

Liversidge Research Lecture

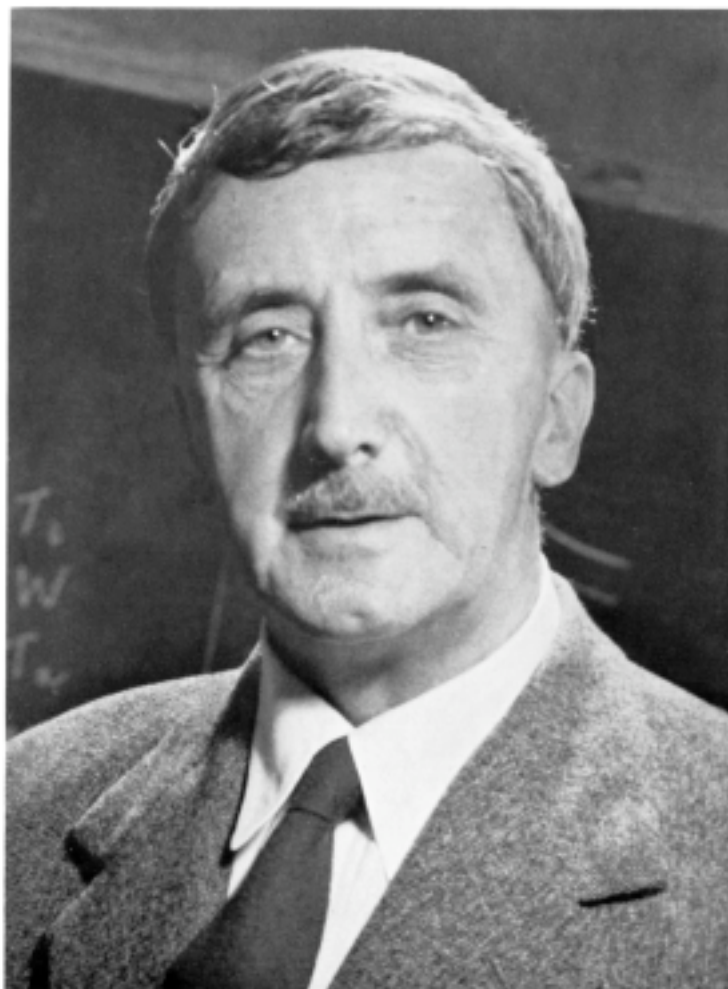
No. 5
1944

THE PHYSICS OF RUBBING SURFACES

F. P. BOWDEN



The Royal Society of New South Wales



Frank Philip Bowden

Frank Philip Bowden

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FRANK PHILIP BOWDEN 1903-1968

Frank Philip (Philip) **Bowden** was born on 2 May 1903 at Hobart. After secondary education at the Hutchins School he spent a year as a junior laboratory assistant at the Electrolytic Zinc Company (Risdon, Tasmania), and then studied science at the University of Tasmania. He graduated B.Sc. in 1924, and then as a Research Scholar under the supervision of Dr A.L. McAulay in the Physics Department, he graduated M.Sc. in 1925. Through representations made on his behalf by McAulay, Bowden was the first recipient of the Electrolytic Zinc Company's Research Scholarship, and he continued electrochemical research with McAulay for another year. In 1926 he was awarded an 1851 Exhibition Scholarship, which, together with a Research Studentship at Gonville and Caius College, Cambridge, enabled him to work under Dr. E.K. Rideal (later Professor Sir Eric) on electrochemistry in the Physical Chemistry Department. He graduated Ph.D. in 1929, and was a Senior Scholar at Cambridge during 1929-1931. He was subsequently appointed Demonstrator in Chemistry at Cambridge, and in 1937 he became the Humphrey Owen Jones Lecturer in Physical Chemistry. In the early 1930s he began research on friction and lubrication, and soon gained an international reputation. In 1937 he was put in charge of the Britannia Laboratory established in Cambridge by the Shell Oil Co. to do research on wear and lubrication. Following a lecture tour of the USA in 1939 he was in Australia when World War II broke out, and he met with Richard Casey (then Minister for Supply and Development, and later Lord Casey), David Rivett [Chief Executive Officer of the Council for Scientific and Industrial Research (CSIR), and later Sir David], and John Medley (Vice-Chancellor, University of Melbourne), explaining his expertise in the mechanism of lubrication, and offering his services to conduct further research in this area as part of the Australian war effort. He was convincing, and in November 1939 he was appointed Officer-in-Charge of the CSIR's newly created Lubricants and Bearings Section, located in the grounds of the University of Melbourne, which was a joint sponsor. After the war this section was renamed Tribophysics, which subsequently became the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Materials Science and Technology. Philip Bowden and his team developed flame-throwing fuels, portable equipment for measuring the muzzle velocity of projectiles, and casting techniques for the production of bearings for aircraft engines. Specific examples of their work were (a) the testing of the prototype of a silver-lead-indium bearing for the single- and twin-row Wasp engine that was used, for example, in the Beaufort aircraft, and (b) development of a copper-lead bearing for the Rolls-Royce Merlin engine. Bowden's group also improved the safe handling of explosives such as nitroglycerine by showing that great care should be taken to avoid the entrapment of gas bubbles.

At the end of the war (1945) Philip Bowden returned to Cambridge where he was promoted to Reader in 1946. In his research he made close ties with industry and in 1952 became a director of English Electric Co. Ltd. Between 1955 and 1962 he was chairman of the executive committee of the National Physical Laboratory. He was appointed to a Personal Chair in surface physics at Cambridge in 1966. He died from cancer in 1968 at the age of 65.

Honours and Awards

1928 Rockefeller Foundation Fellowship for Research in Physics and Chemistry

- 1933 D.Sc., University of Tasmania
- 1938 Sc.D., Cambridge University
- 1944 Liversidge Research Lecture, Royal Society of New South Wales
- 1948 FRS
- 1953 Redwood Medal, Institute of Petroleum
- 1954 Hawksley Lecture, Institution of Mechanical Engineers
- 1955 Elliott Cresson Medal, Franklin Institute
- 1956 CBE
- 1956 Rumford Medal, Royal Society (London)
- 1957 Medal of the Société Française Métallurgique
- 1967 Kelvin Lecture, Institution of Mechanical Engineers
- 1968 Glazebrook Medal and Prize, Institute of Physics and the Physical Society
- 1968 Bernard Lewis Gold Medal, Combustion Institute

Biographical Sources

- (1) Spink, J.A. and McLaren, A.C., 'Bowden, Frank Philip (1903-1068)', *Australian Dictionary of Biography*, 1993, **13**, 228-229.
- (2) Schedvin, C.B., 'Shaping Science and Industry: A History of Australia's Council for Scientific and Industrial Research, 1926-1949', Allen and Unwin (Sydney, 1987), pp. 201-205, 293-295.
- (3) Home, R.W., 'Physics in Australia to 1945: a Bibliography and Biographical Register', Melbourne, 1990.
- (4) Mellor, D.P., 'Australia in the War of 1939-1945; Series 4, Civil, Volume 5, The Role of Science and Industry,' Australian War Memorial, Canberra. 1958, pp. 245, 364-7, 403-4.
- (5) Tabor, D., 'Frank Philip Bowden, 1903-1968', *Biographical Memoirs of Fellows of the Royal Society*, 1969, **15**, 1-38.
- (6) Spink, J.A., 'Frank Philip Bowden - Scientific Entrepreneur', *Chemistry in Australia*, 1989, **56**(5), 157-160.

Scientific Publications of F.P. Bowden

A list of the 188 papers, 6 books and two scientific films published by F.P. Bowden is given by Tabor (ref. 5, above), and his 64 scientific publications of Australian relevance are listed by Home (ref. 3, above).

THE PHYSICS OF RUBBING SURFACES*

F. P. BOWDEN

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Part I.

Introduction

In this lecture we shall be dealing with a very old and very unfashionable branch of natural science - friction - and we wish to discuss some of the physical processes that occur when two solids are rubbed together. The title is a comprehensive one but this is in no sense a general summary of the field, and it does not do justice to other workers. There are many obvious gaps, for example no mention is made of frictional electricity. I thought, however, that the most satisfactory way would be to discuss certain aspects of the subject from my own point of view, and to deal with some of the work of my associates and colleagues. The more recent work was done under the Council for Scientific and Industrial Research in the Chemistry Department of the University of Melbourne, and the earlier work in Cambridge. At the outset I must offer an apology. For the past five years we have been concerned almost entirely with war problems and the basic work we have been able to do has been fragmentary and fitted into odd corners. For the same reason the pressure of immediate work has made it impossible to give the proper thought and preparation that the Liversidge Lecture warrants.

It would be interesting to attempt a lecture on the *chemistry* of rubbing surfaces, but unfortunately our information about this is very scanty. Although we know a great deal about the influence of heat, of light, and of electricity in stimulating molecules to react, we still know comparatively little about the influence of mechanical forces on reactivity and of the effects produced when we seize a molecule by the head and the heels and tear it in half. We shall confine our attention to some of the physical processes that occur when one solid slides over another. There is a resistance to motion which we call friction. What is the mechanism of that frictional force, and from the point of view of a molecule sitting on the surface, what is really happening? We may ask a few simple questions and then endeavour to answer them by direct experiment. To begin with we wish to ask three questions: (i) what is the real area of contact between the solids? (ii) What is the surface temperature of the rubbing solids? (iii) What is the nature of the surface damage?

The Real Area of Contact between Solid Surfaces

It is, of course, a very difficult matter to prepare surfaces which are really flat. Even on carefully polished surfaces hills and valleys which are large compared with the dimensions of a molecule will still be present. The upper surface will be supported on

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these irregularities and large areas of the surfaces will be separated by a distance which is great compared with the dimensions of a molecule. We do not know very much about the size of these small irregularities nor the degree of flatness of the surfaces. Optical methods cannot reveal irregularities much smaller than one-half to one-tenth of a wavelength of light. Although the techniques of grinding and polishing have advanced in the past few years, it is still a difficult matter to prepare surfaces of appreciable size which are flat to within one or two thousand angstroms. Since the range of molecular attraction is only a few angstroms, we may expect that the area of intimate contact, that is the area over which the surfaces are within molecular range, will, even for very carefully prepared surfaces, be quite small. A new and powerful method for studying surface irregularities and surface structure is the electron microscope, and recent stereoscopic pictures taken by Heidernich and Matheson (1944) show in some detail small scratches *ca.* 250 Å. deep on polished metal surfaces.

In general the surfaces used in engineering practice are less flat and the surface irregularities present on them are, in terms of molecular dimensions, enormous. These irregularities may be seen by cutting a section at right angles to the surface and examining it with high power microscope, but a more revealing method is to cut a section at an oblique angle to the surface. This has the advantage that it magnifies the irregularities in the vertical direction and leaves the horizontal magnification unchanged. Taper sections prepared in this way by Mr. Moore which show some characteristic contours of surfaces finely machined and also ground with abrasives of varying degrees of fineness are given in Plate I, Figs. 1-5. It is seen (Fig. 5) that even with the finest abrasive the surface irregularities are of the order of 0.1μ , i.e. 10^{-5} cm.

If the surfaces are polished the effect is to cause the summits of the peaks to flow into the valleys so that the contour resembles rolling downs rather than rugged alpine peaks. But again the surfaces will touch on the summits of the hills and the area of intimate contact will be small.

Some knowledge of the real area of contact between solid surfaces is essential for our purpose and its determination is a matter of some experimental difficulty. Fortunately, an approximate estimate of it in the case of metals can be made by measuring the electrical conductance across the surface of the metals when they are in contact.

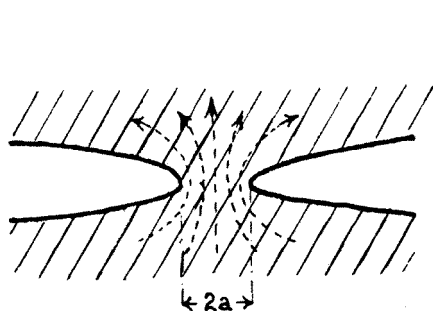


Fig. 1 - The current flow through a constriction of radius a in a metal conductor. The behaviour is similar if two metal surfaces make electrical contact over an irregularity of radius a . The electrical conductance Λ of such a junction is given by $\Lambda = 2a \lambda$.

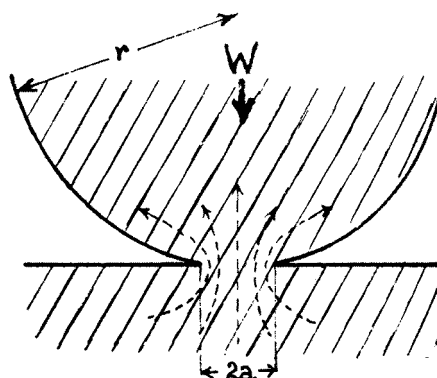


Fig. 2.- The deformation of a spherical surface resting on a hard (undeformable) plane surface. The current flow and electrical conductance are similar to those described in Fig. 1

In the simple case of metal surfaces which make electrical contact over a surface irregularity of radius a (see Fig. 1) it can be shown (Maxwell, 1873; Holm, 1929; Bowden and Tabor, 1939) that the conductance Λ is given by

$$\Lambda = 2a\lambda \dots\dots\dots(1)$$

when λ = the specific conductivity of the metal. A measurement of the conductance will therefore enable us to estimate the area of contact.

Variation of Area of Contact with Load

Hertz (1881), in his classical paper on the elastic deformation of solid surfaces, calculated how the area of contact between curved surfaces should depend upon the load. He showed that, if elastic deformation is assumed, the theoretical radius of contact a between a spherical surface resting on a plane surface of the same material (see Fig. 2) is given by

$$a = \text{const.} \left(\frac{Wr}{E} \right)^{1/2} \dots\dots\dots(2)$$

where W is the load between the surfaces, r is the radius of curvature of the spherical surface and E is Young's Modulus.

From equations (1) and (2)

$$\Lambda = \text{const.} W^{1/2} \dots\dots\dots(3)$$

so that if we assume elastic deformation of the metals in the region of contact the conductance should be proportional to the *cube root* of the load. There is, however, another possibility. We may consider that the metal in the region of contact will flow plastically under the applied load until the cross section of the contact is sufficient to support the load. In this case

$$W = \pi a^2 f \dots\dots\dots(4)$$

where f is the maximum pressure the metal can withstand without flowing. Combining this with equation (1) it follows that

$$\Lambda = \text{const.} W^{1/2} \dots\dots\dots(5)$$

i. e., the electrical conductance should be proportional to the *square root* of the load.

Some experiments were carried out by Dr. Tabor to investigate this point and results obtained for a number of different metals in contact are shown in Figs. 3 and 4. In these experiments two crossed cylinders were used, since geometrically this is the same as a spherical surface resting on a flat one and it is more convenient experimentally. It is clear that the conductance varies in an orderly manner with the applied load. Moreover, an examination of the slope of the lines (see Fig. 4) shows that the conductance is proportional to *the square root* of the load, i.e. equation. (5) is obeyed, and hence the deformation of the surfaces in the region of contact is mainly plastic.

