Video Course on Tribology
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Lecture No. # 09
Wear Mechanisms-2

Welcome to ninth lecture of course on tribology. In my previous lecture, we discussed wear mechanism and we are continuing in this lecture, similar kind of wear mechanisms. We have covered abrasion, adhesion, corrosion and the last one slide we started with erosive wear. We are going to continue with the erosive wear in addition to that will be treating or will be learning additional to two mechanisms; one is a fatigue and other one is fretting. They have a lot of similarity and will be discussing those. This is the previous lecture slide let us review. We say that impact energy is required or kinetic energy is required to initiate erosive wear.

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Erosive Wear

- Caused by the impact of particles (solid/liquid) against a solid surface.
  - Dust particles impacting on gas turbine blades.
  - Slurry impacting on pump impeller.
- Erosive wear is function of:
  - Particles velocity (K.E.),
  - impact angle, and
  - size of abrasive

Particles either solid or liquid, they should come with some velocity impinge on solid surface; and impart some kinetic energy to the other surface; as this is the movement transfer, so angle of impact will be an important parameter. Similarly, is related to kinetic energy, it will be mass of particles as well as velocity of particles will be related, that is why we gave this equation.

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$$V_e = K\, A(\alpha)\; i(v)\, M$$

$$i(v) = (\text{particle_vel})^n$$

$$n = 2 \text{ to } 2.5 \quad \text{for metals}$$

$$n = 2.5 \text{ to } 3 \quad \text{for ceramics}$$

$$M = (\text{particle_size})^3$$

We say that, V_e is a wear by erosion (wear volume by erosion); K is empirical constant; A as a function of alpha, which is an impingement angle, impact angle; i is a function of V, which is the velocity function and M as a function of particle size. Increasing the particle size will increase wear rate; increasing the velocity will increase wear rate and impact angle will affect in one way or other depending what kind of material we are using. Whether material has tendency to absorb the energy, or it has hardness to resist the wear? So, it depends on this two properties, wear rate will be decided.

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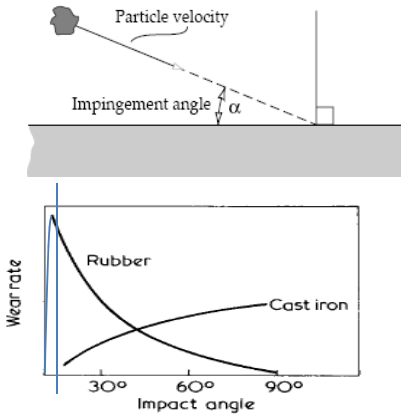
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Now first let us define impact angle in an absolute manner. You see the impact angle not necessary particle coming from 10 meter away and we need to think about what is the angle of implementation but just before impacting what is the velocity? And what is the angle of impingement? Just before the impact in a solid surface that will affect the result. So we say that impact angle is angle between eroded surface, surface which is going to rotate and trajectory the particle immediately before the impact. If impact angle alpha is initially very high or very low but its changing last moment then will be counting only last movement angle that will be alpha that is impingement angle that is impact angle. Both the low and large angles will have different characteristics.

If particle is coming at the low angel, angle of inclination is lower all value of alpha is lower like within the 5 degree, 10 degree, 15 degree then particle shape will also matter how it is colliding with the surface. You know very well kinetic energy will not be transmitted. That much as kinetic energy can be transmitted by 90 degree alpha or alpha equal to 90 degree but in this case the shape of particle will affect the wear rate. It will try to abrade the surface; it will try to cut the surface, it will work as a cutting tool so particle shape will matter in that case. To resist the wear; to reduce the wear rate hardness of the substance need to be higher or hardness of this component need to be higher. Coming to other side, if the angel of impingement; if angle of impact is higher side 75 degree, 85 degree or 90 degree.

Then we require softer material because most of the energy is getting transmitted to the substance or component. Softness is required as mode toughness of a material having more toughness will be important, which can observe the energy and most of the time soft material has more toughness and energy observation capabilities, they can deform by observing the energy. Wear rate will be reduced in that case compared to harder material which will fracture the surface itself.

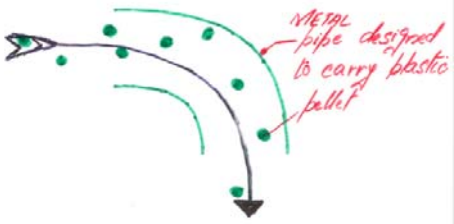
So we have different treatment for low impact angle; we have different treatment for large impact angle and this diagram identifies clearly what is the role of impact angle, can see the impact angle is an x axis; wear rate is on y axis and 0, 30, 60, 90 degrees is been coated for cast iron which is harder material. As impact angle is increasing the wear rate is also increasing, because the cutting action can resist energy observe it cannot be done. So, that is why the cast iron at high impact angle should not be used.

Taking the example of soft material that is rubber, elastomer which can have observed energy. Initially the wear is very high, because they cannot be cut they have very lower

resistance towards cutting, it can be simple chipped away and layer can be simply separated but under compression they can resist much more force compared to this shear force. That is why; the low impact angle, which impacts more sharing cuts away the surface. It is not require or we say that we should avoid wherever there is a high impact angle, more energy is getting transmitted and particle subjected to more compressive load. Rubber material can be used. So, these are three examples that shows what the importance of impact angle is and If we know characteristics of the particles, what is the impact, angle we can choose proper material for that situation. This is what it shows that if impact angle is 0, if that angle is 0. I am talking absolute sense 0, then there will not be any wear rate that is why this initial curve does not show anything. It is not touching this surface impact angle is not coming in to contact at all.

