

FRICITION, WEAR AND LUBRICATION

MEMM 1343

Adhesion

Adhesion is a material interaction of tribo pairs. Due to the contact of two solid surfaces under high pressure, atomic bonds arise. Subsequently, with the renewed separation of the tribo elements, material will be detached from one surface and remain adhering to the opposite surface.

For metallic contact partners, adhesion is also described as “cold welding”. The required energy for the reaction is made available by high pressures and frictional heat.

Every surface possesses a certain degree of roughness. When two surfaces come into contact, only the roughness peaks of the two bodies are directly in tribo contact, which means that the actual contact area is considerably smaller than the geometric area of the bodies in contact.

Very high mechanical stresses occur in these micro-contacts, but these may be further increased by the relative movement of the bodies. Both, elastic and elasto-plastic deformation of the roughness peaks may then take place, with the result that the adhering adsorption layers and reaction layers are destroyed.

Simultaneously, frictional energy is transformed to heat at the micro-contacts, giving rise locally to very high short-term temperatures (flash temperature theory). The interplay of high temperatures, high normal and tangential forces, and exposed high-energy surfaces enables the formation of atomic bonding between the base material and the counter-body, which may have greater strength than the bonding between the two contact partners.

The separation of the two surfaces then no longer takes place in the original contact zone, but below the surface of the contact partner having the weaker cohesion (cohesive failure). This leads to the formation of material fragments, which are then transferred from object A to object B, or vice versa. This process can reverse itself, and loose particles can then arise.

As a counter-measure, chemically inert materials should be chosen for the tribo-body surface. Materials with high fractions of ionic bonding offer very high chemical stability. As these materials (such as Al_2O_3) are also typically very hard, a relationship is frequently seen, for example, between the material hardness and the adhesion resistance.

However, this theory is contradicted by the fact that many polymers [such as polytetrafluoroethylene (PTFE, Teflon)] possess excellent adhesion resistance. Material pairs with different types of atomic bond have also proved to be favorable, as interactions take place preferentially between materials having the same type of bonding.

With the combination of metallic materials, it is necessary to ensure the low solubility of the alloy components in the material of the counter-body. The most common method of protecting against adhesion is to separate the tribo-bodies at the contact surface, by using suitable intermediate materials.

Mechanism of adhesion

Most solids will adhere on contact with another solid to some extent provided certain conditions are satisfied.

Adhesion between two objects casually placed together is not observed because intervening contaminant layers of oxygen, water and oil are generally present. The earth's atmosphere and terrestrial organic matter provide layers of surface contaminant on objects which suppress very effectively any adhesion between solids.

Adhesion is also reduced with increasing surface roughness or hardness of the contacting bodies. Actual observation of adhesion became possible after the development of high vacuum systems which allowed surfaces free of contaminants to be prepared. Adhesion and sliding experiments performed under high vacuum showed a totally different tribological behaviour of many common materials from that observed in open air.

Metallic surfaces free of oxide films under high vacuum exhibited the most dramatic changes and partly for this reason have been widely studied.

Metal-to-metal adhesion

Apart from noble metals such as gold and platinum, any other metal is always covered by an oxide film when present in unreacted form in an oxidizing atmosphere. The oxide film is often so thin as to be invisible and the metal appears shiny and pure. This film, which may be only a few nanometres thick, prevents true contact between metals and hinders severe wear unless deliberately removed.

It has been found in experiments conducted in vacuum that as the degree of surface contamination is reduced, adhesion between metallic surfaces becomes very large. In these experiments the metal was first heated to melt off the oxide film. A schematic diagram of the apparatus to measure the adhesion of clean surfaces under vacuum is shown in Figure 1.

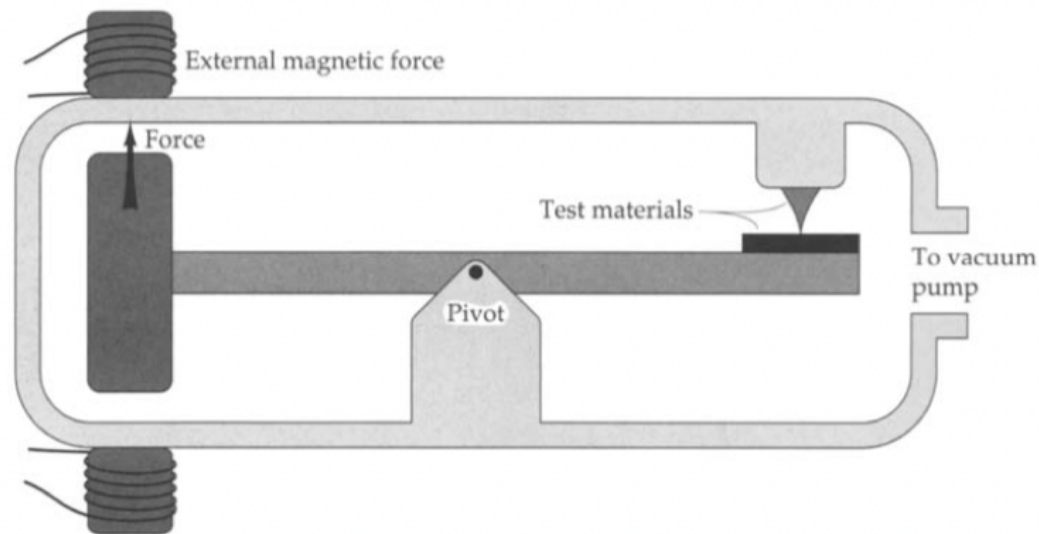


Figure 1: Schematic diagram of the apparatus for measurements of adhesion between metal.

As can be seen from Figure 1, a stylus is loaded against a flat surface and the strength of adhesion is determined by measuring the force needed to pull the two surfaces apart. Adhesion force data for various metals against iron measured at 0.2 (mN) of a contact load and 10^{-10} (Torr) of a chamber pressure are shown in Table 1.

It is evident from Table 1 that in all cases the adhesion or separation force is greater than the contact force. The tendency to adhere does not discriminate between metals on the basis of their mutual solubility or relative atomic size.

The greatest adhesion occurs for a combination of like materials, i.e., iron to iron, but many other combinations of unlike metals also show quite high adhesions.

The ratio of adhesion force to contact force can be very high, about 20 or more in some cases. The bonding process is almost instantaneous and can occur at moderate or low temperatures.

Table 1: Adhesion force of various metals against iron in vacuum.

Metal	Solubility in iron [atomic %]	Adhesion force to iron [mN]
Iron		> 4.0
Cobalt	35	1.2
Nickel	9.5	1.6
Copper	< 0.25	1.3
Silver	0.13	0.6
Gold	< 1.5	0.5
Platinum	20	1.0
Aluminium	22	2.5
Lead	Insoluble	1.4
Tantalum	0.20	2.3

Numerous tests on a wide variety of metal combinations have shown that when there is strong adhesion, transfer of the weaker metal to the stronger occurs as illustrated schematically in Figure 2.

