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THE INFLUENCE OF SURFACE CONDITIONS ON THE FRICTION OF METALS

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Abstract

The present investigation, by an improved tilt method, attempts accurately to determine the static coefficient of friction for metallic surfaces under varying surface conditions in different media. The presence and nature of oxide films materially affect the rise of the friction curve; a thin film acting as an abrasive causes the curve to rise, the rate depending on the normal force, until a layer of increased stability is reached. In terms of surface flow this indicates the formation of a vitreous layer. Thick films of certain oxides act as lubricants of great stability. Area of rubbing, shape of surfaces, and dry gases have no influence on μ; moist inert gases show a capillary effect, moist active gases destroy the surfaces. μ is found to be a linear function of the number of slips of one surface over another.

Introduction

The difficulty of adequately controlling surface conditions involved in friction measurements has been such that no precise interpretation can be made of the phenomena through the values obtained for the coefficient by the usual methods. Methods of cleaning have not been satisfactory, the areas of the surfaces have been too great to give the value of μ at a point, and the effect of atmospheric conditions have been so neglected that, for metal surfaces, values of μ have greatly varied. The conditions of the surfaces just as motion is impending are most easily studied by knowing the static coefficient at a certain point. In this paper, I shall discuss the influence of surface conditions on the friction of some metals and give characteristic values for surfaces under various conditions.

Method of Cleaning Surfaces

(1) Any roughness of surface was removed with no 0.0004 flint paper. (2) The surfaces were carefully polished with Crocus cloth and oil. (3) Fine machine oil was used to clean away the metal dust. (4) The surfaces were washed in CCl_4 to free from oil. (5) The surfaces were boiled in distilled water for 15 min. (6) The surfaces were then washed under the tap and allowed to dry in air. Whatman filter paper was used to wipe and handle the rods. The surfaces were polished to such an extent by the above procedure before each test, that under the microscope fine longitudinal lines were visible but no tears in the surfaces were noticeable. A low power microscope was used. This method gave consistent average results.

Apparatus

The tilt method of determining μ devised by P. E. Shaw[1] was used with an automatic control arrangement and modified for work in vacuo. Fig. 1 shows

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[1] P. E. Shaw, Jour. of Sci. Instruments 4, 222 (1927).

the essentials of the apparatus that was used for the tests in air. A short length of the rod to be tested is clamped across the table of the apparatus. A longer rod of the same material, supported equally by a fine copper wire bifilar at one end and by the fixed rod at the other, slides transversely across the fixed rod when the table is tilted beyond the critical angle by means of weights, the cords of which act on the table arm through pulleys. The sliding rod and one of the end contacts complete a low voltage relay circuit which operates an electromagnetic stopping device. This device serves to stop the tilt by locking the cord of one of the weight pans when the sliding rod breaks the end contact. One weight pan submerged in a vessel of water controls the rate of tilt by opposing the action of the other pan of weights. The system operates smoothly and at a low rate of constant angular speed by simply adding or taking away water from the vessel. An optical lever on the axis of rotation determines the critical angle ϕ. One slide is considered as the result of two tilts of the apparatus, one clockwise and the other counter clockwise. For the work in vacuo, the whole apparatus was enclosed in a brass cylinder with plate-glass ends. A rack and pinion carrying a cleaning strip of Crocus cloth and filter paper served to clean the rods in vacuo at any desired stage of rubbing. Vacua of 0.1 mm were obtained and worked with conveniently. The sensitivity of the apparatus is given in terms of angular speed increase, per increase of pan load. An increase of 10 g in weight increased the angular speed by 1.5° per second.

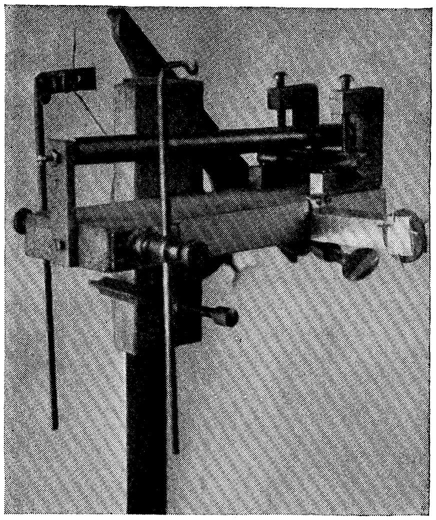
Fig. 1. Apparatus.

