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Lewis Research Center
Cleveland, Ohio

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and Space Administration

Scientific and Technical
Information Branch

Summary

Various concepts concerning wear mechanisms and deformation behavior observed in sliding wear tracks are surveyed. Experimental results previously reported by the present authors are compared with the results of the survey. The mechanism for wear fragment formation is discussed on the basis of adhesion. Also discussed are boundary conditions to which realistic wear mechanisms should be subject and to which fundamental information on adhesion can be applicable.

The essential difficulty in understanding the wear process under unlubricated sliding conditions is overcome by presenting a reasonable explanation based on the concept of adhesion at the interface during the sliding process. Properties of the interface indicate that the interfacial adhesion bonding occurring between contacting surfaces is generally stronger than the cohesive bond in the cohesively weaker of the two materials in solid-state contact. This can be applied to explain the wear process observed during unlubricated sliding. Furthermore the mechanism for tearing away the surface layer from the contact region and forming the sliding track can be explained by assuming that the material removal process is based on the adhesion theory.

Introduction

The wear of solid surfaces in contact can be caused by one or a combination of wear mechanisms. These mechanisms have been conventionally classified as adhesion, abrasion, corrosion, erosion, fretting, cavitation, and fatigue. Among these mechanisms the adhesion wear mechanism is known as the principal wear mechanism. One of the present authors has indicated the many combinations of solid-to-solid contacts under simplified conditions. He has also stated that the interfacial adhesive bond which develops between the contacting surfaces is generally stronger than the cohesive bond in the cohesively weaker of the two materials and that the cohesively weaker metal generally transfers to the cohesively stronger on separation of the surfaces. These behavioral characteristics of the interfacial surface, even if not yet thoroughly elucidated, have explained the phenomenon of material transfer between contacting surfaces.

When discussing the wear mechanism based on adhesion, the assumption is tacitly adopted that the phenomenon of material transfer is the wear process itself. However, a critical counterargument has been frequently offered, that is, that material transfer does not necessarily guarantee the formation of wear fragments unless the fracture or detachment occurs subsequently at or in the contact location. Therefore the subject is still debated, particularly with respect to how wear fragments are produced in the process of relative motion between contacting surfaces.

In this report, the wear mechanism and deformation behavior at contacting surfaces are discussed on the basis of the authors' experimental results and the boundary conditions to which realistic wear mechanisms are subject. Our analysis of the wear process incorporated the fundamentals of adhesion. There are many publications dealing with the deformation behavior of contacting surfaces. Therefore we attempted to arrange the various adhesive wear mechanisms and deformation behaviors of contacting surfaces and to correlate them.

Survey of Points Related to Adhesive Wear Mechanism

Three representative combinations of contacts are illustrated schematically in an exaggerated form in figure 1. In most cases[1] in which solid particles impinge against a softer target material, they will remove some of the surface layer, when leaving the target, by a combination of their movement on the target surface and the effect of normal and tangential forces (fig. 1(a)). Therefore the adhesion between an erodant particle and a target is predicted to play an important role. Even if a single impact cannot remove a surface layer, subsequent impacts may do so. Microcutting or fatigue can also occur at the surface. The material transfer can be reasonably regarded as the principal "wear mechanism" in the weight loss of bulk target for this type of contact. Therefore detachment or fracture between an erodant particle and a "wear" fragment is not necessarily required in order to define the wear process. The foregoing assumption is reasonable and acceptable for most cases of erosion in which adhesion is prevalent. It is important to understand why the interfacial adhesive bond is stronger than the cohesive bond in the cohesively weaker metal in order to explain the wear process.

There are many cases in which the rubbing surfaces are always in contact at the location where the candidate wear fragment may be produced, and deformation or fracture may take place inside or at the periphery of this contact area. Therefore, under these "boundary" conditions, the wear process is more complicated. For example, in figure 1(b), a rider of a soft material slides on a hard material larger in size. The surface layer of the soft rider will probably transfer to the harder mating material

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[1]There are, however, erosion processes in which surface failure occurs without the aid of adhesion or detachment. When fracture takes place at a location not at the interface, fragments are formed, for example, when droplets impact on a solid surface (ref. 1). In this study, however, attention was focused on the solid-to-solid contact problem.