Some actual values of the area of contact between cylinders of steel and between cylinders of silver at different loads are given in Table 1.

TABLE 1.

Area of Contact between Cylinders of Steel and Silver at Various Loads.

Load. Kg.	Area of Contact cm. ² (From Electrical Conductance.)	
	Steel.	Silver.
0.5	-	0.0002
1	0.00013	---
5	0.00061	0.002
50	0.0045	0.018
500	0.042	0.15

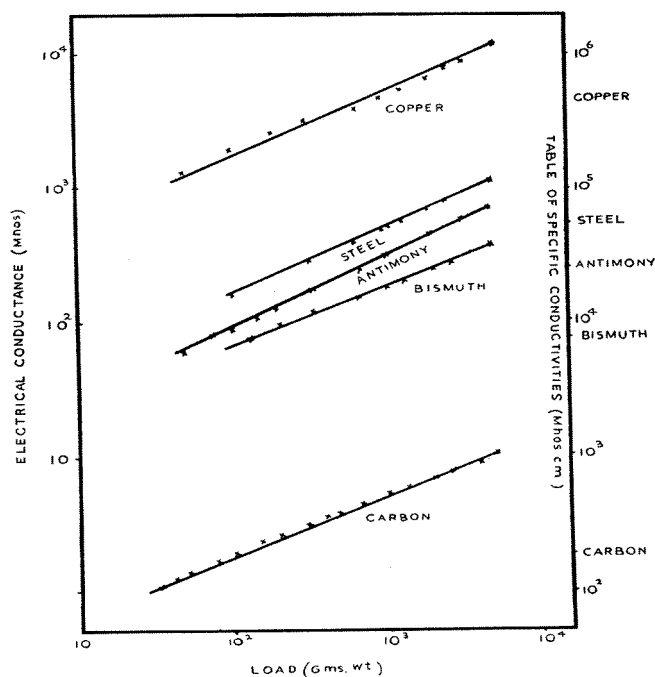


FIGURE 3. The variation of electrical conductance with load for crossed cylinders of various materials. The conductance varies in an orderly manner with load and the position of the curve for each material is in the same order as the specific conductivity of the material.

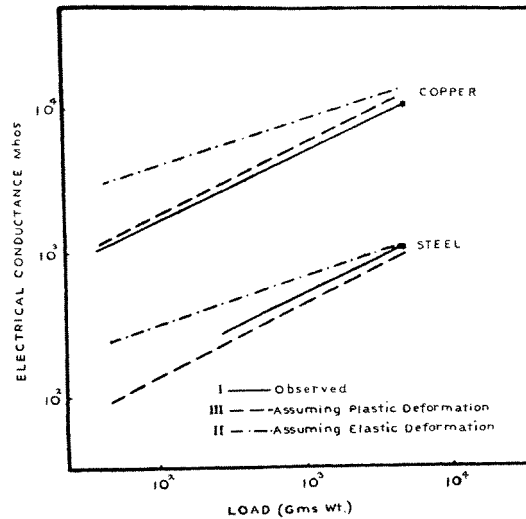


FIGURE 4. Variation of electrical conductance with load for crossed cylinders of copper and steel. The broken lines are calculated assuming plastic and elastic deformation. The observed values show that the deformation is essentially plastic.

Area of Contact between " Flat " Surfaces

It is interesting to compare the conductance across flat surfaces with that across curved surfaces at the same load, and Fig. 5 shows such a comparison. Curve I is for curved surfaces of steel, Curve II (a) for flat steel surfaces 0.8 sq. cm. in area, Curve II (b) for similar surfaces 20 sq. cm. in area. The surfaces were flat to a few fringes. The values for flat surfaces do not lie on a straight line but it is clear that the values of the conductance are not very different from those observed with curved surfaces. The possible area of contact between the flat surfaces is of course enormously greater than that of the curved, but the conductance is of the same order of magnitude. At a load of 5 kg., for example, the area of contact between the curved surfaces is *ca.* 6×10^{-4} sq. cm. If nearly

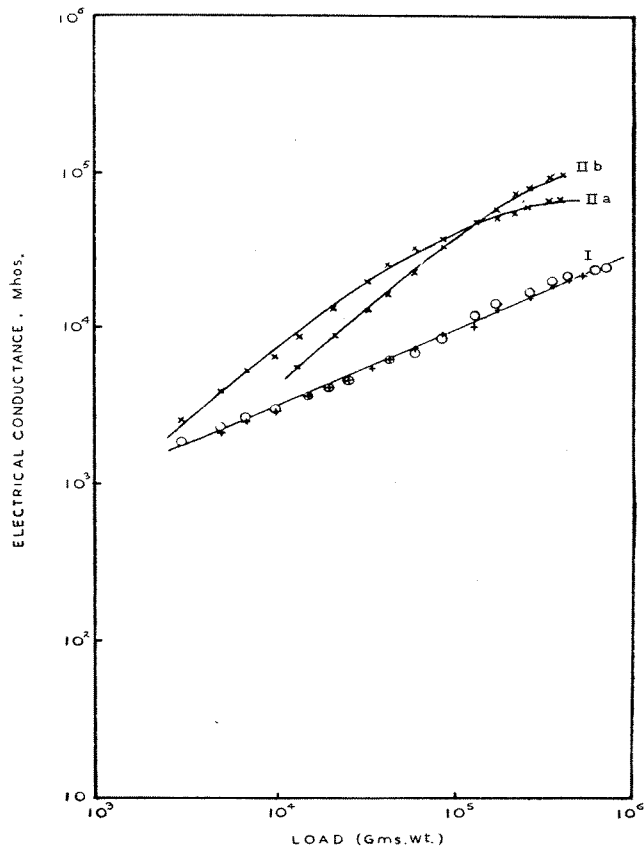


FIGURE 5. - Variation of electrical conductance with load for steel surfaces. Curve I refers to curved surfaces, Curve II (a) to flats 0.8 sq. cm. in area, Curve II (b) to flats 20 sq. cm. in area.

all the surface of the 21 cm. flat were in contact the area of contact would be *ca.* 30,000 times as great and the conductance would be correspondingly increased. Experiment shows, in fact, that it is only twice as great. It is thus clear that only a very small fraction of the flat surfaces can be in intimate contact. It will also be noted that the conductance of both sizes of flats is almost the same although their apparent areas stand in the ratio of 30:1. We can conclude that the conductance is independent of the apparent area of the surfaces. It depends mainly on the load. Experiments also showed that the conductance was little influenced by the degree of roughness of the surfaces. The surface of the steel cylinders was rubbed with a coarse file so that it was as rough as possible and the conductance was compared with that of a finely ground surface. No appreciable difference between the two was observed.

It is clear from these simple experiments that the area of intimate contact between solid surfaces is very small indeed. It varies with the pressure, but for flat steel surfaces it may be less than one-ten thousandth of the apparent area. The real area of contact is not greatly affected by the size of the surfaces nor by the shape and the degree of roughness of the surface. It depends mainly on the pressure.

The general behaviour is consistent with the view that the surfaces are held apart by small irregularities. This means that even with lightly loaded surfaces the local pressure at these small points of contact is very high and may be sufficiently great to cause steel to flow plastically. Although the stresses will cause elastic deformation of the metal in the vicinity of the points of contact the experiments suggest that the summits of irregularities

on which the bodies are supported flow plastically and are crushed down until their cross section is sufficient to enable them to support the applied load.

The fact that the real area of contact is so small has important practical implications. Even when loads of only a few hundred grammes are applied to the surfaces the local pressure between them may be sufficiently great to cause the flow of metal. When large flat surfaces are used it does not mean that the real pressure is much less, but merely that the points of contact are more widely distributed.

As we shall see later, this intense pressure may cause an actual welding together at the tiny points of contact and so produce small metallic junctions between the surfaces. The pressure between the surfaces in the regions where contact occurs is determined primarily by the flow pressure of the metal itself and is only influenced to a secondary degree by the shape and size of the surfaces and by the load which is applied.

It is interesting to note that even when the surfaces are lubricated with a boundary film of a good lubricant, similar conditions hold. The load will again be carried by the surface irregularities and even for light loads the local pressure on the lubricant film will be very high. In the case of mild steel, for example, it will be $\sim 10^4$ kg. cm.² Unless the lubricant molecule possesses an active group capable of attaching it firmly to the surface the local high pressure will force it from underneath the points of contact. In this sense all good lubricants must act as extreme pressure lubricants.

We would now like to consider in some detail the physical processes that occur when we set these solids in motion and cause one to slide over the other. We find that an appreciable tangential force is necessary to start them moving (static friction) or to keep them sliding (kinetic friction). This frictional resistance occurs, of course, over the small localized regions where the solids are actually in contact, and we will enquire into its mechanism.

The Surface Temperature of Rubbing Solids

The energy lost during sliding is dissipated mainly in the form of heat and the first query is, what will be the temperature of the surfaces? Quite primitive calculations of the amount of heat which is liberated and of the rate at which it is conducted away suggest that the temperature rise of the surface layers may be high. If we endeavour to measure this by embedding thermocouples in the solids near the surface we find that the rise is very small, but this is mainly because we cannot get close enough to the surface. An obvious method is to use the surfaces themselves as a thermometer. This can be done by making them of two different metals, and using the rubbing contact itself as a thermocouple. A measurement of the electromotive force generated on sliding then provides a record of the surface temperature. It is apparent that the electrical contact and the friction occur at the same points where the surfaces touch so that the measurement gives information about the temperature of the surface layer of the metal where they are rubbing.

Such measurements confirm in a very striking way the existence of local high temperatures at the points of contact of the rubbing surfaces. As would be expected, the temperatures reached depend upon the load, the speed of sliding and the thermal conductivity of the metals. Also the temperatures fluctuate very rapidly during sliding and it is necessary to use an instrument of high frequency such as a cathode ray tube or high frequency galvanometer in order to record them. Figure 6 shows the maximum

temperature reached when small cylinders of gallium, Wood's alloy, lead, and constantan are slid on a steel surface.

It will be seen that with the lower melting metals we readily reach their melting point and the temperature does not rise above this. With constantan, temperatures of the order of 1000°C are reached. These temperatures are confined to the very thin surface layer and the mass of the metal appears to be quite cool. The rapid and intense nature of the temperature fluctuations is shown strikingly in the cathode ray trace recently taken by Mr. Stone and Mr. Tudor (Fig. 7). It will be seen that the very high temperature flashes of 1000°C may last only for a few ten-thousandths of a second.

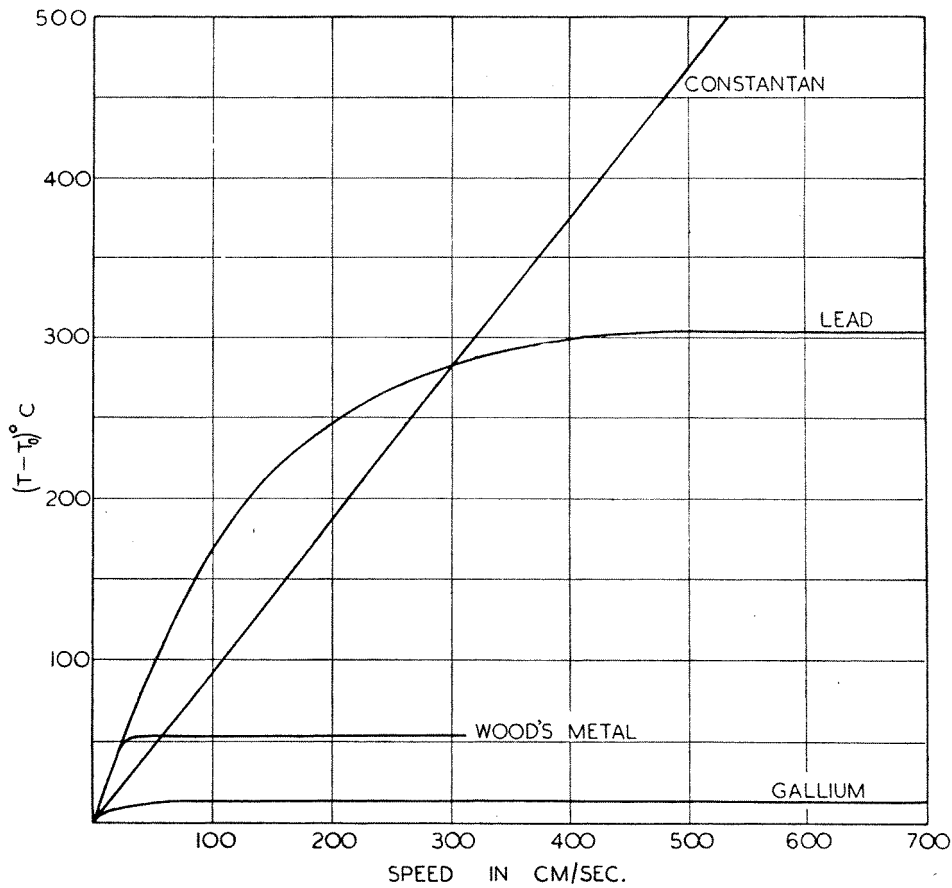


FIGURE 6. - Maximum temperatures reached when small cylinders of gallium, Wood's metal, lead and constantan are slid on a steel surface. The temperature cannot exceed the melting point of the metal.

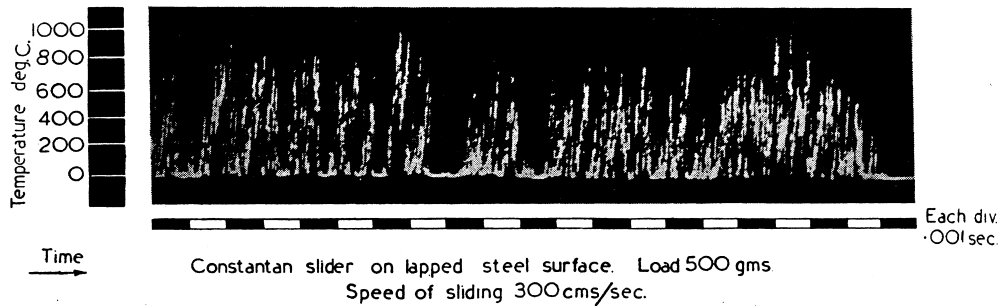


FIGURE 7. - Cathode ray trace of thermal emf. developed between a constantan slider on a lapped steel surface. The temperature flashes are extremely high and of very short duration.

It is interesting to note that if the surfaces are flooded with water the local high temperatures may still occur. If the surfaces are lubricated with a boundary film of good lubricant the surface temperatures are greatly reduced but the experiments show that localized metallic contact may still occur through the film and the surface temperature at the summits of the surface irregularities may still be sufficiently high to cause volatilization and decomposition of the lubricant film.

The influence of the thermal conductivity of the metals on the surface temperature is shown in Fig. 8. It will be seen that, with the metals of lower thermal conductivity such as bismuth, the temperature rise is considerably greater.

