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Physical Properties of Surfaces. I. Kinetic Friction

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XI—Physical Properties of Surfaces

I—Kinetic Friction

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I—Introduction

These papers describe an investigation of the physical and mechanical properties of solid surfaces, and the effect which the surfaces have on matter in their immediate vicinity. It is well known that the properties of gases, liquids and crystallizing solids are profoundly modified in the neighbourhood of a surface. There is, however, some uncertainty as to the magnitude and range of action of this surface force. Most experiments on the adsorption of gases show that the effect is confined to one or two molecular layers at the interface while in the case of liquid crystals we know that the surface effect can extend beyond this and causes an orientation of the crystal aggregates to a distance of several thousand Ångströms.* Some workers† have claimed that films of air or of alcohol *ca.* 40,000 A thick apparently possessed sufficient rigidity to resist a steady pressure equal to several grammes weight. It has been shown,‡ however, that if the surfaces are carefully polished and are free from dust particles there is no evidence for a long range surface effect of this magnitude.

A later paper will deal with the mechanical properties of liquid films; this describes an investigation of the force required to slide one polished surface over another in the absence, and in the presence, of lubricating layers. At the present time we have no very certain picture of the physical processes which occur, during sliding, nor of the nature of the frictional force which opposes the motion. The older view that friction is caused by the mechanical interlocking of the irregularities on the surface has, to a large extent, been superseded by the view that the resistance to motion is due to inter-molecular forces at the points of contact.

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* Grandjean, 'C. R. Acad. Sci. Paris,' vol. 166, p. 165 (1918).

† Hardy and Nottage, 'Proc. Roy. Soc.,' A, vol. 118, p. 209 (1928). Watson and Menon, 'Proc. Roy. Soc.,' A, vol. 123, p. 185 (1929).

‡ Bastow and Bowden, 'Proc. Roy. Soc.,' A, vol. 134, p. 404 (1931).

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An interesting theory of friction has been developed by Tomlinson.* Having made some simple assumptions as to the nature of the attractive and repulsive forces between molecules he is able to calculate the ratio of rolling to sliding friction and to show how the sliding friction should depend upon the elastic constants of the solids. His experimental values for rolling and static friction are in approximate agreement with those calculated from the theory.

The most direct experimental evidence that the friction of lubricated surfaces is intimately connected with the chemical fields of molecules was obtained by Sir William Hardy† and his co-workers, who measured static friction using as lubricants the homologous series of paraffins and their related alcohols and acids. The relationships obtained were unexpectedly simple and the friction was worked out as a function of separate contributions by the solid surfaces, the chemical series to which the lubricant belonged and the number of carbon atoms in its chain. The results were interpreted on the view that the friction took place between monomolecular films of lubricant adsorbed on the solid surfaces.

If friction is due to the attractive force between neighbouring molecules, its measurement can be used to study these extra-molecular fields of force. It is of obvious interest to extend these investigations and to determine whether the same simple relationships hold for kinetic friction.

We may for convenience divide the sliding surfaces into three classes: No lubrication, Boundary lubrication, and Fluid lubrication.

No Lubrication

The rubbing surfaces are freshly polished and clean and no lubricant is interposed between them. The ideal case where the surfaces are completely free from any foreign substance is of course very difficult to realize in practise, since films of oxide or of adsorbed gases are present under most experimental conditions.

In 1699, Amontons's experiments‡ led him to the conclusion that the resistance to relative motion of solid bodies was independent of the area in contact and was proportional to the normal load. Later experimenters have usually concluded that the law holds both for unlubricated surfaces (dry friction) and for boundary lubrication. The published results on the influence of velocity on dry friction are very conflicting. In 1781, Coulomb§ decided that velocity had very little influence upon dry friction between metals. This conclusion has been supported by the

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* 'Phil. Mag.,' vol. 7, p. 905 (1929). See also Derjaguin, 'Z. Physik,' vol. 88, p. 66 (1934).

† Hardy and Doubleday, 'Proc. Roy. Soc.,' A, vol. 100 p. 550 (1922); *ibid.*, vol. 101, p. 487 (1922); *ibid.*, vol. 104, p. 25 (1923); Hardy and Bircumshaw, *ibid*, vol. 108, p. 1 (1925).

‡ "Histoire de l'Academie Royale des Sciences avec les Memoires de Mathematique et de Physique," p. 206 (1699).

§ "Memoires de Mathematique et de Physique de l'Academie Royale des Sciences," p. 161 (1785).

work of HONDA and YAMADA* on abrasion which indicated that the friction did not change over a velocity range from 15 to 40 metres per minute. On the other hand, measurements of the braking action of cast-iron blocks on hard steel tyres, by GALTON and WESTINGHOUSE† indicated that the friction decreased greatly as the speed increased. SMITH,‡ using a dry bearing of magnolia metal, found a similar effect.

Boundary Lubrication

The rubbing surfaces are no longer in direct contact but are separated by a layer of some material which may, or may not, adhere to one or both surfaces. This lubricating layer, is at the most a few molecules thick, and the friction is still influenced by the nature of the underlying surface. Various authors have given different names to this type of lubrication, *e.g.*, " boundary lubrication," " adsorbed film lubrication " and " greasy friction." HARDY has shown that, in order to obtain reproducible results for static friction, it is necessary for the top sliding surface to be convex, so that it can penetrate through the layer of lubricant. He considered that penetration occurred until the surfaces were separated only by the molecular film of lubricant adsorbed on each surface. Slip could then occur between these adsorbed films. This was called " boundary lubrication." The measurements of kinetic friction described in sections of this paper were made with a convex surface under experimental conditions similar to those used by HARDY for static friction and for this reason the term " boundary lubrication " is retained. It will be shown, however, that some abrasion of the underlying surface always occurs with kinetic friction under these conditions, so the term is probably not an accurately descriptive one, " partial lubrication " might be better.

