WEAR – SOME NOTES

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INTRODUCTION AND PURPOSE

This report is part of the graduate course CONTACT MECHANICS AND WEAR. This is a "literature course" during summer of -97. The contents of the course should be equivalent to 6 weeks of full time work.

Note that the comments reflect my thoughts on the paper. I may well have misunderstood some of the contents etc. Also, I have included my own associations and comments in the notes below (not always explicitly stated). So, read the following with a "suspicious mind".

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This paper mainly consists of notes from [1]

1. SURFACE DAMAGE

Surface damage occurs in the surface layers, where structure and composition often are very different from those of the virgin material.

Surface damage can involve

NO EXCHANGE OF MATERIAL
- ❏ Structural changes
- ❏ Plastic deformation
- ❏ Surface cracking

LOSS OF MATERIAL
- ❏ Wear

GAIN OF MATERIAL
- ❏ Pickup of loose particles
- ❏ Corrosion

Disadvantageous results of surface damage can be that

- ❏ Material losses eventually consume the wear part
- ❏ Material losses deteriorate the function
- ❏ Disadvantageous topography, structure, composition etc. deteriorates the function
- ❏ Wear particles deteriorate the function

But the surface damage can also be beneficial to the function (e.g. run-in of mechanical parts).

As for wear, there are several rival mechanisms that contribute. For steady state wear, the relative amount by which a mechanism contributes to total wear (volume) is approximately proportional to the area fraction occupied by the scars of that mechanism.

1.1. SURFACE CRACKING

Two ways that tensile stresses, needed to propagate surface cracks, can be generated in tribological contact are

- ❏ Heat expansion of the surface layer beyond the compressive yield limit followed by cooling. This often leads to cracking in a network pattern.
- ❏ Friction forces that generate tensile stresses at the trailing end of the contact. Surface cracks caused by friction forces usually result in a pattern of parallel cracks perpendicular to the sliding direction.

Surface cracks are less likely to be observed in systems with ductile materials. Also, if the surface layer is subjected to wear rates higher than crack propagation rates (in absence of wear), cracks are also unlikely to occur.

1.2. WEAR AND EROSION

Definition: Wear; damage to a surface that generally involves progressive loss of material and is due to relative motion between that surface and a contacting substance or substances.

Definition: As I understand, erosion is loss of material resulting from a repeated impact from a stream of particles???

Plastic shear deformation of a surface is one sign of wear. This is typically followed by shear fraction, which leads to a scale-like topography. Wear can also be accompanied by a number of other surface damage modes, such as extrusion, chip formation, tearing, brittle fracture, etc.

1.3.   SOME STANDARD COUNTER-MEASURES AGAINST SURFACE DAMAGES

DAMAGE CAUSED BY PLASTIC DEFORMATION
- ❏ Increase the load-bearing area
- ❏ Decrease the load
- ❏ Lubricate
- ❏ Increase the yield stress
- ❏ Cooling (reduces the softening)
- ❏ Surface coating

DAMAGE CAUSED BY BRITTLE SURFACE FRACTURE
- ❏ Lubricate
- ❏ Promote formation of friction reducing oxide layers
- ❏ Lower normal stresses
- ❏ Increase load bearing area

DAMAGE CAUSED BY SURFACE CRACKS
Study the formation pattern to reveal details of contact situation. Depending on whether the cracks are formed by high shear stresses or by heating (see above), the pertinent measure has to be reduced.

2.   WEAR – INTRODUCTORY REMARKS

Wear is a complicated area, where there seems to be few predictive relations. Most of the design criteria seems to be "rules of thumb". In order for these rules to be applicable, they are limited to certain special areas of wear. Thus, wear is usually divided into some subareas. This paper follows the division as presented in TABLE 1.

WEAR	Material loss due to a force that act slides surfaces relative to one another	EROSION	Material loss due to particles that impact a surface
Abrasive wear	Presence of abrasive particles in the contact zone	Solid particle erosion	Gas-bourn solid particles acts as erosives
Sliding and adhesive wear	Sliding of one surface over another with no abrasive	Slurry erosion	Liquid-bourn solid particles act as erosives

Table 1   Definition of different types of wear

WEAR	Material loss due to a force that act slides surfaces relative to one another	EROSION	Material loss due to particles that impact a surface
Polishing wear	Wear leading to polished surface	**Cavitation erosion**	Air cavities acts as erosives
Fretting wear	Wear due to small-amplitude oscillatory lateral movement between two surfaces	**Liquid impingement erosion**	Water drops acts as erosives
Rolling contact wear	Wear due to rolling contact between two solids	**Impact wear**	Repeated impact of one particle into another

Table 1　Definition of different types of wear

3.　ABRASIVE WEAR

Definition:　Abrasive wear; due to hard particles or protuberances that are forced against and move along a solid surface.

Loss rates are not inherent to a material (i.e. not a materials property).

