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Citation for published version (APA):

Landheer, D., & Gee, de, A. W. J. (1991). Adhesion, friction, and wear. *MRS Bulletin*, 16(10), 36-40.

Document status and date:

Published: 01/01/1991

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Adhesion, Friction, and Wear

D. Landheer and A.W.J. de Gee

Introduction

In the context of this article, adhesion, friction, and wear are defined as follows: *Adhesion* is the resistance against separation of two bodies in a direction normal to the common interface. *Friction* is the resistance against motion of the contacting bodies in the direction of the common interface. *Wear* is the gradual change of geometry and loss of material due to the different contact processes that may occur in moving contacts.

Bowden and Tabor¹ have shown convincingly that adhesion, friction and wear are interrelated at least to some extent. This article will review some of the current arguments that support this notion.

The Process of Sliding Contact

If surfaces are not separated by a viscous film, both friction and wear have their origin in the contact phenomena occurring at the roughness asperities of the sliding bodies.

Within one contact cycle, three primary events can be distinguished:

1. In order to obtain a (normal) load-carrying capacity, the contacting asperities must be compressed or indented (Fig-

ure 1), similar to a Brinell hardness test.

2. At the beginning of the contact cycle, the asperities interfere in the direction of sliding (Figure 2). Thus during the first half of the contact cycle, frontal loading of the asperities occurs (Figure 2b).

Particularly if the resulting deformation is plastic (as it will usually be for metals, see Reference 1), the net effect of this contributes to friction, the so-called "ploughing" effect.

3. As soon as the height interference of the contacting asperities is accommodated by action of the ploughing effect, no further geometrical factors resist tangential motion. The velocity difference between the contacting bodies can now be accommodated by interfacial slip alone (shearing at the interface, Figure 3a), for which an interfacial shear resistance τ_i has to be surmounted (Figure 3b). Depending on the ratio of τ_i and the subsurface shear resistance (i.e., the shear strength values τ_1 and τ_2 of the bulk materials close to their surfaces), either interfacial slip or subsurface slip or a combination of these two will occur (Figure 3a, 3c and 3d, see also Reference 2).

Even without going into further details,

it will be clear that both ploughing and interfacial shear resistance contribute to the resistance against tangential motion (i.e., friction), whereas (repeated) normal loading, ploughing, and shear loading may all contribute to wear.

The ratio of the total tangential force F_T to the total normal force F_N is the coefficient of friction f . The contribution f_p of the ploughing effect to f primarily depends on the geometry of the harder asperities. It can be calculated and measured to range from $f_p = 0.01$ for very smooth metal surfaces to $f_p = 0.3$ for sandpaper sliding on aluminium, for instance. Since the measured values of f for dry sliding of smooth metals may, depending on the nature of the contacting metals and the composition of the surrounding atmosphere, easily surpass unity, the contribution f_i of the effect of interfacial shear resistance to the total coefficient of friction f can clearly be quite large.

Empirical Relation Between Friction and Adhesion

A most significant phenomenon, relevant to whether a relation between adhesion and friction exists is that contamination of initially dry surfaces usually reduces both friction and adhesion drastically. For instance, a boundary lubricant film a few molecules thick (i.e., in the nanometer range) can effectively reduce friction (e.g., from $f = 1.0$ to $f = 0.1$), without affecting asperity interaction and, thus, the ploughing effect. So the friction-reducing effect must be due to a reduction in the interfacial shear strength τ_i . Of course, a change in τ_i will also affect how the ploughing phenomenon develops, but that is a secondary effect.

Extreme examples of the combination of high adhesion and high friction with clean surfaces are found in experiments with cleavage surfaces of mica.³ Further, changes in the ratio of adhesion energy to strength (brought about by changes in the nature of the contacting materials) influence adhesion and friction in a similar way, as shown extensively by Rabinowicz.⁴

On the whole, the indications that adhesion and friction, as caused by interfacial shear resistance, are strongly interrelated, are too strong to be a coincidence. Clearly, the matter deserves further consideration. To that purpose the processes of adhesion and interfacial shearing will now be discussed in a more detailed, albeit qualitative way.