DEELEY§ working under " boundary lubrication " conditions found that the coefficient of static friction μ_S was independent of the load and that the coefficient of kinetic friction μ_K, at slow speeds, was practically the same as the static friction. Similar results were obtained by WOOG.|| WILSON and BARNARD¶ using a Deeley testing machine, found that the value of μ_K decreased with increasing speed, and at a velocity of 2·5 cm per sec had fallen to approximately half the static value. On the other hand the work of KIMBALL** and of JENKIN and EWING†† has indicated that the coefficient of friction of a lubricated bearing at very slow speeds is often greater than the static friction and increases with increasing speed ; in one case the friction was three times as large at 0·0056 cm per sec as it was at 0·0003 cm per sec. Few

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[*] ' J. Inst. Metals,' vol. 1, p. 49 (1925).

[†] ' Engineering,' vol. 26, p. 153 (1878).

[‡] ARCHBUTT and DEELEY, " Lubrication and Lubricants," p. 843 (1927).

[§] ' Engineer,' Lond., vol. 131 (1921) ; ' Proc. Phys. Soc. Lond.,' vol. 32 (1920).

[||] " Contribution à l'Étude de Graissage."

[¶] ' J. Industr. and Eng. Chem.,' vol. 14, p. 682 (1922).

[**] ' Amer. J. Sci.,' vol. 13, p. 353 (1877).

[††] ' Phil. Trans.,' vol. 167, p. 509 (1877).

attempts have been made to measure kinetic friction of partially lubricated surfaces at high speeds.

Fluid Lubrication

The rubbing surfaces are separated by a fluid layer of sensible thickness. Here the direct influence of the surfaces disappears and the resistance to motion is due to the viscosity of the interposed fluid.

The classical experiments made by BEAUCHAMP TOWER* in 1883 and the mathematical investigation of his results by OSBORNE REYNOLDS† have shown that, for thick film lubrication, the frictional resistance is due entirely to the viscosity of the lubricant and that the variations of friction with thickness of oil film, velocity, pressure, etc., can be accounted for by the laws of hydrodynamics. Therefore, this type of lubrication can give little information about the surface molecular forces except that the viscosity of the liquid is affected by the close proximity of the surface.‡

It is evident that only for fluid lubrication have different investigators obtained consistent results which yield to theoretical treatment. For the other types of kinetic friction the results are variable and conflicting. It was thought probable that the inconsistencies were due to the use of surfaces which were not highly polished, to the presence of contaminating films, and to the failure to separate completely the different types of lubrication. An attempt has been made to determine the experimental laws governing kinetic friction of clean surfaces and of lubricated surfaces under more controlled conditions and to investigate whether the simple relationships which have been found for static friction also hold for kinetic.

We did not find it possible to make measurements of the coefficient of friction, which were consistently reproducible, to an accuracy of more than *ca.* ± 2% even with the most carefully controlled conditions of polish and cleanliness of the surface and purity of the lubricant. Within these limits, however, the results seemed definite.

The first section of the paper describes measurements of friction with unlubricated surfaces including the effect of load, area of contact, velocity and surface hardness on the coefficient of kinetic friction. The second section deals with lubricated surfaces, including the transition from "fluid lubrication" to "boundary lubrication," and investigates the latter for various classes of lubricants and surfaces, under different conditions of load, area of contact, and velocity. There is evidence that the sliding effects with lubricated surfaces are not confined to the adsorbed layers of lubricant but penetrate deeper causing abrasion and distortion of the underlying metal. For this reason kinetic friction measurements can give only limited information about molecular surface forces.

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* 'Proc. Inst. mech. Engrs. Lond.,' p. 632 (1883).

† 'Phil. Trans.,' vol. 177, p. 157 (1886).

‡ This effect will be discussed in a later paper.

II—Experimental

Apparatus

An apparatus for the measurement of kinetic friction was constructed several years ago by Sir William Hardy. This has been modified to make it suitable for the problems under investigation, and it is this modified form which is described here. Fig. 1 is a photograph of the apparatus. It consists essentially of an accurately balanced flywheel which is set rotating freely and then decelerated by the friction of stationary spherical rubbing contacts which are lowered on to it. Fig. 2 shows the construction of the supporting chassis and the rotating unit with its bearings. The friction surfaces and the method of suspension of the spherical rubbing contacts are indicated diagrammatically. The rotating unit U was an accurately turned and balanced hollow gunmetal wheel 8 inches in diameter, which rode on the single ball B. The top of the shaft was kept in a central position by