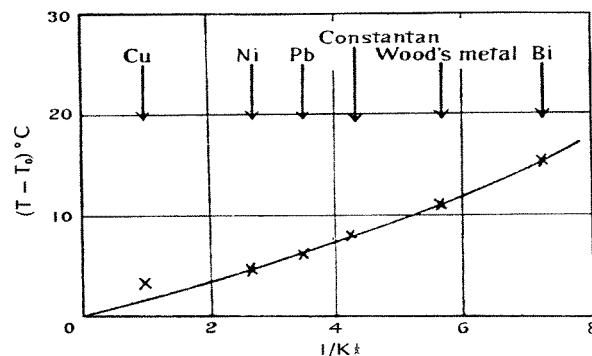


FIGURE 8. - Temperature rise of rubbing surfaces as a function of their thermal conductivity K (load 32 g., velocity 20 cm./sec.).

Visual Observation of Hot Spots

We should expect that these high temperatures would be reached very much more readily on glass and other non-conducting solids. Unfortunately, the thermocouple method cannot be used with these solids but recently Mr. Stone has shown the existence of the hot spots by visual means. If polished surfaces of glass or quartz are used and the apparatus so arranged that a clear image of the rubbing surfaces can be seen it is found that when sliding starts a number of tiny stars of light appear at the interface between the rubbing surfaces. The points of light are reddish in colour at low speeds and become whiter and brighter as the speed or the load is increased. It is clear that they correspond to small hot spots on the surface and their position shifts continuously as sliding proceeds. They can be recorded photographically. The method is not quantitative but, by making one of the surfaces of metal and using alloys of different melting points, it is possible to fix

approximately the temperature at which hot spots first become visible. Experiments suggest that this temperature is about 500°C. These hot spots may occur at very low sliding speeds. For example, with constant sliding on glass under a load of 1 kg. hot spots appear when the sliding speed is as low as 30 cm. per sec. An example of the photographic method of recording the light from the hot spots is shown in Plate II, Fig. 1. The surfaces (steel on glass) are allowed to run continuously for two minutes in a circular track so that a cumulative exposure of the hot spots occurs. The circles of decreasing radius mean decreasing sliding speed. The lowest speed at which the hot spots are recorded under the conditions of the experiment is 70 cm./sec.

The fact that these high temperatures occur so readily is of some interest and it is suggested that they may play an important part in a number of processes associated with the rubbing of solids. Before considering its bearing on friction we may enquire what part it plays in the polishing of solids.

Polishing and the Surface Flow of Solids

The usual method of polishing surfaces is to rub them together with a fine powder between them. By this process a rough surface having visible surface irregularities is changed into one where the irregularities are invisible. If the surface gives specular reflection the height of these irregularities will be less than half a wave length of visible light. The classical work on polishing is that of Sir George Beilby (1921), who showed that the top layer of the polished solid is different in structure from that of the underlying material. It has lost its obvious crystalline properties and has apparently flowed over the surface, bridging the chasms and filling up the irregularities in it. The mechanism of the process has been a subject of discussion for many years. Newton, Herschel and Rayleigh considered that polishing was essentially due to abrasion. Beilby's view is that it is a surface tension effect - that when the polisher tears off the surface atoms the layer below this "retains its mobility for an instant and before solidification is smoothed over by the action of surface tension forces". As we have seen, however, the frictional heat generated at the rubbing surfaces may easily raise the temperature to a high value and this suggests that the local thermal softening or actual melting may play an important part in the polishing process.

The action of a typical polisher may be represented diagrammatically in Fig. 9. The polishing particles of rouge or alumina are embedded in a block of pitch and rubbed on the specimen in the presence of a liquid such as water.

At the points of rubbing contact between the polishing powder and the specimen, hot spots will occur which will cause a local surface softening or melting of the specimen. The melted or softened solid would be smeared over the surface and would quickly solidify to form the Beilby layer.

We may perform a simple experiment to test this hypothesis. If polishing is due primarily to a mechanical abrasion and wearing away of the specimen we may expect the relative *hardness* of the specimen and of the polisher to be of major importance. If, however, it is due to surface melting it is the *relative melting* points which will be the determining factor. If the polisher melts or softens at a *lower* temperature than the specimen it will melt or flow first and will have comparatively little effect on the specimen.

The result of rubbing Wood's metal (M.P. 75°) with a camphor block (M.P. 178°C) is shown in Plate II, Fig. 2. Although the Wood's metal (hardness ca. 2) is very much harder than the camphor, it melts at a lower temperature and it will be seen that surface flow and polishing of the alloy occurs. On the other hand camphor will not polish tin (M.P. 232°C), lead, white metal or zinc, which melt at a higher temperature. A polisher using a powder of oxamide (M.P. 417°) will readily cause flow of all these metals but does not produce any effect on speculum metal (M.P. 745°) (see Plate II, Fig. 3) or copper (M.P. 1083°) which melt at temperatures well above 417°C. Lead oxide (M.P. 888°) will polish speculum metal and all metals melting below it, but has little effect on nickel and molybdenum, which melt above it. These in turn are readily polished by the high-melting oxides such as chromic oxide, stannic oxide, etc.

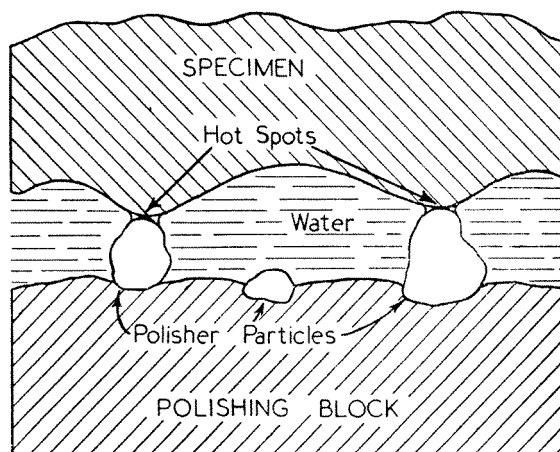


FIGURE 9. - Diagrammatic representation of a typical polisher.

Similar results are obtained with glasses, quartz and some non-metallic crystals; calcite, for example (Plate II, Fig. 4), shows no flow on cuprous oxide which melts a little below it, but is readily polished by zinc oxide which melts above it.

It is well known that the mechanical strength of many metals and solids falls to a very low value at temperatures well below the melting point. The rounding of sharp metal crystals and the low value of tensile strength, hardness, etc., at these temperatures show that metals may lose their rigidity and resistance to shear at comparatively low temperatures. For such solids, surface flow would be expected to take place at temperatures well below the melting point and experiment shows that, in many cases (e.g. gold) this can occur. The rate of flow and polish is, however, very much less and may take hours, instead of the few minutes required by a high melting polisher.

The experiments provide strong evidence, not only that high local temperatures occur, but that they play a large part in the process of polishing. In many cases the frictional heat will raise the temperature to a sufficiently high value to cause a real melting of the solid at the points of sliding contact. The molten solid will flow or will be smeared on to cooler areas, and will very quickly solidify to form the Beilby layer. Polishing under these conditions is rapid. If the sliding is gentle or the melting point of the polisher is low, the surface of the solid may not reach the temperature of melting. Polish and surface flow may still occur under these conditions, provided the temperature reaches a point at which the mechanical strength of the solid is sufficiently low for it to yield under the applied stress or under surface tension forces. Polishing under these conditions is a slow process.

The relative hardness of solid and polisher as normally measured at room temperature is comparatively unimportant. This is shown clearly in the case of Wood's alloy and tin on camphor, or speculum metal and nickel on lead oxide. The harder metal of low melting point is polished, while the softer metal of higher melting point hardly flows at all. Similarly zinc oxide which is comparatively soft (Mohs' hardness 4) readily polishes quartz (Mohs' hardness 7). The amount of surface flow is governed, not by the properties of the solids at room temperature, but by their relative mechanical properties at the high temperature of the sliding surfaces.

The Mechanism of Sliding on Ice and Snow

Another phenomenon where surface melting may play a part is in the sliding of solids on ice and snow - in skating or skiing. It is well known that the friction under these conditions may be remarkably low ($\mu = \text{ca. } 0.03$). The suggestion has often been made that in skating or skiing the surfaces are lubricated by a layer of water formed by pressure-melting (e.g., Reynolds, 1901), but few experiments have been made to support or to disprove the suggestion.

Experience shows that skis slide quite readily on snow at -20°C . Calculations of the pressure necessary to cause melting at this low temperature suggest that it is unlikely that they would be attained. On the other hand calculations of the amount of heat liberated by frictional heating as the ski moves forward a small distance show that it is sufficient to warm up the snow and to melt an appreciable water layer. Some experiments were carried out at the Jungfrauoch Research Station in Switzerland, to determine whether a water layer is formed at all, and if so, whether it is due to pressure melting or to frictional heating. Measurements of the electrical conductivity between metallic electrodes on the bottom surface of miniature ski sliding on salty ice indicated that at low temperatures the surface melting occurred only at localized areas but at temperatures near 0°C a continuous water film was formed.

The effect of temperature on the friction of different solids sliding on ice surfaces is shown in Fig. 10. It will be seen that the friction increases markedly as the temperature falls and at a temperature of -140°C it is some five or six times as great as it is at 0°C . The value for the coefficient of friction ($\mu_k = 0.1$) at these low temperatures is of the same order of magnitude as that observed on other crystalline solids such as calcite. The large influence of temperature on the friction of ice is in marked contrast to the behaviour of most other solids where temperature has only a small influence. It emphasizes the anomalous behaviour of ice and supports the view that the low friction is due to a lubricating water layer. As the temperature falls it becomes increasingly difficult for a water layer to be formed and the friction rises.

It is of particular interest to determine the influence that the thermal conductivity of the ski has on the friction at low temperatures. If sufficient pressure is applied to the ice to lower the melting point to the actual temperature of the ice, it is, of course, capable of melting. An appreciable quantity cannot melt, however, unless heat is supplied from some source at a temperature higher than the pressure melting point equilibrium. Both the heat capacity of the ice and its thermal conductivity are small and this heat can most readily be supplied from some outside source. If the temperature of the atmosphere is higher than either of the ice surfaces, it could be supplied by conduction from the air. Under these conditions we should expect that the friction of a good thermal conductor would be less

than that of a bad one. The friction of a brass ski on cold ice should be *less* than that of an ebonite one.

If, however, the lubricating film is formed by frictional heating, the converse will be true. The frictional heat is liberated at the interface between the sliding surfaces, and if the ski is a good thermal conductor, the heat will be carried away rapidly and less will be available for surface melting. On this view the friction of a brass ski on cold ice should be *greater* than that of an ebonite one. Figure 10 shows the results obtained using a miniature ski of brass and of ebonite.

At temperatures near 0°C the frictions of both skis were the same. At lower temperatures, however, the results showed that the friction of the brass was considerably greater than that of the ebonite. The lower the temperature the more pronounced this difference usually became. These results provide evidence that the frictional heating plays an important part in the formation of the water film.

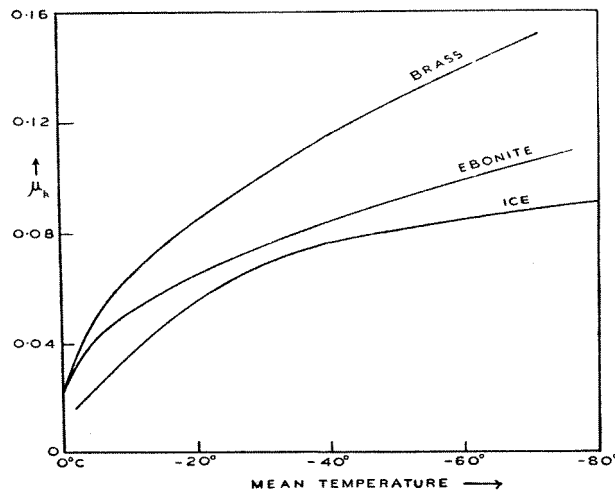


FIGURE 10. - Effect of temperature on the friction of brass, ebonite and ice sliding on ice. The friction increases markedly as the temperature falls and is lower for the slider possessing the lower thermal conductivity.

The observations have an interesting bearing on sledging and skiing. No quantitative measurements of the friction of sledges seem to have been published, but there is general agreement that the friction increases at low temperatures. Many arctic explorers (Wright, 1924, p. 44; J. M. Scott, 1933, p. 273; Cherry-Garrard, 1922, pp. 456-7) have recorded that at very low temperatures, -30 to -40°C, the friction between the snow and the runners became so great that the sensation was that of pulling a sledge over sand. Wright, summarizing the conclusions of the Scott Polar Expedition of 1911-13, says:

"Quite apart from any question of the hardness of the snow, however, the surface temperature has an important influence. Our opinion was that the friction decreased steadily as the temperature rose above zero Fahrenheit (-18°C), the presence of brilliant sunlight having an effect, which was more than a psychological one, on the speed of advance. Below zero Fahrenheit (-18°C) the friction seemed to increase progressively as the temperature fell, as if a greater and greater proportion of the friction were due to relative movement between the snow grains and less to sliding friction between the runner and snow." This steady increase in friction as the temperature of the ice or snow falls is clearly shown in Fig. 10. The effect is less marked at very low temperatures, and it is probable that below -40°C very little surface melting occurs under these conditions.

The influence of the thermal conductivity of the sliding body on the friction, shown in Fig. 10, is also borne out by practical experience. It will be seen from this figure that at low temperatures the friction of a good thermal conductor is considerably greater than that of a poor one. Nansen (1898, pp. 445-6) compared two sledges, one having nickel plated runners and the other maple runners. The temperature was low - the actual value is not given, but the mean temperature during that month was -36.8°C (-34.2°F). He found that the friction of the metal was higher: "The difference was so great that it was at least half as hard again to draw a sledge on the nickel runners as on the tarred maple runners."

The thermal conductivity is also important in skiing. Nowadays, most skis are fitted with brass or steel edges, although sometimes vulcanite or composition edges are used. The friction measurements show that the latter should be faster at low temperatures. If metal must be used, one of low thermal conductivity such as German silver or constantan should be better.

The Surface Damage of Sliding Metals

Returning again to the sliding of metallic surfaces, there are, as we have seen, two major experimental observations. First that the area of contact between them is very small so that the pressure in the local regions of contact is very high and is sufficient to cause plastic flow of the metal, and secondly that at sliding speeds frequently used in practice the surface temperatures may rise to very high values. The third point we need to investigate is the type of interaction between the moving surfaces and the physical changes which occur in them during sliding. Careful examination shows that some surface damage always occurs even with lightly loaded, well-lubricated surfaces. The nature of the damage depends upon the combination of metals which is used. Plate II, Fig. 5, shows the tracks formed (i) on a softer metal when a hard one slides over it, (ii) on a harder metal when a softer one slides over it, (iii) when similar metals are used. In these experiments a heavy load was used and the surfaces were unlubricated so that the effect could be seen more clearly. It will be seen that in (i) a ploughing out and tearing of the softer metal has occurred; in (ii) the harder surface is comparatively little damaged but the softer metal has welded on to it and remains adhering to the surface. With similar metals (iii), which are homogeneous, the damage is more profound and it is this combination which always gives the highest friction. (It should be emphasized that in these experiments and in the ones described below the sliding speed was very slow (a few millimetres per second), so that the temperature rise is inappreciable.)