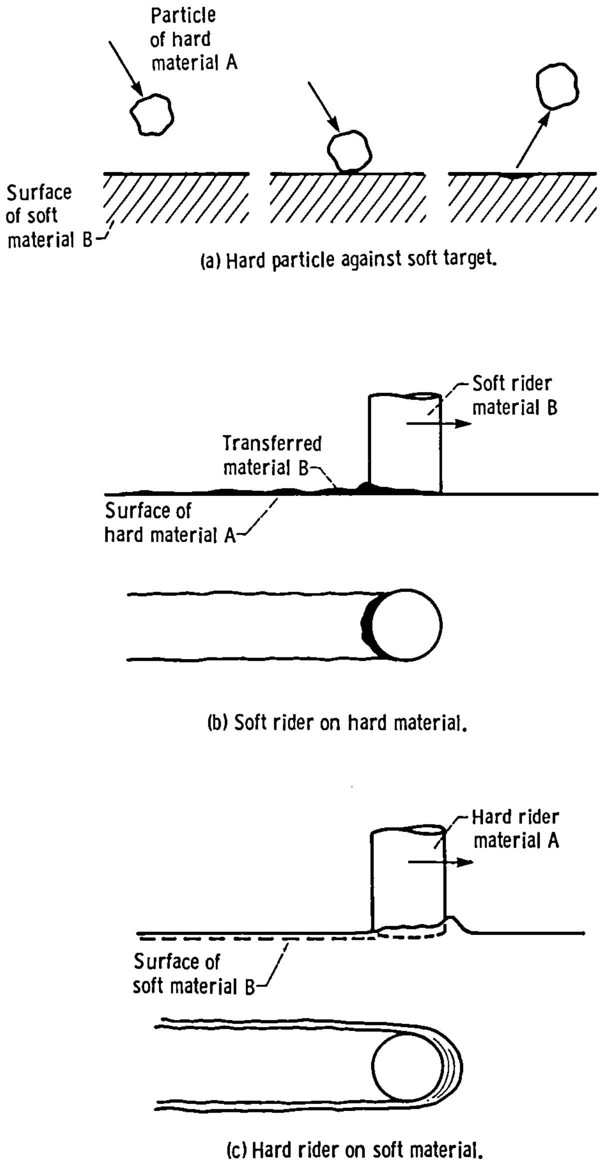


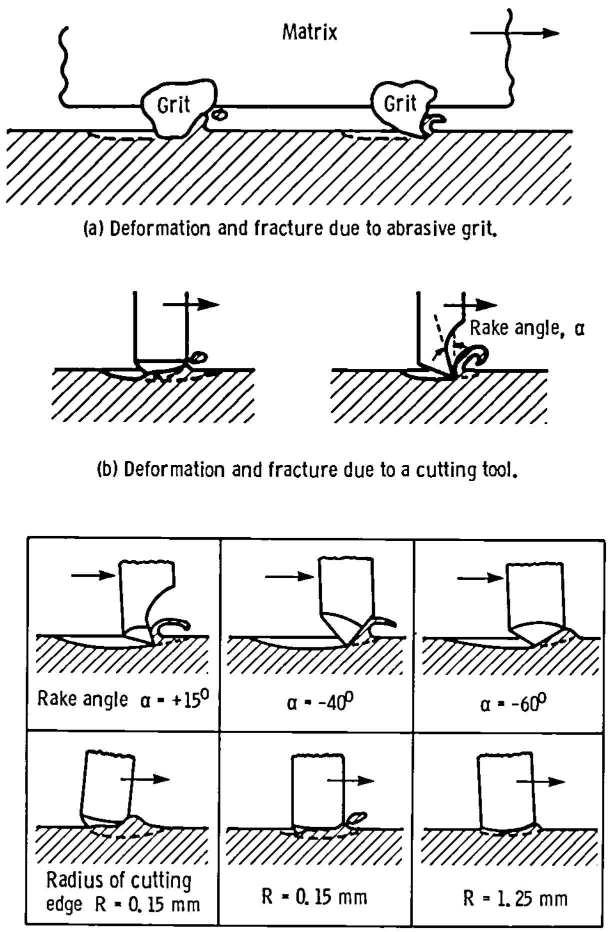
Figure 1. - Representative combinations of contact between hard and soft materials.

by tearing off and smearing; and a certain fraction of deformed material within the contact area will remain attached to the trailing edge of the rider. Furthermore a certain fraction of material accumulated at the trailing edge will be separated intermittently from the rider and will be taken away by the mating material.[2] The ratio of the amount of wear from the trailing edge to the primary amount of wear from the contacting surface may differ depending, for example, on the sliding conditions and the combination of materials. Transferred material adheres to the harder material and is not released from the system unless some other process for material transfer takes place. The repetition of sliding makes the interface between the soft rider and the material transferred to the harder material participate in the sliding process. In this stage a certain fraction of the transferred material will be removed from the contact system as wear fragments. The surface layer of the rider will transfer and repeat the same process again. The weight of the rider generally successively decreases with sliding distance for this combination. The process of losing the soft material is again reasonably defined as wear independently of separation between the harder material and the transferred material. On the basis of morphology, the wear process may be substantially the same as erosion in the sense that material transfer decreases the weight of the rider. An exception is the case where the effect of velocity or strain rate cannot be neglected or where the velocity normal to the target surface contributes to the formation of wear fragments. There also remains unresolved, however, the problem of the fracture process in the same way as it occurs in erosion, that is, how the surface layer of soft material is separated from the bulk material in the contact area and where the crack first appears in the material leading to the formation of the fragment that transfers to the mating material.

The wear process or material transfer mechanism for the combination of a hard rider sliding on a soft material is considerably different and more difficult to define. Figure 1(c) shows a representative case in which the plastic deformation of soft material is relatively large. This is brought about by the action of the leading edge of the rider. A certain fraction of the deformed material may transfer to the peripheral edge of the rider. This kind of deformation has been studied by many investigators for many years. Most of these studies have been carried out in relation to abrasive wear and grinding processes.

Representative deformation behavior caused by an individual abrasive grit is shown schematically in figure 2(a). In the real grinding process, plowing, microcutting, and material transfer can occur at the interface between the abrasive grit and the workpiece. When the rake angle is similar to that of a cutting tool, the wear process can be represented as shown in figure 2(b). Figure 2(c) shows a schematic illustration indicating cutting and deformation of a workpiece. Graham and Baul (ref. 2) described (1) a transition from plowing to cutting as the rake angle increases, (2) microcutting by pyramidal tools having an adequate rake angle and the resulting formation of minute metal chips, (3) fracture resulting in the formation of a piece of metal on the free plastic surface of a spherical tool with an adequate radius of curvature, and (4) plowing in front of and at the edge of the tool when the radius of curvature becomes relatively large.