Adhesion

Adhesion between two bodies is related to potential energies at an atomic scale.

Figure 1. Schematic picture of (a) an unloaded contact between two asperities and (b) the same contact under a normal load ΔF . The load-carrying capacity of the contact is obtained by deforming bodies 1 and 2, resulting in an approach $(a_1 + a_2)$ and in growth of the contact area from ΔA_{r0} to ΔA_r .

Atoms have "social tendencies." In metals, for instance, they mostly prefer to be surrounded by atoms of their own kind. If the distance d between the centers of adjacent atoms is about equal to the atomic diameter, their collective potential energy U_p is at a minimum ($U_p = U_{pm}$, Figure 4) and a thermodynamically ideal situation is reached. Changes in mutual distance require a force F_a and an increase in U_p . Superimposed on this energy condition is a thermally induced vibration around the equilibrium positions with kinetic energy U_k .

Atoms at a free surface are in an energetically less desirable position: they miss a few neighbors so that the average atomic distance around the surface atoms is increased with respect to that in the bulk of the metal. Consequently, the potential energy is increased to U_{pf} (Figure 4). The difference between U_{pf}^* and U_{pm}^* , both taken per unit of area (indicated by the symbol γ) is equal to the specific surface energy.

At an interface (e.g., between two crystals in a metal, or between two bodies), the situation is intermediate. The atoms

along the interface do have neighbors on the other side of the interface, but since their fit is usually less perfect than the fit in the bulk material, the potential energy is increased to U_{pi} , with $U_{pm} < U_{pi} < U_{pf}$. Of course, the actual value of U_{pi} depends on the nature of the atoms that interact at the surface.

On separation of contact between two bodies, the atoms on both sides of the plane of separation undergo a change from an interfacial position to a free surface position. Consequently a change of energy per unit of interfacial area oc-

Figure 2. Schematic representation of a contact cycle between a pair of asperities. Body 1 moves with velocity v parallel to the plane of reference AA' ; body 2 is stationary. Both materials are deformable; ΔF_t = tangential force, ΔF_n = normal force. (a) Before contact occurs, the asperities have a height interference $a_1 + a_2$; (b) During approximately the first 50% of the contact cycle, the geometry of the asperities causes frontal loading; (c) After some tangential motion, the "geometrical resistance" disappears; (d) if the deformations are elastic only, a negative geometric resistance ("pushing effect") arises toward the end of the contact cycle; (e) an ideal plastic contact ends without a "pushing effect."

Figure 3. Schematic representation of the sliding process, depending on the relative measure of the interfacial shear resistance τ_i . Body 1 is deformable and moves with velocity v parallel to the plane of reference AA' ; body 2 is supposed to be rigid and it is stationary. Since the interface is parallel to the sliding direction, there is no geometrical resistance against tangential motion. (a) $\tau_i = 0$: pure interfacial sliding (slip), no subsurface shear; (b) the action of the interfacial shear stress τ_i on body 1 is opposed to its sliding motion; (c) τ_i very high: complete sticking (no interfacial slip), the interfacial velocity v_{1i} of body 1 is equal to zero, the velocity difference between the members is bridged by heavy subsurface shearing within body 1; (d) τ_i intermediate: combination of interfacial slip with velocity v_{1i} and subsurface shear to bridge the velocity difference between the two bodies.

Figure 4. Potential energy and interatomic forces at 0 K. (a) A pair of atoms (or ions) in a metal lattice; (b) potential energy U_p per atom versus the average distance d between the atom and its close neighbors; (c) interatomic force F_a vs. distance d for two atoms within their surroundings. The equilibrium distance d_0 is reached when the net potential energy is at minimum (U_{pm}) and the force is zero. The levels of the potential energy of the atoms at a free surface (U_{pf}) or at an interface (U_{pi}) depend on their crystallographic orientation and on the nature of the contacting material. In (b) they are arbitrarily chosen within the possible regimes $R(U_{pf})$ and $R(U_{pi})$.

curs, i.e., from U_{pi}^* to $U_{pf1}^* + U_{pf2}^*$ (subscripts 1 and 2 refer to bodies 1 and 2). This change in energy is called the adhesion energy Γ_{adh} . Thus we may write:

$$\Gamma_{adh} = U_{pf1}^* + U_{pf2}^* - U_{pi12}^*$$

According to the above reasoning, which is essentially due to Rabinowicz,⁴ separation of contact of area A_r requires a supply of energy, equal to $\Gamma_{adh} \cdot A_r$.