Abrasion is typically categorized according to type of contact, as well as contact environment. The contact can be two-body contact, where an abrasive slides along a surface and three-body contact, where the abrasive is caught between two surfaces. The former case will typically lead to wear loss 10–1000 times as much as those of three-body contact (for given load and path length).

Abrasion can also be categorized as low stress, where the abrasive remains fairly intact; high stress, where the abrasive is crushed; and gouging, where a relative large abrasive will cut the material.

3.1.　ABRASIVE MECHANISMS

Several mechanisms have been proposed to explain how the material is removed from a surface during abrasion. These mechanisms include fracture, fatigue and melting.

Comment:　And also plastic ratchetting, see the work of Kapoor.

No single mechanism can, probably, account for all the loss.

Some of the processes involved in the abrasive wear is

- ❏ Plowing, where material is displaced from a groove to the sides. Does not result in any real material loss.
- ❏ Microfatigue, ???
- ❏ Wedge formation, i.e. the formation of a wedge on the front of an abrasive tip. This requires a ratio of the contact interface shear strength relative to the bulk shear strength of 0.5 to 1. Fairly mild form of wear.
- ❏ Cutting, where a chip is removed. The most severe form of abrasive

wear. For a sharp abrasive particle, a critical angle ($\approx 45° - 85°$) dictates the transition from plowing to cutting. Also, the degree of penetration is critical to this transition (depth of penetration / contact area $> 0.2 \Rightarrow$ cutting).

❏ Microcracking, where small cracks are formed du to high (above the fracture toughness limit) stresses close to the abrasive. This type of wear occur only for brittle materials.

For abrasive wear, the maximum volume of wear that can occur is given by

$$W = Ad \tag{1}$$

where, W is the volume of removed material, A is the cross-sectional area of the groove and d is the sliding distance. The cross-sectional area of the groove can be expressed as

$$A = k_1 p \tag{2}$$

Here, k_1 is a shape dependent constant and p is the depth of penetration, which can be expressed as

$$p = k_2 \frac{L}{H} \tag{3}$$

where L is the load and H is the hardness of the material. k2 is a constant which is influenced by

❏ The plowing / cutting range
❏ Rolling of the abrasive
❏ Break down of the abrasive
❏ …

Combining the equations give

$$W = k_3 \frac{Ld}{H} \tag{4}$$

which is known as Archard's equation. This relation was originally derived for adhesive wear (see CH. 9.), but has proven useful in abrasive wear as well.

Some other wear equations are the empirical equation of Khrushchov

$$W = \frac{k_5}{E^{1.3}} \tag{5}$$

where E is the elastic modulus.

The Zum Gahr equation reads

$$W = f_{ab} A_v d \tag{6}$$

where

$$f_{ab} = \frac{A_v - (A_1 + A_2)}{A_v} \quad \text{(0 for plowing, 1 for cutting)} \qquad (7)$$

and A_v is the cross-sectional area of the wear groove, A_1 and A_2 are the cross-sectional areas of the material displaced to the side of the groove (left and right respectively), and d is the sliding distance.

Comment: Note that load is only implicitly involved in the equations above through the appearance of k_5 and A_v. These have to be related to the load e.g. through (2) and (3))

The wear resistance, R, is defined as

$$R = \frac{1}{W} \qquad (8)$$

3.2. EFFECTS OF MATERIAL PROPERTIES OF ABRASIVE WEAR

There are a variety of material characteristics that have been shown to either have an effect on or correlate with abrasive wear. Some of these properties are

❏ Hardness; linear relationship between hardness (of worn surface) and wear resistance (different slopes for pure materials and alloys).
❏ Elastic modulus

Comment: Doubtful how this would influence. A high modulus would give high contact stresses, which would probably decrease the wear resistance. But the elastic modulus is connected to many other properties so …

❏ Yield strength

Comment: A high yield strength should probably increase the wear due to less fracture. But the occurrence of strain hardening could complicate the situation …

❏ Melting temperature

Comment: This should probably increase the wear resistance due to less softening.

❏ Crystal structure; cubic crystals wear at about twice the rate of hexagonal crystals.
❏ Microstructure; the higher the strain hardening and the ductility, the better the wear resistance. A common way to improve wear resistance is to produce a second phase.
❏ Fracture toughness; a high toughness increases the wear resistance, mainly for brittle materials (figures of proportionality to fourth power of toughness).
❏ Composition; alloying is often used to increase wear resistance.

There are families of materials that have demonstrated good wear resistance. They are typically hard materials that resist scratching. These materials can also be used as coatings on other less resistant materials.

For metals to resist abrasive wear, the primary requirement is hardness. In addition, addition of carbides, especially large such (in relation to the abrasive), and carbide-forming metals, improve wear resistance.

Question: How does this relate to fatigue properties???

Alloyed white cast irons are the most resistive iron-base alloys due to the formation of carbides during solidification.

