

ENGINEERING TRIBOLOGY

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To the most important persons in our lives

Grazyna Stachowiak

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and

Valli M. Batchelor

Vicky & Diana Batchelor

15

FRETTING AND MINOR WEAR MECHANISMS

15.1 INTRODUCTION

Fretting occurs wherever short amplitude reciprocating sliding between contacting surfaces is sustained for a large number of cycles. It results in two forms of damage: surface wear and deterioration of fatigue life. The extent of wear and surface damage is much greater than suggested by the magnitude of sliding distance. Reciprocating movements as short as $0.1\text{ }\mu\text{m}$ in amplitude can cause failure of the component when the sliding is maintained for one million cycles or more.

Contacts which seem to be devoid of relative movement such as interference fits do in fact allow sliding on the scale of $1\text{ }\mu\text{m}$ when alternating and oscillating loads are carried. It is very difficult to eliminate such movements and the resultant fretting. Fretting wear and fretting fatigue are present in almost all machinery and are the cause of total failure of some otherwise robust components.

Surveys reveal that, unlike other forms of wear, the incidence of fretting problems in machinery has not declined over the past decades [1]. Fretting fatigue remains an important but largely unknown factor in the fracture of load-bearing components at very low levels of stress. A knowledge of fretting is therefore essential for any engineer or technologist concerned with the reliability of mechanical equipment which almost always contains a large number of small amplitude sliding contacts.

The most common wear mechanisms which can be classified as minor wear mechanisms are: melting wear, wear due to electric discharges, diffusive wear and impact wear. In present day technology, these mechanisms occur rather rarely or in a few limited instances so that not much is known about them. But with changes in technology, these wear mechanisms may assume greater importance. For example, melting wear is a direct result of frictional temperature rises and careful investigations reveal that it is much more common than widely believed. This is surprisingly not a particularly destructive form of wear and is associated with low to moderate friction coefficients. Wear due to electric discharges occurs in all electric motors and pantograph-cable contacts. It is a specialized but important form of wear. Diffusive wear occurs when two dissimilar materials are in high temperature frictional contact and material diffuses from one body to the other. A classic example of this type of wear occurs in cutting tools where there is a high enough temperature to facilitate diffusion. Impact wear is found when one component impacts or hammers against another, in rotary

percussive drills which cut rock by high frequency hammering, or even in electrical contacts such as relays where impact between components occurs.

The questions of practical importance to engineers are: how can fretting be detected and recognized? Which interfaces are likely to suffer fretting? How does fretting combine with fatigue? Can lubrication prevent or suppress fretting? What influence does temperature have on fretting? What is melting wear and when is it likely to occur? What are the characteristics of diffusive wear and wear due to electrical discharges? In what way does impact wear differ from erosive wear? This chapter addresses these questions and others.

15.2 FRETTING WEAR

The fundamental characteristic of fretting is the very small amplitude of sliding which dictates the unique features of this wear mechanism. Under certain conditions of normal and tangential load applied to the contact a microscopic movement within the contact takes place even without gross sliding. The centre of the contact may remain stationary while the edges reciprocate with an amplitude of the order of 1 [μm] to cause fretting damage. Therefore from a practical stand-point, there is no lower limit to the tangential force required for fretting damage and this fact must be allowed for in the design of mechanical components. One of the characteristic features of fretting is that the wear debris produced are often retained within the contact due to small amplitude sliding. The accumulating wear debris gradually separates both surfaces and, in some cases, may contribute to the acceleration of the wear process by abrasion. The process of fretting wear can be further accelerated by corrosion, temperature and other effects.

Microscopic Movements Within the Contact Under Applied Loads

When two solids are pressed together and then subjected to a tangential force of increasing magnitude, there is a certain value of tangential force at which macroscopic sliding occurs. Although this is a well known experimental fact, it is less widely realised that at levels of tangential force below this limiting value tangential micromovements also occur in response to the applied force. It has been discovered that these micromovements are a fundamental feature of any Hertzian contact subjected to a tangential force [2,3]. There are two models which describe the behaviour of such contacts; an earlier 'elastic' model and a recently developed 'elasto-plastic' model.

Elastic Model for Fretting Contacts

Normal stress ' p ' in a stationary Hertzian contact rises smoothly from zero at the edge of the contact to its maximum value at the centre of the contact as shown in Figure 15.1a. Assuming that the coefficient of static friction ' μ ' across the contact is constant, the frictional stress ' μp ', resulting from the normal stress ' p ', also rises smoothly from zero at the edge of the contact to a maximum value at the centre as shown in Figure 15.1b. If an external tangential force $Q < \mu W$ is subsequently applied to the contact and no slip occurs, then the resulting tangential stress ' q ' rises from some finite value at the middle of the contact to an infinite value at the edges as shown in Figure 15.1b. The distribution of tangential stress ' q ' across, e.g. a circular contact, can be described by the following expression [4]:

$$q_x = \frac{Q}{2\pi a(a^2 - x^2)^{0.5}} \quad (15.1)$$

where:

q_x is the calculated tangential stress along the ' x ' axis [Pa];

a is the radius of the contact area [m];

Q is the superimposed tangential force [N].

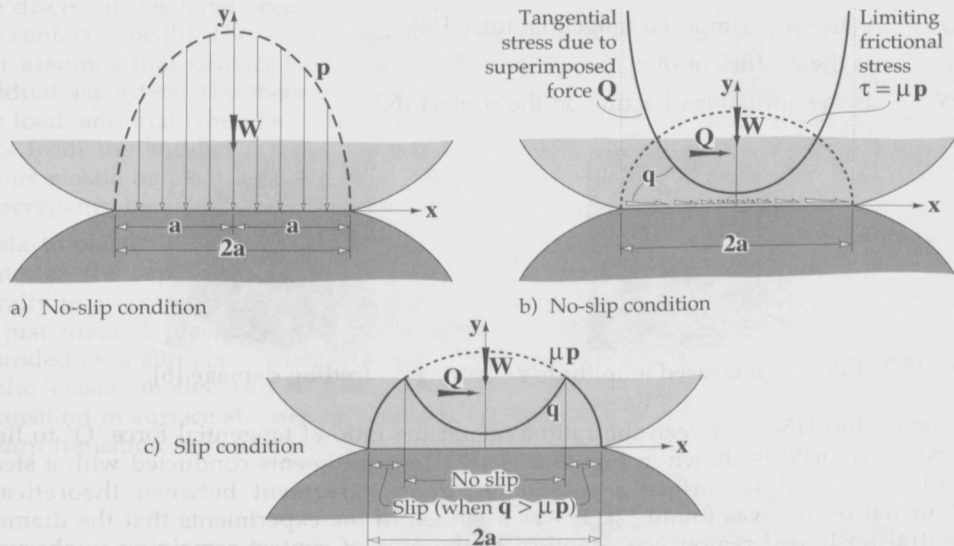


FIGURE 15.1 Normal and tangential stress fields for Hertzian contact with and without slip (adapted from [5]).

Cattaneo [2] and independently Mindlin [3] realized that the no-slip model could not correspond to real contacts and proposed that slip would occur wherever the calculated tangential stress ' q_x ' exceeded the product of normal stress and the coefficient of friction ' μp ' as shown in Figure 15.1c. In the region of slip, the real value of tangential stress was reasoned to be no greater than the product of local contact stress and the coefficient of friction. Therefore assuming, for example, that the normal load ' W ' is constant and the tangential load ' Q ' increases gradually from zero then micro-slip occurs immediately at the edges of the contact area and spreads inwards until ' Q ' approaches ' μW ' and the 'stick' region reduces to a line for the line contacts, a point for the point contacts, etc. If ' Q ' is increased further and exceeds ' μW ', the contact starts to slide.

The contact is characterized by a central no slip region surrounded by an annular slip region. Slip, which reciprocates along with the tangential force, is the source of fretting damage and the edges of the contact are most vulnerable. The existence of a slip and a no-slip region in Hertzian contacts subjected to a tangential load has been confirmed experimentally [6,7]. In one of these studies a steel ball 5 [mm] in diameter was pressed against a glass plate under a load of 9.8 [N] and subjected to reciprocating sliding of varying amplitude [7]. At 1.25 [μm] amplitude, a thin ring of damaged glass surface on the edges of the Hertzian contact was evident. At 2.5 [μm] amplitude, the annular damage zone was much larger leaving only a small circular unslipped region. A further increase in amplitude, above 3 [μm], resulted in gross sliding with no central unslipped zone. An example of the effect of increased amplitude of fretting between a hard steel ball and steel surface is shown in Figure 15.2 [6].

According to the model proposed by Mindlin, the ratio of the radius of the central unslipped region to the radius of the contact area is given by [3]:

$$a'/a = (1 - Q/\mu W)^{1/3} \quad (15.2)$$

where:

- a' is the radius of the central unslipped region [m];
- a is the contact radius [m];
- Q is the superimposed tangential force [N];
- μ is the coefficient of static friction;
- W is the normal load acting on the contact [N].

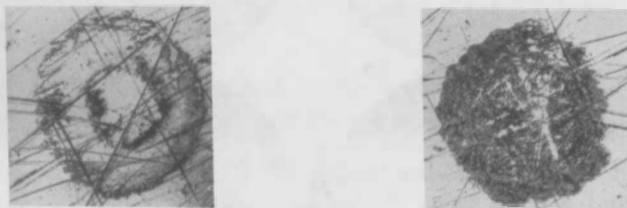


FIGURE 15.2 Effect of increased amplitude of fretting on fretting damage [6].