For the following reasons, assessment of Γ_{adh} by direct measurement of the adhesion force is virtually impossible:

1. In most cases, the surfaces are covered by oxide layers and contaminating layers of organic material, which effectively mask adhesion forces.
2. The contact is not usually severed all at once, but rather by a peeling off process from the circumference of the contact inwards (similar to peeling off an adhesive tape, Figure 5a).
3. Upon unloading of the contact, elastic energy is released from the initially deformed conjunction zone (elastic recovery, Figure 5b).

As pointed out by Bowden and Tabor,¹

Figure 5. Two factors interfere with the measurement of adhesive forces between uncontaminated surfaces: (a) adhesion is tested on the momentary circumference of the contact only, just as when peeling off adhesive tape; (a-1) asperity contact, loaded by a normal force; (a-2) on tensile loading of a contact, possible separation starts at the corners; (a-3) peeling off adhesive tape: local loading of the adhesive. (b) Upon unloading of a contact, elastic recovery forces stress the interface and thus oppose the adhesive forces; (b-1) the elastically deformed zones in contact reach their maximum depth near the center of the junction; (b-2) geometry of contact after unloading in the absence of adhesion; elastic recovery is at maximum in the center of the junction, where the stresses as well as the depth of deformation $z(x,y)$ under load have a maximum value.

the first point may be less important in a sliding contact. Because of the severe plastic deformations that occur at a microscale and because of ploughing effects, protective layers can be removed locally, temporarily exposing the bare metal surfaces to strong adhesive forces. This may lead to adhesive material transfer, a well-known and exhaustively documented phenomenon in sliding systems with inadequate lubrication (see also the following sections on interfacial shear and on wear).

In practice, adhesion in metal systems is known in many applications, such as

the use of "cold-welded" bimetals, applied, for instance, in electrical switches and frying pans (copper cold welded on stainless steel).

Interfacial Shear

The origin of interfacial shear resistance between unlubricated (but not necessarily metallic) bodies, is the atomic (or molecular) interaction across the interface. A comprehensive quantitative theory of such interaction does not exist. However, in the following, a qualitative, "mechanistic" and thus much simplified picture is outlined.

Upon tangential loading, the loaded interface will develop a resistance against the load by deforming. As shown in Fig-

ure 6a, this occurs by atom a moving to the dotted position a' , where its distance to the center of atom c is increased without appreciably reducing its distance to the center of atom b (Figure 6b). According to Figure 4 this causes an increase in potential energy and the building up of a tangential force, opposing the tangential load. Thus the "static" resistance against tangential loading is directly related to the resistance against normal separation of the surfaces, as for adhesion. In fact, the only difference is that the available adhesion energy per pair of atoms (a and c) is only partly involved in the interfacial shear resistance. Beyond some displacement of atom a, its resistance against tan-

gential motion begins to decrease until it reaches the position just above atom b where the resistance becomes zero. Here the attraction a-c is just compensated for by the attraction a-d.

So far, the picture is similar to that recently presented by Ludema.⁵ However, differences emerge from here. In fact, the gain in potential energy associated with the descent of atom a in the cavity between atoms c and d, does not assist atom a in its next uphill movement (i.e., a "roller coaster" model does not apply). Instead, the potential energy is converted into kinetic energy in the form of increased vibration of the neighboring atoms, i.e., in the form of heat. Thus continuous shearing at the interface by the mechanism indicated requires a lasting supply of energy, which identifies adhesion as the origin of interfacial shear resistance.