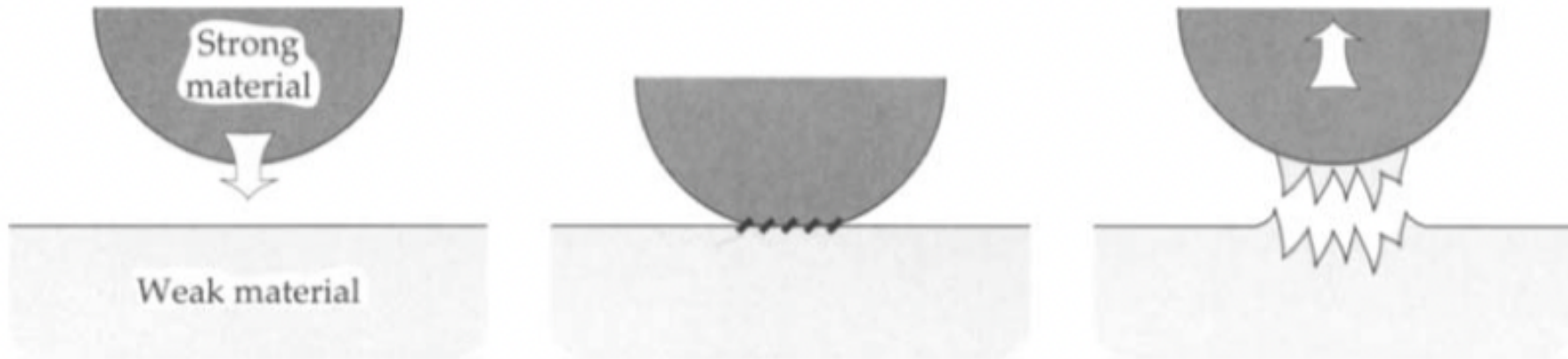


Figure 2: Process of metal transfer due to adhesion.

The strong adhesion observed between metals can be explained by electron transfer between contacting surfaces. Numerous free electrons are present in metals and on contact electrons may be exchanged between the two solids to establish bonding.

The “Jellium model” is used to describe this effect.

The electrons are not bound by a rigid structure and providing that the distance between two bodies in contact is sufficiently small, i.e., < 1 (nm), they can move from one body to another.

As a result the electrons can bond two solids despite their differing atomic structures. It has been found that the calculated values of the strength of adhesion between two metals are considerably in excess of experimental values. This is attributed to the difficulty in determining a true value of the contact area between atoms of opposing surfaces.

It is theorized that when different metals are in contact, the metal with a higher electron density donates electrons to the other metal as illustrated in Figure 3.

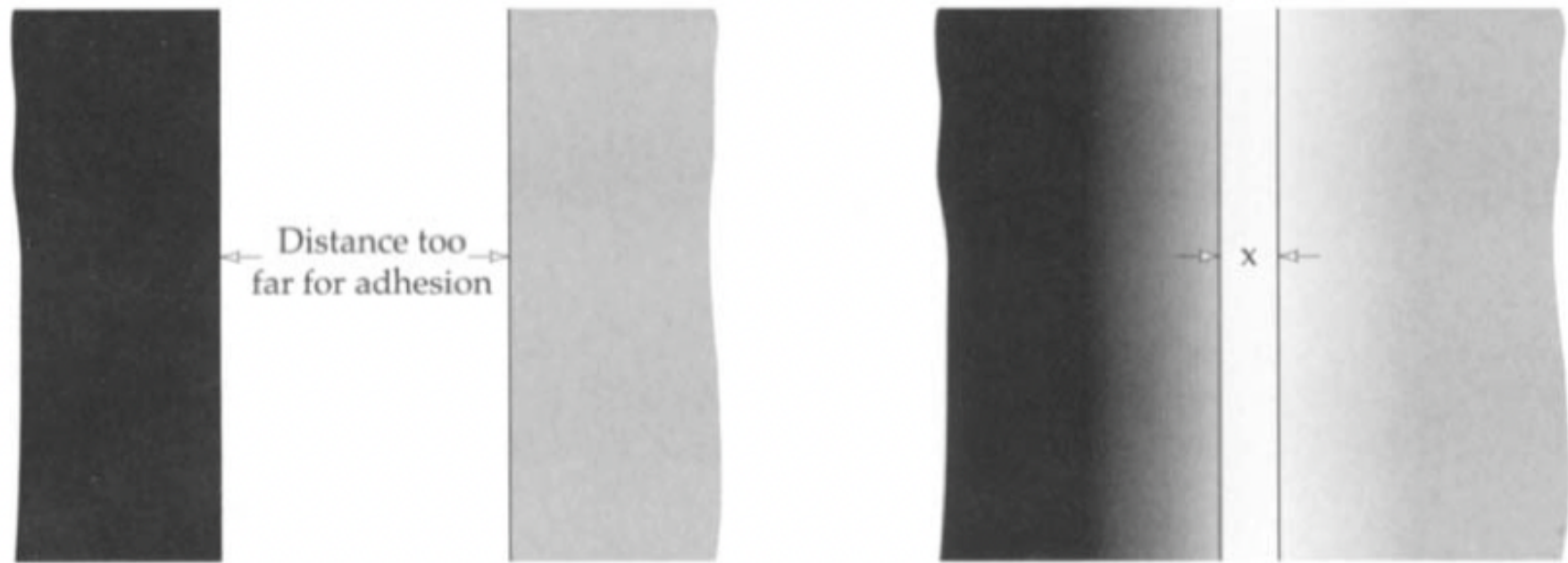


Figure 3: Jellium electron exchange model of adhesive contact between metals; x is equivalent to atomic dimensions, i.e., less than 1 (nm).

All metals show a strong tendency to adhere on contact with another solid but there are significant differences between particular elements.

Metals mainly exist in four principal types of crystal structure:

face-centred cubic,

body-centred cubic,

hexagonal close packed and

tetragonal.

It has been found experimentally that metals with hexagonal close packed structure show much less adhesion than other crystal structures. High hardness, large elastic moduli and surface energy of the metal also suppress adhesion.

Metal-polymer adhesion

In the extensive series of experiments conducted into metal-polymer contact and adhesion under high vacuum it has been revealed that metals and polymers can also show a high degree of adhesion.

Adhesion observed between a tungsten surface and polymers such as polytetrafluoroethylene and polyimide is strong enough to cause polymer to transfer to the metallic surface when the two materials are separated. The strength of adhesion is found to be related to the presence of reactive non-metals, such as fluorine, in the polymer. Surface atoms of the polymer are believed to bond with surface atoms of the metal and this can occur irrespective of the inertness of the polymer in bulk.

Most polymers adhere to other materials by van der Waals forces. In most wear situations, this form of adhesion is not strong enough for lumps of material to be torn out on rupture of the contact.

Strong adhesion between a metal and a polymer based on chemical interaction forms the basis for the mechanism of polymer on metal wear. Van der Waals forces, although they do not directly cause adhesive wear, provide a significant component of frictional resistance for elastomers such as rubber.

Metal-ceramic adhesion

Under suitable conditions, quite strong adhesion between metals and ceramics can occur.