The relationship (15.2) between the ratio a'/a and the ratio of tangential force ' Q ' to limiting frictional force ' μW ' is shown in Figure 15.3a [7]. In experiments conducted with a steel ball oscillating on a glass surface a reasonably good agreement between theoretical and experimental results was found [7]. It was assumed in the experiments that the diameter of the central unslipped region was identical to the area of contact remaining unobscured by wear debris. Typical fretting map showing all three regions of stick, partial slip and gross sliding as a function of contact load and slip amplitude is shown in Figure 15.3b [50,79]. Critical loads and amplitudes at the boundaries of the three major regions as well as boundary slopes depend on material properties, contact geometry and number of cycles.

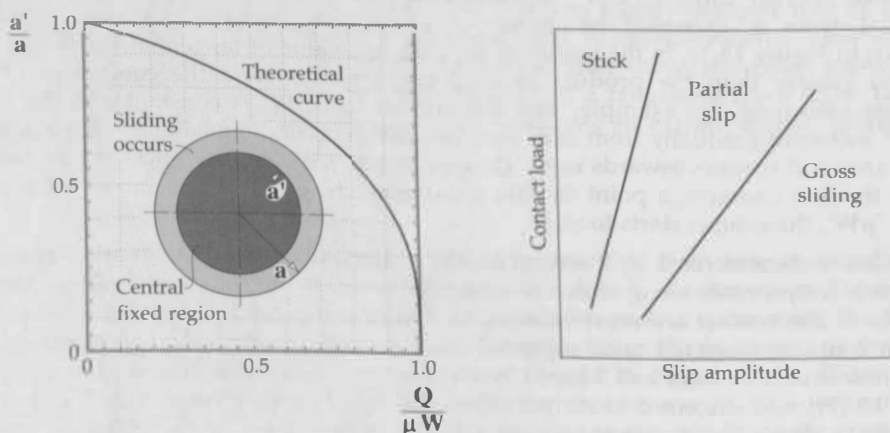


FIGURE 15.3 Relationship between the radius of central stationary zone and oscillating tangential load [7] and schematic fretting wear map.

Elasto-Plastic Model for Fretting Contacts

In the 'elastic' model of fretting it is assumed that relative displacement is accommodated by microslip between the surfaces in contact and elastic deformation of the contacting solids. However, it has been found from fretting experiments conducted on metals of varying

hardness and under sufficiently high load to cause plastic yield, that the maximum displacement amplitude which could be sustained without incipient gross slip was higher than predicted by elastic theory [8].

These discrepancies have been explained in terms of elasto-plastic behaviour of the material in the contact zone [9]. The 'elastic' model of fretting is based on the classical theory of friction which assumes that contact between the solids is achieved through contacts between the individual asperities. The theory assumes that the junctions between the asperities are rigid under load, and that when the surface shear stress exceeds a critical value slip will occur. Slip results from the sudden fracture of the asperity junction which takes place without any previous elastic or plastic deformation. This simplified assumption might be the reason for the discrepancy between the 'elastic' model and the experimental results [6].

The 'elasto-plastic' model of fretting contact has therefore been suggested [9]. According to this model, the asperities under the influence of a superimposed tangential force deform elastically in a central stick zone. This zone is surrounded by a zone in which the asperities have just yielded plastically but not fractured. The plastic deformation zone is in turn surrounded by a slip zone, where the asperities are subjected to fracture in a similar manner as in the 'elastic' model. This is illustrated in Figure 15.4. It can be seen from Figure 15.4 that the transition in surface stresses between the stick and slip regions is rounded as opposed to the sharp transition in Figure 15.1c.

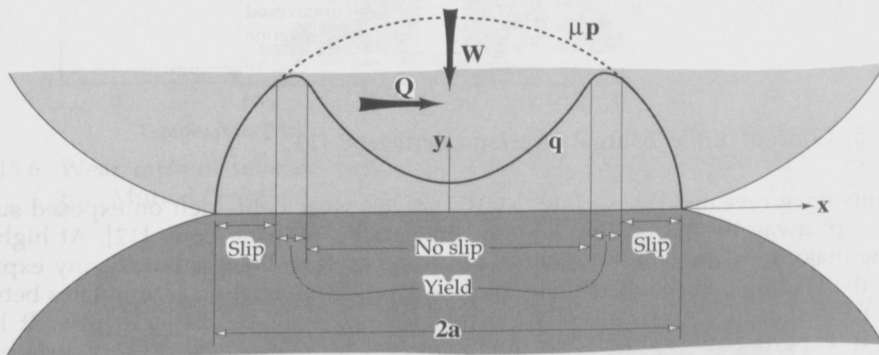


FIGURE 15.4 Surface stress distribution in an elasto-plastic fretting contact [9].

An analysis of a stress field during fretting revealed that plastic deformation occurs even for modest normal loads in most metals [10].

Effect of Amplitude and Debris Retention on Fretting Wear

Although it has been known for a considerable period of time that micromovements within the contact are the inevitable consequence of tangentially applied force and that this is the cause of fretting, a mechanistic definition of this wear process is still lacking. However, it is generally accepted that fretting wear increases with increasing amplitude of slip [11]. Plots for specific wear rates versus slip amplitude are often sigmoidal (resembling an elongated 'S') in shape [80]. The wear rates are low and often constant at low amplitudes (below $10\text{--}25\mu\text{m}$), increase linearly at moderate amplitudes ($20\text{--}100\mu\text{m}$) and again tend to become constant at amplitudes above $100\mu\text{m}$.

One of the special characteristics of fretting is a result of the prolonged retention of wear debris between the sliding surfaces when amplitude of sliding is minute. Debris retention can be explained in terms of the concept of the '**Mutual Overlap Coefficient**' ('MOC') defined as the ratio of the contact area of the smaller of the sliding members to the wear track area [12].

In true sliding wear, the value of 'MOC' is very small, less than 0.1 as, for example, in the case of a piston ring sliding against a cylinder. On the other hand, in fretting wear the 'MOC' value approaches 1. The concept of 'MOC' is illustrated schematically in Figure 15.5 [13].

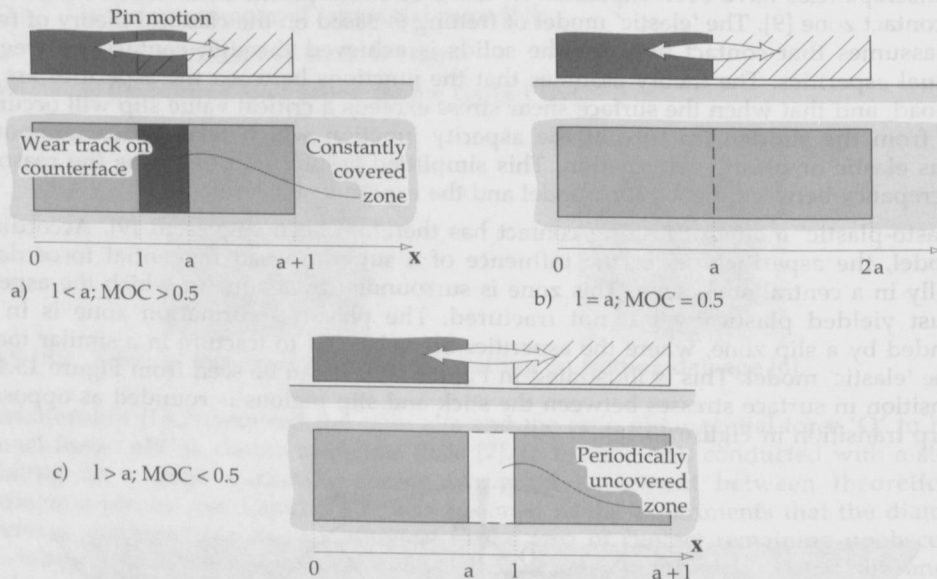


FIGURE 15.5 Concept of the 'Mutual Overlap Coefficient' [13].

Experiments have revealed that at low 'MOC' values, wear debris left on exposed surfaces is quickly swept away by the leading edge of the smaller wearing body [12]. At high 'MOC' values, the majority of the worn surface is never exposed so there is hardly any expulsion of debris by the leading edge of the smaller wearing body. Wear debris accumulates between the sliding surfaces until it is eventually forced out by newly produced debris. It has been observed in experiments conducted with a chalk pin sliding against a glass surface that the wear debris produced could effectively support the load and separate the two surfaces in contact [12]. It has also been found in wear studies conducted with polymer pins sliding against steel surfaces that the 'MOC' can influence the fundamental characteristics of wear. For example, the effect of the 'MOC' on wear/temperature characteristics is illustrated in Figure 15.6 [13].

It can be seen from Figure 15.6 that the wear behaviour of polymers depends on the 'MOC'. The effect of the 'MOC' on wear rates is often radical in scale and the simple principles of practical aspects of wear control such as materials selection differ between ordinary sliding wear and fretting.

A tentative definition of fretting as a wear process which occurs at amplitudes small enough to result in high 'MOC' values with debris entrapment taking place leads to wear characteristics which are completely different from normal sliding wear. It is generally accepted that debris retention is confined to amplitudes below 25 μm for most cases [5]. The process of debris entrapment is illustrated schematically in Figure 15.7.

There appears to be, however, no lower limit to the amplitude of sliding that can cause fretting wear [14]. Accumulation of wear debris at small amplitudes of fretting, e.g. 2.5 μm , may result in apparently negative wear rate readings when wear volume is calculated from the depth of the wear scar [7]. Direct observation of a fretted contact by x-ray microscopy

imaging revealed that debris accumulates in specific locations forming 'island layers' which may separate the fretting surfaces. Debris continues to accumulate in the worn contact until the wear scar becomes saturated with debris, i.e. after at least 10^5 cycles have elapsed. Beyond 10^5 cycles, the fretting surfaces are separated by a layer of debris which is progressively expelled from the wear scar as fretting wear particles [77]. In general, debris entrapment is harmless as long as the sliding surfaces are free to separate. For annular interference fits, however, debris entrapment may result in large increases in contact stresses.