Three additional comments are relevant:

1. The notion that interfacial shear produces heat and thus requires a lasting supply of energy to sustain continuous motion, applies equally well to surfaces completely covered with a boundary lubricant film. Now, however, it is the relative movement of the adsorbed organic molecules that causes the conversion of

Figure 6. Schematic picture of interfacial slip on an atomic scale. Atom a belongs to body 1, moving to the right; atoms b, c, and d are part of stationary body 2. Only the direct interaction between atom a and its partners across the interface is considered. The potential energy, gained by an atom during stages 1, 2 and 3 of the elementary cycle is converted into kinetic energy during stages 3 and 4. The greater part of this kinetic energy is dissipated in the form of heat when atoms a and d collide.

Figure 7. Different options for bridging the velocity difference in the junction between a deforming (1) and a rigid (2) body; (a) interfacial shear strength τ_1 small indicates interfacial shear (slip; see Figure 3a); (b) τ_1 comparatively high indicates subsurface shear (see Figure 3c); (c) τ_1 comparatively high, plus large contact/greater sliding motion indicate subsurface shear plus cracking of the junction material ("prow formation").

mechanical energy into heat. This situation has been treated adequately by Israelachvili and Tabor.⁶

2. In principle, shearing of the interface between two uncontaminated metals is similar to shearing along some plane within a metal. If the atomic spacing on both sides of the interface is such that the atoms of the adjacent planes fit neatly into each other's pits, simultaneous motion of all atoms along the interface will almost certainly require a dislocation mechanism, as applicable in the case of shearing within a metal.

3. The interface represents the smallest section of the contact bridge. So it seems to be the most favorable location for shear (Figure 7a). However, if the interfacial shear strength exceeds the strength of the subsurface zone, shear may well occur at some distance from the interface, particularly for strain hardening materials (Figure 7b). Further, in fracture-prone materials, tensile loading in the vicinity of the junction may initiate crack formation (Figure 7c). This induces material transfer

and, eventually, formation of an adhesive wear particle.

Given the above picture of interfacial shear, the existence of a relation between adhesion and interfacial shear strength in contact between bodies which are not covered fully with a boundary lubricant film can be appreciated readily. Shearing requires the surface atoms of one member to climb repeatedly from pits in the atomic surface of the other member, and this motion is opposed by adhesive forces. So any change in surface condition that reduces the adhesion energy (either by contamination or use of another partner material) reduces the interfacial shear resistance as well.

Finally, note that the above principles apply equally well to metals, oxidic surfaces (also metals fully covered by oxide films), other ceramics, and polymers.

Wear

Several different mechanisms can cause wear.⁴ With the possible exception of wear due to cyclic normal loading (as may

occur on normal impact or in adequately lubricated rolling bearings), all wear mechanisms are directly related (but not necessarily proportional) to friction, i.e., to ploughing (in the case of hard and rough surfaces); or to interfacial shear (in the majority of machine elements such as bearings, gears, and sealings in the absence of abrasive material).

Interfacial shear may cause wear via cyclic shear loading, eventually leading to local descaling effects (delamination, Reference 7) or via adhesive material transfer eventually leading to the formation of wear particles (adhesive wear). In both cases the relation with adhesion is obvious.

In cases of 100% coverage with a boundary lubricant (also at a microscale) wear may (and usually does) still occur as a result of the mechanical removal of "reaction products" (possibly including loose oxides). Although adhesion between adjacent nonpolar parts of the organic molecules may be involved, adhesive forces between the atoms of the contacting bodies (or their oxide films) no longer play a role in this case.

Conclusions

We have seen that interfacial shear strength plays an important role in both friction and wear, and that the ratio of the interfacial shear strength and the strength of the contact bridge in the vicinity of the interface is the determining factor in both friction and wear. Although the process of interfacial shear is not completely understood, the existence of a relation between interfacial shear resistance and adhesion is highly probable. Better theoretical insight into this matter still needs to be developed.

The word "adhesive" in the terms "adhesive friction" and "adhesive wear" should be understood to mean: "strongly depending on interfacial shear resistance"; complete separation of contacts normal to their common interface is usually not involved.

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