By this method, the angle of friction, ϕ, is clearly a function of the number of slips. The procedure was to study the stability of surface conditions by repeating the measurement of ϕ under different conditions. μ, a function of ϕ, was found by means of the tangent relation.

RESULTS

The results in air indicated that the degree of oxidation of the surfaces determines the rise of the friction curve. A thin layer of oxide on brass acted as an abrasive, the nature of the film determining its abrasive character. The rate of rise of the curve depended on the normal force as shown in Fig. 2. The coefficient of friction in this case therefore depended on the normal force.

If the experiment was made a considerable time after polishing, μ was found to be constant, which was taken to mean that the oxide coating on the surfaces of the metal was heavy and the rubbing layers of the oxide film were in a stable condition. No abrasive action appeared in this case and the low value of μ suggests that the heavy film acted as a lubricant to protect the metal surfaces. The constancy of μ for thick films is illustrated in Fig. 3, curve *b*. The data for this graph were taken in vacuo at pressures of about 0.1 mm. Curve *a* of the same figure shows that a like condition of stability was obtained but under different conditions. The curve shows the invariability of μ with change of normal force when two hard vitreous layers are rubbed together. The nature and formation of such layers will later be considered, but the same invariability of μ with normal force was found when thick films of oxide were rubbed together. The rather large deviation of the points about the mean is explained in part by the fact that for each change of normal force, air was admitted and the rubbing surfaces separated. But in the experiment, the normal force was not increased steadily but was varied from a high value to a low one and vice versa; an increase in load caused both a decline and rise of the curve which was due to slightly different surfaces in contact.

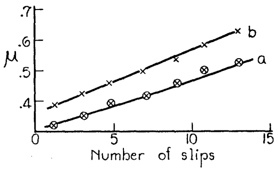

FIG. 2.

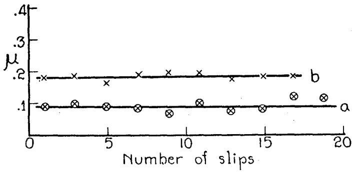

FIG. 3.

Fig. 2. Curves for brass; *a*, normal force is 64 g; *b*, normal force is 83 g; pressure, 0.1 mm.

Fig. 3. Curves for brass; *b*, thick oxide layer; *a*, independent of normal force; 29 g – 40 g; pressure, 1.0 mm.

For aluminium oxide, the lubricating property of thick films was found to be absent and this is probably due to the extremely hard oxide which tore up the metal surfaces. The change in normal force was accomplished by filling a brass tube with substances of different densities to get the desired weight and then closing the ends with brass plugs.

The best controlled experiments were done in vacua with the air exhausted to varying degrees. The data obtained were similar to those found in air. Values obtained in vacuo were generally lower than those obtained in air but this was due to initial cleaning after evacuation. Some of the oxide was cleaned away and conditions were such that the remaining film did not grow. A change in vacuum did not appreciably influence the results because there was little growth in the oxide layer, and the great pressure at the point of contact of the curved surfaces was sufficient to squeeze out the air film.

Typical curves for brass and copper in vacuo are given in Fig. 4, curves *a* and *b*, respectively. The final constant ordinates of the curves show that the rods had attained a constant surface condition. This condition suggests a hard surface formation, a vitreous layer of increased stability formed as the result of earlier surface disturbances. This same sort of surface was produced by polishing rods of brass and copper with Schmirgel and then wiping with filter paper. A source of bright light was so directed on the surfaces that diffraction patterns or lack of them were visible when viewed through a microscope. After the traces of dust had been carefully wiped away, it was found that a regular sort of lattice pattern was visible.