3.3.   ENVIRONMENTAL EFFECTS

3.3.1.   ABRASIVE

Changing the abrasive will change the wear rate. Characteristics of the abrasive that will contribute is

- ❏ Critical angle (see above). A round abrasive will induce less wear.
- ❏ Hardness of the abrasive. When the hardness of the abrasive exceeds that of the worn material, wear will become much worse.
- ❏ Toughness of the abrasive. A tough abrasive will induce more wear.
- ❏ Size of the abrasive

Comment: For a given volume of abrasive, larger abrasive should impose less wear, since there are fewer points of contact and the contact stresses at these points are lower.

- ❏ …

3.3.2.   TEMPERATURE

One could expect more wear as the temperature increases. However, at least for copper and aluminum, the effect is very small. This has been contributed to the fact that small areas of contact are heated during abrasion. The metal will flow at these contact points. For high initial temperature, the flow stress will be reduced, which will result in less heating due to abrasion. The result will be that the points of abrasive contact will have a similar steady state temperature regardless of initial temperature. Thus, the wear rates will be similar.

3.3.3.   SPEED OF CONTACT

The wear rate increases slightly with increased speed in the range 0–2.5 m/s. This may be attributed to a slight increase in frictional heating.

3.3.4.   LOAD

Wear is proportional to applied load, see (4), as long as the load levels do not lead to fracture of the abrasive. In this case, the wear rate will decrease if the abrasive is rounded or may increase if the fractured abrasive have sharp corners.

3.3.5.   HUMIDITY

The effect of humidity on wear rates is far from clear. Results are often contrary. The influence of humidity is of its ability to influence the surface layer (often consisting of oxides).

3.3.6.   CORROSIVE EFFECTS

Abrasive wear is often enhanced by corrosive conditions. A synergism often occurs between corrosion and abrasive wear. The abrasive removes the

(normally) protective surface layers and creates fresh surfaces which rapidly corrode.

4.   POLISHING WEAR

Definition: Interaction between two solids that produces a polished surface on at least one of the contacting surfaces by removing material.

Since "polished" can not be quantitatively defined, the definition is not precise. Also, this has the consequence that polishing wear can be considered as special case of other basic wear processes, mainly abrasive wear. However, there are certain unique mechanisms involved.

Polished wear has mainly been studied for simple systems that are intended to produce a polished surface. Studies for complex engineering systems are rare.

Polishing wear can only occur for materials of high intrinsic reflectivity, mainly metals.

4.1.   POLISHING WEAR WITH ABRASIVES

This is one of the most common causes of polishing wear and polishing wear with abrasives is just a special case of abrasive wear, see CH. 3. The question is under which circumstances abrasive wear systems produce surfaces with a fine topography.

A difficulty of applying concepts of abrasive wear to polishing wear with abrasives is that the former are larger-scale processes. For instance, (micro-) indentation tests are carried out on a much larger scale than the processes occurring during polishing wear. However, it seems as if the similarity principle is valid even for the smallest conceivable indentations.

Comment: Does the similarity principle mean that measured hardnesses for different materials should be comparable. I.e. hardness is a valid materials property even at these small scales???

Still, the comparisons should only be actually valid if the workpiece is fairly homogenous over the entire range of specified indentation sizes. Thus, for metals, an inclusion can be small enough not to influence abrasive wear, nut still large enough to have an effect on the polishing wear behavior.

As for abrasion wear, the mechanical properties of the abrasive and the surface are very important. Also, for a polished surface to appear, the applied force must be below a limiting value (for example ~0.01 N for a workpiece of hardness 1000 HV), since the formed grooves has to be narrow.

4.2. POLISHING WEAR WITHOUT ABRASIVES

Two mechanisms that can induce polishing wear in the absence of an abrasive are

❏ Surface flow; in which the asperities on a rough surface is flattened by the compressive force of another, stronger, solid.
❏ Chemical-mechanical mechanisms; where the corrosion-protective surface film of a metal surface is removed by a rubbing solid. The film is then reformed, during which a thin layer of the workpiece is consumed. Repetition of this process gradually removes the crests and produces a smother surface.

5. SOLID PARTICLE EROSION

Definition: Solid Particle Erosion (SPE) is the loss of material that results from repeated impact of small solid particles.

In this section, only particles entrained in gas are considered. The case of particles entrained in liquid is treated in CH. 8., and the case of repeated impact by another solid is treated in the section CH. 12.

The difference between erosion and abrasion is that erosion refers to a series of particles striking and rebounding from the surface, while abrasion refers to the sliding of abrasive particles across a surface under the action of an externally applied force. Thus, the force that governs erosion is the deceleration of striking particles, while in abrasion the force is externally applied and approximately constant.

Solid particle erosion is to be expected whenever hard particles are entrained in a medium that impings a solid at any significant velocity (greater than 1 m/s).

Manifestations of SPE include

❏ Thinning of components
❏ Macroscopic scooping appearance following the gas/particle flow field
❏ Surface roughening
❏ lack of directional grooving characteristic of abrasion
❏ Formation of ripple patterns on metals (not all cases)

5.1. VARIABLES AFFECTING PURE EROSION

In the absence of corrosion, several variables can affect the erosion rate, E. This rate is commonly given as volume (or mass) of material removed per unit mass of erodent impacted.

