LUBE-TECH

NO.35

TRIBOLOGY BASICS (continued from LUBE-TECH No.34)

WEAR

The first article in this short series dealt with the fundamentals of tribology, which is that branch of science devoted to the study of lubrication, friction and wear. The second article in the series described the basics of lubrication; the third article dealt with the subject of friction, and this, the final article in this short series, addresses the subject of wear.

As with the previous items of lubrication and friction, the subject of wear and its various mechanisms is immensely more complex than one would expect from the simple dictionary definition, i.e. "to deteriorate or cause to deteriorate by constant use or action".

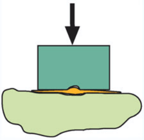
Wear occurs in virtually all types of machinery, in fact in any situation involving the movement of one surface in contact with another. Wear can be reduced by good design and proper lubrication, but can never be eliminated completely. Most wear phenomena are the result of friction. Continuous but almost negligible wear occurs in the region of mixed friction, where layers formed by chemisorption or tribochemical processes are sheared off by abrasive, but usually uniform erosion. This leads to a slow change in the dimensions of the sliding partners but without destruction of the sliding surfaces. In the case of very rough sliding surfaces, or where the viscosity of the lubricant film is too low, the oil film is ruptured and scratches and scars are formed on the sliding surfaces by abrasion. Also, damage of sliding surfaces by the inclusion of foreign particles such as sand, wear debris, etc. where the particle size is larger than the smallest bearing clearance, is again due to an abrasive effect. We can begin to see that there are a number of different wear mechanisms, the main categories being

- Adhesive Wear
- Fatigue Wear
- Erosive Wear
- Pitting
- Controlled Wear
- Abrasive Wear
- Corrosive Wear
- Cavitation Wear
- Micro-pitting

ADHESIVE WEAR

Adhesive wear occurs when there is contact between the asperities of the two surfaces during mixed and boundary lubrication conditions. Bonding or cold welding occurs between the asperity tips, and an adhesive junction is formed. The adhesive forces between the two surfaces can be very small, in which case the two bodies will separate without change; if the adhesive forces are large, cracks can then form in the less resistant body. This process is often known as the 'weld-pull' cycle. Adhesive wear often occurs between two substances of similar unlubricated metallic surfaces of the same or similar composition. In the case of dissimilar materials, e.g. aluminium bronze and steel, adhesive wear is caused by the strong adhesive force that develops between these mating materials. Prior to the surfaces beginning to move relative to each other, minute areas of contact between the mating surfaces become joined together (these are known as 'junctions'). If, when the machine applies a force to break these junctions, the resulting stresses in the metals are small, only small fragments of the metals become detached. In the case of aluminium bronze (and some other metals), these fragments or particles are quickly transferred from the softer metal (aluminium bronze) to the harder metal (steel). They adhere firmly to the steel in the form of a thin layer and are work-hardened. Thereafter, newly transferred particles agglomerate with the existing transferred layer. Some transferred particles may transfer back to the aluminium bronze. Provided adhesive wear is moderate, no debris form and the resultant small degree of wear may be acceptable, depending on the desired service life. On the other hand, metals which adhere strongly are more liable to cause debris and are therefore more susceptible to galling (cold welding).

Fig. 1 Mechanism of adhesive we



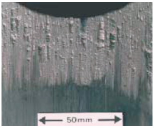


Fig 2 Example of adhesive wear on a gate valve face

Adhesive wear can be reduced by:-

- Using metal combinations which cannot easily bond
- Encouraging the formation of low shear strength additive layers
- Increasing the oil film thickness
- Use of hard coatings and materials such as tungsten carbide, ceramics such as alumina and chromium oxide, cobalt alloys, nickel alloys, ferro chromium chrome carbide, etc.

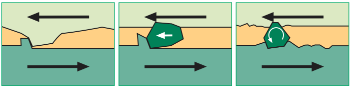
ABRASIVE WEAR

Abrasive wear occurs when small particles are present between the sliding surfaces, particularly where the diameter of the particle is greater than the thickness of the oil film. The particles normally originate from one or both of the two sliding metal surfaces, but may well be harder than the bulk metals due to 'work hardening'.