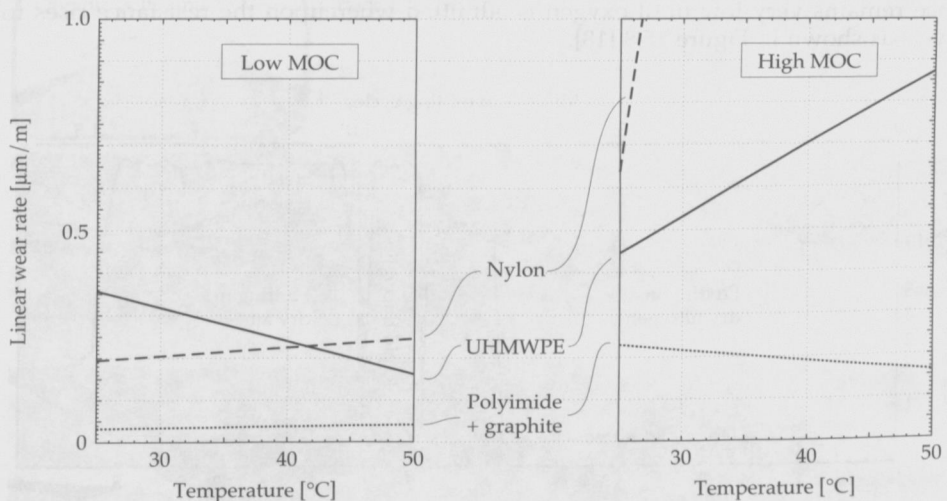


FIGURE 15.6 Wear rates of selected polymers versus temperature at low and high values of the 'Mutual Overlap Coefficient' [13].

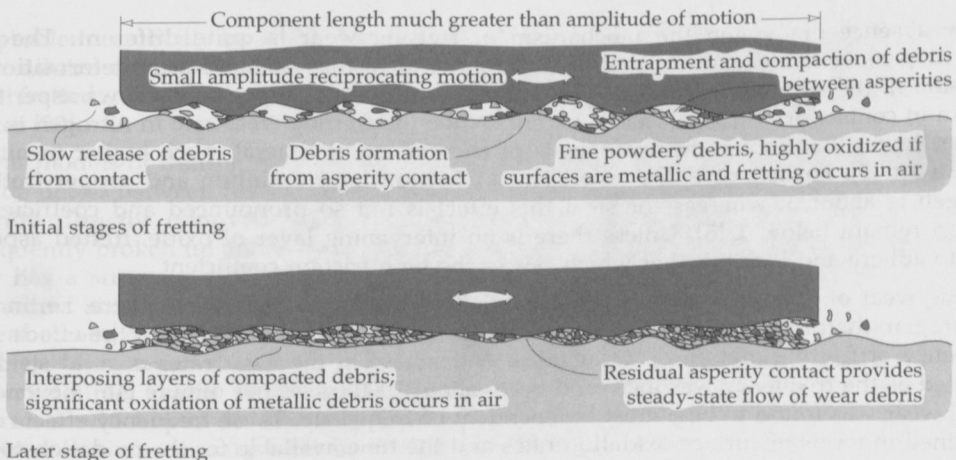


FIGURE 15.7 Mechanism of debris entrapment in a fretting contact.

Environmental Effects on Fretting Wear

Atmospheric oxygen and water have a strong effect on the fretting process, especially in metals [5]. It is generally found that oxygen and water accentuate fretting wear and surface damage [15] and that an inert atmosphere such as argon or nitrogen suppresses fretting of

metals [15,16]. Debris from metallic contacts under fretting is high in oxide content [e.g. 5,17] and consists of a fine powder. When the fretted metal is iron or steel, the debris often shows a reddish-brown colour characteristic of iron oxide, for aluminium the debris is black.

Conductivity tests between metallic surfaces during fretting reveal a rise in electrical resistance consistent with a build up of oxide layer between the two surfaces [5]. It was found that when steel surfaces are fretted together the contact resistance increases from 10 [k Ω] to 1 [M Ω] or more in very dry air [18]. In nitrogen atmosphere, on the other hand, contact resistance remains very low until oxygen is admitted whereupon the resistance rises to very high levels as shown in Figure 15.8 [18].

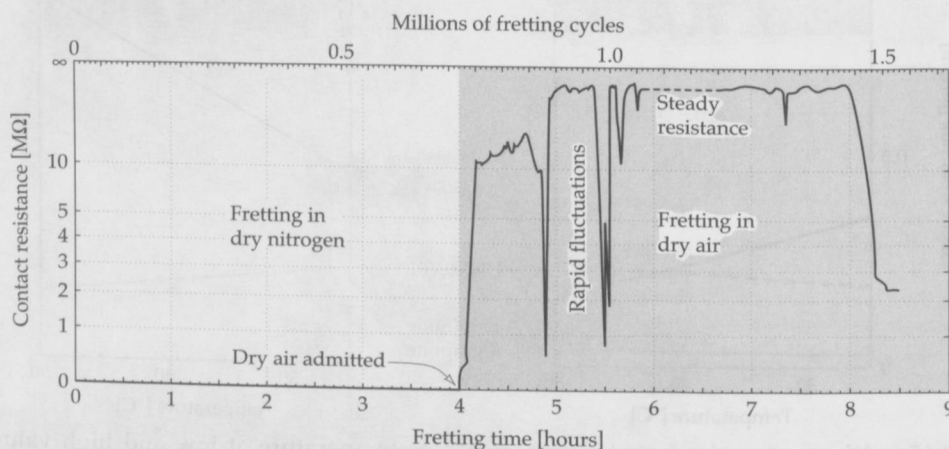


FIGURE 15.8 Variation of contact resistance for steel surfaces fretted first in nitrogen and then in air [18].

In the absence of oxygen the mechanism of fretting wear is quite different. The small oscillating movements characteristic of fretting are ideal for causing plastic deformation and adhesion of the surfaces in contact. The limited amplitude of movement allows asperities to remain in contact or at least closely adjacent. While the fretting wear rate in nitrogen is about 3 times lower than in air, the coefficients of friction are in general much higher in nitrogen than in air [5]. For example, the coefficient of friction for aluminium and copper fretted in nitrogen is about 3, whereas for steel this effect is not so pronounced and coefficients of friction remain below 1 [5]. Unless there is an intervening layer of oxide, fretted asperities tend to adhere and lock together which causes the high friction coefficient.

Fretting wear of non-noble metals is substantially lower in an inert atmosphere, i.e. in argon or nitrogen, than in air [15,16,19]. These findings seem to be consistent with the effects of the frequency of fretting motion on wear rates. A decrease in the wear rates of mild steels was reported as the frequency was increased up to about 1000 cycles per minute [16]. Beyond 1000 [cpm] wear was found to be almost independent of frequency. These frequency effects can be explained in terms of surface oxidation rates and the time available for the oxidation to occur between fretting cycles. With the increased frequency of sliding there is less time for a mechanically weak surface film to form in between asperity contacts, so the wear rate is lower. It is suggested that perhaps corrosion cracking, which seems to be very sensitive to frequency of sliding, contributes to the observed frequency effects in fretting wear [11].

In general in the presence of oxygen the contact resistance between fretting surfaces tends to increase with the number of fretting cycles. This gradual rise in contact resistance which is observed even with noble metals such as gold and platinum can cause many problems with

electrical contacts [20]. It has been found that with noble metals a friction polymer, which accumulates in the fretting contact instead of oxidized debris is responsible for the increase in contact resistance [20]. The friction polymer is derived from organic contaminants in air and its polymerization is facilitated by the catalytic nature of many noble metal surfaces, e.g. platinum [20]. The process of friction polymer formation is illustrated schematically in Figure 15.9.

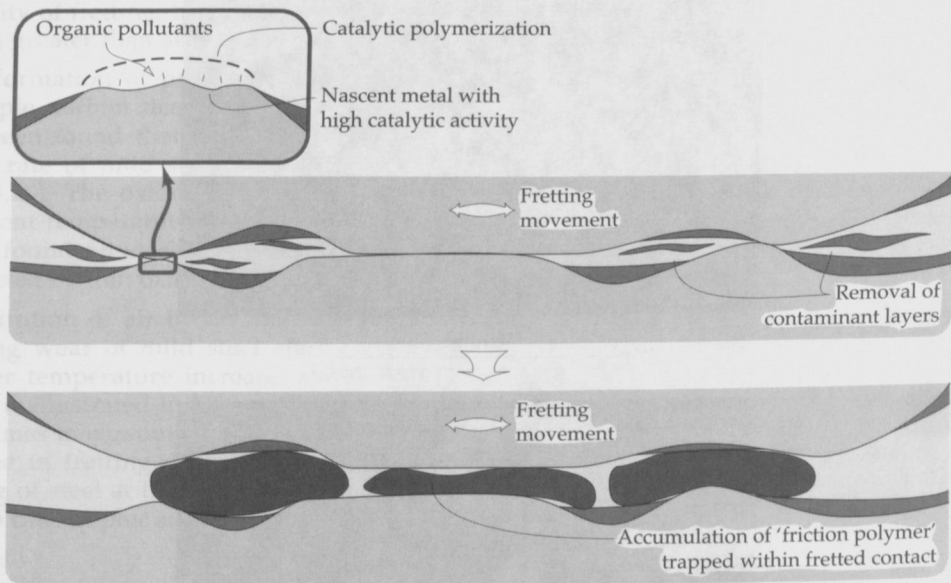


FIGURE 15.9 Mechanism of friction polymer formation in fretting electrical contacts.