So wear rate will be 0, it does not matter to us. Which material we choose is the matter. Now is another concept, said K is empirical constant in this equation, if I go ahead with similar equation what was given by arguer again assume that K is the probability of wear particle formation. Wear particle formation means, the particle is getting this large, it is getting removed from the surface what is the probability the K you can say in term. The K is the probability of that particle formation. So lesser the K better the results if you can reduce this K it will provide very good results to us.

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$$V_e = K\,A(\alpha)\;i(v)\,M$$

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$$M = (\text{particle_size})^3$$

Conventional Solution

- Reinforce elbow
- Quick change elbows
- Redesign shape of elbow
- Select another mat., for elbow

As, we are dealing with a wear and wear we know that is a system property it is not material property. Whenever you talk system property in the number of parameters will affect the results I can change the design; I can change the parameters or I change the material properties for getting good results. To illustrate the elastic, one example is related to the pneumatic transportation. A pneumatic transportation means air or gas is being used as a carrier fluid to carry this pellet, the green colors we see the pellet may be spherical in shape. The pneumatic curve, we say that gas is carried from one end to other end and the major problems come wherever there is a change in an angle. These particles are moving in a parallel pipe, straight pipe. They will follow straight path not much impact angle, low impingement they will not be much wear rate of a surface or wherever there is an elbow or band comes then there is 90 degree change, particle material need to be changed in accordingly.

And we have heard in previous lecture of previous slide, we have discussed that if impact angle is high we should use soft material. This is relative. Same thing; you say that initially may be some other material is used. Now, we are trying to use steel pellets in the same system. A steel pellets having literately more mass so if you push, it will convert get more kinetic energy and will cause more wear rate of the pipe. In addition to that, we want to increase the speed of transportation. It is not only we have changed the mass, we are changing the density also.

You want to go ahead with higher velocity and we know that kinetic V is proportional to V square, sensitivity is increasing if you increase the velocity that may square, effect is coming into picture so we need to think about which material will give the good result. As I think from conversional point of view or simple without much knowledge, we can rein force elbow. May be we can provide some sort of rubber padding inside the pipe; inside the elbow which will sustain impact or that can observe the impact. However the question comes will that be finding a good solution to us? First thing is we need to change elbow. We need to coat a simple or an easier. If it is easier without much cost then we should go ahead with that however we find that this is slightly difficult in addition to that not necessary all the particles are impinging at the 90 degree. There is a possibility the few particles impinging on 5 degree, few particle image or impacting at 15 degree few particle impacting at twenty 5 degree, depends.

With the number of particles and probably they may vary from 0 to 90 degree, main thing is that of course, mean value will be on higher side will be 70 degree, 75 degree, where still particles ,which are getting impact, even impact in the rubber material at the lower angle. so rubber will be weaker and once it starts shearing; once it starts developing crack then it will cause failure, so again we need to replace that kind of elbow very frequently. That is why; we say that rein force may have the quick change in an elbow. May be initially we are changing this elbow after thousand hours operation, normally we can think about changing this elbow after 100 hours.

From this assembly it may appear a problem, in that case it will take more time; more material cost; more labor cost and shut down of the system for some time. Another option, we can think about the redesigning the shape of elbow instead of sharp 90 degree band, we can think about the changing the length on the longer side and very gradual curvature shape. we can gave whether the instead of 90 degree band, we have band often say 10 degree, 12 degree, 15 degree and under similar kind of rubber material can be used but we need to redesign the system we need to have different kind of assembling because we are quick to increase the length of the pipe 90 degree sharp band pipe line may not be that high but when you go for the gradual strength the length of the pipe is going to be increased.

Now we say another one you choose totally a new elbow do not reinforce change the complete elbow material over the multi grey materials may be use the rubber material with a some sort of hardening, so that can do number of experiments on that and choose best material or after doing number of experiments which will suit completely for this kind of problem, I am using the word this all solutions are conversional it can be thought over easily but if only we are understanding the wear mechanism properly. we know very well, wear will take place after sometime it is not spontaneous process, it is going to take few cycles may be 10 is to 3 cycles 10 is to 4 cycles and 5 cycles 10 is to 6 cycles can be utilized can we think from that angle and it is ok.

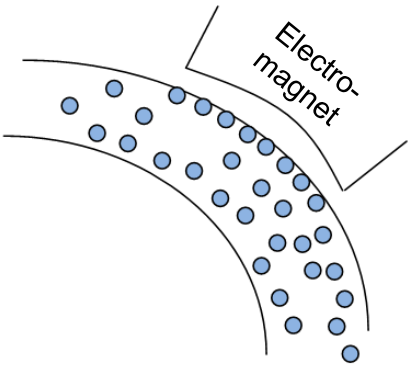
If this is a situation, I can think about the temporary layer, which gets formed and deformed and removed without causing any failure. Can I think about some layer self mate system self as a capability to make layer, remove layer and then form a new layer. So, without much damage may be some damage may be say 0.01 percent damages fine, if that is gone we can think about some layer and this equation is given I can reduce K because i(v) is going to increase, M is going to increase.

Angle of impingement: initially we show that the redesigning a cell shape of the elbow can be adjusted but if I do not want to change in that, alpha will un-change I will be changing because of the input velocity is increasing; M is increasing; so both this increasing, that wear rate is going to increase. If I want to reduce a wear rate, I have to play with K that means, I have to reduce that value of K. The value can be reduced by reducing the number of particles which are impacting number of particles; which will impact the pipe. If I can reduce probability from one to say 0.01, I can get extra life of the components.