Highly magnified taper sections made by Mr. Moore which represent a cross section of these three types of tracks are shown in Plate III, Figs. 1-4. Plate III, Fig. 1 shows a track characteristic of type (i) made on a steel surface.¹ The localized nature of the damage is at once apparent. A considerable area of the surface is unchanged. At a

¹ It is interesting to note that when steel is slid on steel the frictional behaviour and the surface damage are characteristic of *dissimilar* metals. This is because steel is a non-homogeneous alloy. If pure iron or a homogeneous steel alloy (e.g., stainless steel) is used, the friction is considerably higher and the behaviour is characteristic of type (iii).

number of points, however, penetration, ploughing and tearing of the metal have occurred. The depth of these torn channels varies from considerably less than 10^{-4} cm. to about 10^{-3} cm. At other points on the surface the metal is raised above its former level. Some of this torn metal comes from the lower surface and some of it is probably left behind by the slider.

If the upper surface is of a softer metal, this ploughing out is not observed. Instead, small fragments of the softer metal are left welded on the harder one. Characteristic welded junctions of this type, formed when copper (hardness 60 B.H.N.) is slid on mild steel at a low speed are shown in Plate III, Fig. 2. The greater part of the steel surface was undamaged, and isolated fragments of copper were left adhering to the steel and distributed over it. For these junctions the shearing has occurred in the copper itself. In other cases, for example the hollows and pits, C, shown in Plate III, Fig. 2, the copper has *plucked out* small fragments of the steel. Microphotographs of the copper steel junctions at higher magnifications are shown in Plate III, Fig. 3. The white portion of the steel is ferrite, the dark portion is pearlite, and A is a copper fragment *ca.* 5×10^{-3} cm. wide and *ca.* 10^{-3} cm. high. It is clear that the copper is welded on to the steel and that the junction has sheared in the copper itself. It is seen that the forces which sheared through the copper have also caused appreciable deformation of the underlying steel, and have actually raised portions of the steel above the general level of the steel surface. Over a large portion of the surface, however, there is no apparent change in the surface.

A section of the track formed when similar metals slide (copper on copper) is shown in Plate III, Fig. 4. In this case the friction is higher, $\mu \sim 1$ instead of $\mu \sim 0.7 - 0.8$ in Plate III, Figs. 1 and 2, and the damage is great. The ploughing and tearing are very evident. It is interesting to note that the work hardening and deformation of the metal occur to a considerable depth below the actual track.

The Chemical Detection of Metal picked up during Sliding

When the surfaces are lubricated the metallic interchange between the surfaces is very greatly reduced so that its detection, even by the taper section method, is very difficult. It may, however, be detected by a technique described by Hunter, Churchill and Mears (1942), and Mr Moore has applied this method to the examination of the frictional tracks. A gelatine-coated paper is soaked in a suitable electrolyte and pressed while still wet against the surface to be examined. A small current is passed between the paper and the metal so that the metallic ions pass into the gelatine. As they are prevented from diffusing by the gelatine, the ions concentrate in a pattern corresponding to their distribution on the metal surface. By means of a suitable spot reagent the distribution of ions in the gelatine can be shown up. The results obtained with copper sliding on steel are shown in Fig. 11. The copper slider has passed over the steel surface once. The track widths are magnified 15 times.

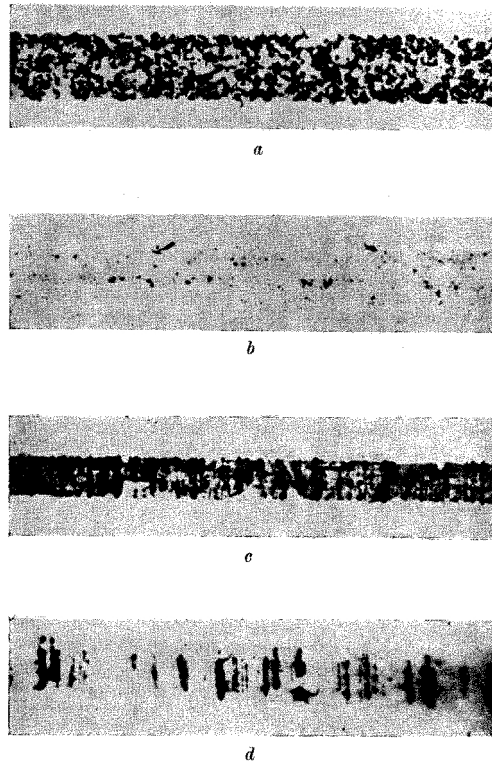


FIGURE 11. - Electrographic surface analysis: magnified chemical patterns showing distribution of copper adhering to a steel surface after traversing the steel surface once. Magnification x 15

- (a) Polished steel surface, unlubricated. This represents the same type of surface as Plate X, Fig. 2, and shows very marked pick-up.
- (b) Polished steel surface, lubricated. Although the pick-up is very much reduced it is still apparent.
- (c) Lapped steel surface, unlubricated. The pick-up is very heavy.
- (d) Lapped steel surface, lubricated. The pick-up is less but well marked. In both (c) and (d) the pick-up is concentrated in regions corresponding to the lapping scratches in the steel surface.

It will be seen that the pick-up of the copper on the polished surface is fairly random with a slight tendency to be arranged in lines parallel to the track. These would correspond to high spots on the copper contact as it is worn down.

However, with the lapped surface the lapping scratches which are across the tracks have influenced the pick-up of copper resulting in a number of regions of high copper concentration stretching right across the track and parallel to the lapping scratches. Under lubricated sliding, the same effects are noted but to a much smaller degree. It is apparent from these pictures that marked pick-up of copper can occur under both clean and lubricated conditions and that it occurs more readily at the high spots of either of the two sliding surfaces.

This method is extremely sensitive and it is probable that the amount of copper on the surface of the lubricated steel is less than a millionth of a gramme.

A still more sensitive method is to use a radio-active metal as one of the sliders and detect the presence of any picked-up metal by a Geiger counter. By this method quantities of the order of 10^{-9} to 10^{-10} grammes can be detected. Experiments using this method were begun by the writer when in Cambridge in 1938, but they were interrupted by the war. Recently, however, and independently, workers at the Massachusetts Institute of Technology in America (Sakmann, Burwell and Irvine, 1944) have applied the method to steel and other metals sliding on radio-active copper beryllium. They have confirmed in a very beautiful way the observations that metal is picked up through the lubricant layer even with light loads, and have measured the amount.

PART II.

Theory of Solid Friction

There have in the past been two main theories of solid friction. According to the first, friction is due simply to a mechanical interlocking of the surface asperities on the solids; according to the second it is due to a molecular attraction between the two solids and should be explicable in terms of surface forces. It is clear, however, from these experiments that the physical processes which occur during sliding are very complex. The friction cannot be regarded as a surface effect. Penetration and distortion occur to a great depth beneath the surface and the frictional force and the nature of sliding are both influenced by the bulk properties of the solids. The physical properties of the solids such as their relative hardness and (if the sliding speed is high) their relative melting point play an important part.

It is suggested that the frictional resistance between unlubricated metals is due primarily to the shearing of the small metallic junctions formed locally at the points of contact and to the work of dragging or ploughing the surface irregularities of the harder metal through the softer one, so that we may write the frictional force F as

$$F = S + P$$

where S is the force required to shear the metallic junctions and P the force required to displace the softer metal from the path of the slider. It follows that $S = As$ where A is the real area of contact of the metals and s the shear strength of the softer metal, while $P = A'p$ where A' is the cross section of the torn track and p is the "flow pressure", i.e. the pressure to cause plastic flow of the softer metal. From this

$$F = As + A' p$$

When the load is applied to the surfaces, plastic flow of the softer metal occurs at the regions of contact until the area of contact is sufficiently great to support the applied load. With any particular metal, therefore, the real area of contact is determined, primarily, by the load W , and $W = pA$.

$$\mu = \frac{F}{W} = \frac{As}{W} + \frac{A' p}{W} = \frac{\text{shear strength}}{\text{flow pressure}} + \frac{A'}{W}$$

If the ploughing term is negligible, it follows that

$$\mu = \frac{\text{shear strength}}{\text{flow pressure}}$$

By using sliders of appropriate shapes we may evaluate S and P separately and see how far experiment agrees with theory.

A simple case experimentally is that of a cylindrical slider of a hard metal (e.g., steel) resting on a flat surface of a soft one (e.g., lead or indium) (see Fig. 12). The force F required to move the slider forward will be made up of two parts. The first is the force P required to displace the softer metal from the front of the slider and will be equal to the cross sectional area of the grooved track A' multiplied by the flow pressure of the softer metal. The second is the force S required to shear the metallic junctions at the points of adhesion between the two metals.

If the length of the cylinder is zero, i.e., if the slider is in the form of a semi-circular spade (Fig. 12) the work of shearing vanishes and all the frictional work is due to ploughing.

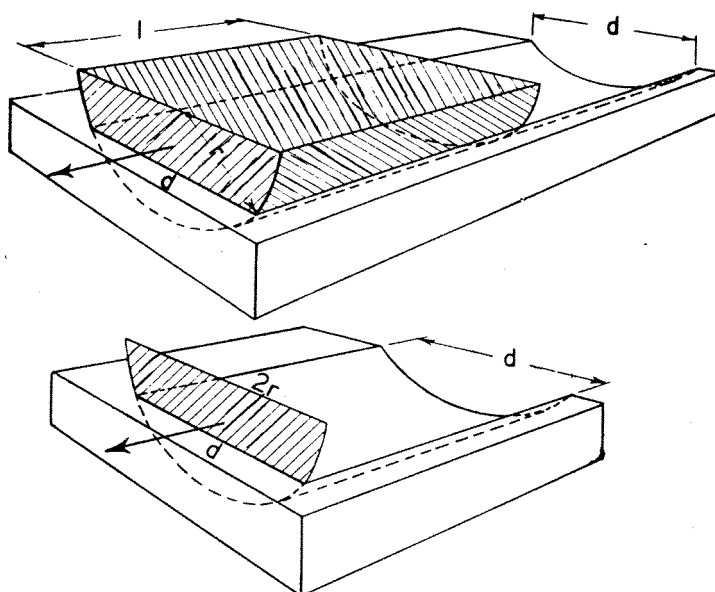


FIGURE 12. - (a) A cylindrical cylinder of steel being dragged through indium involves a ploughing force P and a shearing force S . (b) A semi-circular spade being dragged through indium involves only the ploughing force P .

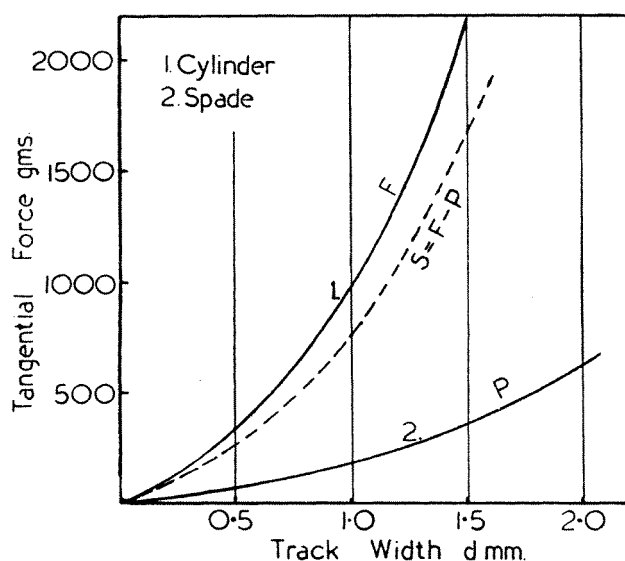


FIGURE 13. - Graph showing the frictional force as a function of the track width for a cylindrical slider (Curve 1) and for a spade (Curve 2) sliding on indium. The difference between Curves 1 and 2 gives the shearing term S .

Fig. 13 shows the result of such an experiment with steel cylinders and spades on indium. Curve 1 (F) represents the experimental results for a cylinder, Curve 2 (P) the results for a spade, and Curve 3 the difference between them, gives the shearing term S . It is then possible to compare these experimental values of P and S with the theoretical ones calculated from the flow pressure and the shear strength of indium, and such a comparison shows that the results are in reasonable agreement with the theory, for indium, lead and other metals. It will be noted that the ploughing term P is small compared with the shearing term S .

Elastic and Plastic Deformation. Frictional Hysteresis

The reality of the welding process is clearly demonstrated when frictional measurements are made with soft plastic metals. With lead or indium, for example, sliding on steel, the value of the friction is very variable and depends on the previous history. If the load is first applied and then decreased or removed altogether, the surfaces continue to "stick" together and the tangential force necessary to cause sliding remains high, although there is no normal load applied between the surfaces. This is not observed on harder, more elastic, metals. For such metals, the frictional force decreases when the load is decreased and the effects are reversible. It is suggested that the elastic deformation of the metals is responsible for this. At the actual region of contact where the local pressures are very high, the deformation of the metals will be plastic. Near this region, however, where the pressures are smaller, the metals will be elastically deformed. When the load is decreased, these stresses will be released and the small movement that results will serve to break the metallic junctions. The area of contact at any given time will, therefore, be determined by the actual load between the surfaces. In the case of a soft plastic metal like indium, however, which shows little elastic recovery, this will not occur, and once the clean surfaces are pressed together they will continue to adhere even when the load is reduced or removed. Similar effects have been observed with gold when its temperature was raised to its softening point. For this reason, measurements of the "coefficient of friction" of an indium slider on a flat steel plate may have little meaning. If, however, the friction is measured as a function of the real area of contact, this difficulty does not arise and consistent results are obtained.

In the experiments described in this paper, the speed of sliding was very low, so that the rise in the surface temperature due to frictional heating was negligible; the melting between the metals is brought about by the intense pressures in the regions of contact. If higher speeds are used, the rise in temperature may be considerable, and a surface softening or local melting may occur. Under these conditions, it is clear that the controlling factor in the frictional behaviour of the metals is not their mechanical properties at room temperature, but their properties at the high temperature of sliding.

The analysis outlined has been applied to metals which differ in hardness. It is clear, however, that the same general considerations apply if the surfaces both consist of the same metal, but since both surfaces are torn, it is not easy to evaluate the ploughing and shearing terms separately. Also the discussion has been confined to metals, but we may expect similar conclusions to hold for many types of non-metallic solids.

Lubrication by Thin Metallic Films

As we have seen, the frictional resistance between solids may (when P is small) be represented approximately by the expression $F = As$. If then we wish to get a low friction we should make both A and s as small as possible. Unfortunately, with most solids this is not possible. If we choose a solid of low shear strength it usually means that it has a low flow pressure so that when we apply a load to the surfaces the area of contact A becomes correspondingly larger. An obvious exception to this is a solid with a plate-like structure such as graphite. This is able to withstand a pressure normal to the plates but will shear readily when a tangential force is applied. The friction of graphite is notoriously low. It is difficult to achieve this condition for metals since they are less anisotropic. If we choose a soft metal of low s , A will be large (Fig. 14 (a)). If we choose a hard metal A will be small but s will be great (Fig. 14 (b)). For this reason the friction of most metals is of the same order of magnitude and $\mu \sim 0.6 - 1.0$.

