Wear
Introduction

Wear is the gradual removal of material obtained at contacting surfaces in relative motion. While friction results in important energy losses, wear is associated with increased maintenance costs and costly machine downtime.

Wear phenomena are intimately linked to frictional processes. If solid surfaces in relative motion are not separated in some way, wear can be expected. Lubricants are used to separate contacting surfaces in relative motion and thus to reduce wear. Lubricants may completely separate the surfaces, as in fluid film lubrication or allow solid-solid contact only at a restricted number of locations (mitigated solid contact) as in boundary lubrication. The focus is on wear resulting from direct solid-solid contact.

Wear phenomena are heavily influenced by the fact that most engineering surfaces are rough (and hence surfaces come in contact at single asperities and the real area of contact is usually much smaller that the nominal contact area). Furthermore, wear behavior is also influenced by the presence of adsorbed species and/or surface layers.

Many different wear mechanisms have been identified. A first classification of mechanisms is based on their relative importance in engineering practice. According to this, the following types of wear are often encountered:

• Adhesive Wear (plus Fretting Wear)
• Abrasive Wear (plus Erosive Wear)
• Surface Fatigue Wear
• Corrosive Wear

Wear phenomena can also be classified based on the underlying physics. According to this, mechanistic-based classifications, the following types of wear have been identified:

• Adhesion and Transfer. Wear takes place by gradual removal of adhered fragments of material picked up by the contacting surfaces during frictional interaction.
• Corrosion Film Wear. Wear is associated with the removal of fragments of protective corrosion/passivating layers from the surface of the worn material.
• Cutting. Wear is the result of intermittent or continuous chip formation in the soft material due to cutting action by a harder tool.
• Plastic Deformation. Wear being associated with the removal of sheared layers resulting from excessive plastic deformation.
• Surface Jetting. Wear resulting from interfacial instabilities associated with localized softening at the contact interface.
• Surface Fracture. Wear resulting from breakage of atomic bonds in embrittled surface layers.
• Surface Fatigue. Wear resulting from subsurface cracking and fracture induced by cyclic loading.
• Surface Reactions. Wear associated with the removal of reaction products from the surface which in turn were produced by frictional flash heating.
• Melting. Wear associated with the melting transition.
• Electrochemical. Gradual wear associated with anodic reactions on the worn surface.

Measurement of Wear

Wear rate measurements are routinely performed using standard or customized friction and wear testing equipment. The same configurations used for friction measurements are also used in wear research. While the occurrence of an initial running-in or breaking-in stage is often detected when measuring wear, experiments tend to focus on the also commonly encountered subsequent stage of the process: steady state wear.

The amount of material worn in a tribological system is measured in relation to the duration and extent of contact. Specifically, a common measure of wear is the volume of material removed per unit sliding distance. Consider a tribological system where a volume V_w of the softer component of the couple is removed by wear in the same amount of time it takes for the sliding distance to become L. The volume of worn material per unit sliding distance is then $w = V_w/L$. The wear rate thus expressed has units of area and it is often useful to compare the observed values of wear rate against the other most important area measure encountered in friction studies, namely, the real area of contact of the friction couple A_r which, for plastically deforming asperities, is simply given by

$$A_r = \frac{F_n}{H}$$

Here F_n is the applied load and H is the hardness of the softer component in the friction couple.

The ratio of the wear in units of volume removed per unit sliding distance to the real interfacial area of contact is a meaningful dimensionless quantity useful in wear studies and is called the dimensionless wear coefficient, or simply the wear coefficient, K. From the above, this is defined as $K = \frac{V_w/L}{F_n/H} = \frac{w}{A_r}$

A couple of useful physical interpretations can be given to the coefficient K. First, since, K is the ratio of two areas, the worn area A_w and the real contact area A_r. One can thus interpret K as the fraction of the real contact area A_r removed by wear. Consider a tribological system consisting of a hard flat surface and a rough surface of a softer material with of identical asperities. Assume the surfaces make contact at N aspertities. Hence, the wear coefficient represents the number n of those asperities were conditions are such the conditions that material is torn forming wear debris, i.e. $K = \frac{A_w}{A_r} = \frac{n}{N}$

This interpretation, together with the commonly found low values of K found in practice indicates that while all asperity contacts contribute to friction only a very small fraction of contacts result in wear. Therefore, while friction is dominated by the contact events that occur without damage, wear is dominated by the (small) chance that a particular contact event results in rupture.