The discussion below has its emphasis on metals. Here, one mechanism of material removal is the deformation of surface material into thin platelets,

which eventually gets detached and forms platelike debris particles. These platelets are often considerably smaller than the average crater dimension. It seems like this platelet mechanism is the predominant mode for 90° incidence angle (see below), whereas, at lower incident angles, the predominant mode is micromachining (as cutting and plowing). However, there is not a general agreement in literature on this.

Another effect that can be significant is the embedding of erosive particle fragments in the specimen surface.

IMPINGEMENT VARIABLES

❏ Particle velocity: Generally a power dependence of the type $E = k v^n$ is found. Here, k is a constant, v is the velocity and n is an exponent that depends on material and erosion conditions. Usually $2 \leq n \leq 2.5$ for metals.
❏ Angle of incidence, α (between indent particle direction and surface [the reference says particle surface, but this is probably a typing error]): Ductile materials have a maximum erosion rate, E, at $15° < \alpha < 30°$ (typically). Brittle materials have E_{max} at $\alpha \approx 90°$.
❏ Flux (particle concentration): Because of inference of rebounding particles with incident particles, the surface becomes shielded at higher fluxes. This leads to an exponential decrease of E with increasing flux.

Comment: Note that E is defined as volume of removed material per unit mass of erosive . Thus, the volume of removed material may increase even if E decreases.

❏ Temperature: This influence is very hard to predict. In some cases E increases, while in other it decreases.
❏ Particle rotational speed: Very hard to measure.

Comment: A rotational speed should probably give an increase in erosion rate.

PARTICLE VARIABLES

❏ Particle shape: Angular particles give higher erosion rate than spheres.
❏ Particle size: The effect is very small as long as the particle size is $\geq$ 100 μm. For particles smaller than 100 μm, the erosion rate decreases rapidly. This is probably due to an increase in the flow stress with decreasing indentation size.

Comment: This would give a greater hardening and thus less wear.

❏ Particle hardness: See material hardness, below.
❏ Particle friability (ease of fracture)

MATERIAL VARIABLES

❏ Hardness: Significant improvements of erosion resistance can be obtained when the ratio of particle to target hardness is less than 1. However, increasing the hardness by work hardening have essentially no effect on E. Probably because the surface reaches saturation

work hardening during steady-state erosion.

Also, for a specified steel (and a specified α), the erosion rate is nearly independent of the hardness.

❏ Work hardening behavior

Comment: The higher the work hardening rate and saturation value, the better (probably).

❏ Microstructure

❏ …

5.2. COMBINED EROSION/CORROSION

The following discussion is limited to the behavior of metals under the influence of gas-bourn particles.

The field can be divided into the following categories

❏ Pure erosion; as discussed above
❏ Corrosion-affected erosion: When the corrosion increases, a thin layer of corrosives is developed on the workpieces surface. The "dimensions" of the induced stress field during impacting particles are greater than this layer, which leads to deformation of both the corrosive layer and the surface. The erosion rate increases. The mechanisms behind this synergy effect are not fully understood. One likely explanation is that bare metal is repeatedly exposed to corrosion.
❏ Erosion enhanced corrosion: Is further divided into three stages:
I. The rate of growth of the corrosive layer is essentially unaffected by the erosion.
II. The presence of erosion increases this growth rate.
III. Erosion-induced spalling of the corrosive layer enters as an additional scale loss mechanism. This leads to a very thin, or absent, corrosive layer and very high corrosion rates. Here, the erosion rate can be very sensitive to the particle loading rate.
The mechanisms governing which of the different stages that will be dominant is complicated and depends on the chemical and mechanical properties of the corrosive laver etc.
❏ Pure corrosion: This is not treated here.

6. CAVITATION EROSION

Definition: Cavitation is defined as the repeated nucleation, growth and violent collapse of cavities, or bubbles, in a liquid.

Cavities in contact or close to a solid surface will collapse asymmetrically forming a microjet of liquid directed toward the solid. Also, the cavities do not act independently, but collapse in concert. This effect leads to an enhanced effect such that the pressures produced by these collapses may cause localized deformation and/or removal of material from a surface in the vicinity of the

cavities. The collapse of a cavity cluster starts at the outer perimeter and proceeds inwards. Much of the energy produced by the outer cavities is transferred inwards. The intensity of the collapse of the inner cavities will thus be very high. Also, there will be a significant, localized, temperature increase (up to 5000 K) associated with the collapse.

6.1. VARIABLES AFFECTING CAVITATION EROSION

CAVITY FACTORS

Some of the parameters that affects the erosive effect of a cavity cluster are

- ❏ Hydrostatic pressure
- ❏ Cavity cluster size
- ❏ Distance of individual cavities from the solid surface
- ❏ Temperature and density of liquid

The erosion rate will be a balancing act between the energy (acting on the solid surface) released by the cavities and the ability of the material in this surface to absorb this energy.