[2]In this report the material taken away in such a manner is not defined as transferred material. The term "transferred material" is taken in a narrow sense; that is, it is defined as the material that was plucked out instantaneously from the contact area by a single interaction of the mating surface.



(a) Deformation and fracture due to abrasive grit.

(b) Deformation and fracture due to a cutting tool.

(c) Deformation and fracture behaviors observed by Graham and Baul (ref. 2).

Figure 2. - Schematic illustrations of deformation and fracture occurring in front of a hard material.

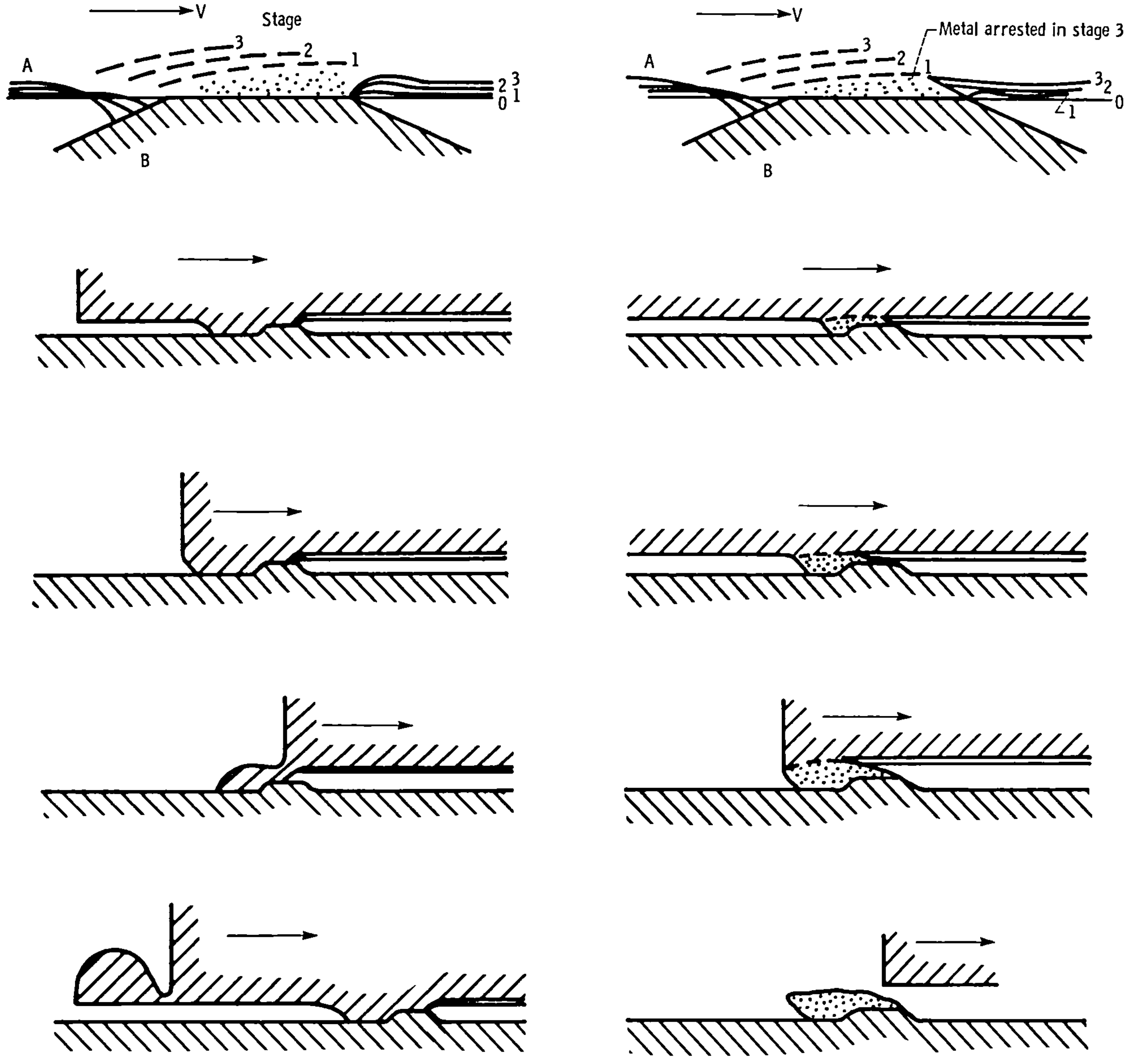
Many fundamental studies have dealt with deformation behavior such as pileup and material displacement in front of a rider (refs. 3 to 5). If the grit or rider has an adequate geometrical shape, the wear fragment will be produced in the microcutting process or in the final process in plowing, independently of the definition of wear and its relation to metal transfer. This is certainly a reasonable position. Thus fundamental knowledge can be partially used for understanding the mechanism of abrasive wear and erosion by the individual grits or erodant particles. There are, however, several difficulties in explaining the phenomenon taking place in the common configurations frequently observed in most tribological systems.

In the case of contact with a well-finished surface, the inclination angle or slope for practical topography is generally small. Therefore most of the negative rake angle effects may exceed the foregoing critical value and the equivalent radius of curvature under which plowing prevails. In other words, the microcutting process cannot be directly applied to the wear mechanism for this kind of contact problem. On the other hand, the equivalent radius of curvature of the profile for an apparent contact surface is far larger than the representative length of the contact area even in the counterformal contact situation frequently observed in rolling-element applications. It is also true in conformal contacts, for example, in the contact between an axis and a journal bearing or in flat-to-flat surface contacts.

