fracture toughness on the severity of individual wear mechanisms. Such an approach of investigation into various wear mechanisms is very much important to the development and design new wear resistant materials. So, let me stop this wear mechanisms part, in coming classes, we will see several case studies where all these mechanisms can be identified. Thank you.