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On the molecular-theoretical mechanism of friction and lubrication

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Introduction

The purpose of the present paper is to throw some light on the problem of friction and of lubrication from the molecular-theoretical point of view1). Although the phenomenon of friction and the lubrication qualities of lubricants were known for a long time, their molecular-theoretical meanings are not yet clear. The meaning of Amontons's, or Coulomb's, law of friction, that the tangential frictional force F is proportional to the normal force N, but independent of the apparent area of contact and of the relative velocity of the contacting surfaces has not been made clear2). Experimental researches concerning the friction which were made hitherto are not completely reliable except those made recently in which great care was taken to ensure the absence of adsorbed atoms or molecules on the surface of metals. Recently many investigations have been made to study the structure of surfaces by mechanical methods or using cathode-ray diffraction methods. On the other hand, molecular theories of properties of substances have made a remarkable progress, and it is the opinion of the time has probably come when the nature of friction will be made clear from the molecular-theoretical point of view.

Intimately connected with friction is the phenomenon of lubrication. Complete lubrication, in which there is a comparatively thick layer or oil everywhere between the faces, is mainly a problem in hydrodynamics. The theory of complete lubrication was first given by Osborne Reynolds. But when the layer becomes thinner we cannot treat it in pure hydrodynamics and molecular structure of the layer has to be taken into account. When we study boundary lubrication, when the surfaces come into contact except for an invisible film, which may often be monomolecular, we must treat it almost exclusively by molecular theory, In the intermediate region between the complete and boundary lubrication we may have resort partly to hydrodynamics and partly to molecular theory so that the problem will be very complicated.

In this paper we shall treat only the extreme case of lubrication, the case of boundary lubrication by monolayers, and it is hoped that the theory will make some contribution to the explanation of still rather mysterious property known as "oiliness".

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1) A. Harasima and H. Sonoda : 応用物理 (Applied Physics) 13 (1944), 347.

2) Tomlinson : Phil. Mag. 7 (1929), 905.

1. Assumptions made for the structure of surfaces of pure metals

It is assumed that sliding friction is due to exceedingly strong adhesion between those part of the surfaces which come into real contact with each other, when two solid bodies touch. When the solid surfaces come into contact, ti bridges are formed between the two surfaces.[3] These bridges are formed by local adhesions strong enough to be classified as welding. These bridges are broken when sliding occur, and the force required to produce friction is assumed to be equal to the force required to shear these bridges.

Next we assume a mosaic structure of metal surfaces, that is, we assume metal surfaces composed of many tiny blocks, each in coherent atomic arrangement, but independent of each other. We assume that real contacts occur between these bolocks.

2. Theory of sliding friction

When two surfaces come into contact and press each other the pressure is supported by comparatively small areas of real contact so that considerably large load is burdened on the area of real contact. If we assume, as

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3) Bowden and Tabor: Proc. Roy. Soc. A.169 (1939), 391.

mentioned in the preceding section, that real contact occurs between two elevated blocks of two surfaces, each block will be forced into the surface so that there will be a relative displacement between the block and the neighboring blocks. We may regard this displacement to be the plastic deformation from the large scale point of view. The slip between blocks occurs at the boundary surfaces shown in dotted lines in Fig. 1.

When any block sinks another block on one surface comes to be in contact with some block on the other surface and a new bridge is formed.

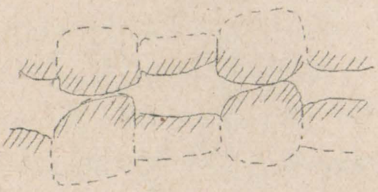

Fig. 1.

This process continues until there are sufficient number of bridges melded blocks to bear the total pressure. We may roughly assume that each bridge bears a definite amount of pressure per unit area which we sh denote by p_o. The pressure p_o may be considered as the pressure at which the solid begins to deform plastically. If we denote the total normal pressure by N the area of real contact, that is, the total cross-section of the bridges formed, is given by

$$S = \frac{N}{p_o} \qquad (1)$$

Thus we see that the area of real contact increases proportionally to the normal force between the surfaces.

Now we consider the process by which two elevated blocks come to contact, welded together and finally separated. When two blocks, each on the respective surface, come to be in contact with each other and push on each other work must be done to cause plastic deformation. We call this work the energy of plastic deformation and denote its value per unit area by $2w$, the factor 2 being introduced to account for the upper and lower surfaces. Next when the two blocks are welded together, that is, the bridge is formed, energy is liberated because of the cohesional potential energy between two blocks. This we denote by $2U$ per unit area. We shall further assume that all the bridges are renewed for a relative displacement ε of the two surfaces. During the interval in which the two surfaces move a distance s, the bridges are built and broken s/ε times.

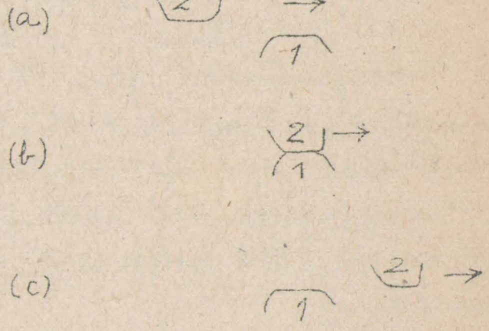

Fig. 2.