In the case of dissimilar materials, again using aluminium bronze and steel as an example, abrasive wear is the result of the hard material cutting or ploughing grooves into the softer material. The harder material may be one of the rubbing surfaces or hard particles that have found their way between the mating surfaces. These may be 'foreign' particles or particles resulting from adhesive or delamination wear. Due to the build up of elastic energy in the transferred layer, some of this layer may eventually, become detached and form tiny debris. These debris have undergone considerable deformation and work hardening and are therefore liable to have an abrasive effect on the softer surface and cause severe galling (also known as scoring or scuffing). It may be possible to arrest this effect by removing the debris. Otherwise, they may lead to rapid deterioration and to machine break-down. Aluminium bronze has however very good galling resistance (see below). It is advisable to give the harder of the two surfaces a finer finish to eliminate asperities that can plough into the softer material and steps need to be taken to prevent the ingress of hard foreign particles.

Fig 3 Process of formation of abrasive wear particles

Abrasive wear can be reduced by:-



- Increasing the hardness of the sliding surfaces
- Introducing a soft coating to embed the wear debris
- Improving oil filtration
- Increasing oil film thickness
- Reducing surface roughness

FATIGUE WEAR

Fatigue wear normally occurs in rolling contacts rather than sliding contacts, where stresses are high and slip is small. It is frequently caused in situations where there are intermittent strong elastic deformations of the surface, typically in high load-carrying rolling bearings. Wear is a result of the loosening of the grain boundaries resulting in the formation of scales on the surface, which can be aggravated by various reactive components of any lubricants present.

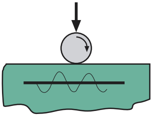


Fig 4 Situation leading to fatigue wear

Fatigue wear can be reduced by:-

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- Increasing the film thickness
- Reducing any influence by entrained or dissolved water
- Reducing sliding motion relative to rolling motion
- Adding fatigue-limiting additives
- Substitution of steel ball by ceramic balls (see below)

Fig 5 Extension of bearing service life by substituting steel balls by ceramic balls

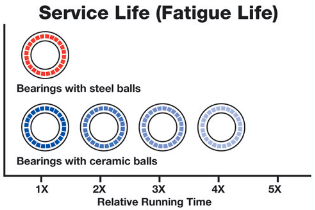


FIG 5. Service life for ceramic hybrid bearings is at least double that of convential steel ball bearings and could last up to five times longer, depending upon operating conditions.

Fig 6 Effect on bearing temperature by the use of ceramic balls

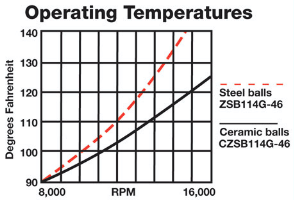


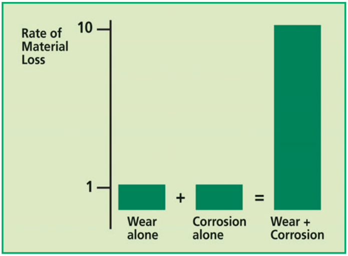
FIG 6. As running speeds increase, ceramic balls will always run cooler than conventional steel balls. With reduced heat build-up, lubricant life is prolonged.

CORROSIVE WEAR

This is characterised when material is removed from the sliding surfaces by chemical reaction.

Corrosive wear occurs when there is a combination of a wear situation (abrasive or adhesive) and a corrosive environment. The rate of material loss can be very high; many times that which would occur should the individual processes of wear or corrosion be acting alone. This is because loose corrosion products are easily removed by wear to continually reveal fresh metal beneath, which in turn can corrode quickly. Likewise, stable oxide films that would normally limit corrosion (in the absence of wear) are instantly worn away. It is not unusual to find this sort of situation.

Fig 7 Corrosive wear



Corrosive wear can be reduced by:-

- Use of corrosion and rust inhibitors
- Using additives of the minimum activity needed to prevent adhesion
- Limiting water access and activity
- Neutralisation by over-based detergents.

EROSIVE WEAR

Erosive wear occurs in when flowing media at high flow velocities such as those encountered in tubes, pumps, etc., impinges on surfaces, particularly when changing the direction of flow and in the case of turbulence. On the macro scale, this is readily observed when a river erodes away its banks at bends, sometimes to such an extent that the river forms a new route by cutting right through an existing bank, and isolating the old part of the river to form the well-known ox-bow lake. Again, on the macro scale, erosion by the impact of wave action is a major problem when endeavouring to restrain the encroachment of the sea in some areas.

Fig 8 Close up view of damage caused by erosion on a gate valve

CAVITATION WEAR

Cavitation wear occurs in situations where the formation and rapid collapse of vapour bubbles occur in a fluid, often the lubricant, which is undergoing rapid and extreme pressure changes.