The common factor in adhesion between various ceramics and metals is their chemical affinity. It has been found that only metals which do not form stable oxides exhibit low friction coefficients against ceramics. In contacts with ceramics, metals such as copper, aluminium and nickel show high friction coefficients while the coefficients of friction of gold and silver (unstable oxides) are low.

Although the oxygen ions present on the surface of aluminium oxide are already bonded to aluminium, an additional interaction with contacting metal atoms is possible according to the laws of quantum chemistry. The trend for contact between other metals and ceramics is similar.

Metals usually have a cohesive strength lower than most engineering ceramics so that on rupture of the adhesive contact, fragments of metal are often left adhering to the ceramic to form a transfer film.

Adhesion of ceramics to metals is greatly reduced by surface contamination in a manner similar to metal-to-metal contacts. Normally, these issues will be discussed in more detail on topic of “Non-Metallic Materials”.

Friction due to adhesion

An adhesive theory of friction was developed almost half a century ago by Bowden and Tabor.

Frictional forces due to adhesion are dominant when there is a total absence of lubrication and such circumstances correspond to the original experiments performed in vacuum.

The friction theory in the simple form presented so far implies that the limiting values of friction are less than unity.

In practice much higher values of the coefficient of friction are observed.

Junction growth between contacting asperities as a cause of extreme friction

The implication of the adhesion experiments conducted in high vacuum is that as the sources of surface contamination are progressively removed, the levels of adhesion and therefore friction rise precipitately. Conversely, when gas or contaminants are introduced to clean surfaces, friction levels decline to the moderate values typically found under atmospheric conditions.

The relationship between the friction coefficient of iron sliding against iron in the presence of various amounts of oxygen is shown in Figure 4.

In high vacuum a total seizure between the contacting samples occurs. As oxygen is supplied to the iron surface, a film of iron oxide forms, resulting in a reduced coefficient of friction. When this film reaches a certain thickness the strong adhesion between metallic iron is replaced by a weaker adhesion between iron oxide which is probably controlled by van der Waals forces.

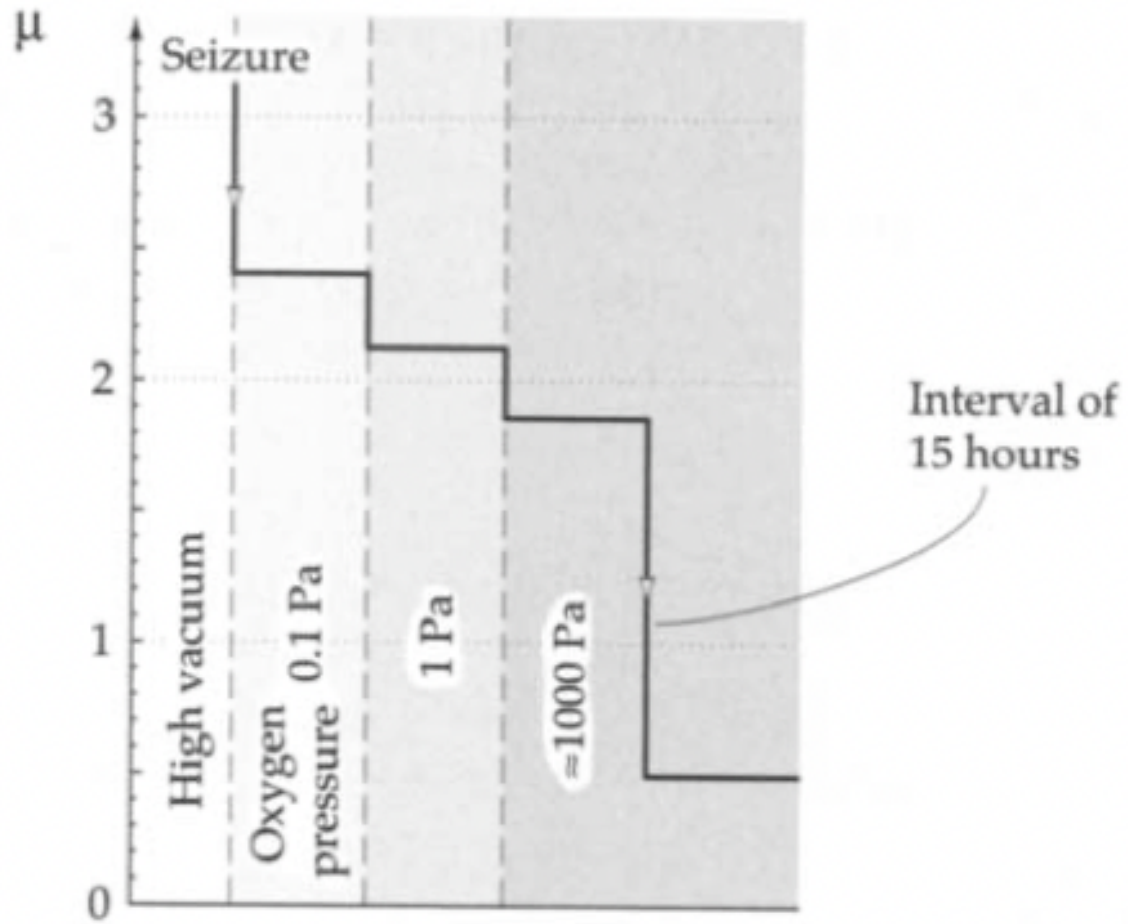


Figure 4: Effect of oxygen on the friction of clean iron.

The coefficient of friction between clean iron surfaces is very high, up to $\mu = 3$.

The simple theory of adhesion, described in the previous section, fails to predict such high values of friction coefficient, and in order to explain this phenomenon the process of “asperity junction growth” is considered.

In the plastically deforming adhesion junction both normal and tangential stresses are involved.

To explain the “asperity junction growth” process assume that initially there is a normal load acting on the asperity which is high enough for the asperity to plastically yield. Since the contact is in the “plastic state”, i.e., material flows, the contact area will easily be increased when the tangential stress is introduced.

The increase in the contact area will result in a reduction in the normal pressure (i.e., the same load is now carried by an increased area), as illustrated schematically in Figure 5. The increased contact area will also enable a larger tangential force to be sustained. The tangential force and the contact area will grow until the maximum (yield) shear stress of the material is reached (it is implicitly assumed here that under sliding conditions each asperity contact is loaded to a maximum stress prior to rupture). As a result the coefficient of friction will also increase. Since the loop with a positive feedback is created, the system may become unstable. The onset of instability is followed by a rapid increase in the coefficient of friction which eventually leads to seizure of the operating parts.