This problem can easily be avoided by depositing on the electrical contact a thin film of liquid which dilutes the atmospheric contaminants and prevents adhesion of the friction polymer to the fretted surface. The polymer is then rapidly wiped off by movement of the fretting surfaces [20].

Current models of fretting wear of metals in air are usually based on the formation of a layer of oxide debris between the fretting surfaces. Oxide debris is assumed to originate from layers of oxide directly removed from the surface and from metallic wear debris which is subsequently broken up and re-oxidized many times [17]. Oxide debris formed during fretting in air has a structure that is either amorphous or nano-crystalline (crystals of only a few nanometres size). A mixture of amorphous and nano-crystalline debris can be generated where the composition is controlled by the rate of formation of the various metal oxides. For example, it was found that in the case of tin both SnO and SnO_2 are formed as a mixture of nano-crystalline grains [76]. The formation of oxidized debris proceeds by the same mechanism which was described for slow speed oxidative wear in Chapter 13. It has been suggested that a secondary wear mechanism of fretting is abrasion of the substrate by hard oxidized debris [17].

It has been shown that debris accumulations can deform the wearing substrate to produce depressions in the worn surface [21]. The formation of such pits in the fretted wear scar seems to be due more to the large contact stresses induced by debris entrapment than to true abrasion. An example of a fretted contact on steel is shown in Figure 15.10a. Characteristic features such as grooving by direct contact between asperities, accumulation of debris layers and the formation of depressions in the wear scar are clearly visible. Under similar fretting

conditions ceramics are more resistant to fretting than steels [78]. Polishing, microfracture and tribolayer delamination are the dominating wear modes in ceramic fretting. An example of a fretted contact on ceramic is shown in Figure 15.10b.

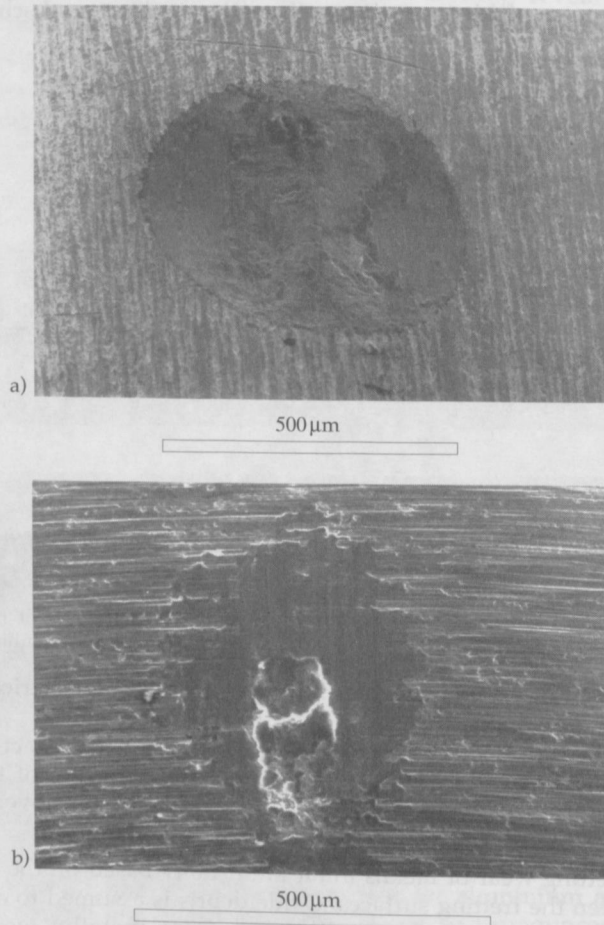


FIGURE 15.10 SEM micrograph of the fretting contacts; a) between two crossed steel wires after 10^6 cycles, 5 [N] load and 25 μm fretting amplitude and b) between two ceramic surfaces after 10^6 cycles, 5 [N] load and 25 μm fretting amplitude.

Polymers, although not prone to oxidative corrosion exhibit fretting behaviour which strongly depends on the presence of water and oxygen [22]. For example, polycarbonate in a fretting contact with a steel ball shows almost no wear in dry argon, nitrogen and oxygen. The wear rate is increased by a factor of 10 when 50% relative humidity air is introduced. Wet (85% relative humidity) nitrogen and oxygen causes a 30 and 50 fold increase in wear rate respectively [22].

Effects of Temperature and Lubricants on Fretting

Temperature may affect the process of fretting in two ways. Firstly, the corrosion and oxidation rates usually increase with temperature, and secondly, the mechanical properties of materials change with temperature. In metals the temperature effects on fretting are best

understood in terms of surface oxidation kinetics. Fretting wear rates usually decrease with increasing temperature if a stable and adherent oxide film is formed on the surface. On first consideration the decrease in fretting with temperature increase may be quite surprising since the oxidation rates of steel increase with temperature. However, thick, stable and mechanically strong oxide films forming on the surface act as a solid lubricant preventing metal-to-metal contact and hence reducing friction and surface damage [11]. The effectiveness of the oxide films formed at high temperatures depends on their mechanical properties and severity of fretting. If damage of these films occurs then fretting wear rates will most likely be much greater than at lower temperature because of the increased oxidation rate [5].

The formation of protective films has been observed in high temperature fretting of, for example, carbon steel [23], stainless steel [24], titanium alloys [25] and nickel alloys [26,27]. It has been found that after the transition temperature of about 200°C is reached the fretting wear rate of mild steel in air falls to a very low value which is maintained up to 500°C [23,28,29]. The oxide films generated vary in thickness and morphology and are formed at different temperature ranges for different materials. The 'glaze' type compacted oxide films were found on steel and nickel alloys [24,26] while titanium alloys were found to be often protected by thin oxide films [25].

Substitution of air by an inert gas such as argon, resulted in a less dramatic reduction in fretting wear of mild steel after a transition temperature of about 200°C was reached. A further temperature increase, above 300°C, caused a sharp increase in fretting wear. This effect is illustrated in Figure 15.11 which shows fretting damage expressed as area of fretting scar times maximum depth of scar versus temperature at two levels of fretting cycles [28]. The decline in fretting damage around 200°C for tests in argon is attributed mainly to strain ageing of steel at this temperature and the rapid increase in fretting wear rate above 300°C is due to catastrophic surface failure by contact fatigue [5].

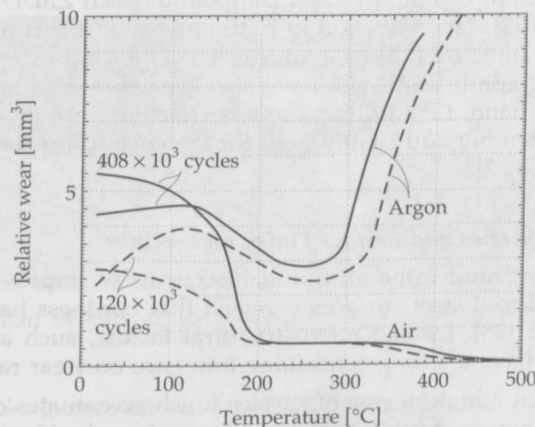


FIGURE 15.11 Effect of temperature and gas environment on fretting wear of mild steel [28].

Low temperatures, on the contrary, cause an increase in fretting damage which generally increases with the number of cycles [16]. An example of this trend is shown in Figure 15.12 [16].

It is generally recognized that because of the very low sliding speeds occurring in fretting, damage cannot be prevented by liquid lubricants [30]. However, they can provide a useful attenuation of fretting. The main purpose of a lubricant is to fill up the contact space and prevent the access of oxygen [5]. Comparative tests of fretting between dry steel surfaces and steel surfaces lubricated by various commercial oils demonstrated large reductions in fretting

wear volume when lubrication was applied [31]. It was found that a simple lubricant such as a base mineral oil is effective in reducing fretting wear and friction [32]. In general, the effect of the lubricant is to suppress adhesive and corrosive wear occurring in the contact and allow wear to proceed by milder fatigue-based delamination wear mechanisms [31,33].

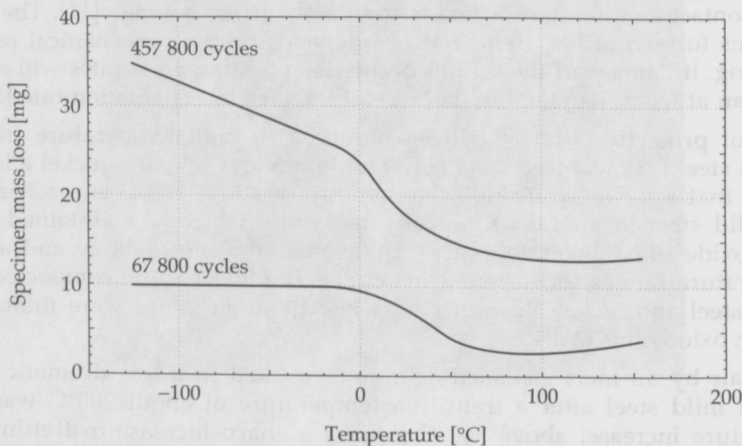


FIGURE 15.12 Effect of low temperatures on fretting wear of mild steel [16].