Note also that the quantity $(F_n/H)L$ has dimensions of volume. This represents the total volume of the plastically deformed zone underneath the surface of a worn area, V_p following sliding by a distance L. Hence

$$K = \frac{V_w}{V_p}$$

Therefore, K also represents the proportion of the plastically deformed volume that is removed by the wear process.

Adhesive Wear

An adhesive wear model assumes that wear is the result of adhesion between asperities followed by fracture. A first simple model of adhesive wear states that the volume of worn material removed V_w as a result of a tribological interaction is directly proportional to the load F_n and also to the total sliding distance L. However, since less wear is observed when the hardness of the softer member of the tribological couple increases, V_w can also be regarded as inversely proportional to the hardness H of the material being worn away. In symbols, the above is represented as

$$V_w = K\frac{F_n L}{H}$$

or expressed in terms of the worn volume per unit sliding distance w

$$w = \frac{V_w}{L} = K\frac{F_n}{H}$$

where K is the previously introduced wear coefficient. This expression is sometimes called Archard's law. Although an equation of this form was first proposed by Holm from his studies on electric contacts, Archard first obtained it using a simplified model of the contact interaction described below.

Note that if the sliding distance is the result of sliding at constant velocity U, it is then given by L = Ut where t is the sliding time. If Archard's law is divided by the nominal (apparent) contact area A_a, substitutes the sliding distance in terms of sliding velocity and time and solves for the time one gets $t = d\frac{H}{K}\frac{1}{p_m U}$

where $d = V_w/A_a$ is the worn depth and $p_m = F_n/A_a$ is the mean or nominal pressure. This is an indication of the life of a wearing component in terms of the admissible worn depth and the material and process parameter H, K, p_m and U.

It is often the case that measured worn volumes vary in direct proportion with the total sliding distance. In contrast, while worn volumes often vary in proportion with the applied load over certain load ranges, abrupt changes in wear rates (wear transitions) are observed at specific critical loads. Such changes are the result on the complex interplay between the softening and chemically reacting behaviors of the material induced by high flash temperatures. Abrupt increases in wear rates are commonly found at high loads and these are often associated with welding and seizure. However, in some cases these high wear rates may revert to low values at even higher loads.

Measured values of K are frequently small and range from 10^{-8} for incompatible metals rubbing against each other with good lubrication to 10^{-3} for clean unlubricated surfaces of like metals. The smallness of these values together with the original interpretation of K given above suggest a probabilistic interpretation of the wear coefficient, namely, it represents the fraction of the actual contact surface which is actually removed by the wear process. It could also represent the probability that any given individual friction contact event culminates with the breakage and removal of a wear particle.

Adhesive wear coefficient correlate well with friction coefficients, however, unlike friction coefficient values, wear rates vary over a very large range.

Other experimental techniques useful in wear research include:

- Microscopic examination of wear debris.
- Metallographic examination of worn surfaces.
- Radioactive isotope methods.

Besides the sharp differences in wear rates that exist between mild and severe wear, the wear debris produced in both cases also exhibits significant differences. Specifically, wear debris resulting from mild wear frequently consists of fine particles (0.01-1 micrometer), many of them oxides. In contrast, the debris resulting from severe wear consists of much larger (20-200 micrometer) plate-like particles consisting of an assembly of smaller particles stuck together.