In counterformal configurations, the deformation in the contact area is restricted mechanically by the mating material. In other words, the surface layer cannot deform as freely as it does in the process involving individual grits or asperities. Therefore the conventional knowledge that has been developed about the effect of the individual grit or asperity cannot be adapted to deformation problems observed in practical counterformal contact applications. The counterargument discussed in the **Introduction**, which is not pertinent to the contact problems described above, seems to be strictly critical for counterconformal contact problems. It is more difficult to explain the mechanism for the formation of a wear fragment in the contact area and its release from the contact system.

Landheer and Zaat offered a simplified mechanism for the development of junction and metal transfer that is presented in figure 3 (ref. 6). In a case where no crack formation occurs even after a long sliding distance, the metal is continuously flowing behind the contact, and at some time the junction reaches the edge of the test piece. When more junctions pass by the edge of the running surface, the material becomes heavily deformed and builds up along the sides of the junction (fig. 3(a)). In a case where the slope of the deformation front rises until an equilibrium value is reached, cracks form in the deformed area, and the metal readily adapts itself to the prow form. The growth of the prow opposite to the direction of motion continues until the edge of the donor is reached, and the prow is left on the mating surface as a transferred particle (fig. 3(b)).

There is, however, scarcely a practical situation such as that depicted, except in abrasive wear, where the simple mechanism can be applied. In most tribological systems, it is not feasible for a junction to develop continuously over the whole contact area. Note that the mechanism indicating "junction growth" is in the vertical direction. Sasada, et al. (ref. 7) offered a mechanism that involves incipient wear fragment formation. In this case, a transferred particle grows larger and larger with repetitions of transfer, and a mature wear fragment ultimately leaves the contact area. This is based on the measurement of variations in the gap between sliding surfaces (transverse movement of the pin specimen with respect to the disk surface; see ref. 7). Cocks and Antler (refs. 8 and 9) also observed a similar deformation behavior for the transferred material between sliding



(a) Stages in development of junction leading to deformation wear.

(b) Stages in development of junction leading to metal transfer.

Figure 3. - Mechanisms of junction development and metal transfer by Landheer and Zaat (ref. 6).

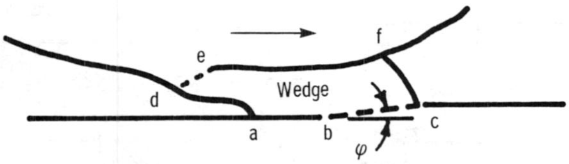
surfaces by using similar configurations. Figure 4 represents Cocks' result.

The plastic shearing takes place in a direction slightly inclined to the surfaces, so that the sheared metal is forced to emerge from the surface and the interface quickly becomes distorted (fig. 4(a)). As sliding proceeds, shearing in the metal adjacent to the lump on the lower flat material (fig. 4(b)) causes the sheared metal to accumulate rapidly and to form a wedge.

Wear Process Predicted from Authors' Experiments

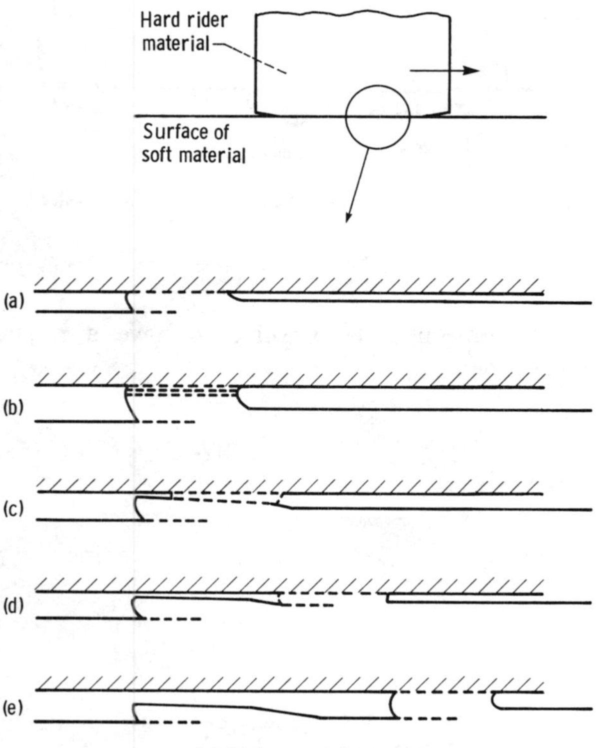
Characteristic modes of deformation and fracture were observed on the surface of 304 stainless steel disks slid against aluminum oxide riders in a vacuum of 10^{-6} Pa and in an environment of 5×10^{-4}-Pa chlorine gas at 25° C (ref. 10). The observations were (1) that an accumulated surface layer is left behind the rider and step-shaped

(a) Configuration of interface after a very short sliding distance.



(b) Wedge formed between contacting surfaces during subsequent sliding.

Figure 4. - Wedge formation between contact surfaces by Cocks (ref. 8).