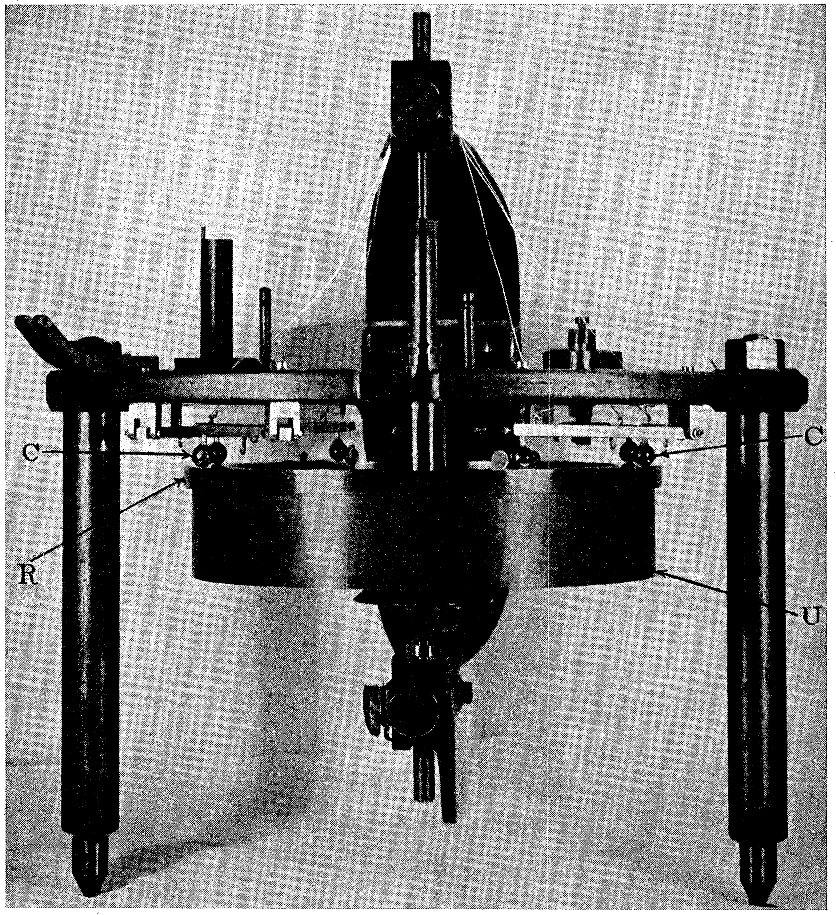

Fig. 1—U, hollow metal flywheel. R, annular ring forming lower friction surface. C, C, stationary rubbing contacts

means of the V-shaped agate bearing G and the tapered steel pin P. The deceleration of this wheel when rotating freely was very small. The lower friction surface R, which could be removed and polished, was in the form of an annular ring fixed to the rotating unit. The six stationary rubbing contacts C were held by screws in the ends of the duralumin arms A which were set tangentially to the surface. The desired load on the rubbing surfaces was obtained by hanging the requisite weight from the centre of the arms A.

The whole apparatus was enclosed in an iron box, with a removable side which was made practically air-tight by means of a lead washer. The box was filled with air, purified and freed from dust by passage through sulphuric acid, soda lime, calcium chloride, phosphorus pentoxide, glass wool soaked in apiezon oil, and fine sintered glass filters. The box was fitted with an arrangement of levers by which the surfaces could be washed with pure alcohol, brushed with clean silk, and the lubricant applied without contamination from the outside air. The rubbing contacts could be held off or lowered on to the surface by a system of fine wires, visible in fig. 1, which passed through a small hole in the top of the box. The rotating unit was set in motion by means of a steel spring belt passing through small holes in the side of the box and driven by a motor. A positive pressure of pure air was maintained in the box during an experiment so that the leakage would be from the inside outwards. The box was fitted with electrical heaters so that the apparatus could be heated to temperatures up to 75° C. This made possible the use of lubricants with high melting points.

The angular velocity of the rotating wheel was measured by photographing on a moving film camera a beam of light reflected from the small mirrors M attached to the rotating unit.

Polishing and Cleaning of Surfaces

The flat ring surfaces were of mild steel, nickel, and glass. The steel and nickel surfaces were prepared by grinding flat with fine emery on cast-iron laps, and final polishing with rouge, following the technique developed by Dr. S. H. Bastow. The glass surfaces were of plate glass, refaced by grinding with fine emery and polishing with rouge. The rubbing contacts were in the form of spheres of 5 mm diameter: they were polished with fine emery and rouge. Glass surfaces could be cleaned by rubbing with the fingers under running tap water. Metal surfaces often had to be rubbed with rouge in order to remove contaminating films. After this treatment, water would adhere to the surface as a continuous thin film.* Final washing was done with pure alcohol and the surfaces were heated to 150° C in an air oven to remove films of moisture or alcohol.

Preliminary Experiments

The moment of inertia of the rotating unit was found by measuring the angular velocity given it by a falling weight; its value was 317,000 gm cm^2 with an experi-

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* Hardy and Doubleday, 'Proc. Roy. Soc.,' A, vol. 100, p. 550 (1922).

mental error of ± 0·5%. The additional moments of inertia due to the bearing surfaces (steel 80,500, nickel 72,000, glass 20,350 gm cm^2) were added to this. In the experiments the observed deceleration included the free running deceleration of the rotating unit which therefore had to be determined. The maximum velocity that could be given without risk of injury to the bearings was 10 revolutions per second, and between this velocity and 1 revolution per second the free deceleration was constant and equal to 0·044 radians per sec per sec. This was repeatable to 5%, and since the observed decelerations in the experiments were at least ten times as great as the free deceleration, this could not introduce an error greater than 0·5% in the final results.

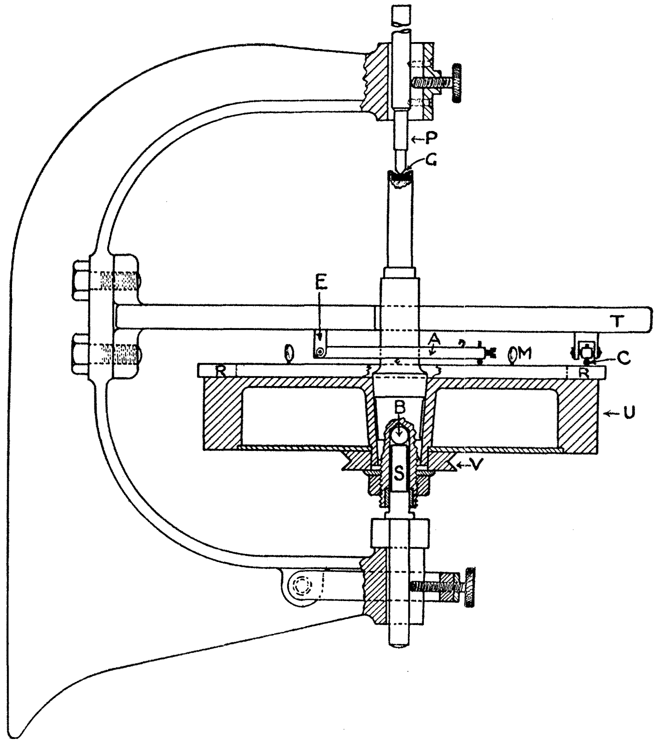

FIG. 2—U, hollow metal flywheel. B, single ball bearing on which flywheel rides. P, G, tapered pin and agate bearing. R, annular ring forming lower friction surface. C, stationary rubbing contacts. A, arms carrying the rubbing contacts. M, small mirrors. V, driving pulley

Fig. 3 shows that the free deceleration increased considerably at velocities less than 1 rev per sec (for work at these low speeds a larger correction must be applied). This correction, however, never exceeded 5% with the smallest friction measured. The free deceleration was not affected by change in temperature from 15° C to 70° C and its value was checked periodically during the course of the work.