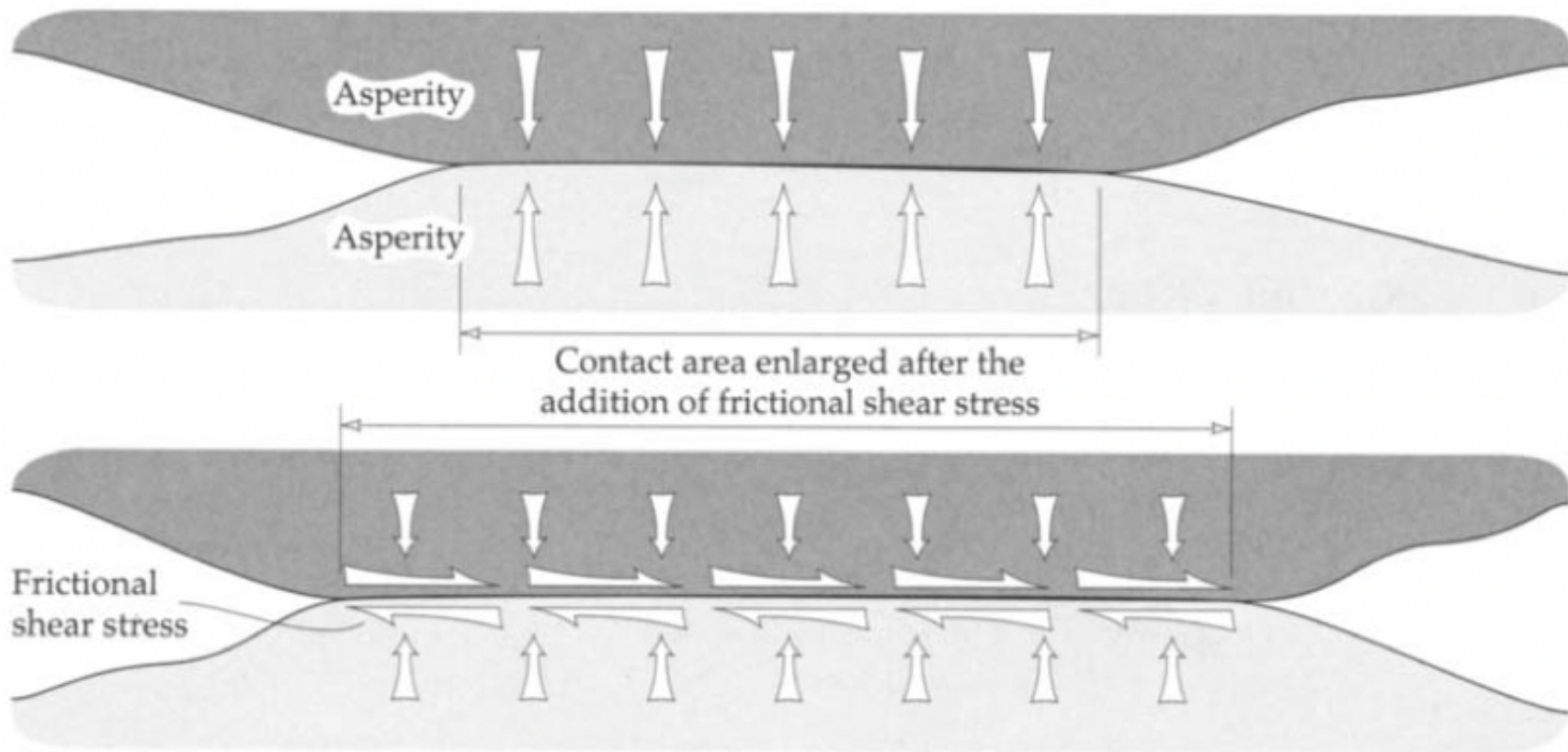


Figure 5: Schematic diagram of asperity junction growth under frictional force.

Seizure and scuffing

Very high friction coefficients found on clean surfaces under a vacuum can also occur in practical mechanical contacts when there is a breakdown or absence of lubrication.

Plain bearings and gear teeth are susceptible to this problem.

Figure 6 shows the typical appearance of scuffed gear teeth. It can be seen that the smooth as machined surface of the teeth is completely disrupted and displays signs of strong adhesion and adhesive fracture.

Under these conditions normal operation of the gear is impossible and considerable damage to the unit from overheating as well as adhesion will result.

In most sliding contacts, such as bearings, gears, chains and cams, the cause of rapid and sometimes catastrophic failures is adhesion and adhesive wear. Although other wear mechanisms can also cause problems, in general, these problems are of a milder form.



Figure 6: Adhesion between gear teeth resulting in scuffing.

Asperity deformation and formation of wear particles

The combined action of adhesion between asperities and sliding motion causes severe plastic deformation of the asperities. To observe and study the events that are likely to occur between sliding and adhering asperities in an actual wearing contact is virtually impossible. To facilitate such studies the contact between two asperities was simulated by two pointed plates as illustrated in Figure 7. The plates are forced together by a vertical load and moved against each other by a hydraulic ram. The entire system can be fitted into a scanning electron microscope for observation.

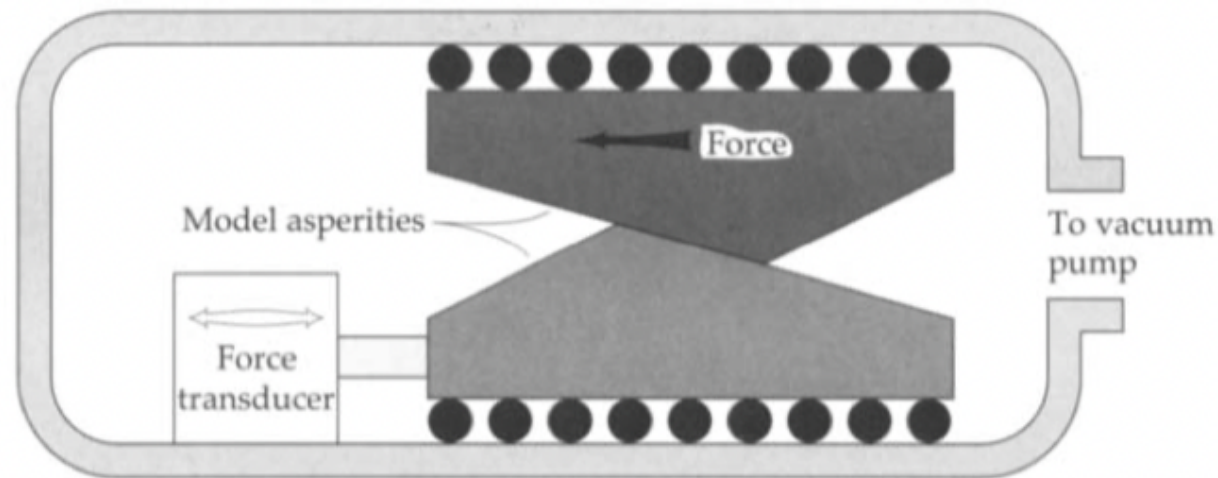


Figure 7: Schematic diagram of the experimental apparatus to study adhesive wear processes.

Since the position of the plates is maintained at a constant level by the slideway, a close representation of a wearing contact where individual asperities move along a horizontal plane and sustain transient loads when in contact with opposing asperities is obtained. The mechanism of shearing and cracking to form a transfer particle in the adhesive contact between asperities is illustrated schematically in Figure 8.