Cavitation erosion can be reduced by:-

- Lubricant selection
- Design of the lubrication pressure feed system
- Engineering design of the bearing or mechanical systems

PITTING

Pitting, which is the removal of crystallites from the metal surface, normally occurs on gear tooth profiles exposed to high loads or on valve tappets of internal-combustion engines or compressors. The cause of pitting is due to the very strong elastic deformation of the metals and a pressure breakdown in the lubricant when the load-bearing surfaces separate, which leads to the creation of a vacuum and loosening of the crystallites.

MICRO-PITTING

Micro-pitting is a form of micro-pitting which has become more common in recent years due to a number of factors.

With improvements in materials, manufacturing processes and design technology, excessive 'safety factors' have been progressively reduced over the years, with consequent reductions in build costs.

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Problems such as micropitting have occurred as a result which had not been anticipated during the design stage.

Micropitting is a form of metal wear, visible only under microscopic examination, which consists of a series of shallow cracks, some of which can be as small as 10 microns in size. As the extent of the pitting increases, the degradation becomes visible as a dull matt area, resembling the appearance of etched glass. The degradation can self-arrest at this stage without causing any further damage. All too often, however, micropitting leads on to macropitting, with the consequent formation of deep fissures and loss of metal. Catastrophic failure can then follow.

Micropitting normally occurs in heavily-loaded, case hardened gear systems, such as:-

- Marine gearboxes
- Plastic extrusion equipment
- High speed turbines
- Wind turbine gearboxes
- Rubber kneading equipment
- Bucket excavators

The lubrication mechanism of the smooth surfaces of rolling element bearings is normally of the elastohydrodynamic variety. However, the lubrication of gear teeth differs in that the surface roughness is large compared with the thickness of the lubricant film. Localised breakdown of the fluid film occurs, resulting in the load being shared between boundary conditions and by the lubricant present in the valleys between the asperities. The very high pressures on the lubricant changes its micro-behaviour, the performance of which can only be predicted by suitable mathematical models. The combination of conditions of localised lubricant starvation and of cavitation, i.e. the formation of tiny vapour bubbles in lubricant subject to compression followed by decompression, is now considered to lead to the onset of micropitting and of other forms of surface distress.

Factors influencing the development of micropitting are numerous, and include :-

- Methods of component manufacture
- Gear design
- Surface finish
- Grinding quality
- Surface treatments (hardening)
- Method and type of heat treatment
- Residual stresses in gear components
- Alignment
- Operating conditions (temperature, load, speed, etc.)
- Lubricant type and additive package

Factors influencing the performance of the lubricant are governed by :-

- Lubricant base fluid type (mineral oil or synthetic)
- Lubricant viscosity
- Additive type and quantity
- Inter-additive compatibility

CONTROLLED WEAR

Controlled wear describes situations where wear rates are deliberately increased in order to improve the subsequent performance of items of equipment. Rough surfaces can be smoothed by using appropriate running-in oils, which can contain polar sulphur or phosphorus-containing additives which act to remove the load-bearing fraction of the sliding surfaces.

FACTORS AFFECTING WEAR

The degree of wear that occurs is the result of the inter-play of a number of factors that apply in a given situation. The correlation between these factors has been the subject of much research with results that are not always applicable to all material combinations, particularly the relationship of the wear rate and the load, the speed, the coefficients of friction and of adhesion, hardness and tensile and yield strength. An approximate indication of how load (W) and hardness (H) affect the wear rate (Q) is given by the following formula by Archard in which K is a "wear coefficient" of the system and is dependent on many of the factors described below:

$Q = KW/H$

OPERATING CONDITIONS

Loading

Loading may be anything from low to high, depending on the application. It may be unidirectional or reversing, continuous or intermittent. It governs the friction and adhesion resistance and consequently the rate of wear of the oxide film. It has therefore a paramount influence on wear. The resistance of metal to severe wear under high load conditions does not always correlate with their wear resistance under less severe conditions. In a sliding wear situation, wear rate increases with load and sliding distance although not necessarily linearly. This indicates that there can be more than one wear mechanism operative.

Velocity

Velocity, like loading, can be anything from low to high, unidirectional or reversing, continuous or intermittent. It is one of the factors that affect the erosion of the oxide film although, in some cases, speed has little effect on wear. In other cases it increases the rate of wear and in yet other cases it reduces it. This is because the effect of speed is related to other factors such as lubrication and the temperature it generates by friction (see "inter-face temperature" below). In the case of fluid erosion (propellers, pumps etc) there is a velocity above which the shear stresses it induces in the metal surface, begins to strip off the oxide film. For nickel-aluminium bronze, this velocity is 22.9m/sec and for aluminium bronze 15.2m/sec.