Since the work done for one seizure and separation is

$$(2w + 2U) \times N/p_0$$

the work done during the displacement of the length s is.

$$(2W - 2U) \times \frac{N}{P_0} \times \frac{S}{\varepsilon}$$

On the other hand if we denote the frictional force by: F, the work must be equal to F·S

$$\therefore \quad F S = (2W + 2U) \times \frac{N}{P_0} \times \frac{S}{\varepsilon}$$

$$\therefore \quad F = 2(W + U) \times \frac{N}{P_0 \varepsilon}$$

Hence the frictional force F is proportional to the normal reaction N and is independent of the apparent area and of relative velocity. This is in good agreement with the law of Amontons or Coulomb. The coefficient of kinetic friction μ is given by

$$\mu = \frac{2(W+U)}{P_0\, \varepsilon} \qquad (2)$$

Now U is the work required to separate the metal blocks which are already welded together, and w is the work required to make plastic deformation. It would be allowed to assume that w is small compared U. So we have from (2)

$$\mu = \frac{2U}{P_0 \varepsilon} \qquad (3)$$

or

$$\varepsilon = \frac{2U}{P_0 \mu} \qquad (3')$$

Now μ, P_0, U are quantities characteristic of each metal, and can be obtained experimentally and ε is a quantity with only a statistical meaning and can be assumed roughly to be the order of the dimension of the coherent blocks.

Bowden and Hughes[4] obtained the coefficients of friction of Ni on Ni, Cu on Cu and Au on Au. Very great care was taken to ensure the absence of adsorbed molecules or atoms upon the surfaces. They found the values of μ to be the order of 5 for these metals. The value of P_0 is very difficult to estimate since it is assumed to be equal to the pressure where plastic deformation occurs. If we take p_0 equal to the stress when plastic deformation becomes observable, its value is 0.092 Kg/mm^2 for Au and 0.10 Kg/mm^2[5] for Cu.

Since V is the energy liberated when the two metal portions are welded together, it is also equal to the energy required to form new surfaces of the metal. So we may assume that the order of magnitude of V is equal to that of the surface tension of the liquid metal. For Au it is between 600 $ergs/cm^2$ and 1000 $ergs/cm^2$ and we assume it to be equal to 800 $ergs/cm^2$. For Cu it is about 1000 $ergs/cm^2$.

Using (13') we have for the values of ε for gold and copper:

$$\text{For Au}: \quad \varepsilon = 0.4 \times 10^{-4}\ \text{cm}$$

$$\text{For Cu}: \quad \varepsilon = 0.4 \times 10^{-4}\ \text{cm}$$

Hence we may conclude that the linear dimension of

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[4] Bowden and Hughes: Proc. Roy Soc. A 172(1939), 263.

[5] Seitz and Reads : J. Applied Phys. 12(1941), 100.

coherent blocks is roughly of the order of 1 μ. This value agrees very well with the dimension of coherent brocks determined from the breadth of spectral lines of X-ray scattered from metal crystals.[6] K. Murakawa[7] has recently observed that metal dust formed by destruction of metal surfaces due to sliding motion consists of particles whose radii are of the order of 1.5×10^{-4} cm. This value is in good accord with the value obtained above.

3. Coefficient of friction in the case of boundary lubrication

We consider the case when a monomolecular film of fatty acids adheres on the surface of the metal. The linear dimension of the coherent block is of the order of 10^{-4} cm, that is, 10^4 Å while the length of a molecule of a fatty acid is of the order of 10 Å. Hence the monomolecular film makes a very thin film which covers the block surfaces (See Fig 3.). We can, therfore, assume that p_0 and ε in (3) have the same values whether the lubricant is present or not.

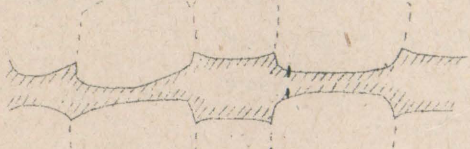

Fig. 3.

The surface energy U alone changes very remarkably. In this case the metals do not contact directly and the friction

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[6] Seitz and Reads : loc. cit.

[7] K. Murakawa : 応用物理 (Applied Physics) 13 (1944), 1.

is due to the adhesions between the organic molecules on the elevated portions of the surfaces where they really touch. The strength of the bridges formed between two metals can no longer be the strength of the metals themselves, but much smaller strength of the adhesion of van der Waal's type between the organic molecules. In this case we can therfore assume U to be roughly equal to the surface tension of the lubricant which is of the order of 20 ergs/cm^2

Thus we have by (3)

for Au : $\mu = 0.06$

and for Cu : $\mu = 0.1$

Unfortunately there are no experimental data of sliding friction when fatty acids are used as lubricant for Au or Cu. In case of Fe the value of μ is, according to Bowden, 0.1.

In conclusion the writer expresse his sincere thanks to Mr. H. Sonoda who helped the writer in this research.