The bearing surfaces and rubbing contacts were prepared and cleaned by the methods described in the preceding sections and were then fixed in position on the machine. The desired weights were hung in place, the contacts being held off the surface. The box was then closed and the air was displaced by a steady stream of dry dust-free air. The rotating unit was then given its maximum velocity by the motor, the belt thrown off, the rubbing contacts let down on to the surface, and the deceleration curve obtained by measuring the velocity photographically at convenient intervals of time.

Unless otherwise stated, all six rubbing contacts were used. These were set at slightly different distances from the centre of the wheel, so that they did not run on the same track. There was no obvious chattering.* If the rubbing contacts and the surface were of approximately similar hardness the friction was not greatly influenced by the initial degree of polishing. A microscopic examination after an experiment showed smooth shallow polished grooves in the surface. Apparently the surfaces polished one another while running. If the rubbing contacts were of softer material, however, the friction was dependent on the initial polish of the surfaces (see p. 340).

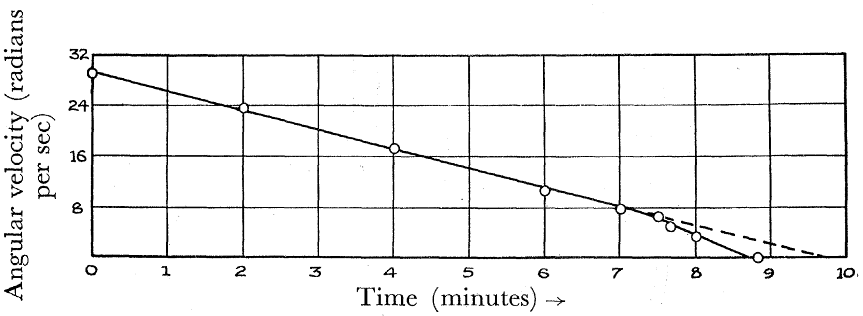

Fig. 3—Free running deceleration curve

When lubricated friction was being measured, the lubricant was applied before lowering the rubbing contacts, by wiping the surface by means of a lever with a piece of clean silk moistened with the lubricant.

This method of measurement has the advantage of obtaining the friction over the whole range of velocity during a single run. A change in friction with change in velocity is shown by an alteration in the slope of the deceleration curve. If, at a certain velocity, Φ' is the free running deceleration in radians per sec per sec and Φ'' is the deceleration observed when the added friction forces are operating as well, then $\Phi = \Phi'' - \Phi'$ is the deceleration due to the frictional force to be measured. We can write

$$I\,\Phi = nWl\mu_K,$$

where I = moment of inertia of rotating unit,
Φ = angular deceleration in radians per sec per sec due to friction force,
n = number of rubbing contacts,
W = the normal force in dynes on each contact,
l = distance from the centre of rotation at which the frictional force is acting,
μ_K = coefficient of kinetic friction.

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* A more detailed investigation of the effectiveness of contact between sliding surfaces is being made.

The reproducibility of the friction measurements with lubricated surfaces was *ca.* ± 2%, with unlubricated surfaces *ca.* ± 3%.

III—Friction of Unlubricated Surfaces

Effect of Contaminating Films

Where not otherwise stated, the measurements were made with polished surfaces and the word " load " means the normal weight in grams on each rubbing contact.

Measurements on steel surfaces showed that reproducible values for the coefficient of friction could not be obtained unless precautions were taken against the presence of films of moisture or other contaminants picked up from the air of the laboratory. Successive measurements of the friction between steel surfaces which had been cleaned and allowed to dry in the air showed that the friction increased as the surfaces were run together. The friction rose from the initial value of $\mu_K = 0 \cdot 27$ to $\mu_K = 0 \cdot 40$ after three minutes of running. When, however, the surfaces were freshly polished, cleaned and dried by heating as described, successive measurements gave a constant value of $\mu_K = 0 \cdot 41$. Contaminating films always caused the friction to be lower than the steady value obtained with carefully prepared surfaces. It is probable that the small amount of contamination present on the prepared surfaces was removed during the first few seconds of running.

Friction and Velocity

If the coefficient of kinetic friction increases with decreasing velocity (as several workers have found) the effect would be to cause an increase in the slope of the deceleration curve at slow speeds. The presence of contaminating films, which are gradually removed as the surfaces are run together, could give rise to the same effect. With surfaces which were not rigorously cleaned we observed this increase in deceleration at slow speeds, but with clean surfaces it was always found that the friction was constant from the high velocity at the beginning of the experiment down to the smallest velocity at which it could be accurately measured (1 rev per sec). A number of these straight line deceleration curves are shown in fig. 4. The coefficient of friction was constant between rubbing speeds of 600 cm and 60 cm per sec. This was true for combinations of surfaces of widely different physical properties, such as glass, steel, nickel, garnet, carbon, etc.