Fatigue

Reversing or intermittent loading result in repeated stressing and un-stressing which gives rise to fatigue. It is particularly prevalent in rolling contact as in ball bearings and gears and may also be caused by the hammering action of cavitation. Fatigue may in time lead to the formation of cracks at or below the surface and hence ultimately to spalling and delamination wear. Aluminium bronze is reputed for its excellent fatigue resistant properties. Fatigue is greatly affected by surface conditions such as hardness and finish, by the structure of the alloy, by residual stresses and by freedom from internal defects. Generous fillets and fine finish reduce the high notch or stress-concentration factors that can lead to accelerated fatigue failure.

Lubrication

The object of lubrication is to reduce friction and the tendency to adhesion and to mitigate their effects. As has been described in a previous article in this series, there are several different types of lubrication mechanism:

- hydrodynamic lubrication in which the mating surfaces are separated by a fluid film resulting from the movement of one surface relative to the other; adhesion is prevented and little surface distortion occurs;
- hydrostatic lubrication in which the lubricant is supplied under pressure and is able to sustain higher load without contact taking place between the surfaces.
- elasto-hydrodynamic lubrication in which the pressure between the surfaces are so high and the lubricant film so thin that elastic deformation of the surfaces is likely to occur and is a feature of this kind of lubrication;
- boundary lubrication in which an oil or grease, containing a suitable boundary lubricant, separates the surfaces by what is known as 'adsorbed molecular films'; appreciable contact between asperities and formation of junctions may occur;
- solid lubricants which provide a solid low shear strength film between the surfaces.

It may not always be possible to lubricate in a given wear situation and there are many demanding unlubricated sliding systems in various industries. In other cases, it may be necessary to adapt to a lubricant dictated by circumstances, such as water.

Surface finish

Surface finish affects wear: A well-polished surface finish - say less than about 0.25m m rms (root mean square distance from peak to trough) - provides more intimate contact between the surfaces. This results in more interaction between them and may lead to local weld junctions forming and therefore a greater susceptibility to galling. Lubricants also tend to be swept away between smooth surfaces whereas shot peening a surface helps to retain a lubricant. If, on the other hand, the surfaces are too rough - say 2m m rms - the asperities will tend to interlock resulting in severe tearing and galling. Most machined finish, however, fall within an intermediate range of surface finish. It is advisable to give the harder of the two surfaces a finer finish to eliminate asperities that can plough into the softer material.

Tribological compatibility and adhesion

As has been shown above under adhesive wear, the tendency of materials to adhere to one another is the major cause of ordinary wear. It is thought to be

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usually related to the degree of mutual solubility in the solid state of the mating materials: the more soluble they are in each other the higher their tendency to adhesion and therefore the less tribologically compatible they are. The less tribologically compatible two materials are the higher the strain hardening of the softer material and the less their suitability as a mating pair. A pair of identical metals are completely mutually soluble and have therefore poor compatibility. As has already been seen, the oxide film affects tribological compatibility. According to Reid et al, compatibility also seems to determine whether metal transfer occurs, but is no guide to subsequent surface damage which is more likely to be a function of the mechanical properties of the adhered surfaces. Tribological compatibility is not to be confused with metallurgical compatibility which, being the degree of mutual solubility of two materials, is the opposite of tribological compatibility.

Coefficient of friction

Since friction opposes motion, it determines the efficiency of a machine. A designer will therefore aim to use the lowest friction combination of materials consonant with other design considerations. It is not clear, however, how significant is the part played by friction in the wear mechanism. Yuanyuan Li and Ngai, have demonstrated that, in the case of aluminium bronze, the effect of changes in microstructure on the coefficient of friction follows the same trend as its effect on the rate of wear. The metallurgical structure and tribological compatibility of mating pairs of materials govern the magnitude of the friction between them with the lowest friction being obtained with most tribologically compatible materials .

There is no general correlation between wear rate and the coefficient of friction. Some metals experience high friction and low wear and others are the reverse. This inconsistency between friction and wear of different materials may however be accounted for by the fact that any effects that friction may have on wear rate, would not only be dependant on the magnitude of the load and the friction force, but also on the nature of the materials in contact. As we have seen, however, lubrication has the effect of reducing both friction and wear rate.