We may, however, achieve this condition efficiently by depositing a very thin layer of a soft metal on to the surface of a hard one (Fig. 14 (c)). Provided the metallic film does not break down the shear strength will be that of the soft metal. At the same time A will

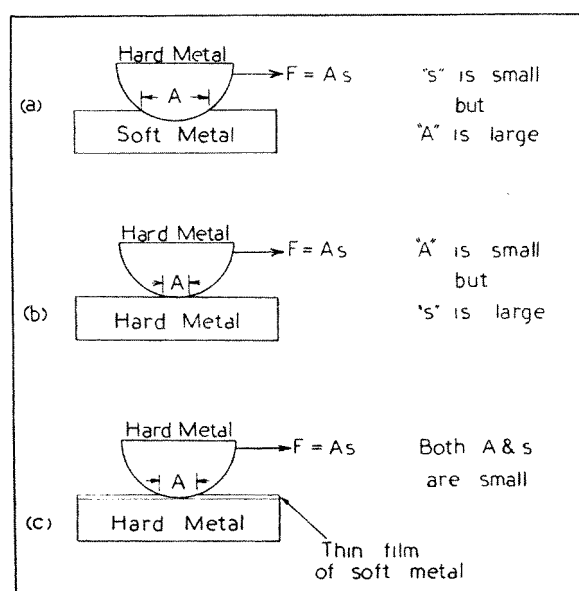


FIGURE 14. - The friction between metal surfaces is not greatly dependent on their hardness. A low friction may be obtained by depositing a thin film of a soft metal on a hard metal substrate.

remain small even for heavy loads since it is not greatly affected by the plastic deformation of the hard metals; it is determined essentially by the thickness of the film and the geometry of the surfaces.

A series of experiments was carried out by Dr. Tabor with films of indium, lead and copper surfaces. The substrate was steel, nickel, copper or silver. The upper surface, was a hemispherical steel slider. It was found that the friction is almost independent of the underlying metal and of the load. The main effect of increasing the load is to cause a slight increase in the deformation of the underlying metal, and so cause a slight increase in the track width d . Since silver is softer than steel the same load will produce a greater deformation. The track width d , and hence the frictional force F for any given load and

film thickness will, therefore, be greater on silver than on steel. This effect was observed. In Fig. 15, F is plotted against d for lead films deposited on various substrates; the

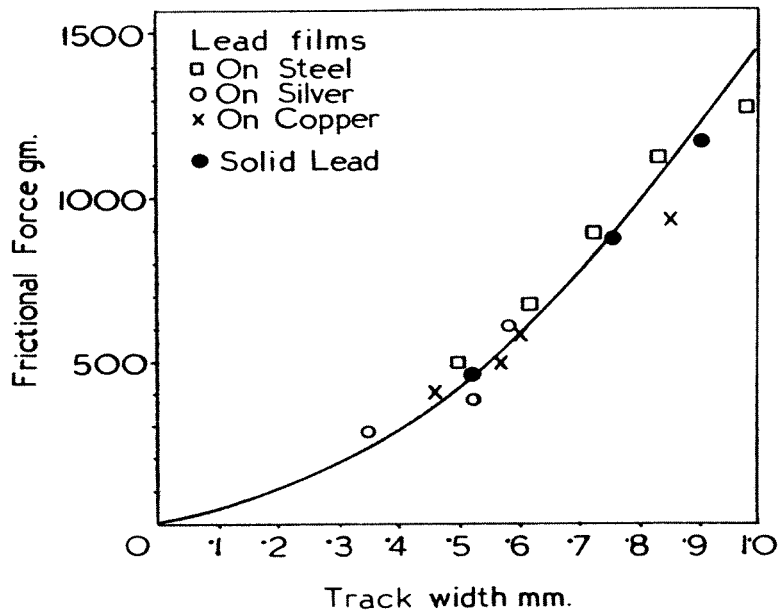


FIGURE 15. - Friction of steel slider on lead films deposited on steel, silver and copper substrates, as a function of track width. It is seen that the friction is determined primarily by the track width, whether the friction is determined on the surface film or on the bulk lead.

different values of the track width being obtained by varying the thickness of the deposited layer and the radius of curvature of the upper surface. It will be seen that in all cases the frictional resistance is determined, primarily, by the track width, whether the friction is measured on the surface film or on the bulk metal. Essentially similar results were obtained for indium and copper films. It was also found, as we should expect, that the value of the friction was proportional to the shear strength of the respective metals and for films of similar thickness the friction of copper > lead > indium.

The Limiting Film Thickness

Experiments were carried out to determine the minimum thickness of the deposited film that would influence the friction. The results for indium on tool steel are shown in Fig. 16. The film thickness was calculated from the quantity of electricity used to deposit it. The upper curved slider was of hard steel (radius 0.3 cm.) and the load was 4,000 g. As one might expect, the friction decreases as thinner films are used because the area of contact A becomes smaller. There is, however, a limit to this, and a minimum friction is reached when the thickness is of the order of 10^{-5} cm. With thickness less than this, e.g. 10^{-4} cm. (or 50 atomic layers) the film ceases to be effective.

The underlying surface of the tool steel was not highly polished nor was it homogeneous. These factors might easily cause the indium to be deposited preferentially in certain regions, leaving patches of the surface uncovered or only very thinly covered. It is possible that if highly polished surfaces of a uniform metal were used as a substrate, very much thinner layers, even perhaps one or two molecular layers, might prove effective.

Breakdown and Wear of Films

If very heavy loads are used, the values of F deviate from the curves shown in Fig. 16. After a certain load has been exceeded the friction increases markedly with load, even though the track width remains essentially unaltered. An examination of the track shows

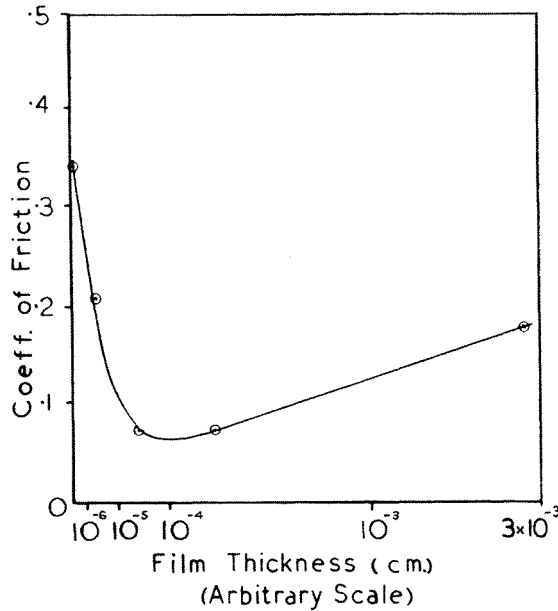


FIGURE 16. - The effect of film thickness on the frictional properties of thin films of indium deposited on tool steel. A minimum friction is obtained for a film thickness approximately 10^{-4} to 10^{-5} cm.

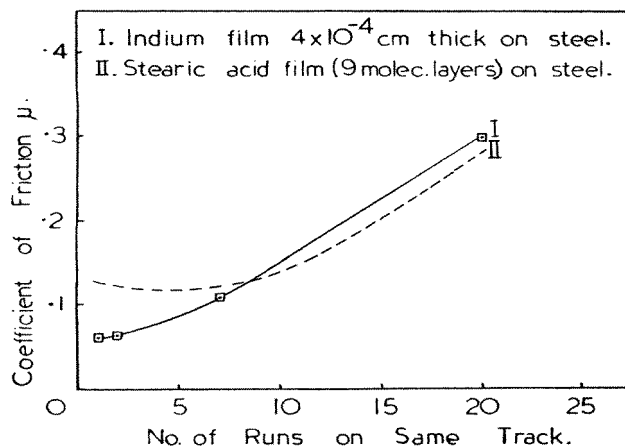


FIGURE 17. - Rise in friction with wear of an indium film 4×10^{-4} cm. thick deposited on tool steel. A stearic acid film two hundred times thinner has similar wear resisting properties.

that this is connected with the progressive breakdown of the film, as the heavier loads are applied. The load at which this breakdown occurs depends upon the film thickness and upon its strength of adhesion to the underlying surface. It is also influenced by the shape of the slider and takes place more readily if this has a small radius of curvature.

The film may also be worn away if the slider traverses the same track a sufficient number of times. With an indium film 4×10^{-4} cm. thick on tool steel the sliding during the first run was smooth and the coefficient of friction was about $\mu = 0.08$. With successive sliding over the same track the friction gradually rose and after the seventh run small "stick slips" set in. The friction and the size of the stick slips increased and after 20 runs μ had risen to about 0.4. Microscopic examination of the surface after the seventh run showed that the indium film had been partially worn away and portions of the steel surface exposed.

The rise in friction with wear of an indium film 4×10^{-4} cm. thick is shown in Fig. 17. With thicker films (not shown in Fig.17) the rise in friction is less rapid, showing that the thicker film is more resistant to wear. This behaviour may be compared with the dotted curve which represents the rate at which stearic acid layers are worn off a steel surface. We have found that with nine molecular layers of the acid an appreciable rise of the friction occurs after 20 successive runs. With 53 molecular layers, i.e. about 10^{-5} cm., no appreciable change was observed after 100 successive runs. It is clear that the metallic films resist wear quite well, but they are more easily worn off the surface than a much thinner film of the fatty acid. One factor that may be of importance here is the surface mobility of the film. The fatty acid molecules have a certain mobility and are able to move over the surface and repair the damaged film. Many metals also possess this ability to wander over solid surfaces, but it is probable that the rate at which this process occurs is less rapid for solid metallic films than it is for the fatty acids.

Metallic Films as Lubricants

Some experiments were carried out to determine the extent to which the coefficient of friction μ is independent of the load (Amontons' law). The results for tool-steel surfaces are shown in Fig. 18. Curve I is for the unlubricated steel; Curve II for steel lubricated with a film of mineral oil; and Curve III for steel lubricated with a thin film of indium approximately 4×10^{-4} cm. thick. The comparative behaviour is striking. The coefficient of friction for the unlubricated steel, and for the steel lubricated with the mineral oil, is independent of the load. With the indium film, however, μ decreases markedly as the load increases.

In the case of unlubricated steel, or of steel lubricated with the mineral oil, the area of contact should be proportional to the applied load, since it depends on the amount of plastic deformation that occurs. For this reason F should be directly proportional to the load, i.e., Amontons' law should hold and the coefficient of friction should be constant. This is in fact observed. For the unlubricated steel surfaces, the coefficient of friction is constant and $\mu = 0.34$, while for the surfaces lubricated with the mineral oil, the coefficient of friction is again constant and $\mu = \text{ca. } 0.14$.

If a thin film of a soft metal is used as a lubricant, however, A will no longer be proportional to the load. The real area of metallic contact now increases only to a slight extent when the load is increased, since the increase in A due to the increased deformation of the underlying steel is small compared with its actual value A . The shear strength s remains constant and is approximately that of metallic indium, so that F should be almost independent of the load. Amontons' law will no longer hold, and the coefficient of friction μ will not be constant but will decrease as the load increases. It will be seen from Fig. 18 that this occurs. The coefficient of friction falls from $\mu = 0.2$ at the light load to $\mu = 0.04$

when the heaviest load is used. If it were possible to lubricate the surfaces with metallic films of molecular dimensions, we should expect a closer agreement with Amontons' law.

In some ways the behaviour of the metallic films closely resembles that of ordinary lubricant films. They produce a substantial reduction in the friction, they can cause smooth sliding, and they protect the underlying metal surfaces. In addition, metallic films are worn off the surface by successive sliding over the same track in a manner similar to that of a lubricant film, except that the metallic films are worn away at a greater rate than the hydrocarbon films. A further point of striking similarity is the effect of melting. The transition from smooth sliding to stick slips when the metallic films are melted, is closely analogous to the change observed when solid hydrocarbon films are heated through their melting point.

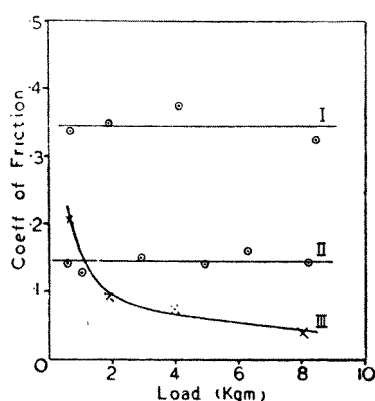


FIGURE 18. - Effect of load on the coefficient of friction for unlubricated steel surfaces (Curve I) steel surfaces lubricated with mineral oil (Curve II), and for steel surfaces lubricated with a film of indium 4×10^{-4} cm. thick (Curve III). The coefficient of friction is independent of load for Curves I and II, but rapidly decreases with increasing load for Curve III.

There are, however, several marked differences between metallic films and lubricant films. The earlier experiments showed that even on rough surfaces a lubricant film need only be one molecule thick to be effective as a boundary lubricant (see also Langmuir). A metallic film must be appreciably thicker, of the order of 10^{-5} cm., if it is to be effective. A further striking and fundamental difference is that lubricant films obey Amontons' law and metallic films do not. With metallic films the coefficient of friction decreases, as the load is increased, and at high loads the coefficient of friction may be extremely low. With the indium films described in this paper the value of μ under heavy load ($\mu = 0.04$) is considerably less than that observed with even the best boundary lubricants. This value is similar to that obtained on ice surfaces.

The Action of Bearing Alloys

The fact that values of friction as low as this may be obtained with unlubricated metals is of obvious practical interest. For a long time it has been customary to use special metallic alloys which have more desirable frictional properties than pure metals. The nature and composition of these alloys - bearing alloys they are usually termed - varies widely. The "white metal" alloys are divided roughly into two classes: tin-base alloys, i.e.

alloys which consist primarily of tin with various additions such as Sb, Pb, Cu; and lead-base alloys which consist mainly of lead with additions such as Sb and Sn. In general these alloys are complex in structure and contain hard particles dispersed throughout a softer matrix. Another bearing alloy which was developed later and which has found a wide application in aircraft and other engines when the conditions of operation are very severe, is the copper-lead alloy. This is not a true alloy at all but consists of a fine dispersion of lead distributed throughout copper. In one type of the bearing the lead is distributed as minute isolated droplets throughout the copper; in the other, the dendritic type, the lead forms the continuous phase round the copper dendrites.

There is no doubt that the friction of these bearing metals is very much lower than that of the pure metals. Typical values obtained by Dr. Tabor are given in Table 2.