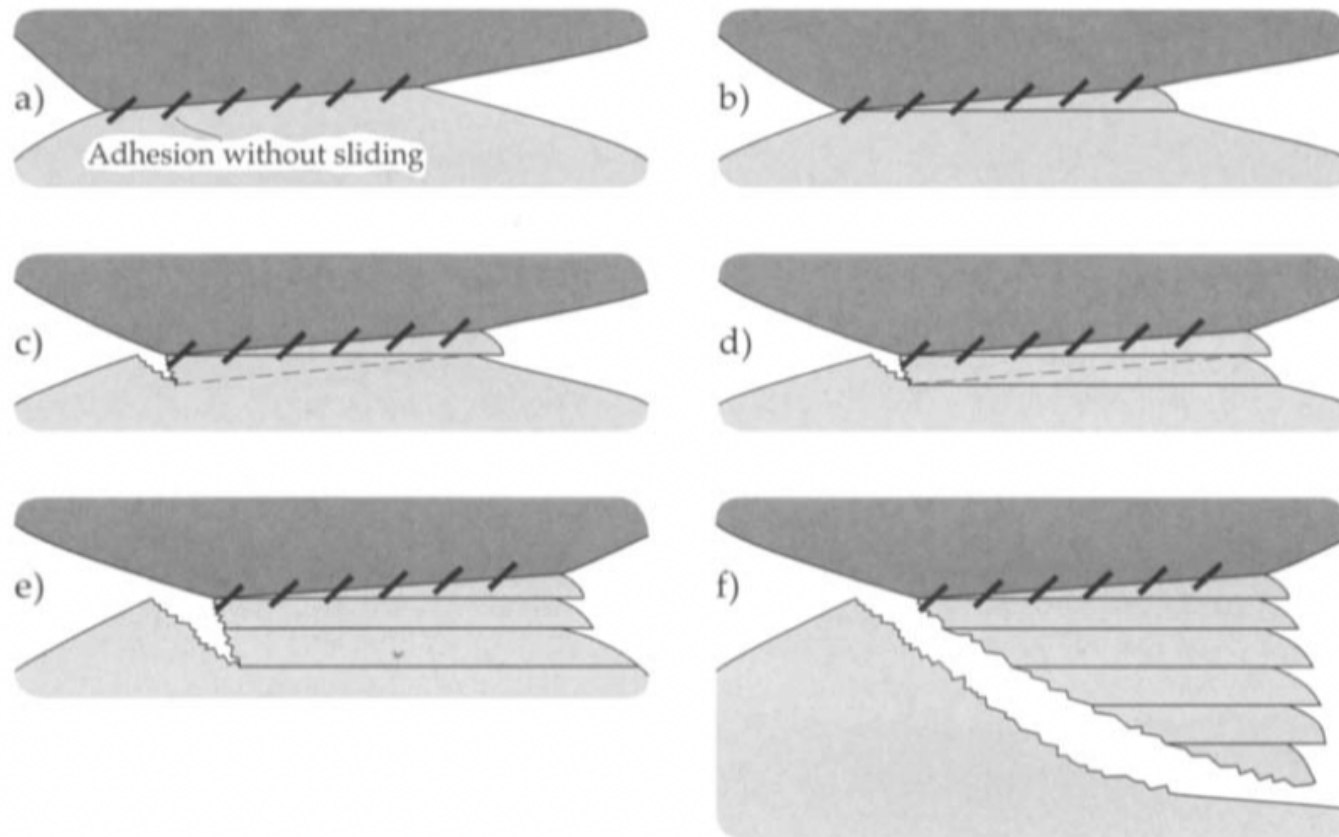


Figure 8: Schematic diagram of the formation of an adhesive transfer particle

Material in the softer or sharper asperity deforms in a series of shear bands to accommodate the relative movement, i.e., there is no sliding along the asperity contact line. When each shear band reaches a certain limit, a crack is initiated or an existing crack progresses till a new shear band is formed. The crack extends across the asperity and eventually a particle detaches from the deformed asperity.

It has been found that asperities with large slope angles, i.e., “sharper asperities”, tend to lose material to asperities with small slope angles.

Material properties have a strong influence on asperity deformation and the severity of adhesive wear. Experiments conducted on model asperities revealed that the contacting asperities of brittle materials tend to break away cleanly with little deformation and produce fewer wear particles compared to ductile materials. It appears that ductility has an undesirable effect of accentuating adhesive wear.

In the contacts between asperities which do not produce wear particles, there may still be extensive plastic deformation as illustrated in Figure 9.