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Case study: pneumatic transportation……

Use magnetic or electromagnetic field fc interaction with object



Conclusion: Magnetic field to provide a protective layer within pipe elbow and reduces the value of K

In that case, we can think from innovation point of view you can say that these are steel balls and will get attracted to magnet. Can I think about the electro magnet attaching on the pipe something like this. There is an electro magnet very near to pipe whether this pipe is a magnetic or nonmagnetic. It does not affect much. Interesting thing is that whenever we are using this kind of electromagnetic or all of steel particles will be coming near to the surface so, if I can control electromagnetic field provide just sufficient fields that one layer is formed not any other layer on that.

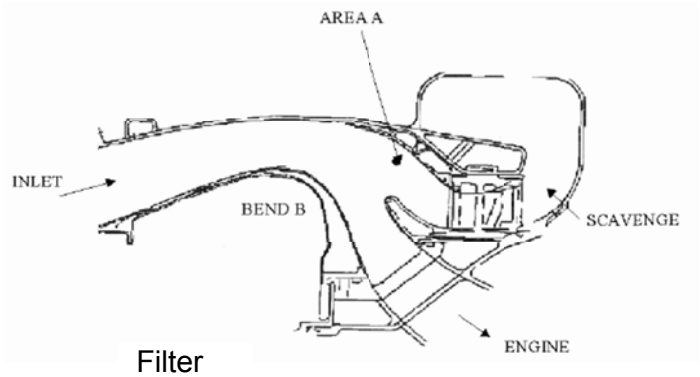
And what will happen there is a possibility of particle come and impact one of the ball, remove this ball because of the movement transfer and get attach to the surface. This will be continuous dynamic process one layer will be there always few particles will be removed; few pellets will be removed in every cycle and new particle will come and replace it so we are bringing almost negligible probability of impacting on the surface. Whatever the particle

comes initially they will remain and may be out of thousand particles or thousand pellets few may be 4, 5 or 10 will be removed.

So, we are coming down to very, low probability this will be effective method to reduce the wear rate. We do not change material we just change the system design; we add few more fields instead of just mechanical field; we add magnetic field to reduce the mechanical effect of the particles. So, this is a one way to deal with the problem, when we talk about the wear so if we understood the wear you can think of in board sense; we can come out of the box or we can think out of the box and get a good solution, much major solution; much more releasable solution ; much quicker solution.

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Ex: Engine particle (sand) separator



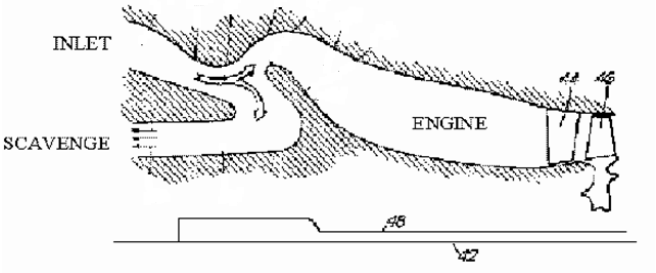
Let’s take another problem, this design is of filter design may be say of aircraft engine or you may say helicopter engine, which remain at the same height where generally concentration is very high in the air. what is the purpose of this design is that we want to suck the air, so that combustion can take place in engine, that means air is sucked and supplied to the engine or we know very well whenever the air is sucked, sand particles also will come along with that so we required one effective filter but we know very well if you use filter it will reduce the pressure that means we have to do separation we have to compress? the gas and we are need extra system for this purpose. To avoid that kind of pressure loss generally they use this kind of design in the use of particle inertia, particles are coming with some velocity when it is getting sucked and they will move in simply in the zone. Air, which can skip from that route can change its route because it has very low inertia can come this side. The problem is that to increase the volumetric efficiency we require really very large volume, the volume of the air.

In addition, this is not a satisfaction? method still there is a possibility the few particles will come. If the particles are coming and hitting the engine cylinder or combustion chamber naturally, there will be a lot of problem in engine operation. It can fail any time. however there are system designs we use a redundant engines, so that even if there is one engine is failed, other engine parts are working or other cylinders are working properly that redundant design is possible but can we reduce this wear rate might changing the system design there is a possibility.

We can think about changing the filter. This is a factor one filter design. We are trying to scavenge the sand particles from this route and air through this route, we can change the route there is another possibility. We can increase the volume of this dot so that more air can be shut and problem is that for any flying object lesser weight will be preferable. We required lesser driving force in that case, so minimization of weight will be one of the major constant, minimization of the volume will be a major concentration. So, if I want to increase the volume of this that will not be acceptable because that is going to increase the volume; increase the weight and we require more driving power, which is not a very sound design.

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Ex: Engine particle (sand) separator



US Patent 5,139,545

Light weight materials to absorb particle energy.

So, there is one pattern which was done in USA in 1995, when there is an inlet change in design, this inlet suck and we know the particle; were trying to generate a hindrance.

So the particle come in imping on this and angle is almost 90 degree, after that there is a parallel particle change and direction is parallel to this. So, I can use this as the proper design material of course, design is already there we can choose proper material which has high impact angle. Air as a scare route also as there is change in curvature, particle will not be able to climb that much, few particle which can climb and again come back it will not be having

that much energy or we say may be having energy number of particles will reduce effectively and will be getting sound design. It has been proved that performance of this kind of design has improved engine life by 40 percent or reduces a wear rate by 40 percent which is substantially high.

You change a design and then get good result that really is very good. We can think about this light weight material. If suitable rubber material is not available, then we can think about some alternative material which can observe energy, does not resist too much and you can see that kind of shape is more like finger shape which has a lot of flexibility. Particle comes in impacted, is slightly flexible if any system is flexible, it will not be around fast.