The apparatus was not designed to measure friction at velocities lower than 1 rev per sec so that it is not possible to decide whether the friction remained constant from very low speeds down to zero velocity. There was some evidence that it did not : occasionally the zero point on the deceleration curve was displaced from the straight line by an amount corresponding to an increase in the average value of μ_K of as much as 20% between 60 cm per sec and zero velocity, see curve 5, fig. 4. It is possible that the increase in friction at very small speeds may be considerable but further work with a modified apparatus would be necessary for an investigation over this range of low velocity.

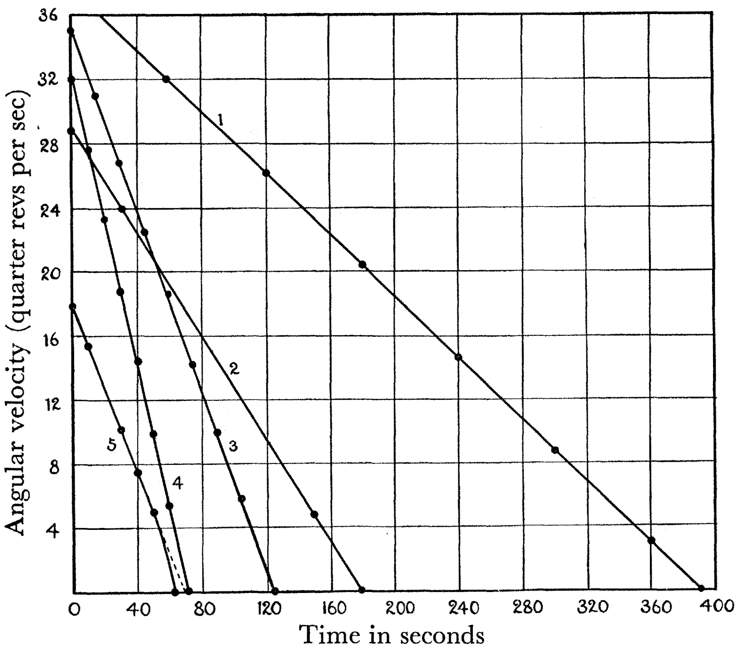

FIG. 4—Dry friction deceleration curves. (1) Carbon on steel, (2) garnet on steel, (3) phosphor bronze on steel, (4) steel on steel, (5) glass on glass

Friction and Load

The effect of contaminating film to give an apparent increase in friction with increasing load is shown in Table I where the measurements were carried out with hard steel contacts on a steel surface contaminated by prolonged contact with the air of the room.

TABLE I—CONTAMINATED SURFACES OF MILD STEEL. APPARENT VARIATION OF μ_K WITH LOAD

Load gm	μ_K
10·8	0·277
22·3	0·295
38·5	0·369
63·8	0·431
10·8	0·371

The measurements were made in the order given and the first four show an apparent increase in μ_K with increasing load. The presence of a contaminating film which is gradually being removed is, however, indicated. The last value of μ_K is considerably higher than the first though the load is the same for each, 10·8 gm.

The increased friction with a heavy load is probably due to the greater effectiveness of the heavy load in cutting through the contaminating film.

When the surfaces were carefully cleaned the coefficient of kinetic friction was, within the limits of experimental error, independent of the load. Table II shows the result for a number of different surfaces.

TABLE II—AMONTONS'S LAW. μ_K INDEPENDENT OF LOAD FOR CLEAN SURFACES

Load in gm	Glass on Glass μ_K	Mild Steel on Mild Steel μ_K	Hard Steel on Hard Steel μ_K	Nickel on Mild Steel μ_K	Carbon on Glass μ_K	Garnet on Mild Steel μ_K
4·0	—	—	—	0·66	—	—
10·8	0·41	0·56	0·41	—	—	0·39
22·3	0·39	—	0·41	0·61	0·18	0·38
38·5	0·40	0·59	0·46	—	—	—
63·8	—	—	0·42	—	—	—
95·9	—	—	—	0·68	0·18	—

Over the range of loading used in these experiments AMONTONS's Law holds for dry kinetic friction.

The Area of Contact and the Degree of Polish of the Surfaces

Prolonged running of the apparatus caused abrasion and flattening of the spherical surfaces, so that the area of contact between the surfaces was greatly increased. There was, however, no change in the friction. With glass contacts rubbing on a glass surface this abrasion was very marked, the area of contact being increased from a point to 4 sq mm after a few minutes running. The constant values of μ_K are given in Table III.

TABLE III—GLASS ON GLASS. μ_K INDEPENDENT OF AREA OF CONTACT

Time of running min	μ_K
1	0·40
2	0·42
3	0·41
4	0·39
5	0·39
6	0·39

TABLE IV—EFFECT OF INITIAL SURFACE POLISH—CADMIUM CONTACTS

Surfaces	μ_K
Polished steel	0·449
Steel ground with fine emery	0·552
Polished glass	0·309
Glass ground with fine emery	0·457

This shows that the friction is independent of the area of contact between the rubbing surfaces. (See later for lubricated surfaces.)

The work on abrasion of HONDA and YAMADA (*loc. cit.*) has shown that the friction may be changed by grinding, with different grades of emery, the flat surface on which the abrasion of the test pieces took place. The measurements in Table IV show the increase in friction when finely ground surfaces of glass and steel are used instead of polished surfaces.

In these cases the rubbing contacts were of softer material (cadmium) than the surfaces. If, however, hard contacts were used on a ground surface of somewhat softer material the effect was to polish the surface and the friction was nearly the same as on a surface which was initially highly polished. Thus, with hard steel contacts on ground soft steel, a number of measurements gave an average value of 0·42 which is the same as the value obtained with polished surfaces. It is probable that the increase in friction found with very rough surfaces is due to the interlocking of the surface irregularities.

The Friction of Dissimilar Surfaces and the Effect of Surface Hardness

When dissimilar surfaces were used the value of μ_K depended upon which material composed the rubbing contact. This is shown in Table V, for combinations of nickel, mild steel and glass.