Further, after the initiation, the rate of erosion as a function of continued exposion is usually non-linear.

MATERIALS FACTORS

There are probably a number of materials factors that will affect the erosion rate of the material. However, due to the dynamic, shocklike nature of the loading, no universal correlation with quasistatic mechanical properties has been found.

CAVITATION EROSION AND CORROSION

Cavitation can also have a variety of effects on corrosion since it can

- ❏ Remove a protective corrosive layer
- ❏ Increase diffusion rates of reactive dissolved gases into the metal surface
- ❏ Increase rate of removal of corrosion reaction products from the vicinity of the surface (i.e. not only corrosion layers, but also gases resulting from corrosion processes etc.)

Unfortunately, no general rules exist on have this combination will affect erosion and corrosion rates, see below.

6.2. SOME GENERAL FACTS ON CAVITATION EROSION

- ❏ No materials are immune to cavitation erosion (as some are to corrosion)
- ❏ Metallic materials that exhibit stress-induced phase transformations have the highest erosion resistance
- ❏ The combination of erosion and corrosion can be either synergistic or

less harmful than either process acting alone. There are no general rules for this.

❏ Coating processes offer a great potential both in designing against cavitation erosion and in repairing eroded surfaces.

7. LIQUID IMPINGEMENT EROSION

Definition: Progressive loss of material from a solid surface due to continued exposure to impacts by liquid drops or jets.

Liquid impingement erosion can be a practical problem primarily where the target body moves at high speeds and collides with liquid drops that are moving much slower.

There are many similarities between liquid impingement erosion and cavitation erosion, since both are, in fact, due to small scale liquid/solid impact. On the other hand, there are very few similarities between liquid impingement erosion and solid particle erosion, even though both involve impact of small bodies. The differences are due to different damage mechanisms, different impact variables and different response of material.

Liquid impingement erosion has some similarities to continuous jet impingement ("jet-cutting"). However, there are differences, since the continuous jet produces stagnation pressure, whereas the discrete impacts in liquid impingement erosion produce much higher shockwave pressures.

Almost all research has been made on two major problem areas: "moisture erosion" of low-pressure steam turbine blades operating with wet stream and "rain erosion" of aircraft or missile surfaces and helicopter rotors.

7.1. MECHANISMS OF LIQUID IMPINGEMENT

The impact pressure can be defined as

$$P = \rho C V \tag{9}$$

where r is the liquid density, C is the shockwave velocity in the liquid and V is the impact velocity. For practical impact velocities, this can be approximated by

$$P = \rho C_0 V \left(1 + k\frac{V}{C_0}\right) \tag{10}$$

where C_0 is the acoustic velocity of the liquid and k=2 for water.

As an example, water impacting at 500 m/s, gives an impact pressure of about 1250 MPa. The stagnation pressure of a continuous jet acting at this speed is about ($\rho V^2/2$) is about one tenth of this value.

The real situation is more complicated due to roundness of impacting droplets and elastic and plastic deformation of the solid surface.

If erosion rate is plotted against time, the following stages can generally be seen

- ❏ Incubation stage; in which there is little or no material loss. This may not appear if the impact conditions are severe enough to cause material loss for a single impact.
- ❏ Acceleration stage; during which rate increases rapidly to a maximum
- ❏ Maximum rate stage; where the erosion rate remains (nearly) constant
- ❏ Deceleration (or attenuation) stage; where the erosion rate declines to (normally) 1/4 to 1/2 of the maximum rate
- ❏ Terminal (or final steady-state) stage; in which the rate remains constant once again indefinitely. However, in some tests, the erosion rate can continue to decline or fluctuate. Also, for some brittle materials, the rate can increase once again in what is called a "catastrophic stage"

The measures that are normally used to quantify a material is the

- ❏ Rationalized erosion rate; which is the volume of lost target material divided by the volume of liquid impinged
- ❏ Rationalized incubation period; which is the number of stress pulses experienced by a typical point during the incubation period

Some variables that affect the (maximum) erosion rate are

- ❏ Impact velocity; At low impact velocity, there is a "threshold" in which no material loss is observed at normal operating times.
- ❏ Impact angle; As a first approximation, erosion depends only on the normal component of the impact velocity. However, once a surface becomes roughened, the effect of a tangential component should probably become more pronounced
- ❏ Droplet size; The erosion rate (i.e. erosion due to a given amount of liquid) decreases with drop size. There is no obvious explanation to this phenomenon.
- ❏ Liquid density; Erosion rate shows dependencies of about the 2:nd to 2.5th power of liquid density
- ❏ Acoustic velocity; Although this variable occurs in the theoretical treatment, see (10), it is unclear how the practical influence is.
- ❏ Cyclic deformation properties; good correlation has been found to erosion rate.
- ❏ Hardness; The hardness of the surface has a strong effect of the erosion resistance of the material. The harder the material, the smaller the erosion rate (about 2nd power of the change in Vickers hardness number). However, this does not necessarily apply when different

materials are compared.