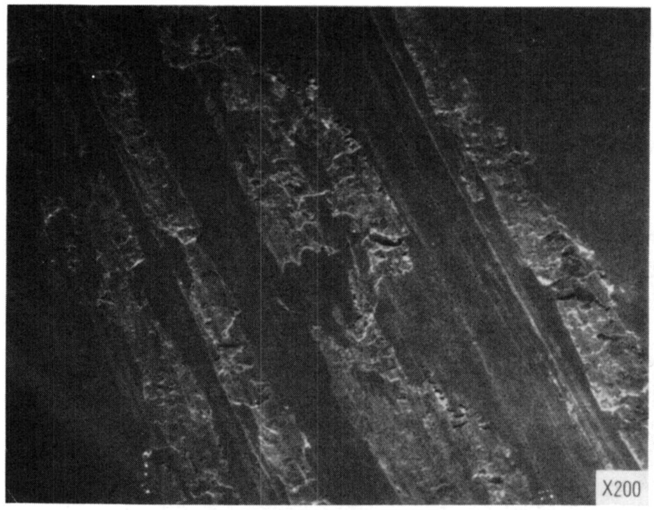


(a), (b) Accumulation process
(c), (d) Separation process
(d), (e) Accumulation process

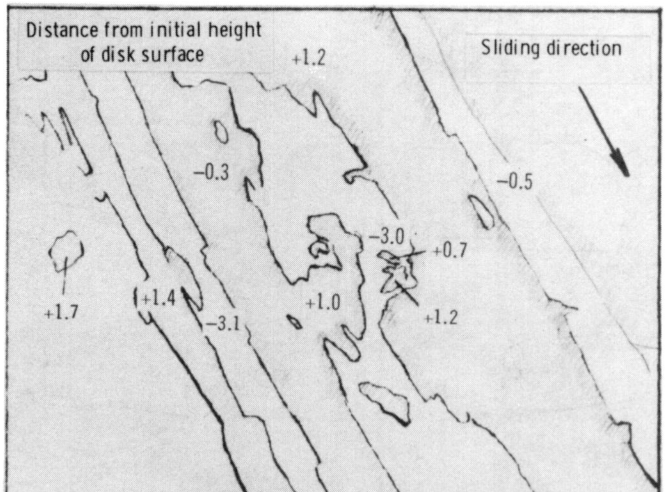
Figure 5. - Process for forming protuberances (ref. 10).

protuberances are developed even after one pass of the rider across the surface and (2) that a matured surface layer having a characteristic morphological profile is gradually torn off (fig. 5). The discussion of the formation mechanism of the step-shaped protuberances in reference 10 takes into consideration the groove, the shape of the protuberances, and the slip marks observed on the sliding track.

The initially smooth disk surface will become rougher with repetitious formation process for the step-shaped protuberances. The protuberances, once formed in the initial stage of sliding contact, may either be removed from the surface as a wear fragment or pressed on the surface and flattened. In this manner, a plateau-shaped surface layer, probably having different mechanical properties, will be formed in subsequent sliding passes. The process of wear fragment formation and sliding track formation can be elucidated by considering the contours formed at the sliding surface, as shown, for example, in figure 6.



(a) Typical sliding track.



(b) Topographical representation of sliding track.

Figure 6. - Typical contour of sliding track (ref. 10).

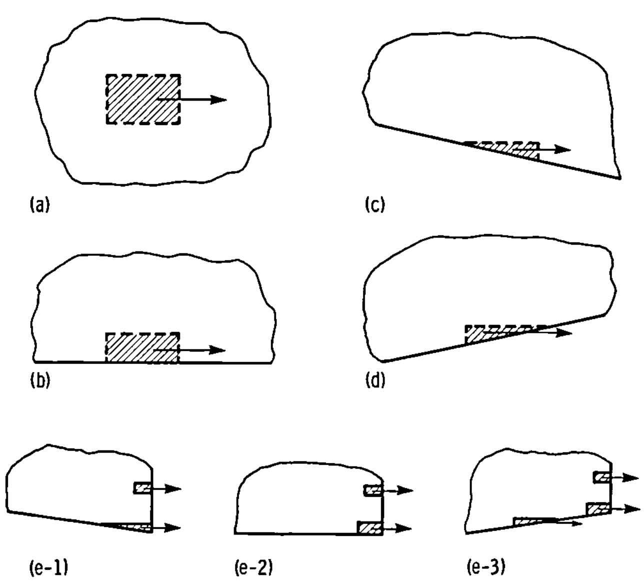
It is generally difficult for any particle of material to move out of the inside of the plateau, as illustrated in figures 7(a) to (c), or from the leading edge of the plateau. On the contrary, if the plateau is shaped as illustrated in figures 7(d) and (e), particles in the surface layer can be taken off from the edges of the plateau more easily than from inside the contact area. Therefore three situations can be modeled, as shown in figure 8. In all cases, no surface layer exists to oppose the detachment of particles. The shape of the particle is assumed here ideally to be a rectangular parallelepiped. The shear strength of the interface between the rider and the surface layer is represented with γ_0. The shear strength at the depth h from the surface is denoted by γ_h. The term σ_t represents the average tensile strength of the surface layer. The average shear strength of the "side wall" of the area defined by $b \times h$ can be assumed to be approximately $(\gamma_0 + \gamma_h)/2$.