Unless this friction occurs at this cross section that is fine but this can give fatigue problem and we design with some fatigue point of view if can design this system which as more than 10 is to 6 cycle, 10 is to 7 cycles, at 10 is to 9 cycles depends on what kind of design we required or what is the life of the system. Many a times when it comes back we can replace this material.

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Fatigue Wear

- Fatigue is attributed to multiple reversals of the contact stress.
- Occurs due to cyclic loading:
  - Rolling bearings, gears, friction drives, cam & follower.
  - Localized fatigue on an asperity scale.

NOTE: Abrasive & Adhesive wear involve a large contribution from fatigue.



Now we are coming to the new mechanism, what we call fatigue wear mechanism even though I am using the word new mechanism but I should say that almost all wear mechanism are in one way other, related to fatigue wear.

We started with abrasion, and then we brought probability into picture. Probability says that particles are not going to immediately dislodge from the surface. They will go under plastic

and elastic deformation and after certain duration only they will come out to 0, it will be removed from the surface. So fatigue one way on other is related to all mechanism it is related to adhesion also. we can give a formal definition: Fatigue is attributed to multiple reversals of the contact stress that means particles are coming into contact solid surface, this stress is induced and relived also that is why we are using the word multiple reversals, that is, a load is applied and removed and it is not constant load.

We can think about the asperities, continuously the particle. When the surface is sliding, asperity comes under load, bends and regains the shape. So loaded and unloaded that is the continuous stresses. we have number of examples related to the fatigue wear, we say that there is a common process if the common phenomena in a rolling bearings that is the rolling bearing have a definite life that is generally calculate based on the fatigue theory similarly, gets contact wear really governs a gear failure. We know very well gears failure can be predicted, can be estimated by using two theories: one is Bending theory;

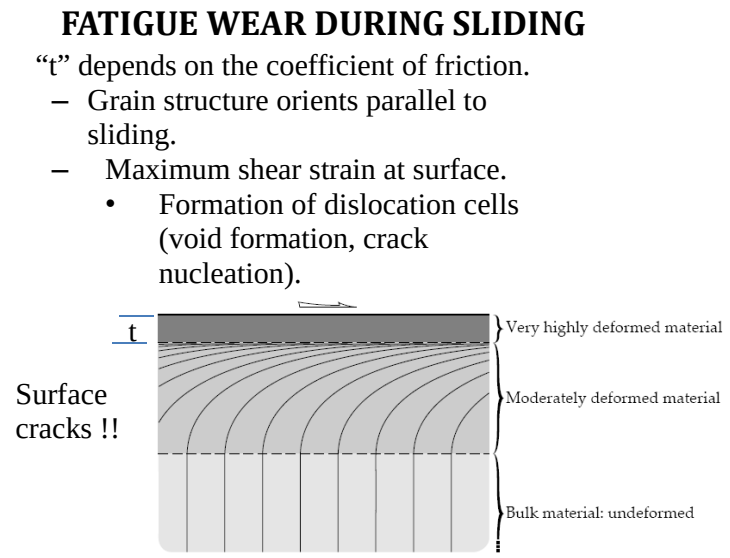
other is contact stress theory, Hertzian theory and 99.9 percent the failure occurs because of the contact stresses fatigue. Bending does not cause much failure surface by and large is almost 3 to 4 in bending while contact stresses factor 30 not be 1.4, 1.5. All friction draws and came follower mechanism, rolling action, rolling fatigue is governed for all wear mechanism but there is other possibility that fatigue by sliding contact and that is more common at a localized one when we are talking about asperity level on a micro or atomic macron level or nano level atomic level.

Just to illustrate what I am trying to convey: Let’s take, this is a well 9 is shown that is a surface layout I am talking about the front view of the surface and surface is visible as a line and one asperities is there that shows the irregular surface. Now if I apply a load on this asperity if either it as to friction immediately with 99.9 percent will not happen, it will change the shape, if the load is applied so as other substance other material or other component comes, passes this surface. When this passes this surface it gains and regains its position but what is there when it changing the position from the straight to the bend position, it is subjected to this stresses the tensile stress and compressive stress. It is happening a number of times during sliding motion, number of times so truly this is a bending problem.

Now, I can deal these as an abrasion or I can deal this as adhesion does not matter just see a micro level phenomenon is fatigue failure. This is one typical example, which was shown in first lecture can see the fits generated on an inner surface of outer ring separate entity and this

is fatigue failure. We know if you see this kind of ring again brings in operation, there will be high irregular performance; lot of noise will be generated and the wear. At the end of this slide say that abrasive and adhesive wear involve a large contribution from the fatigue even though we are using word abrasion or adhesion but they are basically governed with fatigue.

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Just illustrate in detail, let's look at this slide, this one figure says that top layer at different color; second layer slightly different color and then parallel material. We are showing some sort of deformation lines that this line is representing what kind of strain is developed in a surface we know if we try to move surface in a, we try to supply some sort of sliding force in this direction. Top layer will be sustaining maximum strength, then intermediately and then final layer does not have anything to sustain is a superficial phenomenon.