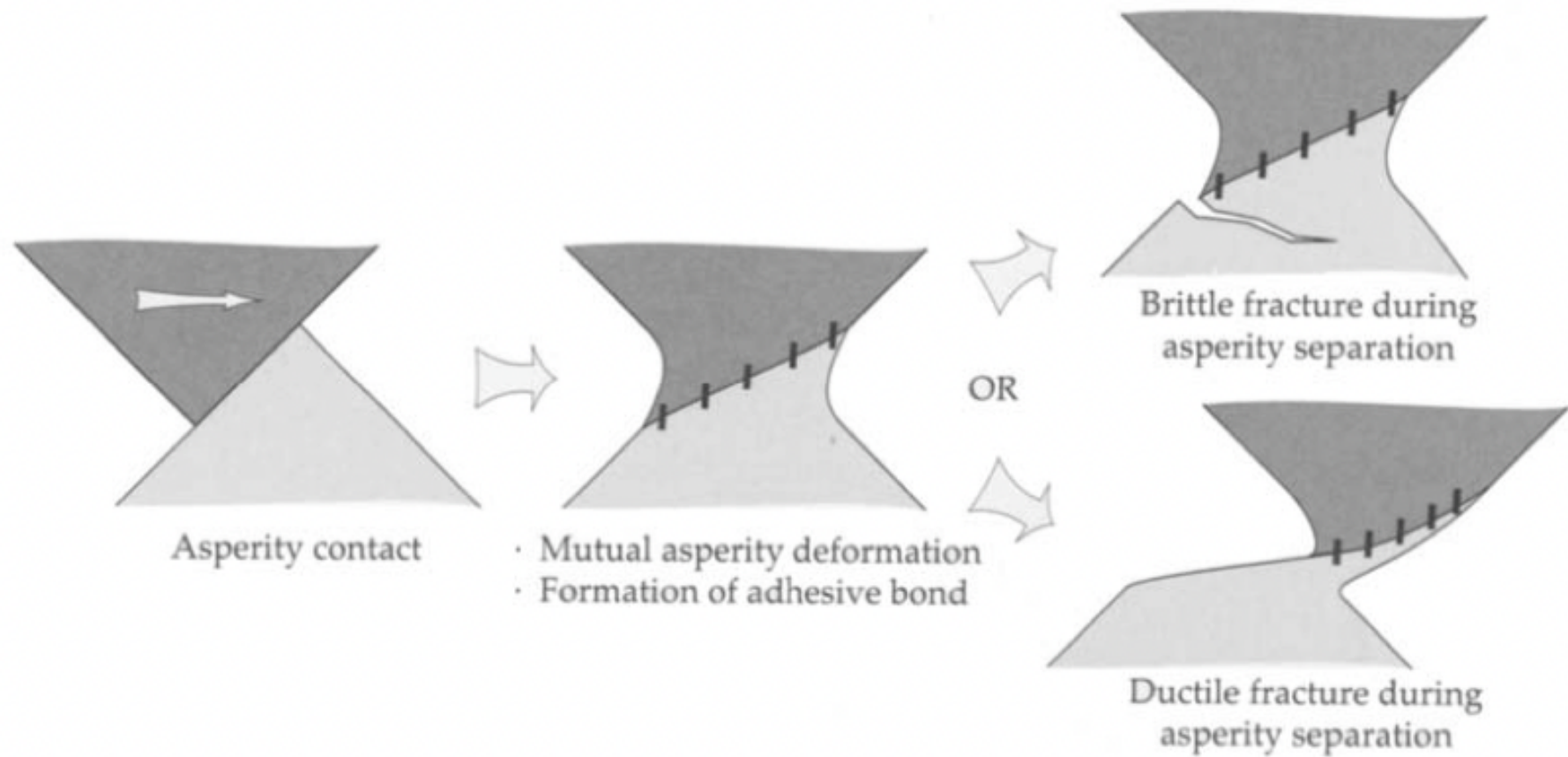


Figure 9: Alternative model of deformation in adhesive asperity contact.

The evidence of such severe plastic deformation and/or surface cracking producing a sharply skewed worn asperity profile has been confirmed by scanning electron microscopy studies.

The particle of metal detached from one of the asperities, i.e., as shown in Figure 8, remains attached to the other surface. Depending on conditions it may subsequently be removed by further asperity contact to form a true wear particle or it will remain on the surface to form a “transfer film”.

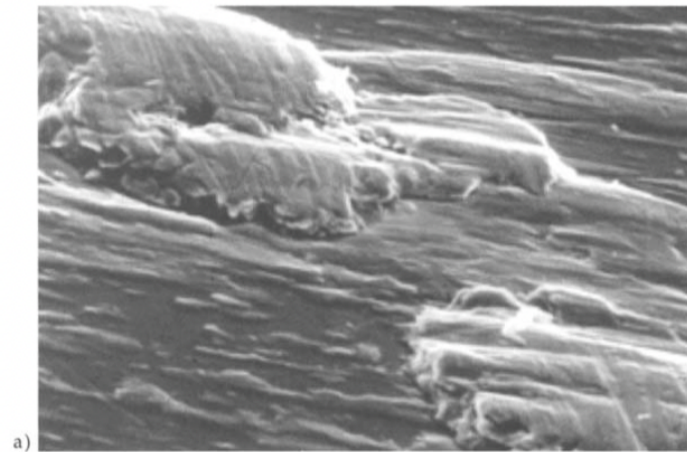
Transfer films

The formation of transfer films is a characteristic feature of adhesive wear where material is transferred from one surface to another before being released as a wear particle. It distinguishes adhesive wear from most other wear mechanisms.

In the early studies of this phenomenon it was found that brass rubbed against steel leaves a film of transferred brass on the steel surface which eventually covers the wear track. The transferred brass was found to be highly work-hardened and probably capable of wearing the brass sample itself.

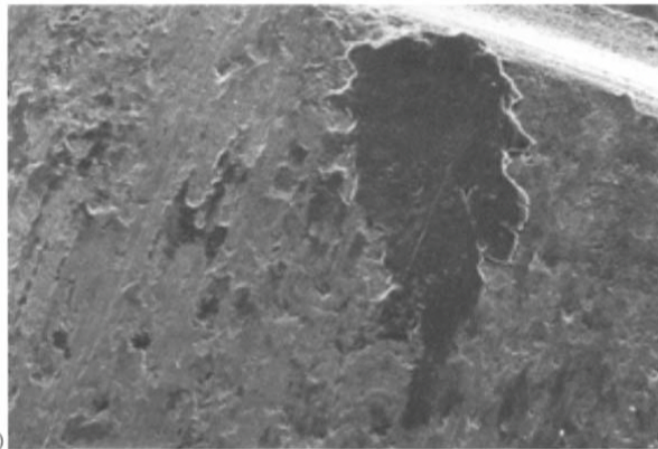
This observation of inter-metallic transfer was confirmed later by tests on a variety of combinations of metals in sliding.

Examples of metallic transfer film are shown in Figure 10.



a)

10 μ m



b)

100 μ m

Figure 10: Examples of metallic film transfer for (a) brass film transfer on alumina and (b) AlSi alloy transfer film onto a piston ring.

The formation of a transfer film or transfer particles can have a dramatic effect on the wear rate.

The process of transfer particle formation and removal is illustrated schematically in Figure 11.