TABLE V—VARIATION OF μ_K WITH RELATIVE POSITION OF SURFACES

Rubbing Contact	Bearing Surface		
	Nickel	Mild Steel	Glass
	μ_K	μ_K	μ_K
Nickel	0·53	0·66	0·56
Mild steel	0·49	0·57	0·61
Glass	0·50	0·51	0·40

This effect is most marked with nickel and steel, where nickel contacts on steel gave a value of μ_K of 0·66, and steel contacts on nickel gave 0·49. One value is seen to be higher and one lower than for either nickel on nickel or steel on steel. It may be noted that for each of the three combinations one value for dissimilar surfaces was greater than either of the values for similar surfaces and the higher value was obtained when the rubbing contacts were made from softer material.

An examination of Table VI shows that there is no very systematic variation of friction with the hardness of the surface. It will be noticed, however, that when the contacts were made from a very soft material (carbon), the order of increase of friction was from hard to soft bearing surface and when very hard contacts (garnet) were used the order was reversed. The carbon contacts did not abrade any of the surfaces, whereas the garnet scratched all the surfaces with scarcely any abrasion to itself. The measurements with a phosphor bronze and the two bearing alloys were made to see whether they would give very low values of friction ($\mu_K = 0·07$) obtained by SMITH (*loc. cit.*) with magnolia metal bearing running dry. The alloys were kindly given to us by Professor HUTTON: No. 1 was 86% tin and No. 2 77% lead. The values of μ_K with phosphor bronze and the high lead alloy were lower than with the other metals except copper-cadmium: with the high tin alloy μ_K was considerably higher; these values with bearing alloys are all much higher than those obtained by SMITH.

TABLE VI—FRICTION BETWEEN DISSIMILAR SURFACES

Rubbing Contact	μ_K Bearing Surface Nickel	Mild Steel	Glass
Hard steel	—	0·415	0·53
Aluminium	—	0·47	—
Copper-Cadmium	—	0·32	—
Magnesium	—	0·42	0·42
Cadmium	—	0·46	0·30
Copper	0·49	0·36	0·53
Phosphor Bronze	—	0·34	0·53
Alloy No. 1	—	0·46	—
Alloy No. 2	—	0·34	—
Ebonite	—	—	0·53
Carbon	0·24	0·21	0·18
Garnet	0·37	0·39	0·45

It is of interest to compare these experimental results with those obtained by TOMLINSON (*loc. cit.*) and by HARDY.* In an important paper TOMLINSON makes the assumption that the magnitude of the frictional force due to the attraction and repulsion of the molecules is approximately the same per molecule for all substances, so that the value of μ should depend only on the number of molecules which come into contact. HERTZ has calculated how the area of contact between two bodies depends upon their elastic constants and has shown that it is proportional to $(\delta_A + \delta_B)^{2/3}$, where δ_A and δ_B are constants involving the moduli of rigidity and compressibility of the solids. From TOMLINSON'S assumption it follows that $\frac{(\delta_A + \delta_B)^{2/3}}{\mu}$ should be a constant for all substances. He has carried out experiments to test this and concludes that it is approximately true. His results for a number of surfaces are shown in Table VI (*a*) and may be compared with the results obtained by HARDY and by the writers.

The measurements of TOMLINSON and of HARDY are both for static friction and so are more strictly comparable with one another. It will be seen that TOMLINSON'S values for $\frac{(\delta_A + \delta_B)^{2/3}}{\mu}$ are only approximately constant, varying from 4·8 to 6·2. His value for glass agrees well with that found by HARDY, but for mild steel the results are very different, 5·6 and 3·2 respectively. In the kinetic friction experiments it was found that the values of μ_K depended upon the order in which the surfaces were used, and it will be seen that " constant " is even more variable (varies

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* HARDY and HARDY, 'Phil. Mag.,' vol. 38, p. 932 (1919).

TABLE VI (*a*)—DEPENDENCE OF μ UPON ELASTIC CONSTANTS AND COMPARISON OF RESULTS OBTAINED BY VARIOUS WORKERS

Sliding surfaces	BEARE and BOWDEN		TOMLINSON		HARDY	
	μ_K	$\frac{(\delta_A + \delta_B)^{2/3}}{\mu_K} \times 10^8$	μ_s	$\frac{(\delta_A + \delta_B)^{2/3}}{\mu_s} \times 10^8$	μ_s	$\frac{(\delta_A + \delta_B)^{2/3}}{\mu_s} \times 10^8$
Hard steel on mild steel	0·415	5·7	0·410	5·47	—	—
Aluminium on mild steel	0·47	7·8	0·605	5·89	—	—
Copper on mild steel	0·36	7·9	0·533	5·43	—	—
Copper on glass	0·53	8·0	0·675	6·24	—	—
Nickel on nickel	0·53	4·4	0·389	6·03	—	—
Nickel on mild steel	0·66	6·0				
Mild steel on nickel	0·49	8·2	0·429	5·44	—	—
Nickel on glass	0·56	8·0				
Glass on nickel	0·50	8·9	0·775	4·85	—	—
Glass on glass	0·40	8·4	0·940	5·24	0·94	5·24
Mild steel on mild steel	0·57	7·0	0·411	5·64	0·74	3·2
		Mean value 7·3		Mean value 5·58		Mean value 4·22

from 4·4 to 8·9). It would appear that the physical processes occurring during sliding are too complicated to yield easily to a simple mathematical treatment. A more detailed knowledge of these processes is necessary before a quantitative calculation of the coefficient of kinetic friction can be made.

Friction in Air, Nitrogen, Oxygen, and Carbon Dioxide Atmospheres

A microscopic examination of the surfaces showed that a continuous abrasion was occurring so that a fresh rubbing surface was always being exposed. In air this fresh surface would be rapidly covered by an adsorbed film of oxygen or oxide. If the frictional effects were confined to this surface layer we might expect the value of the friction to be influenced by the nature of the film. Measurements of friction (mild steel on mild steel) were carried out in air, nitrogen, oxygen, and carbon dioxide to see if any such effects could be detected. The results are given in Table VII and it will be seen that the values of μ_K are equal, within the limits of experimental error.