So it will happen on the top surface and to some extent below that surface that is why we say that this top surface is very highly deform material. See the shear deformation on the material then modally deform. Now over all fatigue behavior will depend on the, t what is the thickness of t we are thinking many times this t is an outer layer when we talk about the bimetallic layer by your talk about the try metallic material with the three layers are there we talk about the multi grid material with numbers of layers and their number of materials are bonded together to give the suitable performance**.**

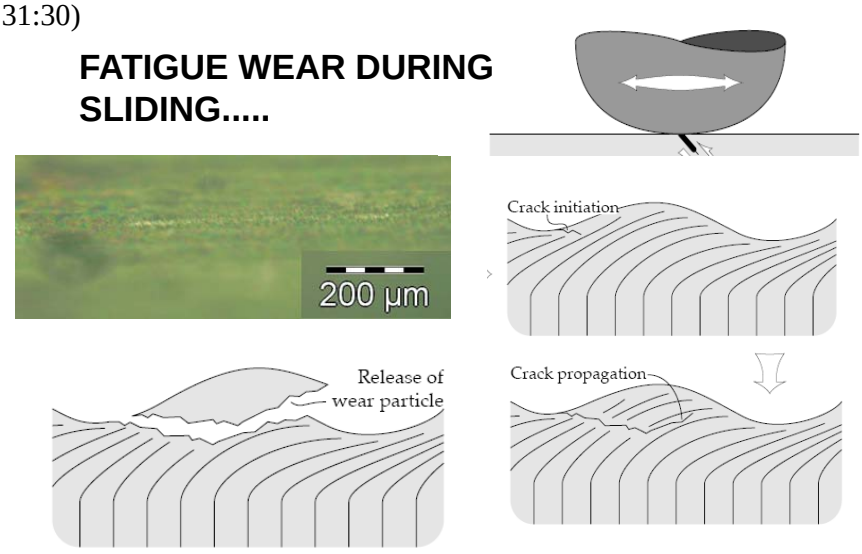
Then this t really affects the results and we say that t majorly depends on coefficient of friction. The coefficient of friction is very high naturally we have to apply more and more

sliding force, more and more sliding force then, more and more grains will be deformed in this direction they will reorient to a certain limit. In average the load is low or high maximum compared to, when we talk about the compression between three layers maximum strain will be on the top surface. If we increase the load, then what will happen at the interface there will some sort of void formation which we have seen number of times when we talk about the rubber material. You are able to see some sort of pose in rubber material. That is the void formation, if there is a void formation that means there is no material.

Stress area is almost the area which can sustain stress and that can tear away easily, layer can be chipped away. This bearing will have many voids fractions. That will remove the complete surface that is the reason why we say that it is smaller how than the bulk metallic material. Top layer is very small in thickness. More bonding lesser number of voids will be generated because of the more bonding but thickness is more on a higher side than the bonding will be slightly lesser and more and more voice will be generated. Delimitation that layer will be much easier that is why we need to design thickness properly or the surface which is undergoing very high shear rate need to be designed properly.

Sometime, we find the surface crack itself what we talk about the void generation and that will be more like sub surface but there is possibility of the surface cracks. Surface cracks we can think with simple manner roughness surface. Roughness itself as some asperities that is a going to create a problem and that is why shown over here.

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NOTE: High µ, but low V and low µ, but high V can be explained.

There is an asperity over here: if it is a residing motion which keeps going on this depth is going to be in last; will be getting extended. Something is clearly shown in this sketch when we move this surface over this surface and there is a possibility of filing of material we know very well when we derive to drive in a muddy road, mud will get piled up in front of the tier same thing is happening over here. Material is getting piled up and this crack which will come directly in front of the load, then it will be along something like this. When the elongation is keep going on again and again the material comes of the force comes immediately with this surface.

It will turn out to be a delimitation removal of that particle from the surface. This one of the common phenomena happens in gears. You can see gear pit over here, if this kind of wear particle comes out may be order of few microns only. We are able to see the pit on the gear. When there is a pit on the gear sliding will enhance pure rolling will be reduced. There is a reduction in pure rolling, increase in a sliding, that is going to cost further more and more tensile load or require more tensile load on the surface, more crack formations; more wear particle generation.

When we understand this kind of mechanism, we can explain one slide which we have seen in my previous lectures, where the high mu high coefficient of friction but low wear value was estimated for some material. On the other hand low value of coefficient of friction but high wear rate was estimated. How as a low rate condition wear volume will be related to square root of one plus mu square that means this is directly related to the friction.

Increase in fatigue coefficient of friction means increase in wear rate. However, when we are talking about the fatigue and we are talking about fatigue mechanism. We can explain this is not 100 percent related for most of the material. Yes, are related but not for every material

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NOTE: High μ, but low V and low μ, but high V can be explained.
Planes of weakness.
Inclusions

Rubbing materials	μ	K_1
Gold on gold	2.5	0.1 to 1
Copper on copper	1.2	0.01 to 0.1
Mild steel on mild steel	0.6	0.01
Brass on hard steel	0.3	0.001
Teflon on hard steel	0.15	$2*10^{-5}$
Stainless steel on hard steel	0.5	$2*10^{-5}$
Tungsten carbide on tungsten carbide	0.35	10^{-6}
Polythene on hard steel	0.6	10^{-7}

So, let us come back to that slide which I showed in previous lecture you say that in this case as a coefficient of friction is decreasing wear rate is decreasing but here coefficient of friction is increasing again but still a wear rate is decreasing. Now what are the reason quite possible, material combination which we are using they have some sort of wrinkles they have some sort of manufacturing defects. If they have manufacturing defects, the voids cracks will form a fraction surface or surface which can be easily fractured or deliminated from the material.

Even though they can show low coefficient of friction talk about carbine materials, when carbide is rubbed about the steel coefficient of friction may be very low value but they have cracks they have voids when they are getting combined they make a surface which can be easily fraction that is why the wear. It will be high even though coefficient of friction is low but wear rate is high. Take another example of copper; about to 99. 9 percent pure copper no void no enclosure high coefficient of friction may be point 6 plus but wear rate will be low because fatigue will not be there. There is no crack generation or void so that material will not be run very fast.