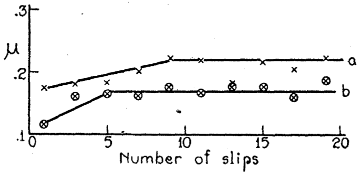

Fig. 4. Curve *a* for brass; curve *b* for copper; pressure, 1.0 mm.

Now if the molecules were displaced from their positions by the mechanical disturbance caused by polishing and a sort of flow resulted in the formation of a non-crystalline or vitreous state, high temperatures should aid the molecules in recovering from the strain and ensure their return to the crystalline state. To see if heating did have this effect, the polished surfaces were heated in two different ways. In the first case, the rods were boiled in distilled water for 30 minutes and were then allowed to cool in the water. After the rods were thoroughly dry, examination failed to reveal any sort of diffraction pattern. The effect approached that seen when the rods were in the crystalline condition. The second method was to hold the rods in the oxidizing flame of a Bunsen burner for about 3 minutes and then observe the optical effect immediately afterward. The possible formation of oxide did not effect the results in this case. Similarly, it was observed that heat released the strain and the molecular rearrangement took place when the elastic constraint was lessened. When rods polished in a similar manner were tested, it was found, as discussed above in the case of thick films of oxide, that μ did not vary with change in normal force.

Thick films of oxide and vitrified surfaces both exhibited stable conditions, as observed by the constancy of μ, for as many as 50 slips although they are of totally different nature. Thick films of oxide are produced by the natural growth of such spicular, granular substances under certain atmospheric conditions. Vitreous solids are produced as the result of a sort of crystalline flow that solidifies and leaves the molecules in a new arrangement which constitutes a hard surface. A much greater force is required to disturb a completely vitrified surface as compared with a crystalline one. Slipping of vitreous layers is accomplished without any appreciable surface deformation; tears in such surfaces caused by the presence of hard foreign particles, or the separation of welded areas are of greater importance in the resultant friction than the consideration of a flow that accompanies crystal slip.

Jeffrey[2] has recently shown that the surfaces of easiest slip for a vitreous solid are curved instead of plane. This offers a possible explanation why individual determinations of μ in the vitreous state fluctuate by an amount greater than the probable experimental error. With moisture in the testing chamber, the variation can be explained by instantaneous oxidation and the subsequent rubbing away of the oxide. The mean value, in this case, may be considered as the average value approached by several, separate, minor

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[2] Jeffrey, Proc. Camb. Phil. Soc. **24**, 23 (1928).

curves which result from the rubbing of oxide particles between the vitreous surfaces; in each case, the constant condition was found after all the oxide had been rubbed away. The linear mean value taken as a constant shows the probable value that would be obtained if ideal rubbing conditions were obtained.

The possibility of gas films adhering to the surfaces of the metals was considered remote as the surfaces were mechanically disturbed by the wearing away action that accompanied each slip.

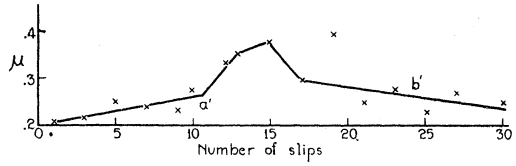

Fig. 5. Curve for zinc; *a'*, moist O_2 let in; *b'*, 20 hours later: pressure, 0.1 mm.

Fig. 5 shows the effect of a moist inert gas on the friction of zinc surfaces. Moist inert gases influenced μ only through capillarity. Dry inert gases, such as oxygen and hydrogen, did not effect μ. This corroborated the experiments of Charron.[3]

Fig. 6, curves *a* and *b* show the action of nitric acid and ozone, respectively, on different surfaces. Nitric acid destroyed the surface layer and left a spongy textured surface that rapidly gave away with each succeeding slip; μ decreased until a new metal surface was exposed. The curve for ozone shows the great oxidizing effect on the surfaces of zinc rods. The increasing steepness of the curve indicated the more rapid growth of the surface film of oxide.

