Adhesion

When the adhesion theory of friction was invented [7], very little was known on the mechanism of adhesion. At present, it is claimed that a science of adhesive joints exists [8] and a model which contradicts this science cannot be true to life.

One of the essential ideas of the new concept of adhesion deals with *weak boundary layers*. If a layer of air, of a soft solid, or another weak material is present between a strong adherend (substrate) and a strong adhesive, and if a destructive force is applied from outside, the rupture is most likely to proceed in the zone of weakness. Thus, if two metal blocks are placed one on top of the other and then pulled apart, the separation occurs in the layer of air present between the two surfaces "in contact." The function of adhesives is to remove the weak boundary layer and to achieve, after solidification, a system "strong adherend–strong solid adhesive–strong adherend," in which no weak phase is present and whose breaking stress is high.

According to the adhesion theory of friction, strong joints (usually welded) form at once when a slider is placed, in air, on a support. If such a formation of junctions really occurred, the manufacture of adhesives would have never been attempted. In reality, weak boundary layers cannot be removed simply by putting one solid (A) on the other (B). The absence of adhesion between the two is readily proved by lifting solid A from B; the force required for separation is exactly equal to the weight of A; no excess force attributable to adhesion can be detected.

The absence of adhesion at a perpendicular translation of a slider was explained [9, 10] by stress relaxation. When a hill of a slider presses against a hill on a support, both are deformed; and when the pressure is taken off, they are said to assume their initial shapes so that no adhesional force remains. Now, too much is known about the rupture of adhesive joints to accept this explanation. When two adherends are glued together under pressure and the pressure then is released, the elastic stresses in the solids frequently will give rise to peeling stresses. The present theory of peeling is sufficiently reliable to state that, when no adhesion can be measured in the absence of pressure, none was present also when the pressure was still on. This conclusion is readily confirmed by the experiment: if a slider is glued to the support by an adhesive, adhesion is noticed during their normal separation whatever the pressure, before or after the test.

The theory of weak boundary layers is confirmed also by systems in which none exists. If the air and the adsorbed films between two solids are removed in a high vacuum, nothing prevents true molecular contact between them, and they adhere to each other [11]. When two solids are pressed together in a high vacuum and then pulled apart, considerable force is needed to achieve separation [12]; this proves that the elastic stresses accused of breaking welded junctions in air are not guilty. In air, there was no need to break junctions as none existed; in a high vacuum, they form and continue to exist in spite of elastic stresses.

"Solid-to-solid" adhesion, i.e., one observed when there is no adhesive between the two solids, is a well-known effect also in air; every nail driven into wood supplies an example. The various mechanisms of this apparent adhesion are discussed in Reference [8]. This phenomenon has no connection with sliding friction, as defined earlier. The force needed to push a nail along the surface of a wood block usually is not proportional to the normal load on the nail, markedly depends on the geometrical area of contact (i.e., on the sharpness of the nail) and is not reproducible (i.e., a second travel along the first path needs a driving force different from that needed for the first trajectory).

Conclusion

In conclusion, the modern concept of adhesion, confirmed by many experiments, cannot be reconciled with the adhesion theory of friction. Consequently, this theory is incorrect.

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DISCUSSION

C. W. Allen[2]

The author has commented on some of the ambiguities which arise in the adhesive theory of friction. Some of these contradictions have also bothered the discusser. However, the "hill climbing" or surface roughness theory is also fraught with difficulties. The author considers a single slider slowly climbing an incline and then falling down the opposite slope. In reality, there would be a large number of asperities in contact at one time; some would be climbing and others descending the slopes. The net result would be an essentially constant height of the slider above the support.

As a simple example, consider a support having a high modulus of elasticity and a slider of low modulus. For low loads the slider asperities can be assumed to deform elastically while the support remains rigid. As the slider is moved horizontally, an asperity on the slider would behave in an analogous manner to a spring loaded cam follower. Considering all such asperities, some would be climbing, some descending, and some would be at the summits or in the valleys, but at any instant the sum of the elastic forces must be equal to the normal load. No real deformation is ideally elastic, and in this respect the discusser would agree with the author that climbing over the hills would introduce some degree of irreversibility.

Most of the theories of friction have attempted to produce a general theory applicable to many diverse conditions. It is the discusser's opinion that the remarkable constancy of the coefficient of friction (0.05 to 0.9 covers practically all combinations) in comparison with other physical constants has led to an unjustified simplification of a phenomenon which must include elastic and plastic deformation, geometry, adsorbed films and surface energy effects.

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R. L. Johnson[3]

The author continues his attempts to discredit the adhesion theory of friction and thereby promote the roughness theory. In the present paper he is using an irrational thermodynamic argument and an improperly advanced concept of fracture to that end.