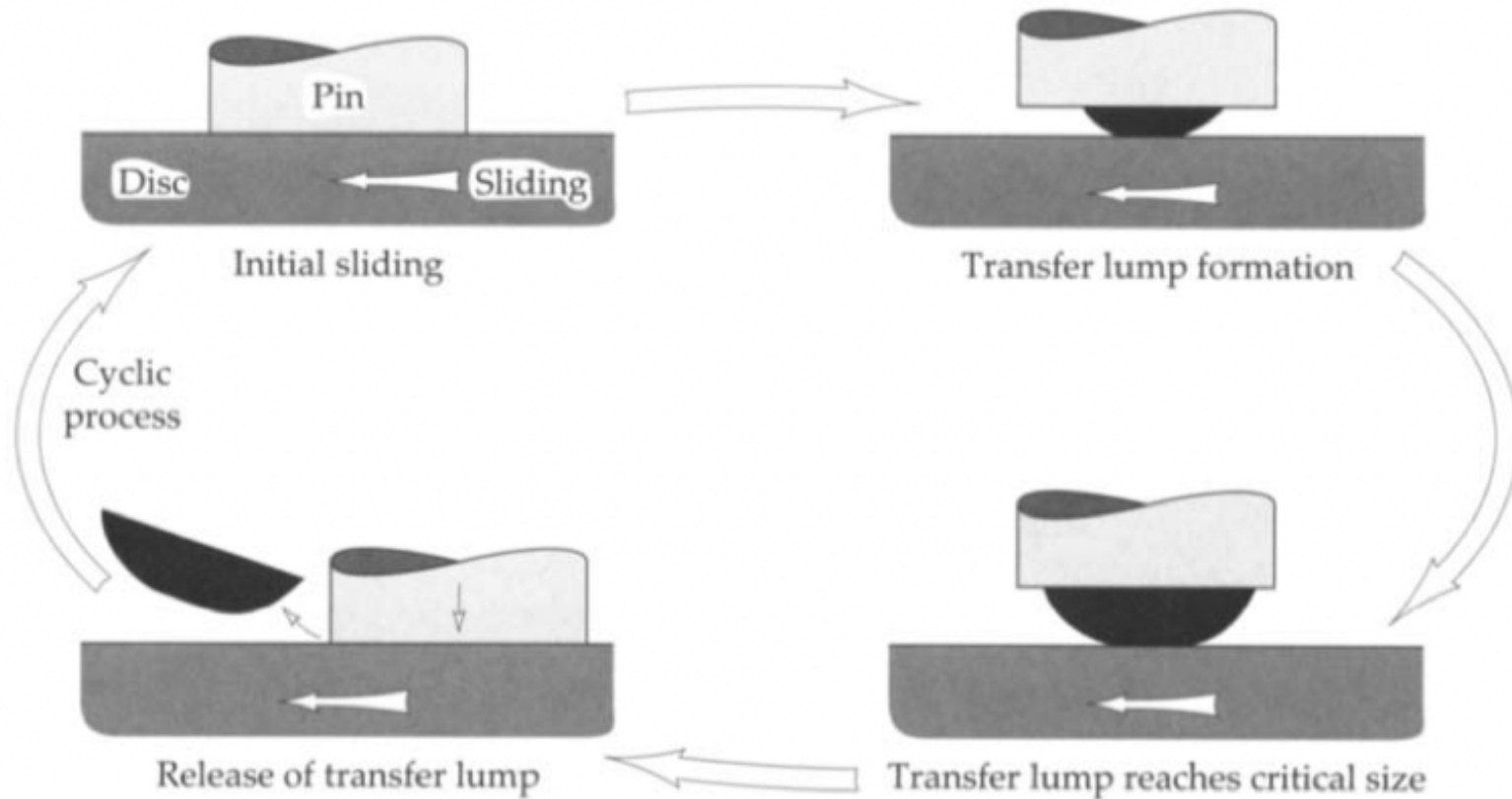


Figure 11: Formation and removal of a transfer particle.

It can be seen from Figure 12, that the transfer particle can lift the pin away from the opposing surface and this causes an apparently “negative wear rate”.

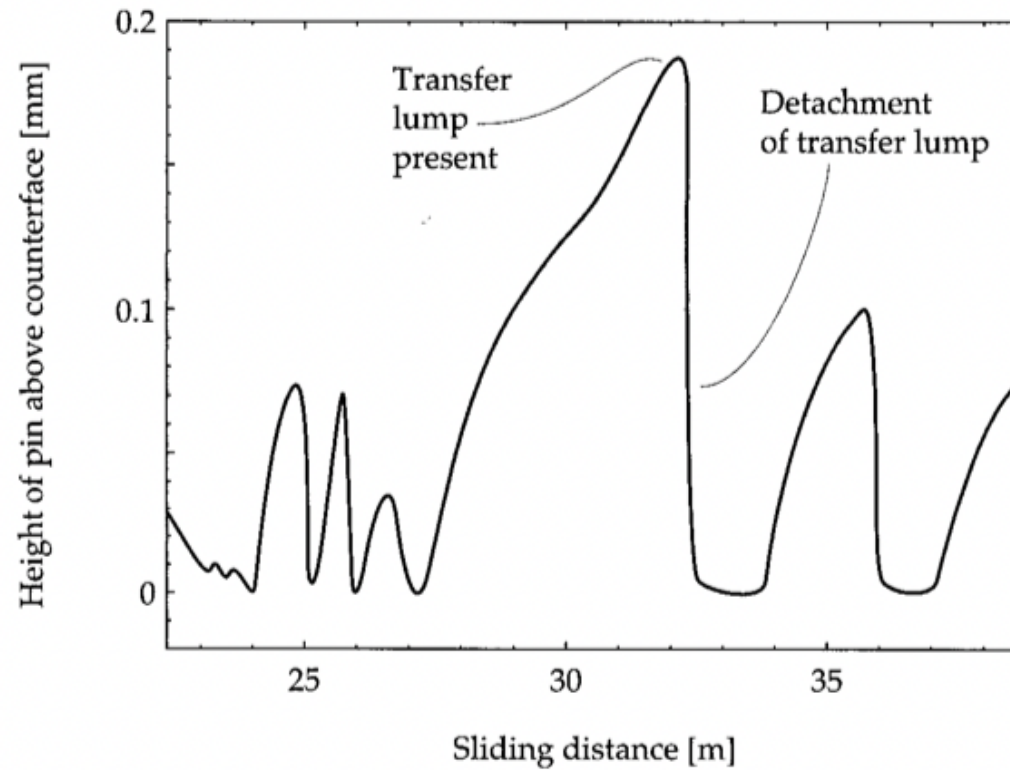


Figure 12: Variation of wear depth with sliding distance for zinc sliding against zinc

The evidence of this phenomenon is illustrated in Figure 13, where the wear depth incurred when a zinc pin is slid against a zinc disc is shown. Periods of apparently negative wear are followed by a step-form of positive wear as transfer particles are formed and released.

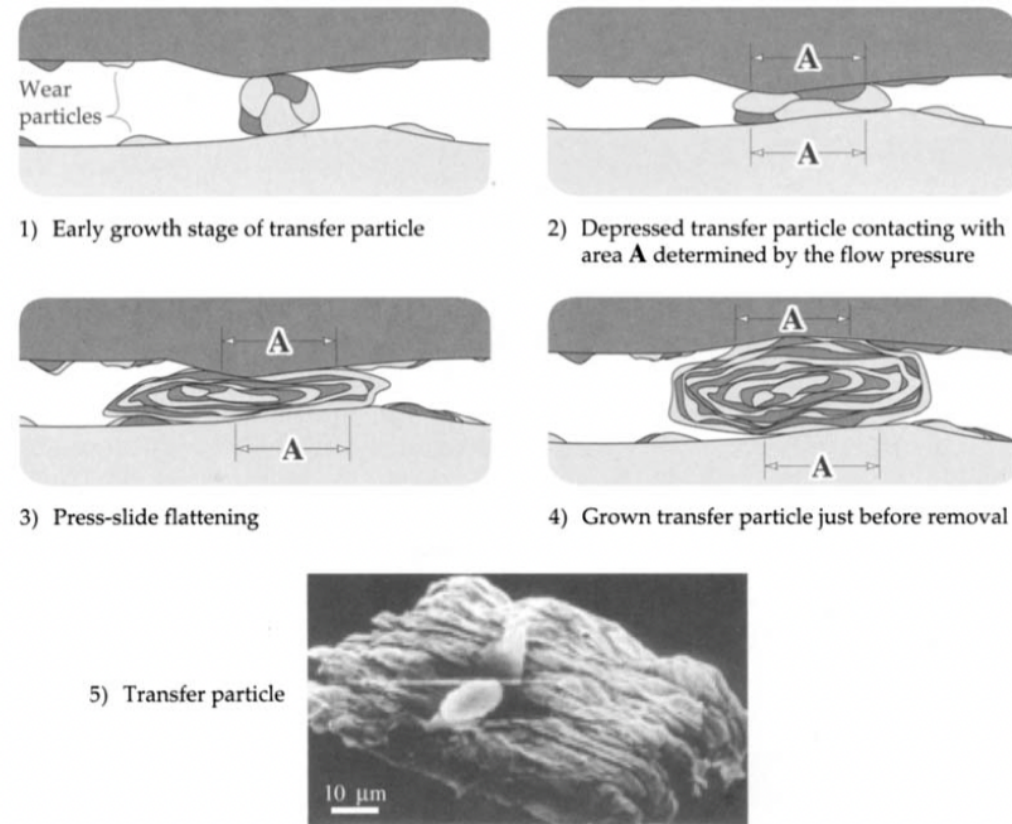


Figure 13: Formation of lamellar structure transfer particles

Groove formation

The mechanism of groove formation involves ploughing of the softer substrate material by work-hardened transfer particles. The ploughing is a very inefficient form of cutting which can lead to crack formation on the worn surface as a result of high tensile stresses. The mechanism of ploughing by transfer particles is illustrated in Figure 14.