Comment: This could be due to different brittleness, and thus different failure modes, for different materials.

There exist empirical formulas to predict incubation times and erosion rates. These formulas predict maximum erosion rates within a factor 3 for most tests. The error for incubation times are greater.

7.2.   MEANS OF REDUCING LIQUID IMPINGEMENT EROSION

Some means are

- ❏ Reduction of impact velocity
- ❏ Modification of surface geometry to decrease normal component of the velocity (i.e. "tilting" the surface)
- ❏ Reduction of droplet size
- ❏ Reduction of time of operation under most severe conditions
- ❏ Selection of resistant material
- ❏ Application of a shielding layer

8.   SLURRY EROSION

Definition: Wear of a material exposed to a high-velocity stream of slurry (mixture of solid particles in a liquid)

The interest of slurry erosion has increased since the starting of mineral transportation through pipelines.

Wear response of a material in a certain slurry does not indicate how this material would respond to another slurry. Similarly, the effect of a certain slurry on one material does not indicate how it would affect other materials.

Slurry erosion consists of several wear modes, such as

- ❏ Abrasion-corrosion wear; which is the result of abrasive rubbing in the presence of a corrosive liquid
- ❏ Crushing and grinding; occur in abrasive metal-to-metal contact
- ❏ High velocity erosion; can become very destructive if velocity is above some 6 to 9 m/s. However, this is unusual.
- ❏ Low-velocity erosion is a low-rate wear mode that occurs there is a flow of slurry at low velocities. Here, the velocity close to the surface is often close to zero and thus, the wear rate is very low.
- ❏ Saltation wear; is due to sediment transportation where particles move forward in a series of short bounces from the bottom surface.
- ❏ Cavitation; see CH. 6.

9. SLIDING AND ADHESIVE WEAR

Definition: Sliding and adhesive wear is wear, where the majority of particle removal is generated by the relative, high-amplitude, sliding of two surfaces in the absence of abrasives.

Comment: This definition is made by me.

No specific agency can be identified as the cause of wear. Thus, if no abrasive can be found, if the amplitude of sliding is larger than in fretting and if the material loss is not governed by oxidation, etc., adhesive wear is said to occur.

However, adhesion is not the cause of wear, but only a consequence of contact. Wearing occurs when interfaces in contact are made to slide and the locally adhered regions must separate. This results in a very wide range of wear rate.

9.1. MECHANISMS OF ADHESIVE WEAR

In the sliding area, metals will usually be covered with a film of oxide, which is covered by a second film of adsorbed gases and oils. The thickness of these films are ≈10 nm. These films intervene in the adhesion (bonding) of substrate materials. Variations in thickness and properties of these films is one reason for the wide range of friction data.

When two surfaces slide against each other, there will be some contact between these layers. If the contact pressure is high, a layer may fracture and expose substrate material (especially if the bulk material deforms plastically). Small regions of the two surface materials may then come in contact and bond. The strength of these bonds will depend on the materials. Also, the conformity of the contacting surfaces influences the bonding.

The most widely known equation of adhesive wear is due to Archard, see (4). This equation can also be expressed the rate of wear (i.e. volume removed per time unit) as

$$\Upsilon = k\frac{LV}{H}$$

(11)

where Υ is the wear rate, L is the applied load, V is the sliding distance and H is the hardness of the softest material. k is a constant that sometimes is referred to as the wear coefficient. It ranges from 10^{-3} for unacceptable wear rates to $\leq 10^{-7}$ for practical systems. However, these numbers are just very broad guidelines for anticipated wear rates.

Adhesive wear actually seems to involve over 25 variables, some of which are difficult or impossible to measure. Thus, there is no general applicable equation and simulative testing should be performed.

For steels (0.12% C), some observations are

- ❏ Increasing load may decrease wear rate; presumably by increasing the contact temperature and thus forming austenite.
- ❏ Wear debris is a mixture of oxides
- ❏ Increased hardness decreases wear rate since it diminishes the transition to severe wear.
- ❏ Inert gas broadens this transition region, whereas oxygen narrows it.
- ❏ In the mild wear regime, initial wear becomes high if oxides are chemically removed.

Comment: Thus, the transition from mild to severe wear seems, mainly to be a question of if the deformation is high enough to crack the oxide layer.

9.2.   MEANS OF REDUCING ADHESIVE WEAR

- ❏ Avoid sliding similar materials (particularly metals) together
- ❏ High hardness is a desired property (if fatigue is not to be expected). However, hard metal sliding should be avoided in lubricated systems due to the risk of scuffing.
- ❏ Consider the effect of relative hardness of different phases.
- ❏ Lubrication will reduce wear.
- ❏ Lubrication can be applied by providing a corrosive atmosphere, which will produce surface films.