There is no reason that the friction process, per se, should be considered a complete thermodynamic cycle; previously, no one has suggested it is reversible. Frictional heat dissipation is but one part of a larger thermodynamic cycle that also includes the total heat balance including the source of energy to cause motion.

Griffith's concept of fracture applies only to completely brittle materials; it was accepted in 1922 but is now out of date. Modern dislocation studies, however, give reason to question if any crystalline slider materials used in engineering practice can be considered brittle. Even lithium fluoride shows ductile behavior [13].[4]

The author accepts the role of surface films in preventing adhesion and indicates that finite force is needed to separate clean contacting surfaces in a vacuum but denies the relevance between friction and adhesion. His statement that elastic stresses are not important in breaking adhesive junctions is out of context. All that need be implied by the data cited is that the adhesive junctions are much stronger than the elastic forces present; with other materials and surface conditions that may not be true. It is, however, a step forward in having the author concede that adhesion does exist between clean surfaces in vacuum. Starting on that point of agreement, the following table presents relevant data (reference [14]) for some experiments at Lewis Research Center using single and polycrystalline copper with an apparatus capable of measuring both adhesion and friction.

Copper form and orientation	Adhesion coefficient before sliding$^{(a)}$	Coefficient of friction$^{(b)}$ start of sliding	finish of sliding	Adhesion coefficient after sliding$^{(c)}$
Single crystal (100) matched planes and directions	1.02	5.1	>40	>130
Single crystal (110) matched planes and directions	0.61	3.4	>40	50.0
Single crystal (111) matched planes and directions	0.30	2.0	21.0	10.5
Polycrystal	1.00	3.0	>40	100

$^{(a)}$Load 50 g, 10^{-11} torr.
$^{(b)}$Load 50 g, sliding velocity 0.001 cm/sec, 10^{-11} torr.
$^{(c)}$Load 50 g, distance slide in preferred slip directions 0.735 cm, 10^{-11} torr.

Adhesion was measured before and after a very short period of sliding without changing specimens. Friction increased linearly during that sliding until values usually beyond the measuring ability of the apparatus ($f > 40$) were experienced. Subsequently, adhesion measurements were made that also showed drastic increases in adhesion over the values obtained prior to sliding. Certainly, these data show a relation between friction and adhesion. The increases are attributed to junction growth and improved matching of orientations with shear and also to work hardening. Thus, the cross-sectional area of adhesive junctions and the strengths of these junctions were increased and caused higher friction (shear strength) and greater adhesion (tensile strength). Similar results for other materials could be cited. It should also be significant that these materials were carefully formed and chemically polished and cleaned surfaces with as little roughness as is technically possible. A friction coefficient greater than 40 with microscopically smooth surfaces is hard to explain on the basis of roughness in those cases.

Auger spectrometry and Low Energy Electron Diffraction and ion-emission microscopy in adhesion measuring equipment are giving us added insight into adhesion and deformation processes important to sliding friction. Those studies identify transferred materials and show that adhesion bonds are so strong that the cohesive bonds of the weaker material are usually fractured. An atomistic mechanics approach to the adhesion is essential to understanding of friction and wear. There are several sets of data like that given above and much engineering experience to show the relevance of the adhesion concepts of friction and adhesion, per se [15]. It is ridiculous to use such irrelevant examples as peeling adhesive and nails driven in blocks of wood to discredit concepts that have been supported not only by research data but by engineering practice. The author should substitute definitive data for conjecture.

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T. E. Simkins[5]

I feel that the theme of Dr. Bikerman's paper should be carried down to an atomic level since as far as we know friction would still occur between atomically smooth surfaces. Thus while macroroughness may constitute a sufficient surface state to produce friction, it probably is not absolutely necessary.

There appears to be some confusion among investigators when an atomic theory of friction is proposed. Some say that it is hard to understand how frictional losses can occur atomically since the force fields of atoms are conservative and thus the work required to cause one surface atom to approach and pass by another is regained in departure. On examining this argument, one can think of only two situations in which the conclusion it draws is true. The first is if each of the two sliding surfaces involved are surfaces of rigid bodies. The second is if the relative surface velocities are infinitesimally small. Clearly neither of these situations represents the physical process of sliding. In reality the atoms are not bound rigidly to any framework and relative surface velocities are not infinitesimal. True, the force surrounding any atom is a function of position only, but this position is taken

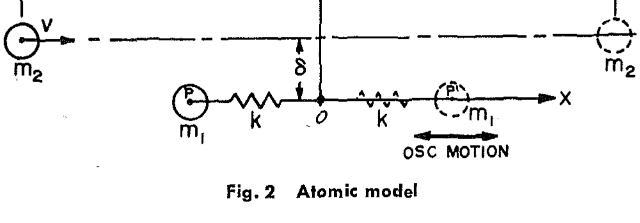

Fig. 2 Atomic model

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[4] Numbers in brackets designate Additional References at end of paper.