TABLE VII—SHOWING KINETIC FRICTION, STEEL ON STEEL, IN VARIOUS GASES

Gas	μ_K
Air	0·57
Nitrogen	0·57
Oxygen	0·58
Carbon dioxide	0·57

This lends support to the view that the frictional effects are not confined to the first molecular layers but extend below this and cause distortion and abrasion to some depth within the metal.

Summary of Friction Results with Unlubricated Surfaces

The coefficient of kinetic friction has been measured for a number of different highly polished unlubricated surfaces. Within the limits of experimental error μ_K is independent of the load (range of 1 to 25) of the apparent contact area (" point contact " to several square millimetres) and of the velocity (range of 600 cm per sec to 60 cm per sec). The presence of contaminating films on the surface can give apparent deviations from these relationships. There is no very systematic relationship between surface hardness and kinetic friction except that, when the rubbing contact is of soft material (which does not readily abrade the bearing surface), the friction is least when the bearing surface is hard and it increases as softer bearing surfaces are used. When the rubbing contact is of hard material (which abrades the bearing surface) the friction increases with increasing hardness of the bearing surface. Apparently the frictional effect is not confined to the surface layer of the metal but causes distortion and abrasion to a considerable depth below it.

IV—FRICTION OF LUBRICATED SURFACES

The necessity for extreme purity of the lubricant, when investigating the effect of chemical constitution in friction, has been shown by Sir WILLIAM HARDY,* and his co-workers. A large number of highly purified alcohols, acids, paraffins, and esters were very kindly given us by Dr. J. C. SMITH, several pure hydrocarbons by Dr. N. K. ADAM and some pure oleic acid by Dr. A. S. C. LAWRENCE. Other substances from less reliable sources were purified by fractionation. The commercial oils were used as supplied.

Transition from Fluid to Partial Lubrication

It was indicated above that the discrepancy in the data on kinetic partial lubrication was, to some extent, due to the difficulty of separating it completely from fluid lubrication. If the surfaces are moving at relatively high speed the fluid lubricant may force surfaces apart and form a thick film between them ; when this takes place the friction follows the laws of fluid lubrication. This effect can be minimized by making the area of contact as small as possible, so that the pressure between the surfaces is large, and by using a thin film of lubricant. Even with this apparatus, which was designed with small spherical contacts to reduce this effect to a minimum, it was apparently possible for the lubricant to separate the moving surfaces and to give conditions which approached those of fluid lubrication. The

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* ' Dept. Sci. Ind. Res. Lubrication Res. Ctee,' Tech. pap. No. 1, 1930.

observed deceleration curves were divided sharply into two parts with different slopes. This is shown in fig. 5 for octyl alcohol on steel. The first part of the curve, part F, occurred at high speeds and when there was a deep layer of lubricant on the surface. It usually had a smaller slope, corresponding to a smaller μ_K, which depended upon the velocity and upon the viscosity of the lubricants. The second part of the curve, part B, had a steeper slope (larger μ_K) which was independent of the velocity and bore no relation to the viscosity of the lubricant. It is probable that in part F the surfaces were separated by a relatively thick layer of lubricant while part B corresponds to boundary lubrication conditions. It was found that the heavier the load, the shorter the time for which part F of the curve could be maintained. Some measurements of the time of persistence of part F at different loads are given in Table VIII.

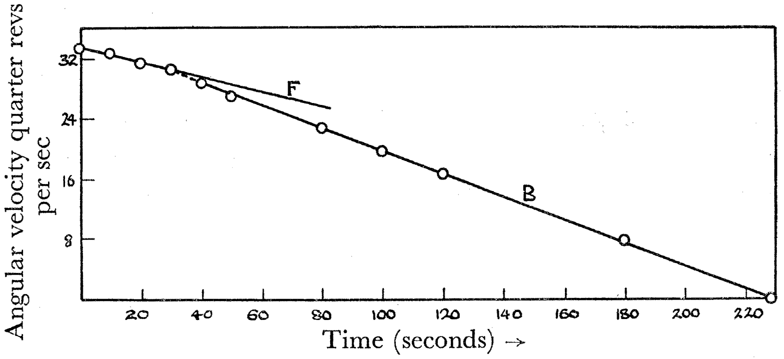

FIG. 5—Deceleration curve. Octyl alcohol on steel, load 22·3 gm showing fluid and partial lubrication. Fluid $\mu = 0{\cdot}02$ (approx.), Partial $\mu = 0{\cdot}073$

TABLE VIII—TIME OF PERSISTENCE OF FLUID FRICTION, OCTYL ALCOHOL ON STEEL

Load gm	Time sec
3·83	50
11·49	25
22·3	20
50·0	10

When the apparatus was allowed to run for some time, the film of lubricant was gradually thinned by centripetal force and the transition from F to B could occur. If the surface were then re-flooded with lubricant it was possible to re-establish part F. After a short time it would again revert to part B. When the removal of the lubricant by centripetal force was prevented by a metal rim attached to the outer edge of the bearing surface, it was found that F could be extended over a longer period. However, even if the surface were flooded it was not possible to obtain part F at speeds below a certain minimum. In the case of a mobile lubricant such as octyl alcohol it was not possible to extend fluid lubrication, part F, below a rubbing speed of 250 cm per sec even with the lightest load (3·8 gm) and with excess lubricant present. A viscous lubricant could, however, keep the rubbing surfaces apart and maintain fluid friction at relatively slow speeds. The behaviour of glycerol on steel is shown in fig. 6. Curve 1 shows the deceleration curve obtained with a relatively thick film placed on the bearing surface by wiping with clean silk moistened with glycerol. The coefficient of friction was not constant but decreased with decreasing speed (μ_K fell from $0 \cdot 17$ at 7 rev per sec to $0 \cdot 12$ at 1 rev per sec). There was no break in the curve, indicating that fluid friction prevailed down to very slow speeds. Extremely thin films of glycerol formed by carefully wiping off all excess gave a straight line deceleration shown in curve 2, fig. 6 (μ_K constant and equal to $0 \cdot 12$ over the whole range).