10.   FRETTING WEAR

Definition: Fretting is small-amplitude oscillatory movements between contacting surfaces, nominally at rest.

One of the consequences in normal atmospheric conditions is production of oxide debris, thus the term "fretting wear" or "fretting corrosion". Fretting wear is closely related to early initiation of fatigue cracks, i.e. "fretting fatigue".

There are cases where the movement is not simply tangential, but is complicated by a normal force that also oscillates to the extent that the surfaces lose contact in each cycle. This leads to a hammering effect, which is termed "impact fatigue" (see CH. 12.). In this case, the phase relationship between the two motions can be of importance.

In fretting wear, damage can be caused by movements with amplitudes as small as ≈125 nm. However, relative movement between the surfaces has to be present in order for fretting wear to occur.

There is an effect of synergy between fretting wear and corrosion (strength reduction factors of 2–5 and even greater). Fretting also greatly accelerates the crack initiation process. Thus, in "normal" fatigue, crack initiation may account for 90% of fatigue life, whereas in fretting fatigue, initiation could occur in ≤5% of the fatigue life.

Comment: This should be very dependent on the loading conditions. Also, one could turn the

argument around and state that small cracks propagate very slowly under fretting conditions, presumably due to the influence of compressive loading.

10.1. LOAD PARAMETERS AFFECTING FRETTING WEAR

❏ Amplitude of slip: A relative movement is essential (see above). The wear rate relationships are "sigmosoidal" with constant wear rates for amplitudes >100µm (i.e. for a specific sliding distance). This small-amplitude characteristic of fretting is an important feature of the process. Relative velocities of the two surfaces will thus be much lower, even at high frequencies, compared to unidirectional sliding.

❏ Normal load: In contact between conformal surfaces, plastic deformation is to be expected at contacting high points. The actual area of contact is thus directly proportional to the applied load. Because fretting occurs only at these high points, it follows that the amount of wear should be proportional to the applied load. This is generally found to be the case.

❏ Frequency: There is an increase in wear volume at low frequency for a given number of cycles.

❏ Type of contact: The ease with which debris can escape from the contact region is of importance (it can also give rise to other problems due to contamination of other machine parts). If debris is allowed to escape, this will lead to more frequent metal-to-metal contact and higher wear rates. See also below.

❏ Type of vibration: In subresonant loading, the damage is said to be "typical fretting damage". In resonant conditions, the wear rates will be much lesser due to the lower dissipation of energy. In superresonant conditions, there will be a tearing of the surface due to 90° phase shift between the tangential and normal vibrations.

❏ Impact fretting: The combination of impact and fretting is, for some cases, more severe than fretting alone. In other cases, there is little influence and continous contact is more damaging. An important variable is the phase relation between normal and tangential vibrations.

❏ Surface finish: The more highly polished the contacting surfaces, the worse the damage. Shot peening can be used to produce a rough surface and also work hardening and residual compressive stresses in the surface. In experiments, a shot-peened surface with very low fretting wear rate experienced wear rates similar to unpeened steels after polishing.

Comment: Polishing could influence the residual stress field if surface temperatures are raised high enough. This could perhaps account for some of the effect.

❏ Residual stresses: This should be a parameter of high importance if fatigue is a damage mechanism in fretting wear. However, the fretting process itself can produce residual stresses. Experimental results show that the depth of the wear scar increased with tensile- and decreased with compressive residual stresses. Also, the presence of a

static tensile stress can lead to propagation of fretting induced cracks.

10.2. MATERIAL AND ENVIRONMENTAL PARAMETERS AFFECTING FRETTING WEAR

In some investigation, a formation of a white, etch-resistant layer has been detected in fretting of carbon steels. This material is extremely hard and tends to develop cracks. It is often referred to as martensite.

Comment: This phenomenon occurs in railway wheel/rail application.

As expected, metals that rely on a protective oxide film can suffer considerable fretting damage.

For different materials in the interface, their mutual solubility is an important parameter. High solubility leads to high damage.

As for debris, the accumulation of debris between the accumulation between surfaces tend to reduce wear. Abrasion by the oxide debris gives no significant contribution.

In vacuum, little wear takes place. However, there are considerable surface damage due to adhesive transfer of material. This effect ceases for pressures above ≈ 0.1 Pa.

Most metals (including iron) shows a peak coefficient of friction at values of relative humidity between 10% and 15%. This gives a corresponding peak in wear.

For very low temperatures (4 K), steel show little wear, but high friction, similar to the case of vacuum. At 77 K, the wear rates were similar as for 293 K. For temperatures of 500°, there is a great reduction in friction and wear. This is for oxidizing atmospheres, where many alloys develops a very smooth oxide surface ("glaze" oxide). In argon, however, surface damage is severe at this temperatures.