The literature available on the effects of lubricant additives on fretting is limited. Early work showed that phosphorous compounds, e.g. tricresylphosphate (TCP), diethyl hydrogen phosphite, etc., are effective in reducing fretting damage [34]. More recent studies have confirmed the effectiveness of commonly used compounds such as ZnDDP [31,35] and sulphur based antiwear additives [32]. The reduction in fretting wear and friction is achieved through the formation of reaction films by lubricant additives on the contacting surfaces [e.g. 32,34]. Solid lubricants such as graphite and MoS₂ have also been shown to be effective in reducing fretting [36]. On the other hand, EP additives are less effective since the temperatures attained in fretting contacts are often not sufficiently high for the chemical reactions to take place and protective films to form [33,37].

Effect of Materials Properties and Surface Finish on Fretting

Manipulating hardness is found to be an unreliable means of improving fretting resistance [5]. Fretting studies of alloyed steel surfaces revealed that hardness has no direct relation to the level of fretting wear [38]. Instead microstructural factors, such as whether the steel is martensitic or austenitic, have a strong controlling influence on wear rate [39].

It is commonly known that a high degree of surface finish accentuates damage due to fretting and to minimize the damage rough surfaces are preferred. At elevated temperatures, however, the converse is true, i.e. surfaces with better surface finish suffer less damage than rough surfaces [28].

Fretting Fatigue

Fretting fatigue is a phenomenon where the surface of a component subjected to alternating bulk stresses is also fretted, resulting in a severe reduction in fatigue life. For steels, there is often no endurance limit when fretting is combined with fatigue. A comparison between the number of cycles to fracture for pure fatigue and fretting fatigue for austenitic steel is shown in Figure 15.13 [40].

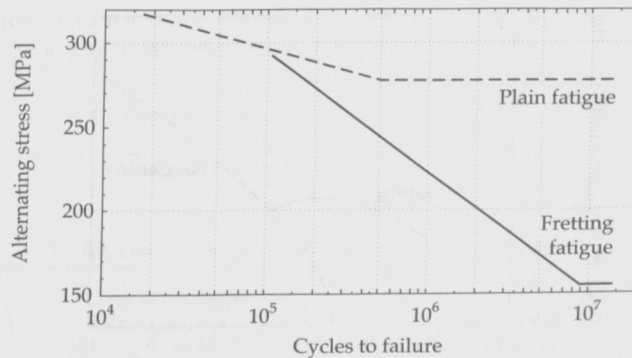


FIGURE 15.13 Example of a reduction in fatigue life due to the combined effect of fatigue and fretting [40].

Although fretting causes an alternating frictional surface stress to be superimposed on the pre-existing bulk cyclic stresses, of much greater importance is the generation of surface microcracks by asperity contact. Surface microcracks can be initiated due to repetitive fretting contacts as shown schematically in Figure 15.14. The number of surface microcracks increase with the increased amplitude. This is because the initiation of the microcrack relaxes the surface tensile stresses adjacent to it and to initiate another crack the contacting asperity must move a distance that is large compared to instantaneous crack length [11]. It has been found that fretting fatigue life rapidly decreases with increasing amplitude up to about 8 μm and after that is relatively insensitive to further increases in amplitude [11,75].

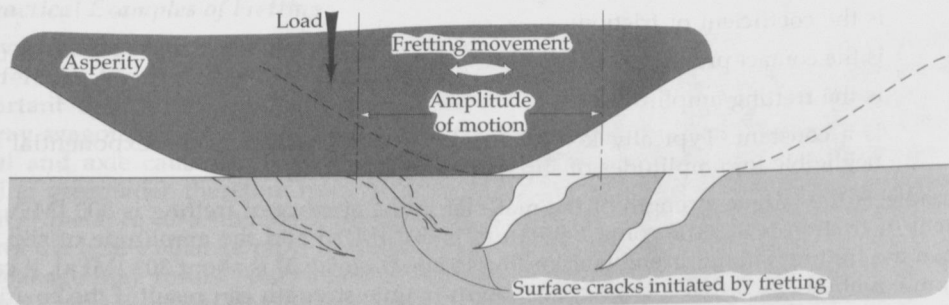


FIGURE 15.14 Mechanism of surface microcrack initiation in fretting contacts (adapted from [11]).

The surface microcracks generated due to fretting accelerate the initial stages of fatigue. An example of this effect is illustrated in Figure 15.15 which shows the relationship between the rate of crack propagation ' da/dN ' and the crack length ' a ' (' N ' is the number of cycles).

Although there are differences in the course of crack propagation depending on the loading conditions, the overall trend of higher initial crack growth rates for fretting fatigue is quite distinct. Adhesion, oscillating movement and tensile loads between fretting asperities are the basic cause of acceleration of early crack growth. A strong adhesive bond can form between a pair of fretted asperities, and instead of producing a wear particle, the bond may result in crack formation since the asperities never move very far from each other [5].

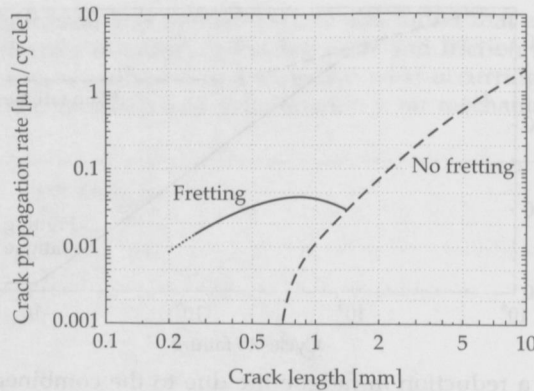


FIGURE 15.15 Crack propagation curves for normal and fretting fatigue (adapted from [41]).

Fretting fatigue cracks tend to occur at the boundary between fretted and non fretted regions where shear stresses are sufficiently high [5]. A reduction in fatigue strength due to fretting can be estimated from the following expression [42]:

$$S_{fr} = S_o - 2\mu p_o [1 - e^{(-l/k)}] \quad (15.3)$$

where:

- S_{fr} is the fretting fatigue strength [MPa];
- S_o is the fatigue strength in the absence of fretting [MPa];
- μ is the coefficient of friction;
- p_o is the contact pressure [MPa];
- l is the fretting amplitude [μm];
- k is a constant. Typically $k = 3.8$ [μm] [19], which renders the exponential term negligible for amplitudes of slip greater than 25 [μm].

For example, if the fatigue strength of the material in the absence of fretting is 800 [MPa], the coefficient of friction is 0.5, the contact pressure is 500 [MPa] and the amplitude of slip is 20 [μm] then the fretting fatigue strength according to equation (15.3) is about 303 [MPa]. It can be seen from equation (15.3) that a large reduction in fatigue strength can result if the coefficient of friction between the fretting surfaces is high.

It has been found that at elevated temperatures, providing that an alloy is able to produce thick surface oxide films which result in reduced adhesion and friction, the fretting fatigue life generally improves [11,43].

The combined action of corrosion and fretting can result in further reductions in the fatigue strength of some materials. For example, the fretting fatigue of steel is intensified in the presence of air compared to argon atmosphere [44,45]. Similar effect was observed when fretting fatigue tests were conducted in sodium chloride (NaCl) solution [46]. Fretting only accelerates corrosion-fatigue when surface oxide films which can effectively prevent corrosion are disrupted. If a protective oxide film is broken, the nascent surface exposed is so reactive that the lack of corrosivity of air compared to salt-water makes little difference. In both cases fretting fatigue in air and fretting fatigue in a corrosive medium, i.e. NaCl or salt-water, are accelerated by intensified localized corrosion at oxide film cracks, producing pits which initiate cracks and promote fatigue. Therefore fretting usually accelerates fatigue in corrosive environments in cases of alloys which depend on protective surface oxide films for

corrosion resistance. The effect of combined corrosion and fretting on the fatigue life of corrodible and corrosion resistant metals is shown in Figure 15.16.

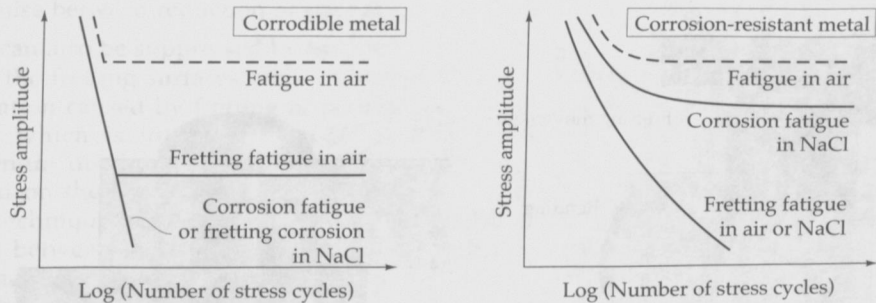


FIGURE 15.16 Effect of combined corrosion and fretting on fatigue life of corrodible and corrosion resistant metals [40].

The corrosive contribution to fretting wear and fretting fatigue is in fact quite large compared to the mechanical contribution alone. For example, it was found that the fretting fatigue of an aluminium alloy in a vacuum is about 10 - 15 times that in air [47]. Viewing fretting as a process dominated by corrosion, it would be expected that the wear rates would decrease with increased frequency of sliding since there is less time for a corrosion film to form. More information of the effect of combined corrosion and fretting on fatigue life can be found in [40].

Practical Examples of Fretting

Many contacts which are nominally fixed in practice suffer fretting. These include most interference fits and devices subjected to vibration. The suppression of vibration is most important in the prevention of fretting wear and fretting fatigue. For example, in most railway wagon designs, steel wheels are press-fitted onto a steel axle. The rotation of the wheel and axle causes fretting and more importantly, fretting fatigue. Interference fits of rotating assemblies therefore need to be carefully designed [5]. Heat exchangers provide a classical instance of a nominally static assembly which in fact suffers wear. Turbulent flow around the heat-exchange pipes causes them to vibrate against the baffle-plates. Fretting wear and leakage may result. Assemblies of plates held together by rivets, i.e. air-frames, are also prone to fretting when vibration occurs. Typical examples of fretting occurring between the bearing outer ring and housing and in a riveted joint are shown in Figure 15.17.