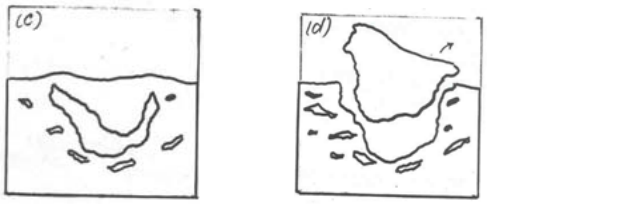
So, those kinds of mechanism allow us to understand what the difference between coefficient of friction is and wear rate. They are not always related; they are not always in harm with each other quite possible high wear coefficient of friction but low wear rate on another hand

low wear rate but high coefficient of friction. Understanding this kind of mechanism helps us to design better and better systems. What we expect adding this slide is the plane of weakness if material as a planes, which are weaker that means they are weaker than surfaces. Then, wear rate will be high or if there is inclusiveness in the material wear rate will be very high. Will discuss later about this when we cover one case study in next lecture how inclusiveness can create more proper.

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FATIGUE WEAR DURING ROLLING

- Steps leading to generation of wear particles:
  - ❑ Application of normal load that induce stresses at contact points
  - ❑ Growth of plastic deformation per cycle
  - ❑ Subsurface crack nucleation
  - ❑ Expansion of crack due to reversal of stress
  - ❑ Extension of crack to the surface due to traction force
  - ❑ Generation of wear particles



We discuss fatigue due the sliding or during sliding motion, but there another fatigue which is more common that is what we call as fatigue wear during the rolling. We know wear well rolling induces very high concentrated stresses or we say that contact stresses are generally very high in rolling motion because area of contact is very low. So what are the possibilities? You say that this steps which are leading to the fatigue wear that is why we are applying a normal load that induce very high stress of the contact points. Blaming contact is stresses and bearing are almost 2 to 3 giga Pascal which is very difficult to imagine, we say either steel as only 560 mega Pascal as a strength, how can you sustain at 2 giga Pascal as a three times factor just 0.3 and still bearing can show number of cycles so that the contact stress are very different from the tensile stresses.

And they need to be having a different kind of equation; different kind of behavior or different kind of treatment, when we try to solve problems. They are more and more or less compressive in nature that is why we use a material which are stronger in compression;

competitive attention. By and large we have common thinking of steel to iron or ductile material they are similar. They have similar behavior in compression intension but it does not happen with all the materials or when you work hard in the surface, it will have more compressive strength than the tensile strength and we want to bring the compression strength within a 3 giga Pascal plus. So that a results of rubber to us.

Now, when we apply very high but not very high normal load but if you apply normal load which induce high contact stress, there is a possibility of elastic and plastic deformation. Elastic deformation is not problem for us it will regain the shape that is the possibility of the plastic deformation some sort of depth in that. Once there is a d shape comes on the surface then problems will start. You say that after d shape or plastic deformation there will be some surface crack nucleation possibility. That d shape itself is generating nucleus or providing nucleus for the crack and one duals loading continues loading and unloading there is a possibility of expansion of the crack, subsequent to that extension and finally, generation of the wear particles.

I can show you the image whenever we discuss on this slide using some pictures. Let us take this in a surface slightly irregular. We are talking about the loading and unloading reversal of the loading. So loading is a compression. When the load is reverse then it should come to the 0, what is the possibility of the rest the stresses. We are loading something in compression and believing in it quite possible a later direction, we know that the new factor later direction. There will be tensile stresses and that tensile stress can generate some sort of nucleus or some sort of voids in material if number of voids they come closer to each other. They will make a bigger void, a larger side void.

And if it is loaded and unloaded continuously this void will extend up to the surface and the whole thing will come out that will generate a pit on the surface. So, rolling as well as sliding is generating the pits; but with different kind of mechanisms. Here the later direction force met as large it deforms the surface in compression but when the compression load is removed, then it gets expanded. When it gets extension on that then we are getting tensely stresses on the perpendicular direction. What I am trying to say if I am loading this surface, compression is increasing but when we are reliving it, material has to relax it.

So that is why the stresses will be generating in perpendicular direction this direction and this direction that is what the crack is nucleated and expanding towards this direction. It does not

come directly under the load it is going beyond this side and this side. That is happening because the later crack or a force or tensile stresses which are in later direction.

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Cracking

- Meaning = breaking, splitting, or snapping apart
- Results : Complete failure
- Causes : Excessive load with vibration.
  - Loose fit, excessive impacts
- Solutions
  - Correction of fits
  - Vibration isolation