Case a: Detachment from Corner of Plateau

The required critical condition for the balance of forces allowing the detachment of a particle from the corner of a plateau (fig. 8(a)) can be described as follows:

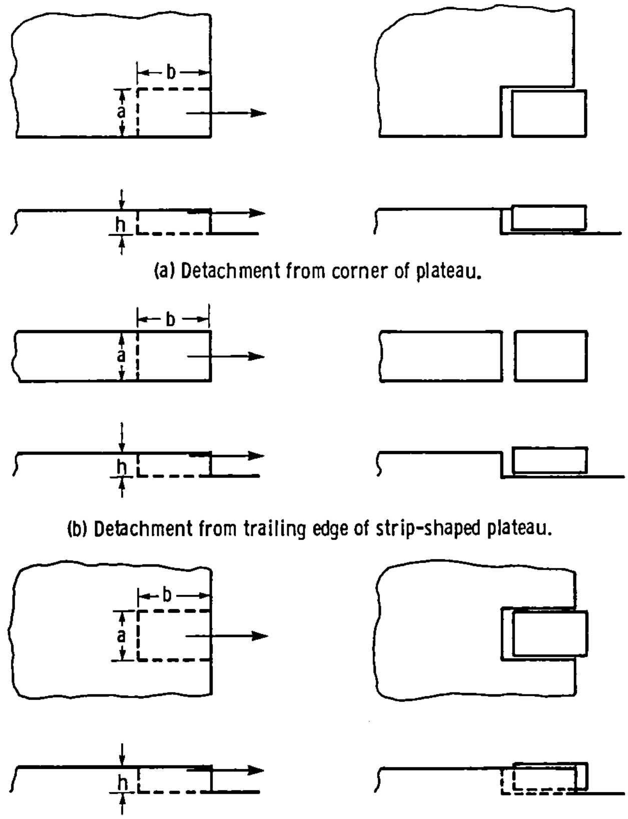
$$\tau_0 ab > \sigma_t ah + \tau_h ab + \left(\frac{\tau_0 + \tau_h}{2}\right) bh \tag{1}$$

$$\left\{(\tau_0 - \tau_h)a - (\tau_0 + \tau_h)\frac{h}{2}\right\} b > \sigma_t ah \tag{2}$$



(a) - (c) Contours where lumps are not easily removed.
(d), (e) Contours where lumps are easily removed.

Figure 7. - Illustrations of various contours on sliding track, where particles are removed from the surface layer.



(a) Detachment from corner of plateau.

(b) Detachment from trailing edge of strip-shaped plateau.

(c) Detachment from trailing-edge inside plateau.

Figure 8. - Three models for detachment of particles from a plateau.

The left term must be positive to have a physical meaning. Then

$$(\tau_0 - \tau_h)a > (\tau_0 + \tau_h)\frac{h}{2} \tag{3}$$

Again for equation (3) to have physical meaning,

$$\tau_0 > \tau_h \tag{4}$$

Therefore requirement (3) is reduced to

$$a > \left(\frac{\tau_0 + \tau_h}{\tau_0 - \tau_h}\right)\frac{h}{2} \tag{5}$$

and requirement (1) is reduced to

$$b > \left[\frac{\sigma_t}{(\tau_0 - \tau_h)a - (\tau_0 + \tau_h)\frac{h}{2}}\right] ah \tag{6}$$

Case b: Detachment from Trailing Edge of Strip-Shaped Plateau

The required condition for the detachment of a particle from the trailing edge of a strip-shaped plateau (fig. 8(b)) is simpler:

$$\tau_0 ab > \sigma_t ah + \tau_h ab \quad (7)$$

$$(\tau_0 - \tau_h)b > \sigma_t h \quad (8)$$

For the equation to have a physical meaning, the same equation as (3) must be valid. Then equation (7) becomes

$$b > \left(\frac{\sigma_t}{\tau_0 - \tau_h}\right)h \quad (9)$$

Case c: Detachment from Trailing-Edge Inside Plateau

The equation for the balance of forces that can cause the detachment of a particle from the trailing-edge inside plateau (fig. 8(c)) is as follows:

$$\tau_0 ab > \sigma_t ah + \tau_h ab + \left(\frac{\tau_0 + \tau_h}{2}\right)2bh \quad (10)$$

$$\left\{(\tau_0 - \tau_h)a - (\tau_0 + \tau_h)h\right\}b > \sigma_t ah \quad (11)$$

For equation (11) to have a physical meaning, the left term must be positive

$$(\tau_0 - \tau_h)a > (\tau_0 + \tau_h)h \quad (12)$$

Again, if assumption (4) is valid, equations (11) and (12) are reduced to the following equations, respectively:

$$a > \left(\frac{\tau_0 + \tau_h}{\tau_0 - \tau_h}\right)h \quad (13)$$

$$b > \left[\frac{\sigma_t}{(\tau_0 - \tau_h)a - (\tau_0 + \tau_h)h}\right]ah \quad (14)$$

As indicated above, the most fundamental equation assumed here is equation (4). In our example, the cohesive bond of the 304 stainless steel disk is weaker than that of the aluminum oxide rider. If an interfacial adhesive bond develops in the contact area, it is generally stronger than the cohesive bond in the cohesively weaker of the two materials. The detachment should therefore occur in the 304 stainless steel disk. Then the assumption of equation (4) is not in contradiction to the foregoing phenomenon.

Taking into account the schematic geometry of figures 7(d) and (e) and the principal categories of figure 8, initial configurations should have a tendency to change gradually into a final stable profile that is more parallel with respect to the sliding direction, as shown in figure 9. The contour of the sliding track corresponds to that shown in figure 6. On the other hand, in the steady state, particles are torn away from the plateau, and the area within a groove that has formed in the process of removing the plateau begins to participate in the contact process. It forms both an element of a new plateau and step-shaped protuberances. It should be noted that a particle that detaches from the plateau does not necessarily become a wear fragment. A detached particle will probably be crushed into smaller pieces, and in some cases small fragments adhere to each other between the contacting surfaces to develop into a wear fragment.