Other common examples of fretting contacts can be found in flexible couplings, rolling bearings used for small oscillatory movements, wire ropes, electrical switch gears, etc. Some types of flexible couplings consist of interlocking gear teeth or a toothed connection. Since the teeth slide relative to each other by a few micrometres in a reciprocating mode during rotation of the coupling, fretting results. The debris from fretting wear can be sufficient to jam and seize the coupling or the teeth can wear out [5]. Rolling bearings are in principle not intended for small oscillatory movements but are often used due to the lack of a suitable alternative. Elastohydrodynamic films are unlikely to form when the rolling speed is extremely low and wear results. A wear scar forms under each roller or ball and this is known as 'false brinelling'. The individual wires of a wire rope must slide between each other for the rope to flex. The contacts between wires are therefore subjected to fretting and fretting fatigue [48,49]. It is extremely difficult to monitor the extent of fretting between wires without dismantling the rope. Fretting proceeds unnoticed until a wear scar has cut through half the thickness of a wire and that wire fractures. The performance of electrical relays,

switches and selectors is extremely sensitive to fretting, since the formation of oxide layers on the contact surfaces creates electrical resistance. More examples of case histories of fretting are described in [5,40].

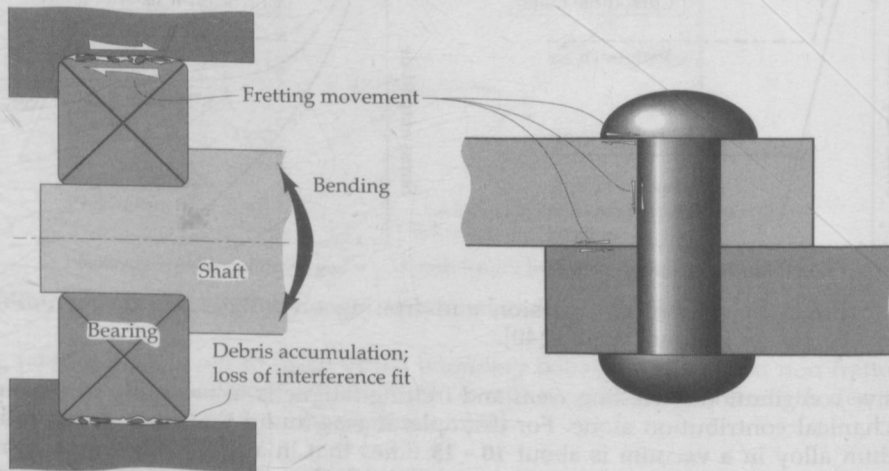


FIGURE 15.17 Examples of fretting occurring between two stationary surfaces due to oscillatory motion in a bearing assembly and in a riveted joint.

Means of Controlling Fretting

Fretting can be effectively controlled through design optimization and through the applications of surface treatments such as coatings and shot peening.

The suppression of fretting by design optimization usually involves geometric modifications of components aimed at eliminating excessive shear stress concentrations at the interface. An example of design optimization to minimize fretting is illustrated in Figure 15.18 where a press-fit shaft assembly is shown.

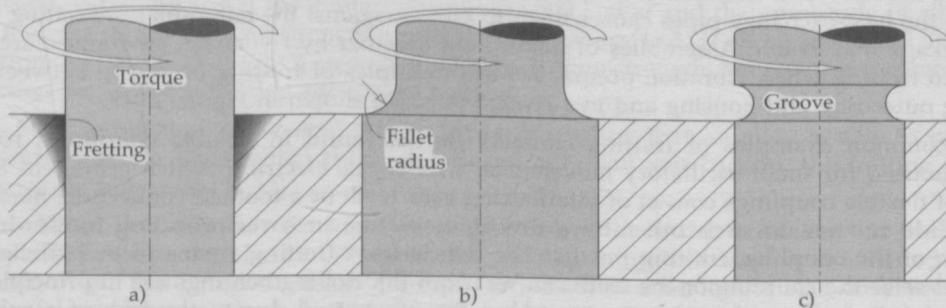


FIGURE 15.18 Suppression of fretting by design optimization in a press-fit shaft assembly (adapted from [5]).

Fretting occurs at the edge of the press-fit where slip is most likely to be present (Figure 15.18a). One of the solutions is to enlarge the press-fit diameter compared to the shaft diameter as shown in Figure 15.18b. Although increased rigidity of the press-fit suppresses slip and the resulting fretting, attention should be paid to the fillet radius on the shoulder

between the two diameters. If it is impossible to allow an increased press-fit diameter then a groove could be machined close to the edge of the press-fit as shown in Figure 15.18c. This will also result in suppressing fretting. However, in this case of design optimization there is a compromise between reduction of strength caused by the groove and relief from fretting [5].

Fretting can also be suppressed by the application of surface coatings [5]. The basic principle is to cover the fretting surfaces with a non-metallic layer which suppresses adhesion and stops the oxidation caused by fretting of plain metal surfaces. The surfaces can be covered with a polymer which is intended to wear sacrificially [11]. An inorganic lubricant such as molybdenum disulphide or an anti-wear compound such as titanium carbide can also be deposited on the surfaces [11,40]. The efficiency of these coatings depends strongly on the coating technique applied as described in Chapter 9. A major problem is to ensure good adhesion between the coating and substrate to prevent spalling of the coating. It has been shown that some coatings can reduce the fretting wear volume by a factor of about 100 or increase the fretting fatigue life by a factor of about 10 or more [11]. However, due to the great variability in the performance of coatings, care should be exercised in coating selection for a specific application.

One way of controlling fretting fatigue is perhaps best illustrated by equation (15.3) which shows the beneficial effect of reducing the coefficient of friction between the fretted surfaces. This can be achieved, for example, by introducing low friction coatings. Fretting fatigue can also be reduced by the introduction of compressive stresses in the surface layers of the fretted metal which suppress the growth of cracks quite effectively [40]. The compressive stresses can be introduced by the process of shot peening. It has been found, for example, that in rotating bending tests on an austenitic stainless steel shot peening almost cancels out the loss in fatigue strength due to fretting [40]. Tests with other metals and alloys showed a similar beneficial effect obtained from shot peening [40].

15.3 MELTING WEAR

This is a universal form of wear since any material which melts without decomposing will show melting wear under appropriate conditions. The present concept of melting wear is based on the phenomenon that when sliding speed and load is increased, the frictional surface temperature also rises until the melting temperature is reached and layers of molten surface material begin to influence friction and wear [51]. This mechanism is illustrated schematically in Figure 15.19.

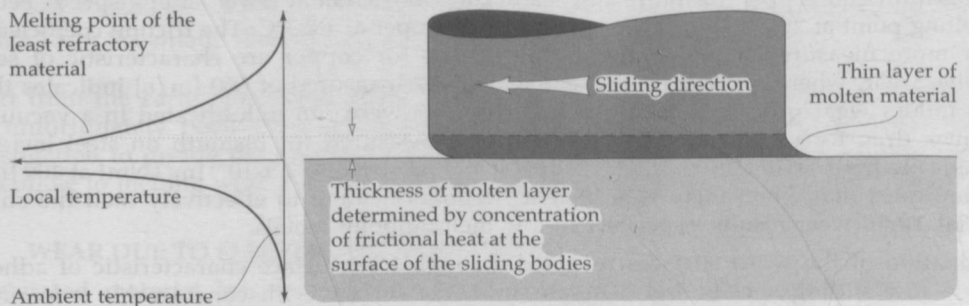


FIGURE 15.19 Schematic illustration of the formation of molten layer.

The generation of the layer of molten material usually dramatically reduces friction and this is the reason why snow-skis and skates slide easily and why friction is reduced to dangerously low levels during the skidding of tyres at high speeds. For example, during skiing there is

sufficient frictional heat to melt a layer of ice producing a film of water at the points where the asperities touch the ski. The skier simply hydroplanes on the layer of water generated by the friction. When the temperature drops below a critical level, about -10°C , the heat is conducted away too quickly to allow for this melting to occur and ice asperities adhere to the ski and are sheared during the sliding. At these conditions the coefficient of friction rises dramatically from about 0.02 to 0.4. The increase in coefficient of friction with progressive decrease in temperature caused considerable hardship to early polar explorers, since with the temperature drop pulling the sleds was increasingly harder.

One important practical use of the melting wear phenomenon is found in guns, at the interface between the gun-barrel and the shell. Close contact between the shell and barrel is needed for accurate shooting while a low friction and wear coefficient is desirable to provide a long life for the barrel. The sealing rings on each shell are coated with a low-melting point metal alloy to facilitate melting wear. It has been calculated that when gilding metal (90% Cu and 10% Zn) is used in shell sealing rings, the friction coefficient rapidly falls to about 0.02 [52]. An example of the reduction in coefficient of friction with increased sliding speed is shown in Figure 15.20 [51].