[5] Watervliet Arsenal, Watervliet, N. Y.

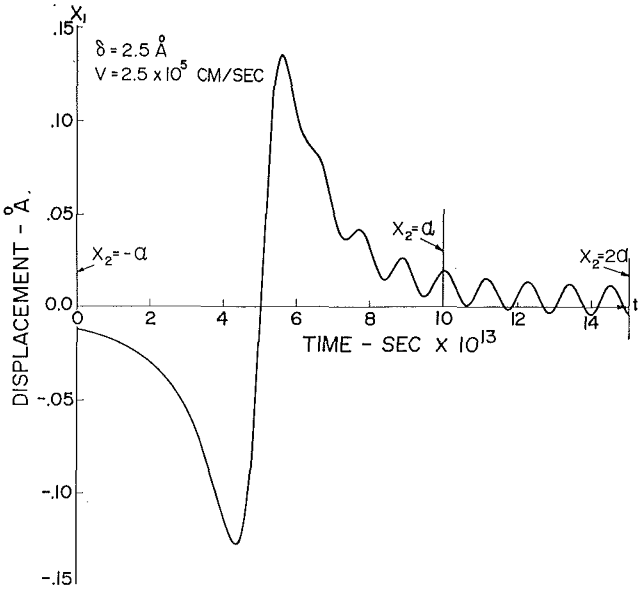

Fig. 3 Displacement of m_1 as m_2 moves from $-a$ to $2a$. (Quiescent initial conditions).

relative to the coordinates of that atom. These coordinates during the sliding process are time-variant and in general there is no such thing as a time-variant conservative force field.

A demonstration of the energy exchange can be given for the highly simplified case of a single atom m_2, which is somehow constrained to pass by another m_1 via rectilinear motion. m_1 is supposed to be bound by a linear force law to a fixed lattice location taken to be at the origin. The force law governing the m_1, m_2 interaction is derived from the potential function applicable to NaCl and thus is nonlinear. The force binding m_1 to the origin is the linear approximation to this force law. For further simplification the velocity V of m_2 is held constant and all motion is constrained to the x-direction. Fig. 2 schematically represents the system and shows m_1 traveling from $x_1 = -a$ to $x_1 = a$ at constant velocity V. Fig. 3 shows the result, i.e., the energy of m_1 has been increased due to the passing of m_2 as can be seen by the oscillatory component not present during the approach phase of the motion. ($x_{1,2}$ are the coordinates of $m_{1,2}$). This oscillatory motion would correspond to thermal energy in the physical situation.

The large value of V for the model was chosen mainly to shorten the computation time. It may be however, that since it is the highest frequency mode of vibration which is excited, such a large velocity would indeed be required. However, in any multiatom system, many modes are available having much lower frequencies and these could be excited by a lower sliding velocity.

D. Tabor[6]

Dr. Bikerman's ingenuity on behalf of the roughness theory of friction continues to fascinate me. His paper is lively and intriguing. I am sorry if I am not convinced.

There are two points I wish to make. Dr. Bikerman suggests that work is done in dragging one body up the slope on the other, but that it shoots down on the other side and like a stretched spring which is suddenly released, dissipates energy. It cannot do this simply by sliding: if energy is to be consumed it must do so by plastic deformation when it "hits the ground." His roughness theory is therefore an indirect way of describing a deformation process. If this is not what he means it can only be that the first body accelerates down the slope and so is able to surmount the next slope and use up its kinetic energy in this way. In that case the situation resembles a frictionless roller-coaster in which no net energy is lost if the overall height remains constant. Furthermore a real extended body provides multiple contacts so that while one contact is ascending a local slope another is descending some other neighbouring slope. The emphasis he places on a slow climb up and a quick slide down is an artificial, arbitrary and unreal situation. I think that Dr. Bikerman may be confusing macroscopic with atomic processes. One atom approaching another will attract it and bonds will be formed. As the approaching atom moves away the bond will be stretched until it snaps. The released atoms then flick back into their equilibrium position and vibrate so dissipating energy as heat. As Tomlinson showed forty years ago this could provide an atomic mechanism for friction as atoms slide over one another. But it is in essence an adhesion process where an attempt is made to describe adhesion in atomic terms. Its main defect is that it says nothing about the role of dislocations in the shearing process.

The second point concerns fracture of junctions. Certainly as far as metals are concerned Dr. Bikerman has got the picture quite wrong. As every solid-state physicist knows the fracture of ductile materials involves so large a plastic component that the contribution of surface energy to the energy-balance is quite trivial. For this reason one cannot use Griffith type measurements to determine the surface energy of ductile solids.