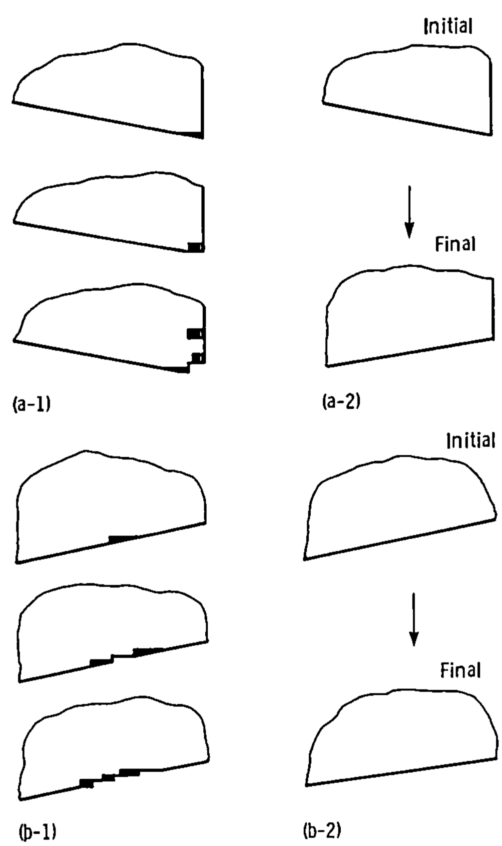


Figure 9. - Two types of transformation of initial contours into stable ones on sliding tracks.

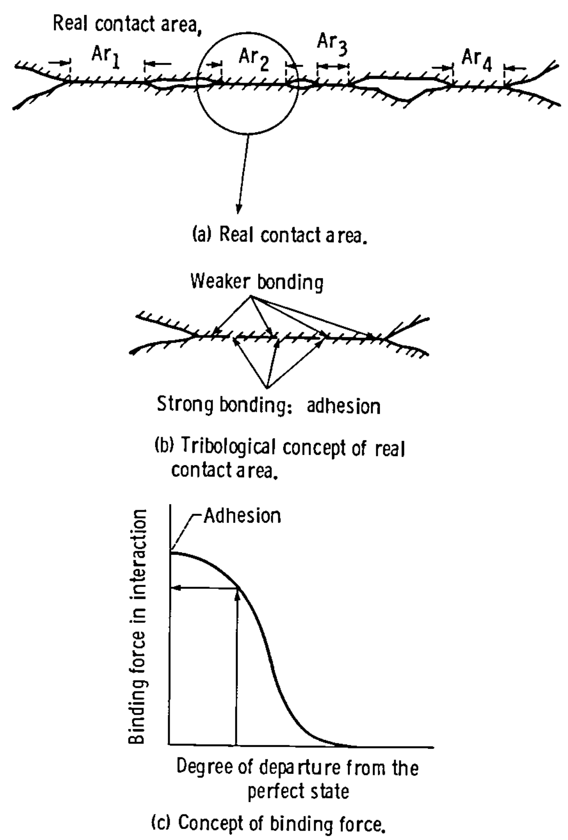
Wear Mechanisms Based on Adhesion and Fatigue

There is a view that wear fragments are produced in a fatigue process through repetitive loading applied either in single- or multipass sliding on the mating surface. In single-pass sliding the repetition is assumed to be realized by the multiple interactions of the surface asperities within the contact area. The essence of fatigue is the phenomenon that a microcrack begun in the material can propagate only under repetitive loading and cannot develop under static loading of the same magnitude. When the concept of fatigue is adapted to wear, a more exact comparison must be made on the basis of reasonable mechanics. The phenomenon of crack growth in fatigue is of course related to the separation of the surface layer at some depth in the parent material during the wear process. However, metal transfer, which implies the separation of surface layers, can take place during one pass of the rider, as well as in multipass sliding. Metal transfer has been observed after a single contact and sliding pass. In other words, separation and fracture can always occur in the material without the aid of repetitive loading at the contact surface. Therefore the most essential problem in a wear process under the unlubricated condition is not introducing the concept of repetitive loading (i.e., fatigue) but presenting a reasonable explanation, based on the concept of adhesion, as to how the interface can be separated again during sliding.

Investigators who emphasize the concept of fatigue pay much attention to the behavior of material properties that change with the number of repetitive passes of sliding. This viewpoint is frequently applied to the wear process for moderate sliding contact, where material transfer does not prevail. Some material property may change and deteriorate into the situation that facilitates the crack formation leading to the wear fragment. The fracture criterion is generally determined from the material properties and stresses involved in the fracture process and is based on knowledge of fracture mechanisms. Therefore, if the assumption is made that material deterioration lowers the fracture criterion for crack initiation or propagation by loading, the variation of material properties can be treated with and included in the mechanical conditions. This can be done independently of applying the concept of fatigue.