The mechanism of this reduction in friction is, however, by no means certain. It has been maintained in the past that an essential characteristic of a bearing alloy is that it should possess a duplex structure consisting of hard crystals embedded in a relatively soft matrix. It is suggested (see, for example, Greaves and Wrighton, 1939) that the function of the hard crystals is to resist wear and that of the softer constituents to permit a more uniform distribution of the load, by allowing any of the hard crystals that are heavily loaded to sink so that the load is spread over a greater area. It is also suggested that the hollows worn in the softer material serve as reservoirs for the lubricating oil. There is probably something in these suggestions, and it is certainly true that many successful bearing alloys do possess a structure of this type. It is clear, however, that it is not a complete explanation and in many cases is certainly not true at all. Many bearing alloys, e.g. copper-lead alloys, may consist of a matrix of the harder metal with a small amount of the softer metal finely dispersed through it.

TABLE 2.

Friction of Steel Sliding on Pure Metals and on Bearing Alloys.

Metal.	Coefficient of Friction.
Tin	0.9
Tin base alloy	0.7
Lead	1.0
Lead base alloy	0.35
Copper	0.9
Copper lead alloy	0.18

In the case of the non-dendritic copper-lead alloy, for example, the hard copper forms the continuous phase so that it is not possible for it to "sink" into the lead. Why then is the copper-lead alloy so effective in reducing the friction? An obvious suggestion is that it is due to the smearing of a lead film over the surface of the copper. In order to test this a series of experiments was carried out with thin films of lead electrodeposited onto the copper.

Thin Films of Lead on Copper

The relation between the track width and the friction of a curved steel contact sliding on a copper surface which has been coated with lead films of varying thickness is shown in Fig. 19.

A film of lead 10^{-6} cm. thick (Curve II) causes very little reduction in the friction. As the thickness of the film is increased, the friction for any given track width decreases, and reaches a minimum when the film is 10^{-3} cm. thick (Curve V). Further increase in film thickness produces no further change. The frictional force is now governed by the shear strength of the lead and the width of the track and is not influenced by the substrate

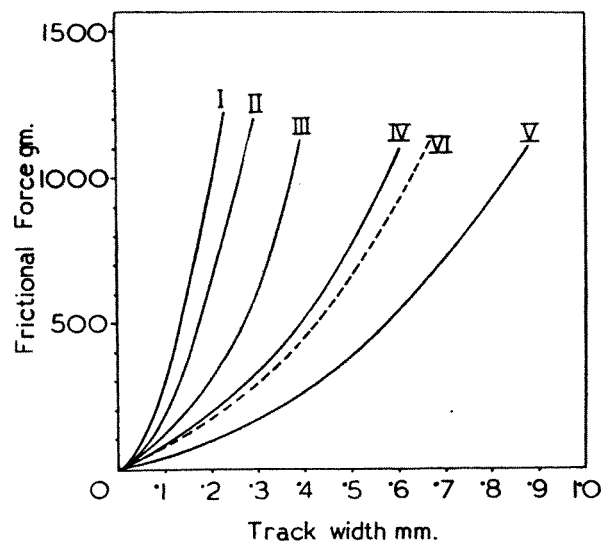


FIGURE 19. - Friction of a curved steel contact sliding on a copper surface coated with lead films of varying thickness. I, clean copper; II, lead film 10^{-6} cm. thick ; III, lead film 10^{-5} cm. thick; IV, lead film 10^{-4} cm. thick; V, lead film 10^{-3} cm. thick and more and solid lead; VI, lead-copper alloy. The behaviour of the alloy suggests that a thin film of lead is extruded and lubricates the copper matrix.

(except in so far as this may affect the track width). When similar measurements are made on solid lead, the points lie on Curve V (Fig. 19). It is clear that after the film has reached a thickness of about 10^{-3} cm. the friction is due to the interaction between the steel and lead. This minimum film thickness of 10^{-3} cm. for lead films on copper is greater than that observed when the films are deposited on steel. It is also greater than that observed when indium films on steel. As pointed out earlier, the minimum film thickness for complete "lubrication" is influenced by the hardness of the metal substrate. With softer metal substrates, such as copper, which are more readily deformed, thicker films are necessary. It is also influenced by the fineness of the original surface finish and by the state of cleanliness of the substrate since this affects the strength of adhesion of the deposited layer.

Copper-lead Alloys

The frictional behaviour of both dendritic and non-dendritic alloys at room temperature was similar. Steel on the alloys gave smooth sliding and a coefficient of friction of about $\mu = 0.18$. The tracks were smooth grooves showing little tearing. Some

signs of smearing of extruded lead could be detected. The alloys on steel gave stick-slip motion, the maximum value of the friction being about $\mu = 0.3$. The tracks showed that some metal from the upper contact had been welded on to the steel surface but the extent of this was considerably less than the welding observed with pure copper or lead.

It is at once apparent that the friction of these alloys does not lie between the values of their constituents. The friction of steel on copper, for example, is about $\mu = 0.9$, and for steel on lead $\mu = 1.0$. With steel on the copper-lead alloys, however, the friction is about $\mu = 0.18$. The alloys and the pure copper have approximately the same flow pressures at room temperature, so that the area of contact A is nearly the same for a given load. Nevertheless the friction of the alloys is less than one-quarter that of their pure constituents.

The relation between the friction F and the track width d for the alloy is plotted on the broken curve (Curve VI) in Fig. 19. It will be seen that these results lie very close to those obtained when a lead film 10^{-4} cm. thick is artificially deposited onto copper. This at once suggests that the lead in the alloys is extruded during sliding and forms a thin "lubricating" film of effective thickness between 10^{-4} cm. and 10^{-3} cm. on the copper. This is borne out by a microscopic examination of the track which showed traces of lead smeared over the surface.

The Role of Thin Films in the Action of Bearing Metals

We see, therefore, that the frictional behaviour of a copper-lead alloy resembles very closely that of a copper surface on which a very thin film of lead has been deposited. The actual value of the friction of the alloy is the same as that of a copper surface on which a lead film 10^{-4} cm. thick has been artificially deposited. Additional experiments showed that the temperature coefficient of friction was the same in each case. The increase in friction with wear was also very similar except that, in the case of the alloy there is evidence that the potential supply of lead is greater since it may continue to be expressed from the alloy during the sliding process. With a thin film of lead deposited on copper the supply is, of course, limited to the amount which is actually present on the surface at the beginning of sliding.

These results show the important part which may be played by thin surface films of metal in reducing the friction and wear of bearing alloys and support the view that in certain bearing alloys the anti-frictional and anti-seizure properties may be due, primarily, to the spreading of thin films of the soft low melting constituent, over the surface of the harder constituent.

Certain solids are able to provide their own surface films. This is the case, as we have seen, with ice. Under the frictional heating local melting of the surface layers may occur and may provide a lubricating film, while the bulk of the solid remains hard. With most pure metals it is difficult to achieve this, because of the progressive softening of the metal as the temperature is raised which leads to a corresponding increase in the area of contact, so that the friction is little affected. The problem is to keep both the area of contact A and the shear strength s as small as possible.

We see, however, that the condition of small s and small A may be achieved artificially by putting a very thin film of a soft metal on to the surface of a hard one. This

may be done by deposition beforehand, or it may be achieved by selecting an alloy of suitable composition and structure so that the film is spread during the sliding process.

In this connection the importance of surface tension is apparent. The soft low melting constituent must spread readily on the harder one to form a thin film. This is borne out by experiment. It was shown, for example, with lead, indium and mercury films on steel, copper and silver that unless the soft metal readily wetted the harder one, it was, under severe conditions of sliding, relatively ineffective as a lubricant.

Although it is desirable that these metallic films should adhere to and wet the substrate, the converse should be true about the other moving surface, e.g., the journal of a bearing. Provided the metallic film does not break down, the smaller the adhesion and the less the tendency of the metallic film to spread on to this surface the better. As has been pointed out in Part I, one important function of a lubricant is to reduce the adhesion between the two moving surfaces and help to reduce the effective shear strengths of the metallic junctions.

Apart from these surface tension and spreading effects the *availability* of the soft constituent is important. The dendritic copper-lead alloy, for example, may under certain severe conditions of sliding be more resistant to seizure than the non-dendritic alloy. In the former alloy the pockets of lead are all interconnected so that potentially a greater supply of lead is available to any particular area of the surface which may be in need of it. With the non-dendritic alloy the pockets of lead are isolated so that a local exhaustion of the lead may occur and a seizure on to the copper surface may take place. This difference is shown by the "sweating" out of the lead (see Plate IV, Fig. 1). When the non-dendritic alloy is heated, the lead appears as a fine mist of droplets over the surface. When the dendritic alloy is heated the lead collects in one or two large drops, by a surface tension effect (see Plate IV, Fig. 2). The dendritic alloy thus has a three-dimensional supply of lead to the surface while with the non-dendritic alloy it is restricted to the surface layers.

Lubrication by these thin metallic films may be used effectively in a number of practical problems. One of the newer type of bearings which is used in modern aircraft is the silver-lead bearing. The bearing surface consists of pure silver on which is deposited a thin layer of lead or of lead and indium. The silver itself has very desirable mechanical and thermal properties but it gives a high friction and readily seizes on steel. It may, however, be effectively lubricated by a thin film of a soft metal such as lead and indium. It is interesting to note that Atlee, Wilson and Filmer (1940) find that steel ball bearings in a vacuum tube may be effectively lubricated with thin sputtered films of barium and other metals. It is probable that thin metallic film lubrication will find an increasing application in a number of practical operations such as the pressing, drawing and heavy working of metals.

The Effect of Temperature Changes on Bearing alloys

As we have seen, the frictional heat liberated during running may raise the temperature of the surface layer of a bearing to high values, and this may have a marked effect on the mechanical and frictional properties of the bearing. In addition, however, to this localized surface heating the bearing as a whole may be gradually warmed up and cooled down as the engine is started or stopped or as the temperature of the oil changes, and we may enquire what effect these thermal cycles may have on the bearing alloy. If, as

is frequently the case, the alloy is bonded on to another metal, we may expect that the difference in the thermal expansion of the two metals may set up thermal stresses near the boundary. In the case of a typical lead-base alloy the coefficient of thermal expansion is $24 \times 10^{-6}/^{\circ}\text{C}$., while for steel it is ca. $12 \times 10^{-6}/^{\circ}\text{C}$.. If the bearing is heated and cooled through 100°C or so, the difference in expansion may cause a deformation and cracking of the softer metal. A characteristic example of this is shown in Plate IV, Fig. 3. This effect, which might be expected, is of practical importance, but it is of comparatively small scientific interest. Some recent experiments by Mr. Honeycombe have, however, revealed a new effect. He found that if he heated and cooled a tin-base bearing metal, *unattached* to any steel, through a temperature range of ca. 100°C , deformation and cracking occurred throughout the mass of the metal (see Plate IV, Fig. 4). A lead base alloy treated in the same way showed no such effect. The rate of heating and cooling did not affect the phenomena. In some cases the heating and cooling for a single thermal cycle took as long as seven hours. This shows that the effect is not due to a thermal gradient in the specimen, i.e., it is not due to a heating of the outside (with consequent thermal expansion) while the inside is cool.

To what, then, is it due, and why does it occur with tin-base and not with lead-base alloys? A study of the behaviour of pure metals carried out jointly by Dr. Boas and Mr. Honeycombe (1944) has given the explanation. It is found that pure lead shows no deformation. On the other hand pure tin shows plastic deformation as indicated by distortion at the grain boundaries (see Plate IV, Fig. 5). In cadmium and zinc the deformation is still more pronounced, and slip lines can be detected in these metals when they are heated through only one cycle between 30°C . and 150°C . Migration of the grain boundaries is also observed. The progressive deformation of cadmium with successive cycles is shown in Plate V, Figs. 1-6 and the deformation is shown even more clearly in Plate IV, Fig. 6. The effect of a larger number of cycles on zinc, cadmium and tin is shown in Plate VI, Figs. 1-3. As the number of cycles is increased signs of plastic deformation appear in more grains and become more pronounced in individual grains until finally most grains are affected.

Now pure lead is a cubic metal. It is isotropic and its coefficient of thermal expansion α is the same along all the crystal axes. These other metals are non-cubic and their expansion along the different crystal axes is different. With tin, for example, α parallel to the crystal axis, is twice as great as α at right angles to the axis. In the case of zinc it is about four times as great. It is this anisotropy of thermal expansion along the different crystal axes which is responsible for the deformation. In the polycrystalline metal, if we consider any two crystal grains in contact, the chances are that their orientation will not be similar so that when the metal is heated, the expansion on two sides of the grain boundary is different. This necessarily results in plastic deformation and slip in the crystals. This behaviour is therefore a fundamental property of polycrystalline metals themselves. It means that it is very difficult to prepare any anisotropic metal, or in fact any anisotropic crystalline solid, in a state free from strain, since the preparation usually involves some heating or cooling. Even if it is initially free from strain, these strains are readily set up by small changes in temperature. The results are therefore of some theoretical interest from the point of view of the theory of the strength of materials and the physical properties of metals. The work is still in the early stages and it is not yet possible to say of what importance it is practically. It may be a contributing cause to the deformation, cracking, and failure of bearing and other alloys which are observed in service.

The Influence of Surface Films

The Addition of Films

We have seen that the effect of sliding one surface over another is really a pretty far-reaching and disastrous one. Although to the naked eye, or even to the high-power microscope, there may appear to be little change, yet on a molecular scale an enormous tearing, welding and deformation has occurred. If the sliding is continued this ultimately becomes manifest as a wear or perhaps as a seizure of the surfaces. From time immemorial it has been customary to add various films, lubricants or greases to the surfaces in an attempt to prevent or to mitigate this damage. The first really systematic investigation of thin film lubrication or boundary lubrication was made by Sir William Hardy (1936), who measured the static friction between surfaces using homologous series of long chain paraffins, fatty acids and alcohols as the lubricants. In a series of simple and beautiful experiments he showed that the coefficient of *static* friction decreased linearly with the increasing chain length of each family of compounds. The friction also depended on the nature of the underlying solid surface. He was thus able to show that the friction was a function of separate contributions by the solid surface, the chemical series to

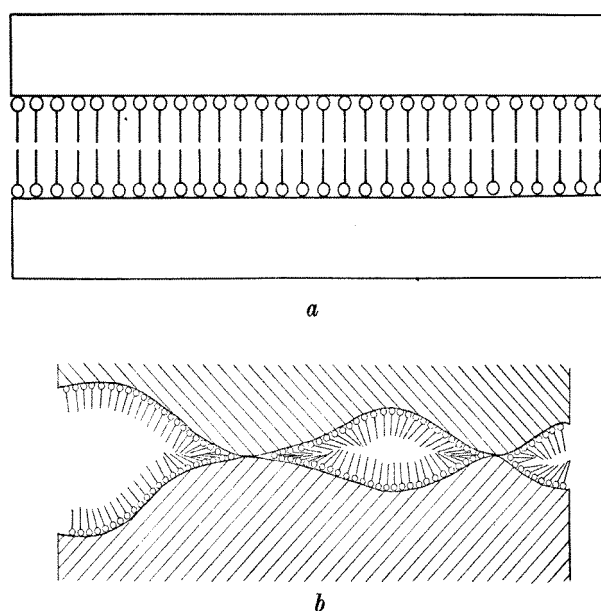


FIGURE 20. The sliding of solid surfaces under conditions of boundary lubrication.