Friction can also have an indirect effect on wear by causing inter-face heating (see below).

Tensile properties

As mentioned above, the load and anti-adhesion force together subject the sub-surface of the mating materials to a strain gradient. It is the mechanical properties of the material that resist this strain and governs the amount of deformation that will occur. Yuanyuan Li and Ngai found that, in the case of aluminium bronze, wear rates for different microstructures are inversely proportional to the corresponding yield strength and, less markedly, to tensile strength.

Since machinery that is subject to wear may also be subjected to bending and other loads, as in the case of gear teeth, it is an attractive feature of aluminium bronze that the structure that gives the best wear resistance should also have the best tensile properties.

Elastic property

The elastic properties of the softer of two mating materials ensures that deformation can take place under stress without rupture occurring, resulting in delamination and galling.

Thermal conductivity

The thermal conductivity of at least one of the materials in a mating pair determines the rate at which the heat generated by friction is dissipated and therefore helps to control the inter-face temperature (see below) to an acceptable level.

Hardness

When comparing the wear resistance of different materials, the harder materials are often found to be the most wear resistant. There is considerable service experience to show that an aluminium bronze with a hard surface has excellent galling resistance (see below). It was thought therefore at one time that wear was inversely proportional to the hardness of the surface being worn away. The relationship between wear and hardness is not so clear-cut, however, as more recent researchers have found. Harder materials do not imply lower adhesion and metal transfer nor lower galling resistance.

According to Reid and Schey, there is no correlation either between the coefficient of friction and overall hardness. Yuanyuan Li and Ngai have come to a similar conclusion.

Although hardness is undoubtedly an important factor in wear performance, its role is more complex than was once thought and, as explained above, is closely linked to the structure of the materials involved. It is evident that the combination of one hard and one less-hard material is an important feature of a successful matching pair. The hard surface controls the interaction and the softer surface conforms. The softer material is able to embed hard abrasive particles thereby minimising damage to the surfaces. Its lower shear strength means that, should contact occur in a lubricated bearing, seizure is less likely to happen. The softer material, being the one that experiences most wear, can be designed to be the cheaper and more easily replaced component.

It has been found, in the case of aluminium bronze, that the presence of hard intermetallic particles in a soft constituent of the microstructure is an advantageous feature in resisting wear .

Metal defects

Gas porosity, inclusions or shrinkage defects are all liable to have a very detrimental effect on wear resistance.

REDUCING WEAR BY SURFACE MODIFICATION

Surfaces of sliding surfaces may be modified by a number of techniques, both chemical and physical, to reduce wear rates. The anodising of aluminium surfaces by oxidation, for example, is one of the more familiar forms of surface modification.

One of the commonest and most effective techniques is that of thermal spray-coating. Such coatings have and are used in a very broad range of wear resisting surfaces and for the repair of wear resisting surfaces. The main advantage being that thermal spray coating can provide the surface properties and the component substrate material can be chosen from the bulk requirements be it strength, weight or cost without the need to consider it's inherent wear resistance or other surface properties.

Selection of the best coating for an application is not often straight forward. Selection based on hardness or from standard wear testing would indicate coatings like HVOF tungsten carbide/cobalt, plasma sprayed chromium oxide ceramic or fused coatings as giving the ultimate performance. Indeed, these coatings do provide the best solution to many applications, but they are certainly not universally suited to all applications. Other factors must be considered:

- Cost
- Corrosion
- Effect of process on substrate material
- Surface finish or profile
- Lubrication
- Loads and speeds
- Ability to work harden
- Coefficient of friction
- Life expectancy
- Counter surface
- Temperature
- Abrasives
- Impact, shock or fatigue
- Severity and angle of attack
- Porosity

Other specific coating properties may be required

- Thermal barrier or conductor
- Non-magnetic
- Electrical insulator or conductor
- Special surface profiles
- Abradable (requiring erosion resistance, but sacrificial to counter surface)
- Abrasive (required to abrade or grip counter surface)
- Very low coefficient of friction or non-stick properties

A later development is the use of carbon coating of components, which was previously only achievable under high temperatures. However, new technologies involving the use of laser-created arcs operating in a vacuum have enabled to carbon coating process to operate at such low temperatures that even plastic and glass surfaces can be coated. The resultant coating is claimed to have the same outstanding lubricating qualities as graphite coupled with the hardness of diamond, and the application of this technology could well revolutionise the manufacture and longevity of components used in automotive applications.

This is the final article in the 'tribology' series.

David Margaroni