The authors' opinion as to how the interface can be separated again during sliding is based on the concept of adhesion, which is described as follows: In the contact process a certain amount of elastic strain energy is stored in the material near the interface, even under extremely light loads. The elastic strain energy is produced through the relative microdisplacement at the interface and the plastic deformation in the interacting area. This is especially true in such a mechanical process as sliding, where displacement accompanied by plastic deformation occurs at the surface both in the normal and tangential directions. The order of elastic strain at the elastic limit does not usually exceed 10^{-4} for ordinary metals. If the representative length of the real contact area relative to adhesion is assumed to be 10 μm, the absolute displacement corresponding to the strain is 1 nm. The occurrence of 1-nm displacement fluctuations is mechanically unavoidable either in the tangential or normal direction, even when the sliding conditions are carefully controlled. With a relatively soft material, annealed aluminum or copper, for example, the elastic strain energy stored in the material will be released easily by the subsequent plastic deformation process.

What kind of mechanism can be assumed to occur for metals other than soft ones? The real contact area generally consists of each of the contacting "spots" Ar_1, Ar_2, etc., in contact, as shown in figure 10(a).
Because of the character of the interactions, there are a variety of binding situations in the real contact area, for example, interposing of the environmental gas molecule and mismatching in the metal structure. Therefore the tribological concept of the real contact area is illustrated in figure 10(b). The binding force in the interfacial surface may be distributed as shown in figure 10(c). If a



(a) Real contact area.

(b) Tribological concept of real contact area.

(c) Concept of binding force.

Figure 10. - Concept of real contact area.

shear force is applied to the real contact area, the cohesively weaker region may be detached. When the spot involved in the bonding escapes from the environment pressurized by the interaction, the interface is partially separated at the area bonded more weakly by the release of elastic strain energy. The separated area functions as the extremely sharp-edged preexisting crack that generally causes the large stress concentration at the interface. Therefore the average shear force required for detaching the specific "apparent real" contact area decreases markedly. This latter force may be less than that separating the interior bonding of the same magnitude. In other words, the average shear force required for separating the specific real contact area at the tribological surface can be greater than that of cohesively weaker material only under the condition that the interface is pressurized by the normal component of external loading. Even if the fracture occurs below the interface, its location should be close to the interface because the real contact area is predicted to be very small in this stage.

As described in a previous report (ref. 10), the rider inevitably moves up and down in the sliding process. Therefore the interface of some spot can be separated in the process of upward movement without the aid of the tangential force. This behavior facilitates the aforementioned separation mechanism at the interface. The following characteristics for the separation behavior should be noted: Protuberances can develop partially by shearing as a result of the tangential movement of the rider that takes place below the interface, as was explained in detail in reference 10. As observed, in single-pass sliding, the surface layer partially accumulated and developed is detached after the rider slides some distance (ref. 10). This does not contradict the strength properties observed in the relationship between the interface and the cohesively weaker material. Several protuberances, with different growth rates, are generally produced at the contact area. Therefore the surface layer is detached at or near the interface of one protuberance by the upward movement of the rider surface. This upward movement is caused by the protuberances developed at other locations. The tendency also does not contradict the separation mechanism described above.

As already stated, repetitive loading is not the only mechanical factor that causes surface layer fracture and metal transfer in the sliding process. Therefore the application of the fatigue theory must be limited to certain situations, for example, (1) where a sufficiently large tangential force cannot be expected to occur, (2) where constraint is unavoidable at the surface in the normal direction, or (3) where the relative displacement is comparatively small in the tangential direction between contacting surfaces. An example of situation (1) is a wear process where the surfaces are sufficiently lubricated. An example of situation (2) is ordinary rolling-contact fatigue under the condition of small roll-slip ratios. An example of situation (3) is fretting. In these situations, the term "fatigue" has been used adequately, and a mechanism similar to that described in this study cannot be expected to hold.

Conclusions

Various concepts concerning wear mechanisms and the deformation behavior observed in the sliding wear track were surveyed. Experimental results previously reported by the present authors were compared with the results of the survey. The mechanism for wear fragment formation was discussed on the basis of adhesion. Boundary conditions to which a realistic wear mechanism should be subject and to which fundamental adhesion information can be applicable were also discussed.

The principal conclusions reached from the results are as follows:

1. The primary key for understanding the wear process is to resolve the confusion arising from the adhesive wear mechanism by making the assumption that the phenomenon of material transfer is a wear process itself.
2. The essential difficulty in understanding the wear process under unlubricated sliding conditions can be overcome not by introducing the concept of fatigue but rather by presenting a reasonable explanation based on the concept of adhesion and how the interface is separated during the sliding process.
3. The fundamental concept that an interfacial adhesive bond between contacting surfaces is generally stronger than the cohesive bond in the cohesively weaker of the two materials is applicable to the general interface and can be adapted to explain the wear process during unlubricated sliding.
4. If the material removal process is simplified by assuming it to be based on adhesion theory, the mechanism for tearing away the surface layer from the contact area and forming the sliding track contour previously reported by the authors can be explained very well.
5. From the authors' model relative to the real contact area, the arguments against the adhesive wear theory can be overcome.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 30, 1982

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Takashi Yamamoto, University of Tokyo, Tokyo, Japan, and National Research Council - NASA Research Associate; Donald H. Buckley, Lewis Research Center.

16. Abstract

Various concepts concerning wear mechanisms and deformation behavior observed in the sliding wear track are surveyed. The mechanism for wear fragment formation is discussed on the basis of adhesion. The wear process under unlubricated sliding conditions can be well understood by presenting a reasonable explanation based on the concept of adhesion at the interface during the sliding process. The mechanism for tearing away the surface layer from the contact area and forming the sliding track contour is explained by assuming the simplified process of material removal based on the adhesion theory.

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