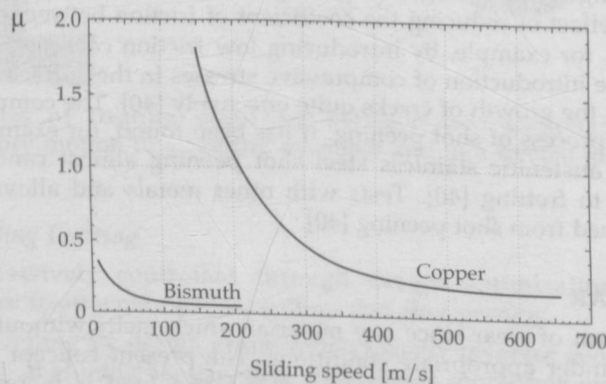


FIGURE 15.20 Effect of sliding speed on the coefficient of friction measured between bismuth on steel and copper on steel combinations [51].

It can be seen from Figure 15.20 that a continuous decline in the friction coefficient occurs for both bismuth and copper. Bismuth shows a decline in friction at lower sliding speeds because its melting point at 271°C is far lower than that of copper at 1083°C . The friction coefficients of 1.5 or more measured at moderate sliding speeds for copper are characteristic of severe adhesive wear, whereas the friction coefficient of 0.2 measured at 600 [m/s] indicates that a much milder wear process is taking place. The tests were run unlubricated in a vacuum to minimize drag forces on the ball. The wear rate measured for bismuth on steel increased dramatically from $5 \times 10^{-13} \text{ [m}^3/\text{Nm]}$ at 100 [m/s] sliding speed to $2.5 \times 10^{-11} \text{ [m}^3/\text{Nm]}$ at 400 [m/s]. This indicates that when there is sufficient frictional heating to effectively melt the surface material, rapid wear results, especially in low melting point metals.

Examination of the worn surfaces revealed a rough torn surface characteristic of adhesive wear at low sliding speeds and a much smoother surface with considerable smearing of surface material at high sliding speeds. With a low melting point metal such as bismuth, droplets of metal were also found to adhere to the surface just outside the contact. It has been speculated that films of molten material can even effectively separate two sliding surfaces, and hydrodynamic lubrication models have been developed to support the hypothesis that there is sufficient frictional heat to form the lubricating films of molten material [53,54].

A similar decline in friction was found for high melting point metals such as tungsten (melting point 3410°C). A coefficient of friction of 0.3 was measured at 200 [m/s] sliding speed, and a coefficient of friction of 0.1 at 700 [m/s], but clear signs of surface melting were not found. Instead, mutual diffusion of 'W' and 'Fe', and steel film transfer were observed [51]. The non-metals, glass, rubber, PTFE and nylon also showed a decline in coefficient of friction with rising sliding speed and surface melting at high sliding speeds [51,55]. The mechanism of melting wear is illustrated schematically in Figure 15.21.

Although it is usually implied that extremely high sliding speeds are a prerequisite for melting wear of metals [e.g. 55-57], it has been found that melting wear can occur also at moderate sliding speeds [58]. Therefore this form of wear could be of much greater practical significance than is generally supposed. Tests with cast iron sliding on cast iron in a vacuum at speeds of 5 [m/s] revealed the presence of ledeburite which is a form of re-solidified cast iron on the worn surface [58].

Severe sliding conditions often result in the formation of hard white layers on the worn surface. These layers do not etch to reveal a microstructure and simply appear as white areas under the metallurgical microscope, hence the name. In some cases these layers form after rapid solidification of the molten top surface [e.g. 58-60]. For example, in gun barrels, where there is a combination of high stress, high temperature and a hostile environment, the white layers are formed by rapid solidification of molten material [60]. Investigation of the nature and formation of white layers on steels revealed that they consist of re-solidified metal with large amounts of iron carbides and oxides mixed in [59]. Wear particles were formed not by the escape of molten metal but by the fracture of the re-solidified layer and detachment from the surface. The grain structure of the white layers was found to be extremely fine because of the very rapid cooling associated with transient frictional temperatures.

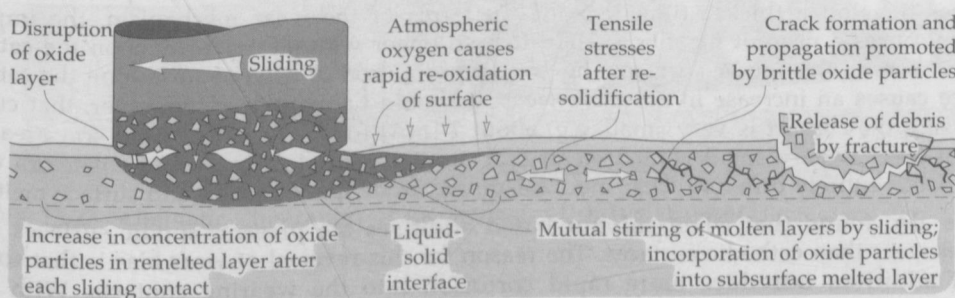


FIGURE 15.21 Schematic illustration of the mechanism of melting wear.

Apart from the early pioneering work of Bowden and Tabor [51] research on melting wear has unfortunately been very limited and it is still a matter for thorough experimental investigation to decide the conditions under which melting wear occurs. Polymers are quite susceptible to melting wear and more information of this topic can be found in Chapter 16.

15.4 WEAR DUE TO ELECTRICAL DISCHARGES

Accelerated material loss caused by electric arcing between sliding surfaces occurs, for example, in pantograph-cable systems and between the slip-ring and commutators of an electric motor. It is believed that arcing between the two surfaces when they are momentarily separated is the cause of accelerated wear. The average duration of such an arc is a few milliseconds and a close correlation has been found between the duration of arcing periods and the periods of separation between sliding surfaces [61]. Material from the contacting surface which is usually metal is thought to be vaporized or oxidized by the electrical energy

discharge to leave a small pit. The mechanism of wear due to electrical discharge is illustrated schematically in Figure 15.22.

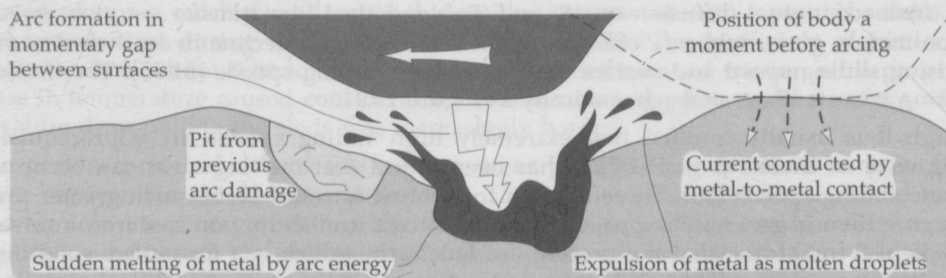


FIGURE 15.22 Schematic illustration of the wear mechanism due to electrical arcing between sliding surfaces.

Wear rate due to electrical discharge has been found to be proportional to the amount of arcing, with almost no wear occurring in the absence of arcing [62]. Wear rate tends also to increase with speed decrease, e.g. the wires of a pantograph-cable system suffer very rapid wear below 14 [m/s] (about 50 [km/h]) [63].

The electric current can also significantly affect wear and friction of steels under lubricated conditions [64]. It seems that the current direction is more important than the current intensity, e.g. cathodic surfaces were found to wear more than anodic surfaces. Cathodic surfaces suffer more wear because the development of protective films is suppressed by the imposed voltage. On the other hand, because of the favourable corrosion potential, anodic surfaces develop a thicker film of oxide. In terms of the wear mechanism, the imposed voltage causes a nascent metallic surface to last longer without oxide films on the cathodic surface than on the anodic surface. The greater proportion of nascent surface on the cathodic surface causes an increase in adhesive wear. It should be mentioned, however, that current traversing the contact is very small, e.g. about 1 [mA] for 0.2 [mm²] of wear scar area. This current level is very small compared to that occurring in electric current collectors which suffer from entirely different wear mechanism, e.g. from spark erosion and surface melting.

It was also found that when sulphur based additives are present, anodic surfaces suffer greater wear than cathodic surfaces. The reason for this reversal of wear bias is that sulphur based additives introduce more rapid corrosion into the wearing contacts. With rapid corrosion taking place, the anodic surface suffers corrosive wear while on the cathodic surface corrosion is suppressed to a level closer to the optimum balance between corrosive and adhesive wear [65]. In contrast, phosphorus based additives which appear to function by decomposition on the worn surface as opposed to corrosion, suppress the wear on both cathodic and anodic surfaces [65]. A study of the wear between two bodies of dissimilar size under boundary lubricated conditions also revealed that self-generated voltages induced by wear cause the smaller of two sliding bodies to gain a positive charge (become anodic) and suffer accelerated wear [66].

15.5 · DIFFUSIVE WEAR

When there is true contact between the atoms of opposing surfaces and a high interface temperature, significant diffusion of chemical elements from one body to another can occur. The most widespread example of such a contact is the rake face of a cutting tool close to the cutting edge in high speed machining. In this situation, there is almost the perfect contact between the tool and the metal chip due to the extreme contact stresses and very high temperatures, reaching 700°C or more [67]. The metal chip represents a continually refreshed

supply of relatively pure metal whilst the tool is a high concentration mixture of some radically different elements, e.g. tungsten and carbon. Therefore, there is a tendency for some of the elements in the tool to diffuse into the chip where solubility conditions are more favourable. When the surface material of the tool loses a vital alloying element it becomes soft and is very soon worn away by the chip [67]. The mechanism of diffusive wear is illustrated schematically in Figure 15.23 with a tungsten carbide tool as an example.

In the early days of the introduction of carbide tools, tungsten carbide was widely used. Problems arose in machining of steel since the tungsten was rapidly lost to the chip. Slightly changing the tool composition by adding titanium carbide or tantalum carbide was found to remedy the problem. A similar mechanism is believed to be responsible for the excessive wear of silicon based ceramic cutting tools in the machining of steel. This time it is silicon which diffuses through grain boundaries to the workpiece [68]. The diffusive wear rate of cutting tools depends on the tool material solubility limits in the workpiece. The mechanism of diffusive wear has also been modelled mathematically [69].