To gain insight into adhesive wear mechanisms it is useful to examine in some detail the results of selected wear experiments carried out in well characterized systems. The advantage of this approach is that the resulting information has been reproduced and the underlying processes are generally well understood. The systems examined below include:

• Wear of plain carbon steel rubbing against itself in air.
• Wear of leaded brass (59Cu-39Zn-2Pb) rubbing against stellite in air.
• Wear of 60-40 brass and ferritic stainless steel against tool steel in air.

Details about the observed wear mechanisms in these two systems are now described.

In the first case, wear observations are performed on a plain carbon steel pin rubbing against a disk of the same material in air as a function of load under dynamic but otherwise steady-state conditions.

When the applied normal load is relatively small, fine metal particles are removed from the rubbing surfaces and at least some of them are rapidly oxidized while dispersed in the gap between the contacting surfaces. The oxide particles then act as abrasive medium producing further wear. However, the observed wear rates are relatively small, and this is called mild wear.

As the load increases, larger metal particles are torn from the rubbing surfaces. The oxidation rate induced by flash temperature is not large enough to fully oxidize the wear particles and many particles are ejected from the gap and discarded as wear debris. Because the wear rates involved are larger, this is called severe wear.

For the highest loads, the resulting high flash temperatures lead to rapid formation of oxides and a hard, tempered layer on the contact surfaces. Fine metal particles are formed, oxidized and removed from the gap between the rubbing surfaces as wear debris. Since the contacting surfaces harden rapidly, the resulting wear rate is relatively small. This is known as the high temperature regime of mild wear.

When one uses instead a leaded brass pin and rubs it against a disk made of stellite in air the following scenario results. At the smallest loads (< 0.1N) and low temperatures, the contacting surfaces meet at fairly isolated asperity contact points. Small, discrete particles of brass are transferred to asperities on the stellite counter face and some oxidize rapidly. On further rubbing, the accumulated particles on counter face are smeared over and diffuse into the stellite surface and form a continuous thin layer of brass containing oxidized particles mixed with counter face material. Later on, material from the smeared layer at the counter face transfers back to the pin forming a micro-composite hard layer on the pin surface while small composite particles break away from the pin and the disk forming loose wear debris. As a result of the above, the wear rate is relatively low (mild wear).

As the applied load - and the resulting temperature - increase, the following distinct sequence of events is obtained. The real area of contact increases and electrical contact resistance at the interface reaches a minimum. Particles of brass are transferred to asperities at the counter face and at least some oxidize rapidly. The accumulation of discrete particles on the counter face results in aggregation into larger clusters on the surface of the disk. These clusters subsequently break away from the disk forming loose wear debris and the resulting wear rate is high (severe wear).

At the highest loads, the contacting surfaces meet at over a much larger contact area.

The resulting high flash temperatures lead to rapid surface oxidation. Particles of brass are transferred to asperities at the counter face and oxidize rapidly. The oxide particles are smeared over the contacting surfaces and effectively form an intervening layer between the rubbing