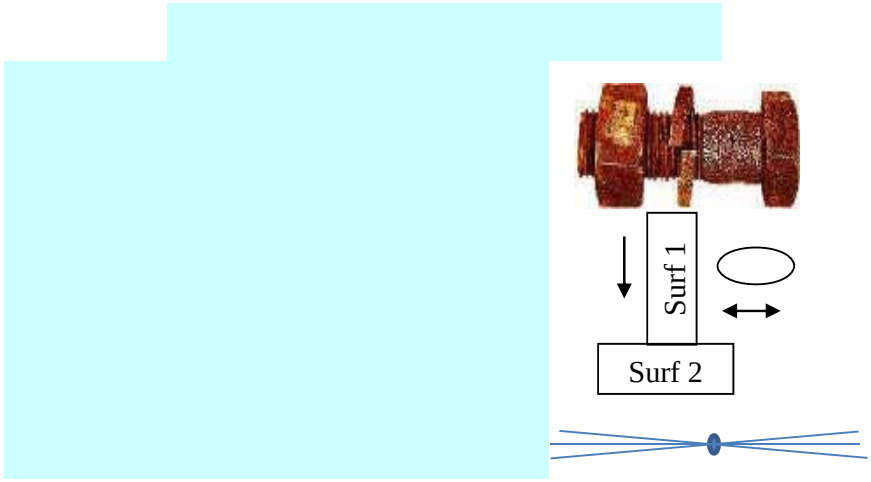
So, end of the fatigue comes with the cracking, many times when we apply very high load on the surface, not intentionally but because of the some main function; some sort of over load or some sort of misalignment or some problem in assembling the components, then what in that case happens is very high load will generate a crack through and through from top to the bottom surface.

This is known as an extreme case of the failure that may happen spontaneously within few 100 cycles. Whenever we talk about fatigue, we talk about large number of cycles but this may happen even 100 hours and not 100 hours we say when 100 cycles. So, what we say that the cracking is ultimate failure may be intensive also. It is going to spilt the component, when component is a plate nature it will not have any function or functionality will be 0.

It is a complete failure, it cannot sustain it, and we do not have any time left for its operation. Majorly happens with excess load but here in addition to excess load the vibration is also there. The vibration of the reversal load is there or some sort of impacting is there, then this kind of failure will occur. When, we are talking about the vibration we are talking along with loss fit. If there is a form fit, vibration will not affect there but there is loss fit vibration, going to affect the results is going to impact again and again. The way we understood the erosion, where individual particles were there but the whole bulk material metal will impact with much larger velocity with much larger impact energy.

We can solve this kind of problem by providing suitable fits, choosing proper fits so that wear is getting a solution from the fits, from the system design. similarly, we can think about vibration as solution again .We are saying that wear phenomena, the cracking is getting solution from some other thing not in material is not choice of lubrication but it is the complete system design. If I want to remove this kind of problem I need to think from other the angle. We have one case study on cracking related to the roller bearing which we will be discussing in my next Lecture. Let's discuss about the final wear mechanism for this course.

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As, I mentioned initially; there are more than 34, 35 wear mechanisms. We cannot cover all the wear mechanisms because this course is a not exclusively for the wear. We have selected 6 wear mechanisms. Fatigue wear is the last mechanism.

This term was coined in Tomlinson. A famous person, who gave the molecular theory of friction. It should share that there is a molecular attraction between surfaces and he proposes some sort of empirical relation to find out what will be the coefficient of friction and it could show that softer material will have more problem related to molecular friction. When we talk about fatigue we are talking about, very low magnitude vibration, low magnitude and high frequency vibration, energy is coming but at a low magnitude or low amplitude is proper word for the low amplitude. Amplitude is in terms of 1 to 3 hundred micron, it will not be detected easily. Some machine is running and will not be able to see the vibration as such but 1 to 3 hundred micro vibrations between two components happening and that is calling in the fatigue wear. This is the high frequency; low amplitude so over all energy comes in higher side. Addition to that is the oscillatory motion, are some we are saying this kind of mechanism, this kind of failure generally occurs in assemblies. Number of possibilities it can

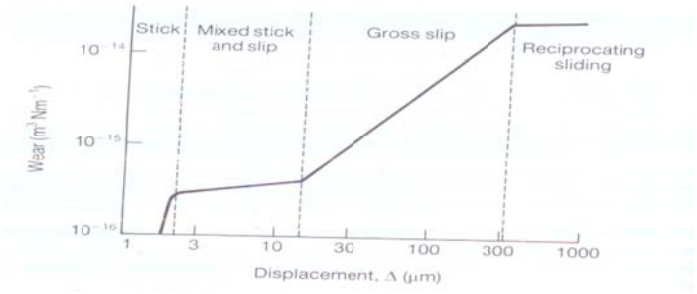
press fit; it can be coping; it can be riveted joint; it can be bolted joint where there is a possibility of a micro slip.

So, we have studied about the friction mechanism, static and kinetic coefficient of friction. We know very well when we are applying the force, there will be some asperities on irregular surfaces and one surface has to climb on other surface quite possible. Some force, low magnitude surface will move and the micro and nano scale may come back that will not be easily diagnostics from the outside but it is happening and that is, that micro motion; that low amplitude motion is causing the fatigue wear. Now this is one of the common example of course. What I have shown a sample is more like rusted assembly but we are not talking about the failure because the corrosion, we are talking about the failure because of the fatigue.

If you open this nut from the bolt, will find some sort of powder that will not be corrosive powder but that will be a particles coming from iron or related to that. Of course, corrosion is increasing the wear rate but it is not initiating. Initiation happens because of the fretting and after that there is more and more surface areas are reliable some chemical activity of this particle is on higher side. That is causing failure. Just to demonstrate the same thing, let us take one surface and other surface they have a contact under the load, that means contact is under the stress. In addition they are getting some sort of oscillatory motion; some sort of predict motion which continues and we are talking about this motion in terms of the micro-meter, which will not be detectible. That is going to cause a problem.

In other word, I can think about engine mechanism. You can say there is plank and there is inch, this engine not going to will be a stationary a point which is plane point, plane line which is related to the inch will remain stationary but this line will move up and down continuously. It will be vibrating so what will happen is there is a relative motion; it will impact upper surface; it will impact at the lower surface and that impact is going to generate micron sized particles continuously. Micron and nano sized particles will be removed from the surface and as particle removal increases, this oscillation also will increase with the wear. If there is nothing to restrain this plank amplitude, then amplitude will continuously increase.