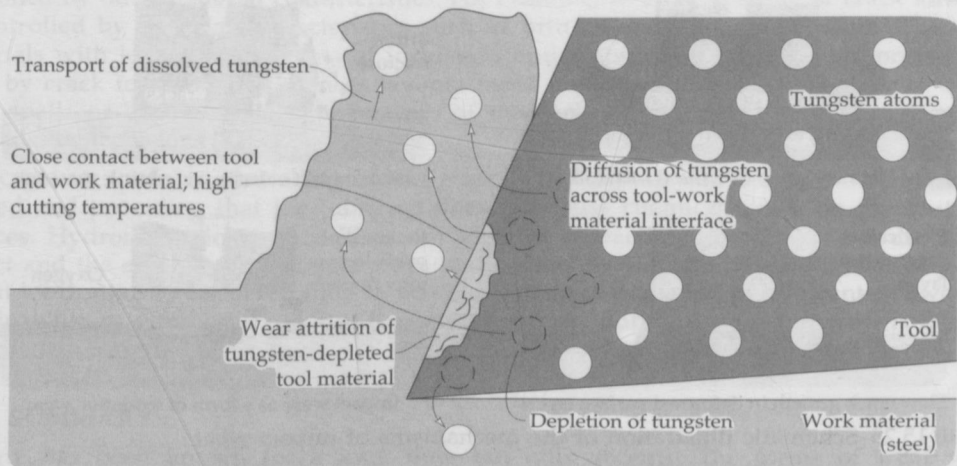


FIGURE 15.23 Schematic illustration of mechanism of diffusive wear.

15.6 IMPACT WEAR

Impact wear is caused by repetitive collision between opposing surfaces. A classic example of this form of wear is found on the heads of hammers. This form of wear involves flat surfaces or nearly flat surfaces with a large radius of curvature compared to the size of the wear scar. This feature distinguishes impact wear from erosive wear where a sharp particle indents a flat surface. In impact wear the surface is subjected to repetitive impact by a series of pulses of high contact stress combined with some energy dissipation in each impact as shown schematically in Figure 15.24.

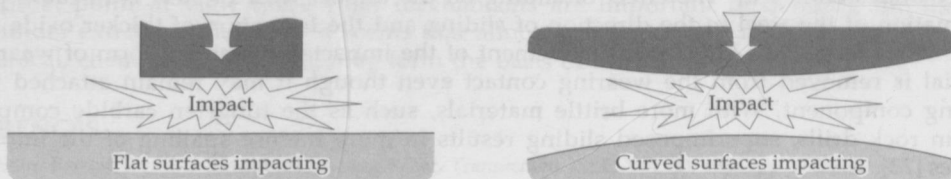


FIGURE 15.24 Repetitive stress pulses under impact wear.

The mechanism of impact wear involves elastic and plastic deformation when impact energy is high and/or fatigue accompanied by wear debris release due to crack formation [70,71]. If oxygen is present and the wearing material can be oxidized then a corrosive or oxidative wear mechanism can also take place. Iron and steel components are susceptible to impact wear by tribo-oxidation especially at elevated temperatures at which rapid oxidation occurs [70]. The mechanisms of impact wear are illustrated schematically in Figure 15.25.

In general, impact wear is dependent on the formation of deformed layers, particularly when wear by fatigue or crack formation is predominant [72]. In such cases, subsurface cracks extend parallel to the surface in a manner very similar to 'delamination' wear. The material through which the cracks propagate is very often plastically deformed and work-hardened as a result of contact stresses during impact [72]. Spallation and wear by crack formation can also occur in relatively brittle materials [73] so it seems that the presence of surface plastic deformation, in some cases, is not essential to this form of wear.

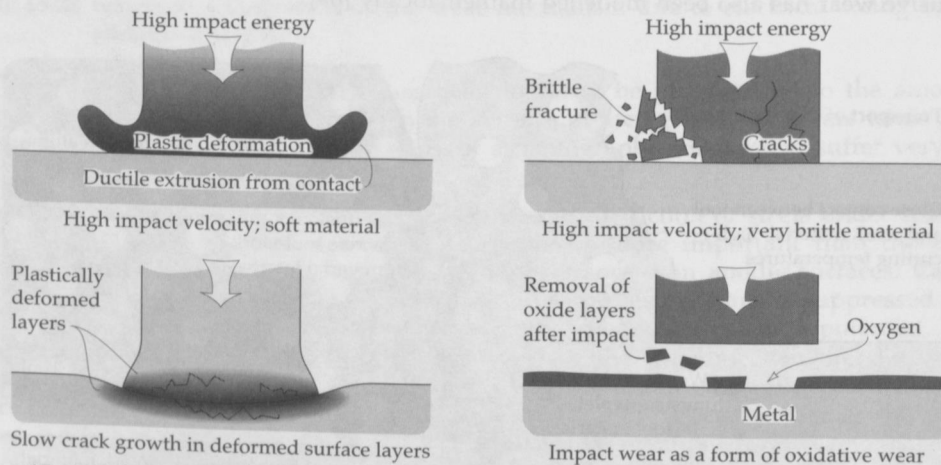


FIGURE 15.25 Schematic illustration of the mechanisms of impact wear.

The type of material sustaining impact wear has a strong effect on the wear mechanism. Metals are prone to an oxidative form of impact wear while ceramics wear by cracking and spalling. Polymers tend to wear by plastic deformation, fatigue cracking or by chemical attack from hot compressed layers of oxygen and pollutants at the moment of impact.

The process of repeated impacts between mechanical components is often accompanied by small sliding movements and these can affect the wear mechanism occurring. Movement tangential to the contacting surfaces during impact is usually caused by elastic deformation of the supporting structures. For example, if a wearing surface is supported by a cantilever then the deflection of the cantilever will cause sliding movement during impact. Superimposed sliding during impact caused by elastic deflection is illustrated schematically in Figure 15.26.

Superimposed sliding can cause an acceleration in wear, for example, by fretting, and is usually undesirable [70]. The effect of sliding on the impact wear of steel is to cause plastic deformation of the steel in the direction of sliding and the formation of thicker oxide layers on the worn faces [74]. This lateral movement of the impacted metal is a form of wear since material is removed from the wearing contact even though it may remain attached to the wearing component. With more brittle materials, such as the tungsten carbide composites used in rock drills, superimposed sliding results in more intense spalling of the impacting surfaces [73].

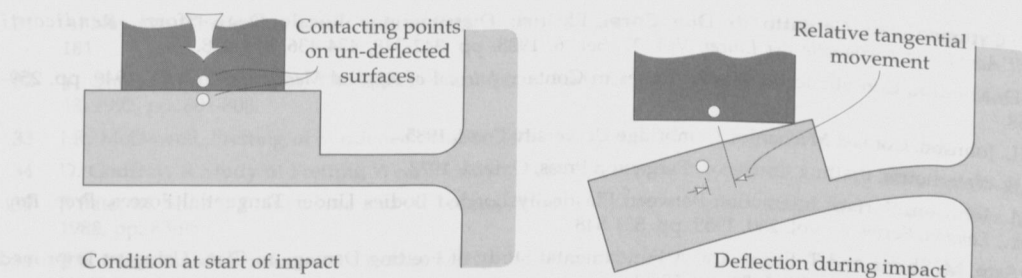


FIGURE 15.26 Sliding movements during impact wear caused by elastic deflection.

As may be expected, sufficient hardness of the impacted component is necessary to prevent rapid wear or extrusion of material from the contact by plastic deformation. In most situations this condition can be fulfilled by assuring an adequate hardness and then wear is controlled by other material characteristics. For example, wear by spalling or crack formation is controlled by material characteristics such as brittleness and microstructure. The use of materials with low concentrations of inclusions and material flaws would suppress impact wear by crack formation. Brittleness favours rapid crack growth and the formation of very large spalls or even macroscopic fracture of the component [73] while crack initiation is facilitated by inclusions [72].

Lubricants are useful in controlling impact wear in applications where they can be reasonably applied and providing that the lubricant does not cause chemical attack on the contacting surfaces. Hydrodynamic squeeze films can separate contacting surfaces for the duration of impact and the absence of sliding ensures that contact temperature rises are relatively small so that lubrication by adsorbed films is feasible. The basic limitation of lubricants, however, is their inability to significantly reduce the contact stresses during impact and wear is therefore only partially suppressed.

15.7 SUMMARY

Fretting has been known for a long time but only recently the forms of wear which distinguish it from other wear processes have been identified. The special feature of fretting is debris entrapment in the contact due to the restricted amplitude of sliding and the debris layer structures formed between fretting surfaces. The nature of the debris layers control the fretting characteristics of a material. Fretting is very sensitive to local conditions and small changes in system design may solve a fretting problem and avoid an expensive equipment failure. Where such remedies are not available, a lubricant or surface coating may be effective. Fretting fatigue can cause quite unexpected reductions in fracture stress of components particularly when combined with corrosion. Nominally static contacts such as interference fits are prone to this form of damage.

Knowledge of wear mechanisms dominated by extremes of energy, i.e. frictional, electrical and impact, transmitted across the sliding interface is limited because under normal operation they do not occur or are limited to a restricted range of applications. From a conceptual point of view these wear mechanisms are important in defining the limits to wear under extreme conditions. It seems that almost any process of material transformation, mechanical, chemical or physical, may form the basis of a wear mechanism.

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