surfaces, while small particles continuously break away from the pin and the disk forming loose wear debris. The observed wear rate in this case is relatively low (high temperature mild wear).
When the same pin and disk experiment is carried out using a stainless steel pin rubbing against a tool steel disk one finds that Stainless steel exhibits mild wear for loads below 30 N and there is a transition to severe wear mode for larger loads. When the pin and disk experiments are performed in a high temperature environment, a somewhat different behavior is observed. Specifically, for the case of a brass pin at low sliding speeds one finds that the imposed high temperatures produce some softening of the material while the low flash temperatures resulting from the low sliding speed lead to minor softening and oxidation. Small discrete particles of brass are transferred to asperities at the counter face and oxidize. The brass particles are smeared over the counter face forming a continuous thin layer of micro-composite material consisting of a brass matrix containing oxidized particles and tool steel. The material from the layer continuously transfers back to the pin forming a corresponding micro-composite hard layer on the pin surface while small composite particles break away from the pin and the disk forming loose wear debris. The resulting wear rate is low (mild wear).
For the same system, as the sliding speed increases the increased flash temperatures lead to further material softening and oxidation, while the prevailing high temperatures produce additional softening of the material. Small discrete particles of brass are transferred to asperities at the counter face and accumulate there resulting in larger aggregates on the surface of the disk. Such aggregates break away periodically from the disk forming loose wear debris and the resulting wear rate is high (severe wear).
If besides increasing the sliding speed, one also increases the temperature of the pin and disk system, one observes additional softening and significant oxidation (due to both the high flash temperatures as well as the experiment temperature). Small particles of brass are transferred to asperities at the counter face, oxidize rapidly while they accumulate and smear over the counter face forming a continuous thin and micro-composite layer containing large amounts of oxidized particles and counter face material that make it relatively hard.
From time to time, small composite particles break away from the pin and the disk surfaces forming loose wear debris. As a result, the wear rate is relatively low (mild wear). Many studies similar to those described above have been performed and a couple of generic observations are the following. Wear occurs in both materials of a tribological system regardless of the differences in hardness of the materials involved. However, in most systems, the softer material wears out at a faster rate, as expected. Transitions from mild wear to severe wear are the result of the competing processes of surface oxidation and surface softening. At high oxidation rates, intervening oxide layers form readily reducing both friction and wear. When the softening rate predominates large material removal rates result.

Adhesive Wear Modeling

In the adhesion theory of friction, asperities of the contacting surfaces come in contact against each other briefly forming an adhesive junction. Assuming, correctly, that plastic behavior prevails at the asperities, the friction coefficient becomes

$$\mu = \frac{F_t}{F_n} = \frac{\tau}{H}$$

where τ is the shear strength of the junction and H the hardness of the softer material. The adhesive junctions formed during frictional processes play a key role in the development of the adhesive wear mechanism and in the production of wear debris.

The following wear model was first proposed by Archard. Consider two asperities in a tribological couple. The asperities first approach each other, then establish adhesive contact and finally move past each other. As a result of the interaction, a wear particle may be created. To simplify, consider asperities of hemispherical shape and radius a and assume the volume of the wear particle δV_w is approximately given by

$$\delta V_w = \frac{2}{3}\pi a^3$$

Moreover, let the normal load δF_n supported by the (plastically deforming) asperity be given by

$$\delta F_n = \pi a^2 H$$

where H is the hardness of the softer component in the contact couple. Finally, the sliding distance for this asperity interaction is $\delta L = 2a$.

Only a small fraction of contact interactions result in worn particles, therefore, let the proportion of interactions resulting in wear be κ so that the volume of material removed per unit sliding distance δw is given by

$$\delta w = \kappa \frac{\delta V_w}{\delta L} = \kappa \frac{\pi a^2}{3}$$

The total amount of wear (per unit sliding distance) w is the sum over all interactions, while the total load is the sum of all the loads supported by individual asperities. The wear rate is then given by

$$w = \kappa \frac{F_n}{3H} = K \frac{F_n}{H}$$

where $K = \kappa/3$ is the wear coefficient.

Archard's model yields an expression for the wear rate as a function solely of the macroscopic quantities F_n and H. It is well known that other factors significantly influence adhesive wear rates, the most important include

• Material Compatibility.
• Crystal Structure.
• Microstructure.

These effects are accounted for only implicitly in Archard's model though the wear coefficient K.

Other Forms of Wear

Material can be removed from a surface in a tribological couple by mechanisms other than adhesive/sliding wear. Particularly important are abrasive wear mechanisms involving either hard asperities or third bodies, erosive mechanisms involving high velocity swarms of particles and wear assisted by chemical reactions.