- (a) Hardy's view which envisages interaction between the outer surfaces of the adsorbed monolayers, without any metallic contact occurring.
- (b) Mechanism involving a breakdown of the lubricant film at small localized regions. The metallic junctions so formed are mainly responsible for the friction and wear observed.

which the lubricant belonged, and the number of carbon atoms in the chain. Hardy explained these results by a very simple and elegant theory. He assumed that the friction between unlubricated solids is due to the surface fields of force. When the lubricant is added the lubricant molecules orient themselves at each of the solid surfaces to form a unimolecular adsorbed film. The solids sink through the lubricant layer until they are separated by only the unimolecular adsorbed film of lubricant on each surface. Slip then

takes place between these two adsorbed films; the friction is due to the interaction between the outside surfaces of the two adsorbed monolayers (see Fig. 20(a)).

As pointed out earlier, however, the interaction between moving solids is not confined to the surface; also we find that a layer even of the best lubricant is not able to prevent the occurrence of contact between the surfaces. Small localized breakdowns of the film occur (see Fig. 20 (b) and when sliding takes place the surfaces are damaged to a great depth.

Unfortunately there is not space in this lecture to deal with the interesting subject of lubrication. Before finishing, however, I would like to mention one more point, that is, the effect of removing the surface films which under normal conditions are always present even on the cleanest surfaces.

The Removal of Surface Films

Experiments on electron diffraction and electron emission as well as optical and other methods have made it abundantly clear that when a solid is cleaned in air by any ordinary method its surface is still covered by a film of oxide, water vapour, and other adsorbed impurities. The surface film is often many molecular layers in thickness. Any complete theory of friction must take this film into consideration. Most experiments on the friction of metals are not made with metallic surfaces at all but with a metal coated with this surface film. If a lubricant is used, it is not added to the metal directly, but is superimposed on a film of the contaminant.

It is difficult to remove the last adsorbed film and to maintain the surfaces clean. With metals, for example, this can only be done by heating to a high temperature in a very low vacuum. Dr. Hughes (1939) has carried out experiments of this type with a metal cylinder sliding on a wire. The experiments were carried out in a vacuum of ca. 10^{-6} mm. of Hg and both the cylinder and the wire were cleaned and degassed by heating to 1000°C . The effect of removing this adsorbed film of oxygen and other contaminants from nickel and tungsten surfaces is shown in Fig. 21 (a). When the surfaces are really clean the friction rises from its normal value of $\mu = \text{ca. } 0.3$ to $\mu = \text{ca. } 6$. Similar results for copper are given in Fig. 21 (c).

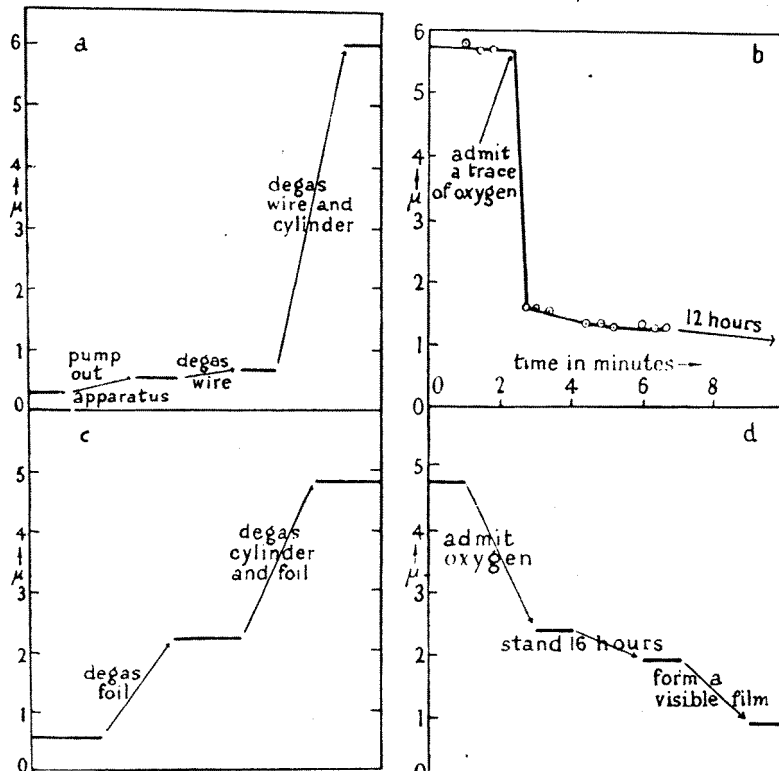


Fig. 21.

(a) and (c) Effect of removing the adsorbed film of oxygen and other contaminants from metal surfaces, (a) nickel on tungsten, (c) copper on copper. The friction rises by a factor of nearly twenty.

(b) and (d) Effect of deliberately adding a trace of oxygen, (b) nickel on tungsten, (d) copper on copper. There is a rapid reduction in the friction.

If the clean surfaces are allowed to stand at room temperature in a vacuum of 10^{-5} to 10^{-6} mm., a steady decrease in friction occurred. This decrease occurred in a few minutes and is due to the gradual contamination of the surfaces by residual gases in the apparatus. If we can get rapid contamination under these conditions it is clearly impossible under ordinary experimental conditions to get surfaces which, from the frictional point of view, are really clean.

The effect of deliberately adding a trace of oxygen is shown in Fig. 21. It is seen that there is a rapid reduction in the friction. On the other hand, adding pure hydrogen or pure nitrogen had no effect in reducing the friction of clean surfaces.

The observation that the friction of naked metals is very high (some 20 times greater than that of the normally clean metals) makes us realize how fortunate it is that, in engineering practice and, in fact, in many everyday affairs, metal and other surfaces are contaminated with oxides and other films. If it were not for the fact that metal surfaces (even when we think that we have cleaned them thoroughly) are coated with comparatively thick layers of oxide, "dirt" and other contaminants, much of our machinery would come to a sudden and disastrous stop.

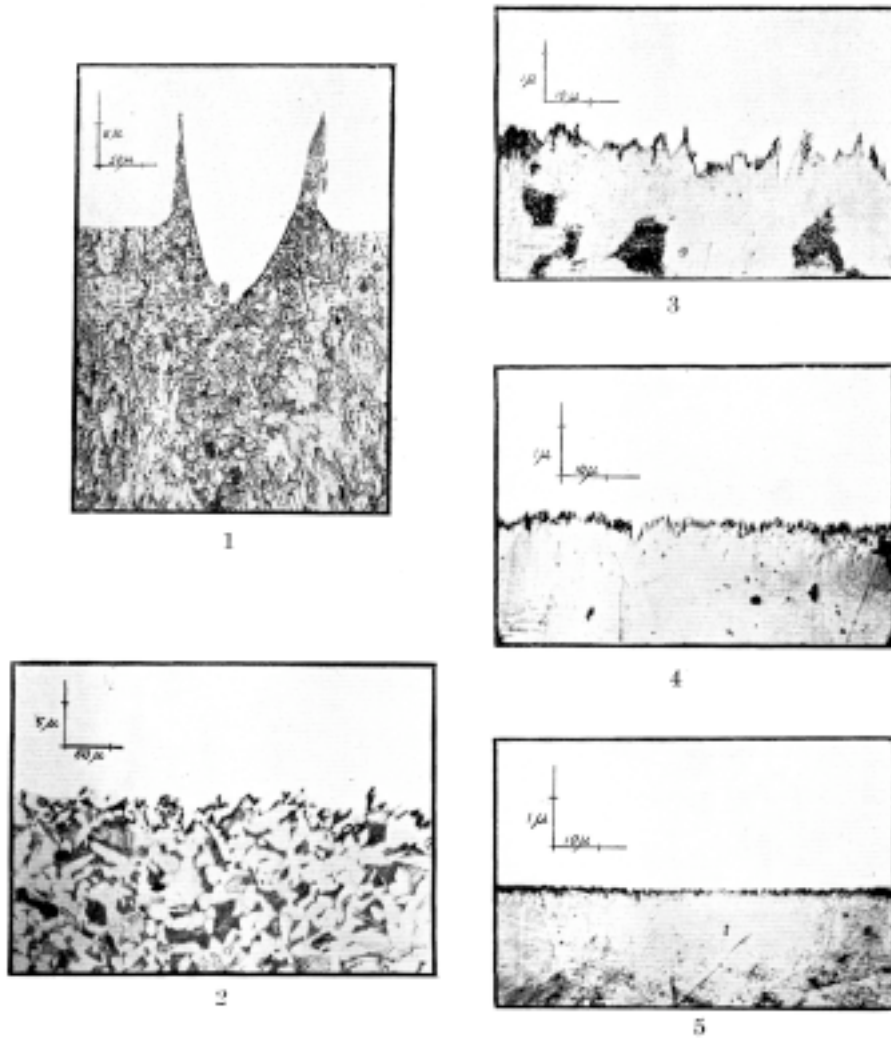
Acknowledgement

I would like to express my thanks to the Royal Society of New South Wales for inviting me to give these lectures and for its generous and genial hospitality during my stay. I am glad to have this opportunity of acknowledging my indebtedness to the Executive of the Council for Scientific and Industrial Research, with which I have been associated (although necessarily in a temporary capacity) for the past few years. There is no doubt that the stimulating atmosphere within this organization, the encouragement that is given to fundamental work, and the facilities provided for it, are such as to attract to Australia scientific workers of the first rank. I would also like to thank the University of Melbourne for its active collaboration, and in particular Professor E. J. Hartung, who has provided us with laboratory accommodation and with wise guidance.

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PLATE I.



Taper Sections of Metal Surfaces prepared in various ways.

(Note: $1\mu = 10^{-4}$ cm.)

Fig. 1. Pin scratch made by fine steel pin on copper surface. Horizontal magnification x 130; vertical magnification x 1300. Note the built-up edges and also the work hardening of the metal which extends to a considerable depth below the original surface.

Fig. 2. Finely machined steel surface. Horizontal magnification x 130; vertical magnification x 1300. The surface irregularities are of the order of 1.2μ .

Fig. 3. Steel surface lapped with 150 wet carborundum paper. Horizontal magnification x 650; vertical magnification x 6,500. The surface irregularities are of the order of $0.3 - 1\mu$.

Fig. 4. Steel surface lapped with 320 wet carborundum paper. Horizontal magnification x 650; vertical magnification x 6,500. The surface irregularities are of the order of $0.2 - 0.4\mu$.

Fig. 5. Steel surface lapped with 600 wet carborundum paper. Horizontal magnification x 650; vertical magnification x 6,500. The surface irregularities are of the order of 0.1μ .

PLATE II.

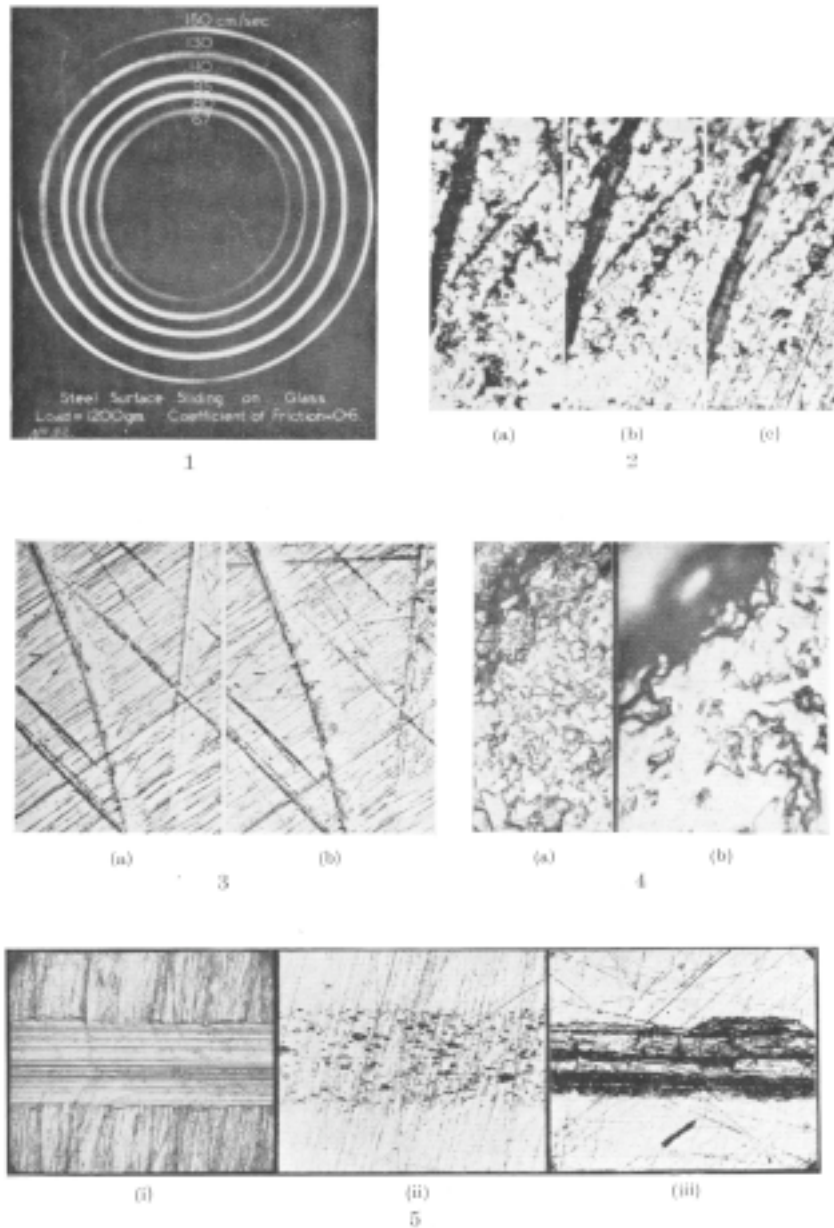


Fig. 1. Photographic record of hot spot produced by a steel pin running on a glass plate (load 1, 200 gm., coefficient of friction 0.6).

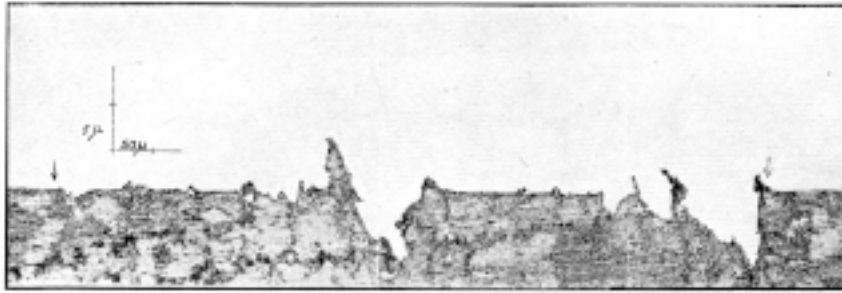
Fig. 2. Result of rubbing Wood's metal (M.P. 69°C.) on a camphor polisher (M.P. 178°C.) x 145. (a) Start (b) After 1 hour (c) After two hours of polishing. Surface flow has occurred.

Fig. 3. Result of rubbing speculum metal (M.P. 745°C.) on an oxamide polisher (M.P. 417 °C.) x 153. (a) Start (b) After half hour of polishing. No surface flow has occurred.