10.3. MECHANISMS OF FRETTING WEAR

The progress in time for fretting wear (under conditions where escape of debris is not easy) is:

❏ Initial stage; of a few thousand cycles. Here metal-to-metal contact is prevalent, resulting in local welding, roughening of the surface and high friction. Fatigue cracks, if initiated, are initiated in this stage.
❏ Formation of debris beds; with a corresponding fall in coefficient of friction.
❏ Onset of a steady state; in which friction is more or less constant.

Fretting can be prevented by

- ❏ Improved design; in which relative movements between surfaces are prevented
- ❏ Surface treatment; in which the surface is made rougher
- ❏ Coatings; in which a hard coating is applied. Caution is to be observed since the coatings, if brittle, may crack under plastic deformations of the bulk material and act as an abrasive.
- ❏ Inserts; which will separate the two surfaces.
- ❏ Lubricants; which will smoothen the contact. However, it is often difficult to maintain the lubricants in the area of contact.

11. ROLLING CONTACT WEAR

Definition: Rolling contact wear (RCW) results from the repeated mechanical stressing of the surface of a body rolling on another body.

Because rolling contact wear (RCW) is generally produced by mechanical stressing of the affected surface(s), it is often associated with or even referred to as rolling contact fatigue (RCF). As a distinction, one can define that in RCF, fatigue is the damage accumulation process that eventually results in wear particle formation. Further, the pits of RCW may act as nucleation sites for additional fatigue cracks. As a result, RCF and RCW are very closely related.

Rolling contact wear is often difficult to detect in its early stages. The precursor flaws may be hidden from view as they grow beneath the contact surface.

In many types of rolling contact arrangements, lubrication is important to minimize the deleterious effects of slip.

11.1.   RCW OF DIFFERENT SYSTEMS

GEARS
- ❏ The wear modes usually involves both rolling and slip or sliding.
- ❏ The design against RCW includes
- ❏ Stress limitations
- ❏ Material choices
- ❏ Adequate form and finish
- ❏ Adequate lubricants and lubrication systems
- ❏ Rust and contaminant protection
- ❏ Elastohydrodynamic considerations

ROLLING-ELEMENT BEARINGS
Pitting, smearing and spalling are important RCW manifestations.

The depth of the spall tends to be related to the location of the maximum Hertzian shear stress below the surface.

The fatigue spalling life can be expressed as

$$L = \left(\frac{C}{P}\right)^{p} \tag{12}$$

where P is the equivalent dynamic load, C is the load capacity and p is an exponent that depends on the type of loading. For ball bearings, p=3; for roller bearings p=10/3.

The situation can be complicated by complex combinations of different loading.

11.2. MECHANISMS OF RCW

Mechanisms of RCW can involve subsurface fatigue, where intersecting subsurface fatigue cracks form surface pits in rolling elements. It can also involve mild abrasion from lubricant contamination, it can be affected by water or acids in lubricants, etc.

Initially, the material may be stressed beyond its elastic limit, causing some plastic deformation. As repeated rolling occurs, elastic shakedown, when no further plastic deformation occurs, can set in.

The processes of RCF and RCW generally involves the following steps:

- ❏ Accumulation of dislocations caused by repetitive stressing of the subsurface microstructure.
- ❏ Nucleation of voids or microcracks in regions of maximum Hertzian stress or close to discontinuities, pores or inclusions.
- ❏ Propagation of microcracks in the subsurface.
- ❏ Linking of the cracks and propagation of the crack tip toward a free surface.
- ❏ Creation of flakes, pits and/or spalls.
- ❏ Spread of the damage to adjoining parts of the surface.
- ❏ Initiation of major fatigue cracks from surface or subsurface defects sometimes causing catastrophic failure.

Comment: From the 5th point, the influence of lubricants "exploding" the crack may be of importance. (In the article, it says from the 3rd point, but this is probably a printing error since the crack hasn't reached the surface by then).

Composite materials may be interesting since they contain internal "crack stoppers" or crack branching interfaces (which will dissipate energy).

Wear particles may give rise to additional damage as they contaminate the contact.

Improved wear life can be produced by lubrication with adequate load-bearing capacity.

Increased (fracture) toughness of the solid material increases the wear life since it enhances the crack propagation resistance.

Reduction of porosity and inclusion content of the solid material will increase the wear life since it decreases crack initiation.

12. IMPACT WEAR

Definition: Impact wear can be defined as wear of a solid surface due to repetitive exposure to dynamic contact by another solid body.

The wear mechanisms are, among other, dependent on

- ❏ Materials used: For example, in polymers, thermal wear can occur.
- ❏ Contact stress range: Compare with contact fatigue vs. fretting fatigue.
- ❏ Impact speed: Increased speed can result in a transition from low-stressed fretting wear to severe adhesive wear.
- ❏ Loading modes: The relative size of sliding vs. normal impacting speed components.

From theoretical studies of impact dynamics and experimental studies of wear of different materials, semi-empirical impact wear theories have been derived.

REFERENCES

1.   ASM International, ASM Handbook, vol. XXX, xxx pp., Materials Park, Ohio, U.S., 19XX