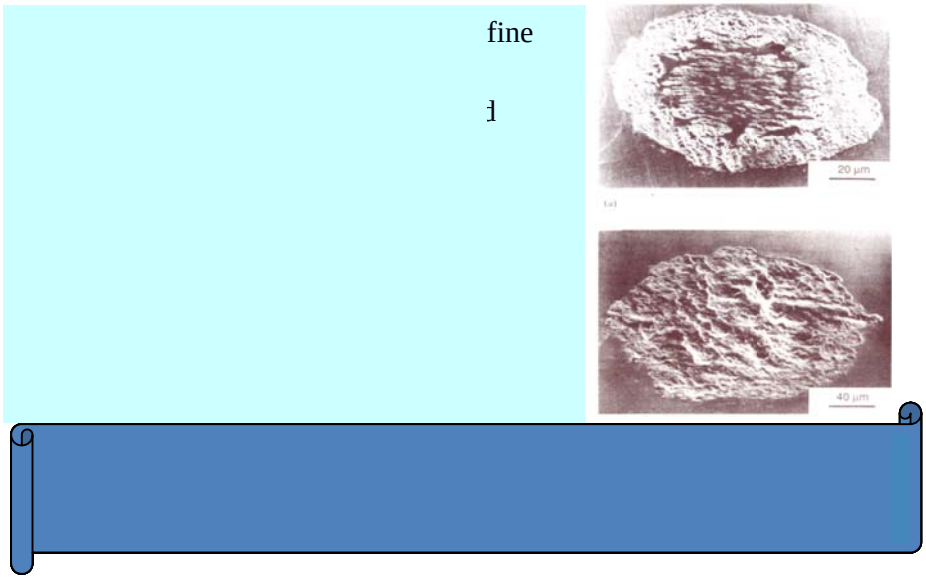
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So from micro slip to slip and the gross slip phenomena will happen like that and that is why we are saying that fretting happens something like that. Initially there is stiff phenomena we are pushing it to certain value and relieving. If the load we do not bring intentionally but load is coming from outside of from other factors will cause some slip micro slip. Initially the slip is a low magnitude slowly material is getting removed from the surface, the slip will turn out to be gross slip and then that gross slip is harmful it is something like that we brought a new component new assemble even never used it was lying on the table or this is some assembly, which was vibrating with very small magnitude, that magnitude vibration created a problem and whole system collapsed. Because of the fretting corrosion of fretting wear, this is what mentioned many times in nut and bolt connection. Kept as it is when you open it after that, it will not be able to try, reason being that most of the powder from the nut and a bolt will be removed.

Thread profile will get damaged and you again retry in the nut bolt connection, it will not be because there will be loss of connection or thread otherwise. We need to recondition those threads if you want to reuse the same way. So this is what I mentioned about. It introduces micro slip to the gross slip and that causes failure.

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These are the couple of pictures from outside surface. It looks very nice, very shining and no problem as such. When you open it and look at them, micro scale of this is 20 micrometers in scale. You can see the pit. Pit is generated outer the surface is not damage much of course, you are seeing an irregular surface but pit is generated at the center of this. Where outer surface remain without much motion but at the center most of the material is been removed and it depend on the material, they have different color something like if I am using aluminium material I will find some sort of black color. Aluminium oxide mounting when I open assembly, the failure will be there. Similarly, when we are talking about the iron material, is iron material than it can be either iron oxide or ferrous oxide or can be the black powder which we generally observe that is iron oxide again and there are red colored ferric oxide, which we can see.

So, either black color aluminium or black color iron oxide is one option and red color which is most frequently we get because of the rusting nature and is slight difference within rust and corrosion. We use word corrosive wear initially but here the word is coming with rust is only the small change. We say that corroding media if it is in water then it is a rust if corroding media is something else then it is corrosion. So, with the wide water is acting as corrosive media then whatever the phenomena happens that is rusting otherwise it is corrosion.

And we understand the kind of fretting corrosion, fretting wear. In this case, I am using word again and again fretting corrosion, because fretting is starting point and when it generates number of particle and if there is air available or medium is available in a manner all those

particle will get oxidized. When they get oxidized, the hardness also increases and that is why they increase the wear rate. Many times we use the word fretting wear and many times we use word fatigue corrosion because fatigue mechanism leading to the corrosion and overall increase in a wear rate. So fatigue cum corrosion and mechanical action is termed as fatigue corrosion wear.

Now, we say that if we know the material table we know which material are susceptible towards the fatigue phenomena then we should never use those material, if we know the vibration phenomena is going to happen there like titanium. Titanium very well is the very costly material, if it is not used properly it will cause failure. You must have heard about this fatigue failure of the bone joints. we know, there is a bone cement which will be rustic in the motion of implant but if there is some micro crack in that there is a motion that will give you almost some micro stabilizing in the gross slip, that will cause damage of the impact so that is also related to the fatigue wear which can be studied in detail if you go to micro scale, nano scale.

Now this is the last slide on the fretting wear, we can continue wear topic in our next lecture. I will prefer to use a word wear analysis where we try to analyse the wear mechanism. Now, we have studied various mechanisms but when we see the failure in totality without any one wear mechanism is going to be pointed out or you will give the results or combination of the wear mechanism are going to give these results. so that kind of wear analysis important, whether we should choose material or we change the material or we should provide a lubricant or we change the system design; how to deal with the problem that will come in a wear analysis. That is what we are going to discuss in the next lecture; thanks. Thanks for your attention.