Author's Closure

Unfortunately, Dr. Johnson missed the essential condition stressed in the beginning of my paper: surface roughness causes only that resistance to sliding for which "the" law of friction (Amontons, Coulomb) is valid. This law is strikingly invalid for the data presented in Dr. Johnson's table. Instead of the coefficient of friction being independent of the normal load, the "frictional force" is, with the consequence that the "coefficient of friction" is approximately inversely proportional to the acting load; if the load of 50 grams were removed before sliding, this coefficient would have become infinitely great. The independence of the "frictional force" of the visible area of contact also would not be observed in the tests in a high vacuum. Finally, the results are not reproducible in repeated sliding: a shift of only 7 mm is sufficient to raise the "coefficient of friction" from, for instance, 2 to 21. In the Coulomb region of sliding no such change occurs.

Thus, in Dr. Johnson's experiments, no friction in the usual sense of the word was present, while adhesion obviously existed; this is an example of the general rule that adhesion and friction are mutually exclusive.

Griffith's theory of fracture was rejected by me in two publications;[7,8] but ductility is not the reason. I am looking forward to a more detailed treatment of the "larger thermodynamic cycle" envisioned by Dr. Johnson.

Dr. Simkins believes that friction would occur also between atomically smooth surfaces. The only surfaces which are smooth within the amplitude of atomic (or molecular) vibrations are those of low-viscosity liquids. If a light liquid is placed on top of a heavy liquid in a vertical cylinder, the interface is horizontal in the gravitational field of the Earth. If now the cylinder is slightly tilted, the interface soon becomes horizontal again. Thus, the angle of repose is zero, that is, the static friction between two truly smooth surfaces is zero.

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[6] Surface Physics, Cavendish Laboratory, Cambridge, England.

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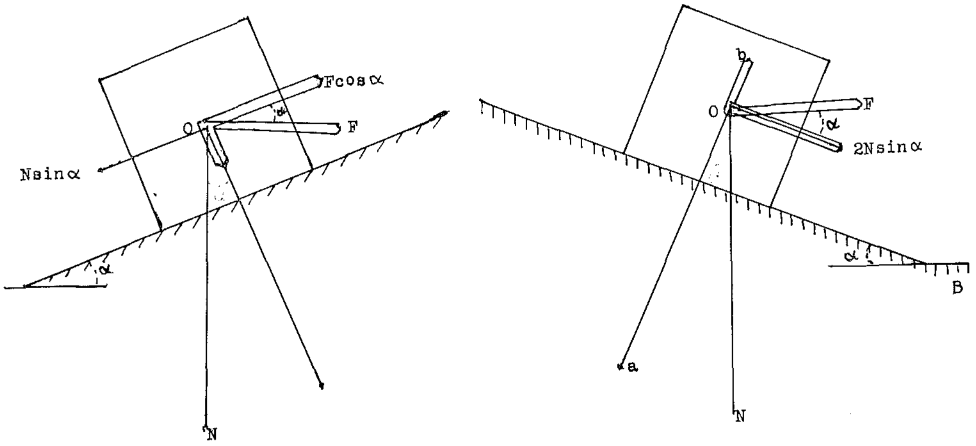

Fig. 4

It is hoped that Dr. Simkins will present an expanded explanation for the oscillation visible in his Fig. 2.

Dr. Tabor states that the slider cannot dissipate energy simply by sliding. Fig. 4 may make it clearer why I disagree with him. For the sake of simplicity, consider a symmetrical hill whose slope is $\alpha°$ both at the left and at the right. The horizontal pull F on the slider is shown by a double, and the normal load N, by a single line. The left hand sketch shows, in the usual way, that $F/N = \tan \alpha$. The right-hand sketch demonstrates that, when the slider moves down the opposite slope, the force acting on it parallel to the slope (and downward!) is $2F \cos\alpha$ or $2N \sin\alpha$. This force acts unchecked, the "leg" of the slider moves with acceleration and causes vibrations when it hits the valley bottom at B; the energy which the slider has just before the contact is transformed into heat, and no plasticity is needed anywhere. The force pressing the "leg" to the support is $\overline{Oa}$-$\overline{Ob}$; as $\overline{Oa}$ is $N \cos\alpha$ and $\overline{Ob}$ is $F \sin\alpha = N \sin^2\alpha/\cos\alpha$, the resulting force is $N(\sin^2\alpha-\cos^2\alpha)/\cos\alpha$. It is positive as long as $\sin\alpha > \cos\alpha$, i.e., as long as α is smaller than 45 deg; this is the usual condition on common surfaces.

My criticism of Griffith's theory escaped also Dr. Tabor's attention.