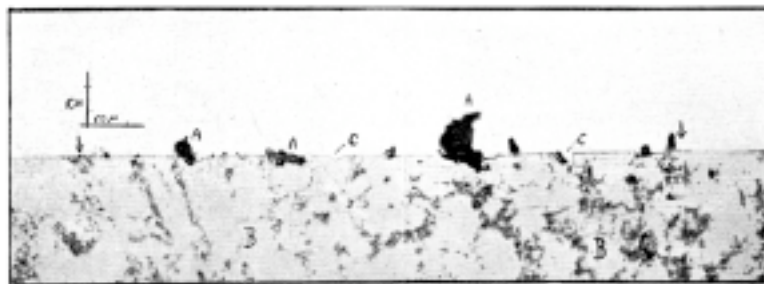
Fig. 4. Effect of rubbing calcite (M.P. 1333°C.) (a) on cuprous oxide polisher (M.P. 1235°C.), after half an hour there is no sign of surface flow; (b) on zinc oxide polisher (M.P. 1800°C.), after five minutes there is marked surface flow.

Fig. 5. Tracks formed (i) when steel slides on copper; the steel has ploughed out and torn the copper surface. (ii) When copper slides on steel; the steel is scarcely damaged but fragments of copper remain adhering to the steel surface. (iii) When nickel slides on nickel; the damage to the surface is very heavy.

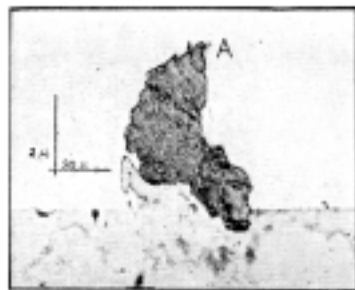
PLATE III.



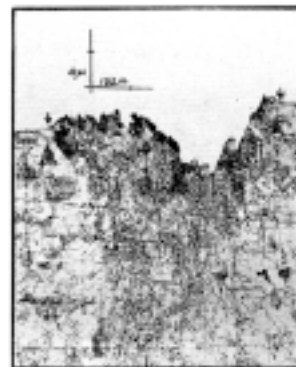
1



2



3



4

(Note : $1\mu = 10^{-4}$ cm.)

Fig. 1. Characteristic taper-section of steel sliding on steel. Horizontal magnification x 120; vertical magnification x 1200. A considerable portion of the surface is undamaged but a number of regions show marked penetration, ploughing and tearing of the surface. The depth of the torn channels is 1-10 μ .

Fig. 2. Taper-section of copper sliding on steel. Horizontal magnification x 120 ; vertical magnification x 1200. Fragments of copper *A* are left welded on the hard steel surface *B*, whilst the steel itself is scarcely damaged except at the hollows and pits *C*, where the copper has plucked out fragments of steel.

Fig. 3. Higher magnification of a copper fragment *A* welded on to a steel surface. Horizontal magnification x 300; vertical magnification x 3000. Note the portion of steel which has been dragged above the original surface level. This illustrates one mechanism by which a soft metal may cause wear of a harder metal.

Fig. 4. Taper-section of copper sliding on copper. Horizontal magnification x 60; vertical magnification x 600. There is marked ploughing and tearing and the deformation and work hardening of the metal extend to a considerable depth below the surface.

PLATE IV

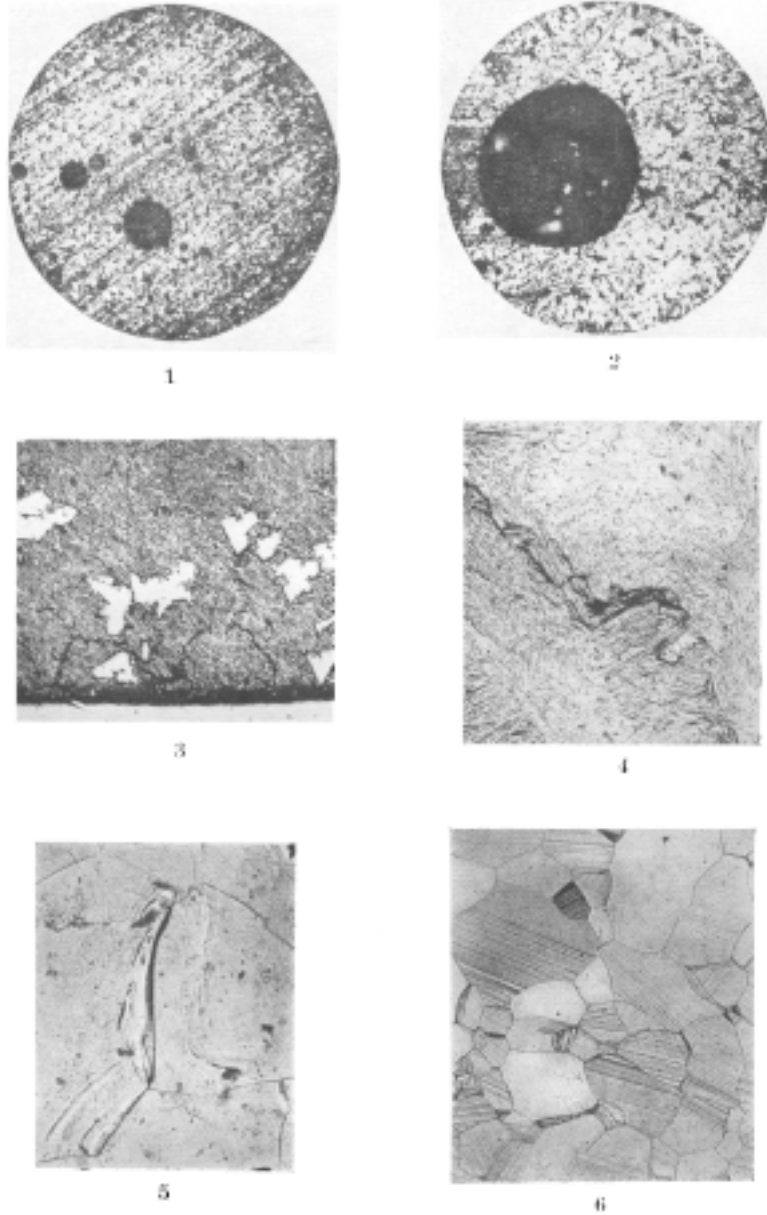


Fig. 1. The " sweating " out of the lead from non-dendritic copper-lead alloy.

Fig. 2. Dendritic copper-lead alloy after heating above 330°C. (x 36.) With the dendritic alloy the lead collects into a single drop on account of surface tension effects. With the non-dendritic alloy the lead globules remain unconnected.

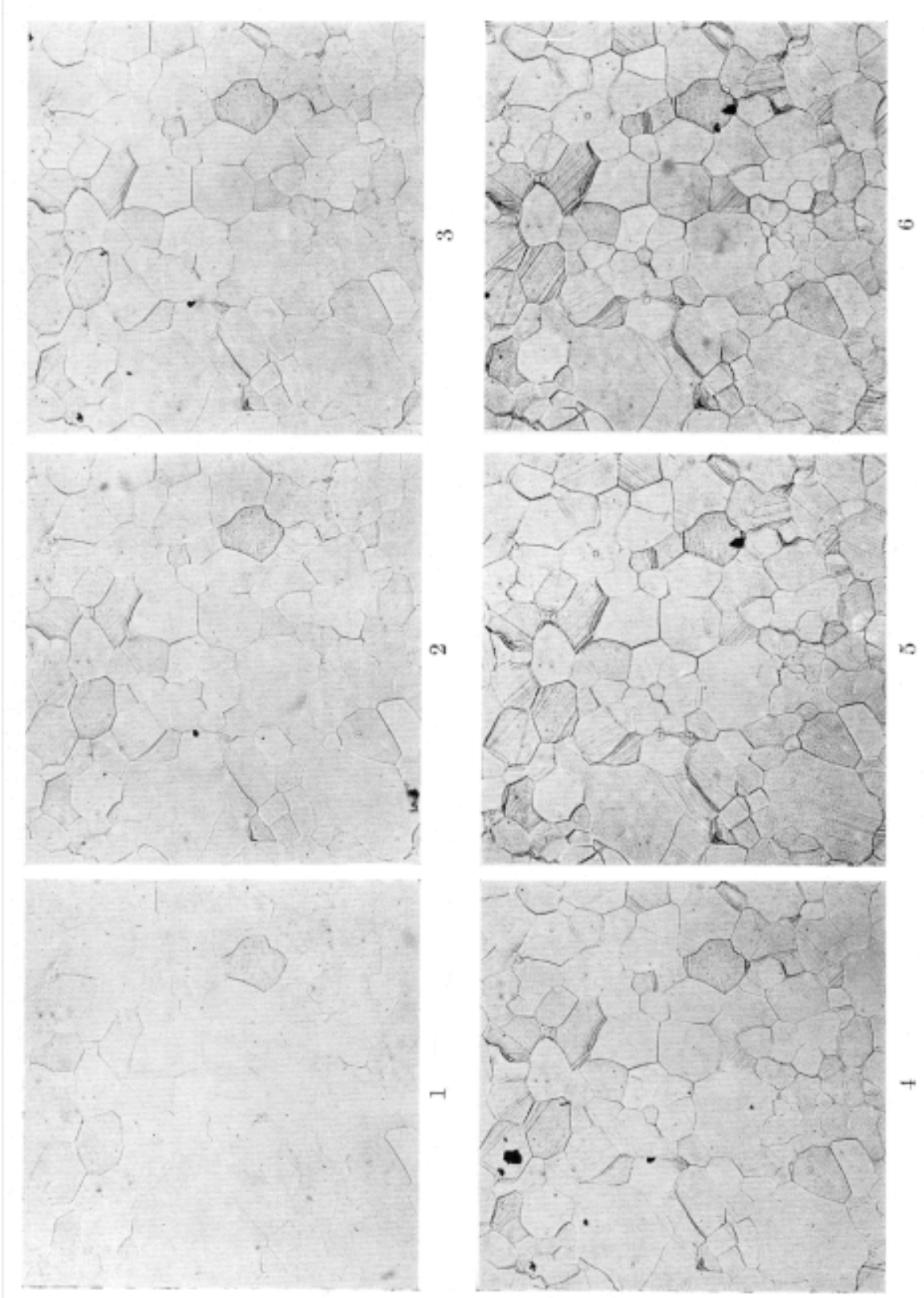
Fig. 3. Cracking at the bond between a lead-base bearing alloy and steel. (x 165.)

Fig. 4. Area of a tin-base bearing alloy after 50 cycles between 30°C. and 150°C. (x 33.) The alloy was not attached to a steel shell.

Fig. 5. Tin, showing distortion at a grain boundary after 50 cycles between 30°C. and 150°C. (x 330.)

Fig. 6. Cadmium showing deformation produced after 10 slow cycles between 30°C. and 150°C.(x 65.)

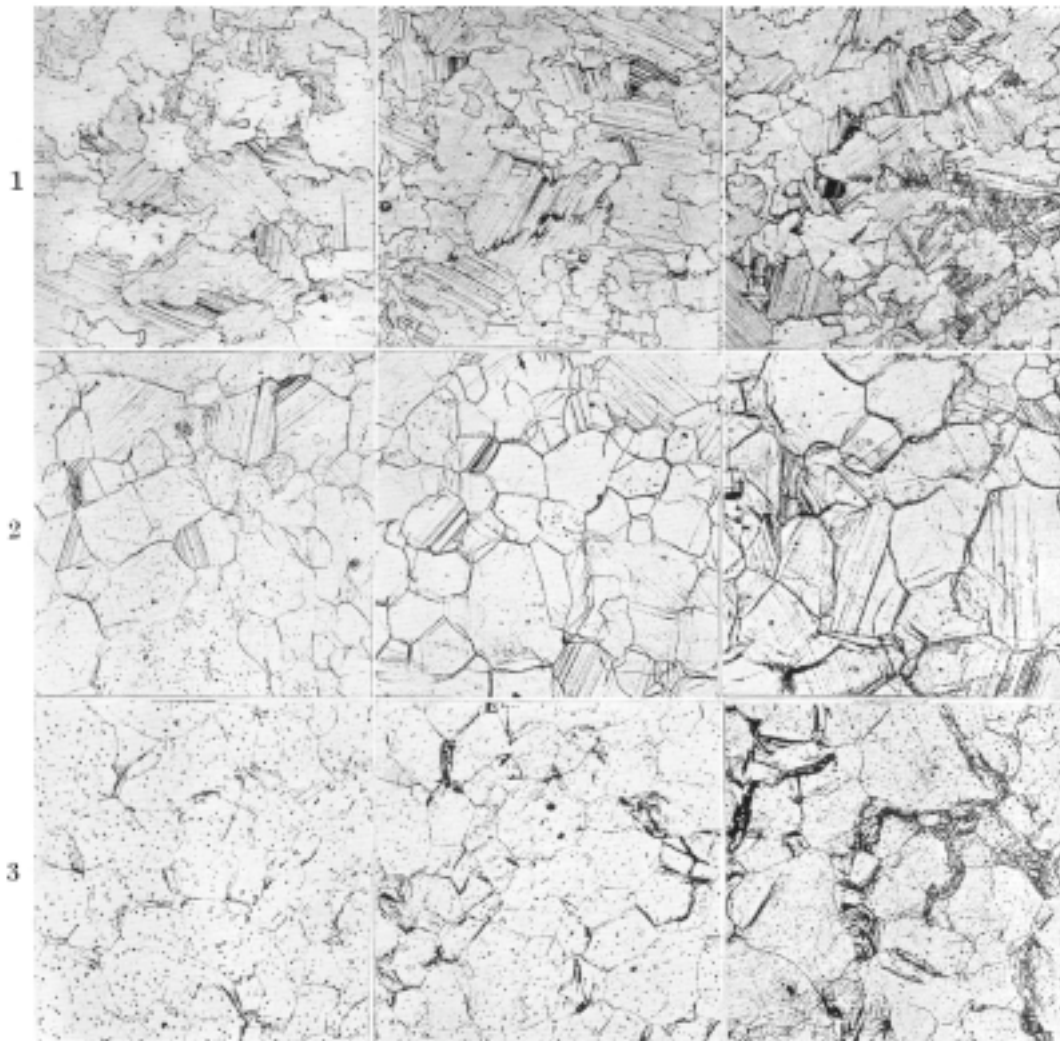
PLATE V.



An area on a cadmium specimen after various numbers of thermal cycles between 30°C. and 150°C. (x 63.)

Fig. 1. As polished. Fig. 2. 1 cycle. Fig. 3. 3 cycles. Fig. 4. 5 cycles. Fig. 5. 10 cycles. Fig. 6. 15 cycles. The progressive deformation is very clearly marked.

PLATE VI.



Deformation produced after 50, 100 and 200 cycles between 30°C. and 150°C. (x 70.)
Fig. 1. - Zinc. Fig. 2. - Cadmium. Fig. 3. - Tin. The deformation after 200 cycles is
extremely marked for all three metals.