The formation of such coarse grooves on worn surfaces is frequently observed when adhesive wear occurs. These grooves are usually formed on the sliding member with larger wear track area, such as on the disc or ring in pin on disc/ring machines.

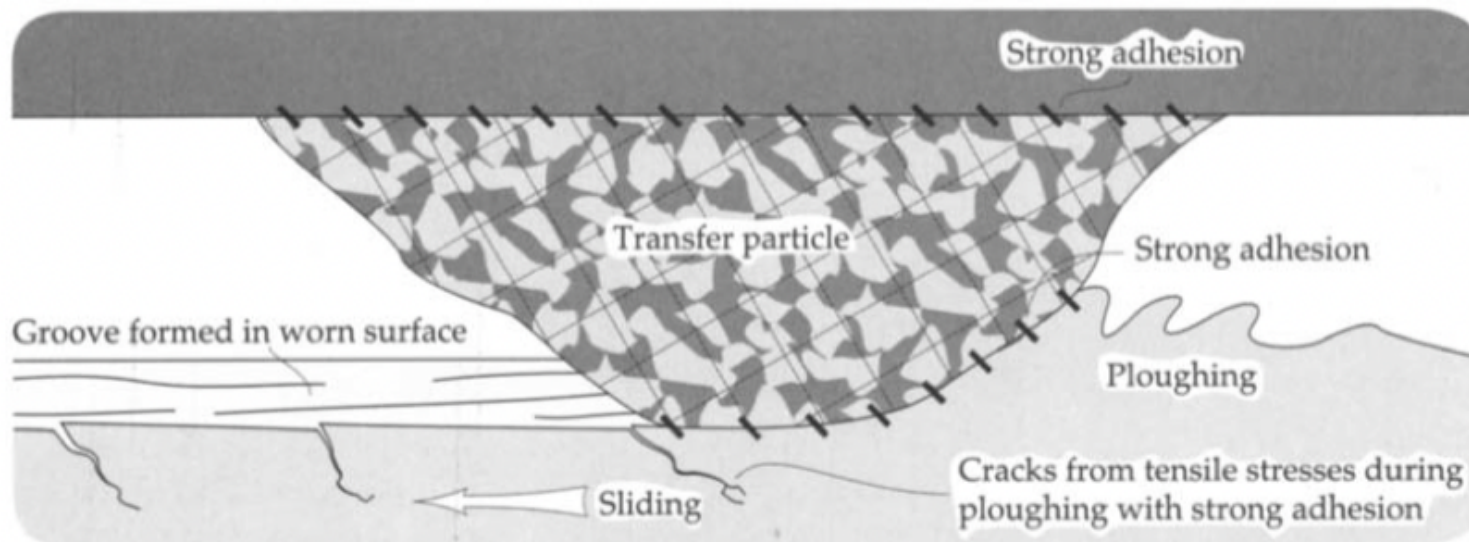


Figure 14: Mechanism of groove formation on worn surfaces by work-hardened transfer particles.

Summarizing, transfer films can greatly modify the sliding characteristics of materials.

When a transfer film is present as thick lumps, smooth sliding is impossible and the load is carried by a few or just one transfer particle. When a transfer particle is released there is an abrupt movement of the sliding surfaces to compensate for this.

In extreme cases the transfer particles can fail to detach and grow to cause total seizure of the sliding interfaces.

However, not all transfer films are undesirable.

The wear of polymers, in particular, depends on very thin transfer films which allow for low friction.

Solid lubricants also function by forming thin layers on the wearing surfaces. These layers can be transferred from one wearing surface to another which is useful when inaccessible contacts have to be lubricated.

Control of the adhesive wear

If adhesive wear is allowed to proceed uncontrolled, various undesirable consequences can follow. High friction with the possibility of seizure and the growth of transfer particles can result. In some cases transfer particles can jam the sliding contact, e.g., if it is annular. A further problem caused by adhesive wear is an extremely high wear rate and severe surface damage.

Experimental results have shown a much higher probability of wear particle generation due to asperity contacts during adhesive wear compared to, for example, abrasive wear.

Rapid wear is therefore a main reason why adhesive wear must usually be carefully controlled and suppressed.

Contaminant Layers Formed Due to Surface Oxidation and Bulk Impurities

Oxidation of metal surfaces can lower adhesion to acceptable levels. Almost all metals, when exposed to air, form very rapidly an oxide film of about 5 (nm) in thickness. A 5 (nm) film is so thin that it is transparent and the metal remains shiny, but it radically changes the surface properties of the metal.

The oxidized surface can be considered “contaminated” as non-metal atoms are present on the surface. Oxygen, but not passive gases such as nitrogen or argon, is very useful as a universal “lubricant”.

Moisture accentuates the effect of oxygen but the reasons for this are not yet clear. For example, adhesive wear of ceramics is notably reduced by adsorbed moisture.

Surface oxidation of metals occurs rapidly even at low temperatures and the rate at which oxidation proceeds is often limited only by the supply of oxygen until the critical 5 (nm) thickness is reached.

This means that under atmospheric pressure, oxide films, if removed, are reformed in just a few microseconds. This rapid re-growth means that a protective oxide film in a wearing contact can be sustained indefinitely. It is only under a vacuum or under a thick layer of oil that oxygen starvation may cause problems.

Lubricants

The primary purpose of a lubricant is to suppress adhesive wear by providing a superior form of surface “contamination”.

Fatty acids and other polar organic substances are usually blended into lubricating oils. If these fatty acids adsorb on the top of the existing oxide layers, further reductions in friction and wear are obtained.

Certain oils also contain additives rich in sulphur, phosphorus or chlorine. Metal surfaces can form sulphide, phosphide or chloride films just as readily as oxide films. These films are intended to form when oxide films break down to provide a protective surface film against very high friction or seizure.

Favourable combinations of sliding materials

The likelihood of severe adhesive wear occurring varies significantly between different combinations of sliding materials. A careful choice of materials can yield benefits of minimized wear and friction. An example of this is the combination of steel and bronze used for the shaft and bush in journal bearings. The general rule is to avoid sliding similar or identical materials against each other.

The effects of mutual solubility of metals on their adhesion are still far from clear. Strong arguments have been made that metals which are mutually soluble should not be slid against each other. However, closer examination of the data published shows that of the metals slid against iron, aluminium, which is only of a limited solubility in iron, causes higher friction than chromium, which is completely soluble.

This can be explained by Buckley's hypothesis which suggests that chemically active metals are electropositive, i.e., electron donors, and show much stronger adhesion to iron than passive or inert metals. Since aluminium is more electropositive than chromium its adhesion to iron is stronger than that of chromium.