Abrasive Wear

Abrasive wear takes place when hard asperities or third phase particles rub under load against a relatively softer surface. If the wear process involves only two materials it is known as two-body abrasive wear. If extraneous abrasive particles are used one has three-body wear. In general, wear rates for two body wear are higher than for three bodies since loose abrasive particles tend to roll over the soft surface while abrading asperities firmly attached to the abrading surface do not.

Depending on the attack angle and the interfacial shear strength three modes of abrasive wear are usually encountered in ductile metals:

• Ploughing: Ridges form along the sides of wear track.
• Wedging: A short wedge forms in front of the abrading asperity.
• Cutting: A long ribbon-like chip forms in front of the abrading asperity.

In all cases wear particles form when ridges, wedges or chips fracture and detach from the underlying surface, perhaps by a process of delamination.

The Archard wear equation derived for adhesive wear situations has also been found useful in the representation of abrasive wear. Consider for instance the case of an abrasive surface consisting of conical asperities of included angle _ that ploughs through the surface of a softer material.

Fatigue Wear

Subsurface cracks may also form in more ductile materials by fatigue processes associated with cyclic loading. While little wear may be observed prior to fatigue events extensive pitting may be observed once fatigue sets in. Consider again a tribological system formed by a large number of microscopic contacts. Each individual asperity experiences multiple contact interactions with asperities of the counter face. When fatigue failure takes place at a particular asperity contact, the volume of material removed can be expected to be proportional to a^3 where a is the contact radius.

Fatigue wear may also occur in rolling contacts even if they function under a fluid film lubrication regime. The reason for this are the large cyclical stresses transmitted through the lubricating film. The resistance of bearings against rolling contact fatigue is estimated statistically through their lives.

Impact Wear

Impact wear is the gradual wastage of material due to repeated impact by particulate streams (erosive wear) or by continued hammering with a hard object (percussive wear). In solid particle erosion, the kinetic energy of impacting particles is transferred to the worn surface where is transformed into work of plastic deformation. Worn particles may then by removed by ploughing, wedging or cutting (ductile materials) or by fracture (brittle materials).

Liquid impingement erosion may result when liquid droplet sprays hit a surface at high speeds due to the high pressures developed when the kinetic energy of the fluid particle is transferred to the surface. Erosion can also result from imploding bubbles near the surface since implosion results in a fluid micro-jet directed at high speed against the surface.

When a surface is subjected to repetitive hard body impact, multiple wear mechanisms may become simultaneously active. The wear volume is estimated per impact cycle.

Wear associated with Chemical Reactions

Tribological systems embedded in a corrosive environment often experience chemical attack.

Also, the localized heating produced by flash temperatures stimulates chemical reactions which may also result in wear Fretting Wear, the wastage of materials subjected to oscillatory motions of small amplitude is often associated with chemical reactions. As asperities on one surface slide past the surface of the counterface, the latter may be rapidly oxidized. The oxide layer may be intermittent or continuous and may stay in place or be removed by subsequent sliding.

Depending of the fate of the oxide layer, the surface clearance may increase leading to sloppiness or undesired seizure may occur.

A model of corrosive wear can be developed by considering that the contact interaction takes places in a reactive environment that leads to the formation of a tribofilm on the wearing surface.

Examination of Wear Debris

Insight about wear mechanisms may be obtained by careful examination of wear debris. Microscopic (optical and electron), Coulter analysis and Ferrography have all been used. Particular interest exist in the deployment of wear debris examination methods for on-line condition monitoring of tribological systems since abrupt changes in wear debris characteristics are indicative of changes in wear mechanisms.

Wear Mechanism Maps

The various wear regimes and transitions observed in practice can often be usefully summarized in the form wear mechanism maps. A map is usually a two dimensional graph of normalized applied pressure against normalized relative velocity. Depending on the application, other combinations of coordinates may be selected. Regions within the map indicate process regions where a specific wear mechanism is dominant. Many different types of wear mechanism maps are now available for a variety of tribological systems. These are useful since one can identify at a glance specific values of tribosystem parameters that are most likely to yield desired results.