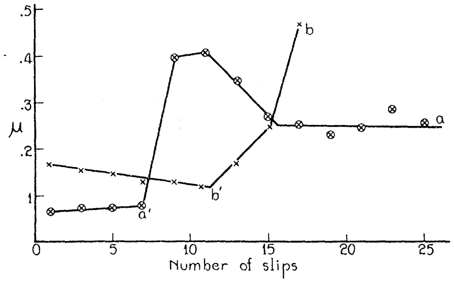

Fig. 6. Curve *a* for Cu; *a'*, HNO_3 let in. Curve *b* for Zn; *b'*, O_3 let in, pressure, 0.1 mm

CONCLUSION

The results suggest the following interpretation. Thick films of oxide, particularly soft oxides on hard metal surfaces, act as lubricants, the surface molecules re-orienting freely, yet the film being so thick that its stability is not effected by relatively slight changes in surface conditions, so that μ remains constant. Thin films break readily and the crystal structure of the metal is sheared with each rub. The mechanism of crystal slip is not completely known. The idea of a surface flow, such as the Beilby flow, that resolidifies into a vitreous layer after each slip seems useful in explaining the increased molecular stability that results from each slip until a final constant condition is reached. From the figures, it is evident that μ is a linear function of the number of slides. Analytically, this means that dy/dx is a constant. If we call y, the formation of vitreous material with each slip x, the rate of formation of vitreous material is constant with each slip until the resulting laminated structure, which is composed of alternate layers of crystalline

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[3] Charron, Comptes Rendus **146**, 1013 (1908).

material sandwiched between layers of vitreous material, cleaves and two vitreous layers slip over each other, y then remains constant while x increases. This interpretation agrees with the results that should be obtained according to the Beilby idea, and the experimental results seem to justify the reality of such a flow. From this viewpoint, the nature of the flow is not the same as that of a viscous liquid, for in the present case there is a sharp transition point when the rise of μ suddenly stops and remains constant, independent of the number of following rubs. No attempt is made to estimate the thickness of a vitreous layer that results from a single slide. It must necessarily be very thin. The formation of each vitreous layer can be considered apart from the one next to it for the time of surface flow at a point is much less than the time required for one slide. Friction curves have usually been represented by a curved line, dy/dx changing until the curve asymptotically approached a constant value. This does not seem to be the case according to the above interpretation.

On the other hand, when the surfaces are covered with a heavy oxide layer, the mechanism is essentially that of one particle sliding over another, the metal surfaces being cushioned by the layers of oxide whose internal resistance to separation is less than the adhesion between the oxide and metal. If surface flow occurs, it should be governed by the kinetic theory. It should exhibit the properties of surface tension which should decrease with rise in temperature. Such a picture explains the decrease of μ found by Jacob[4] up to 200°C. The increase of μ with increase of temperature above 200°C would indicate the rubbing of vitreous layers together.

This work was done by me while a graduate student at Clark University and it is a pleasure to acknowledge the help and inspiration of Dr. R. H. Goddard who made this work possible. I am also very grateful to Professor P. W. Bridgman for advice regarding the preparation of the manuscript.

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[4] Jacob, Ann. d. Physik **38**, 126 (1912).

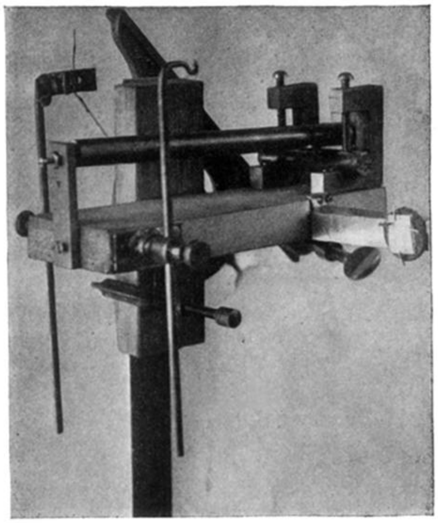

Fig. 1. Apparatus.