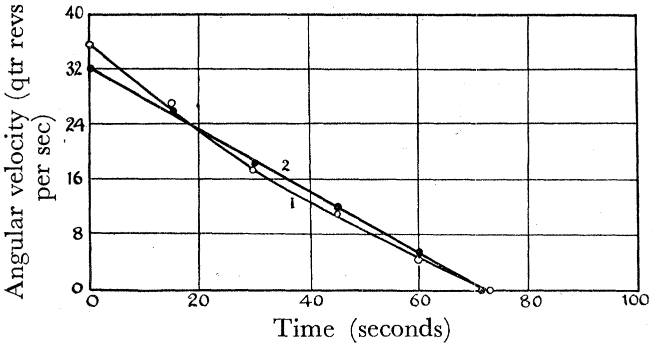

FIG. 6—Glycerol on steel. Thick film, curve 1 ; thin film, curve 2

Experiments with a number of viscous lubricants showed that if thick films were present μ_K was always dependent upon velocity and was greater the greater the viscosity of the lubricant. With very thin films, however, μ_K was constant at all velocities and its value had no relation to the viscosity of the lubricant indicating that in this case the conditions are those of boundary lubrication.

When using mobile lubricants, such as paraffins, acids and alcohols, the quantity put on the surface was unimportant because the shape of the deceleration curve showed distinctly when the break between fluid and boundary lubrication took place. With viscous lubricants extremely thin films had to be used in order to obtain boundary lubrication.

Boundary Lubrication and Velocity

The straight line deceleration shown in part B of the curve in fig. 5 and in fig. 6 as well as those obtained for a variety of lubricants and surfaces in fig. 7, shows that the friction, under partial lubrication conditions, is independent of velocity. This relation holds for speeds varying from 600 cm to 5 cm per sec. The behaviour at speeds lower than this has not been investigated.

Effect of Size of Spherical Contact and of the Rubbing Area

During a run some abrasion of the spherical contacts always took place. The effect was to wear " flats " on them so that the area in contact became many times larger than when the contacts were perfectly spherical. Measurements showed that contacts having "flats" of 1 mm diameter gave the same friction as new spherical contacts (see Table IX).

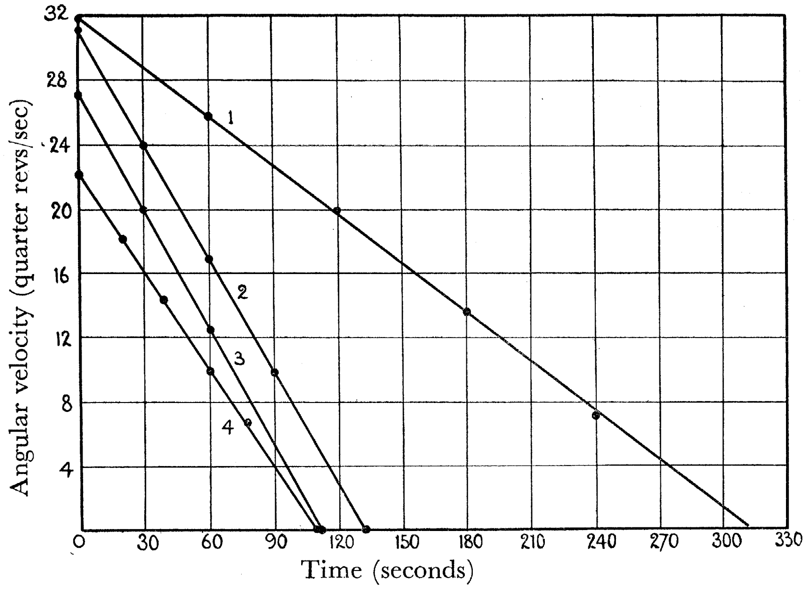

FIG. 7—Boundary lubrication. (1) Heptylic acid on steel, load 10·8 gm; (2) myristic acid on steel, load 38·5 gm; (3) hexadecyl alcohol on glass, load 38·2 gm; (4) triolein on nickel, load 10·8 gm

TABLE IX—SHOWING μ_K INDEPENDENT OF AREA OF CONTACT. HARD STEEL CONTACTS ON MILD STEEL

	New spheres "Point contact" μ_K	Worn spheres "1-mm flats" μ_K
	0·082	0·074
	0·084	0·083
	—	0·081
	—	0·079
	———	———
Mean	0·083	0·079

TABLE X—SHOWING μ_K IS INDEPENDENT OF RADIUS OF RUBBING CONTACT. HARD STEEL CONTACTS ON MILD STEEL. LUBRICANT—OCTYL ALCOHOL. LOAD 22·3 GM

Radius of Spherical contact (in 1 mm)	μ_K
2·3	0·083
3·1	0·083
4·7	0·081
5·5	0·079
7·0	0·081

The friction was therefore independent of any change in the area of contact caused by abrasion of the surfaces. The coefficient of friction was also found to be independent of the diameter of the sphere used for the rubbing contact. Table X shows the results for a number of new steel balls of different sizes.

The fact that the coefficient of friction is independent of the curvature of the rubbing contacts also shows that there is no disturbing viscosity effect in the measurements of boundary lubrication. With all measurements of boundary lubrication, some abrasion of the surfaces took place, the spherical contacts were worn, and there were slight marks on the flat bearing surface. This abrasion occurred with surfaces which were apparently well lubricated and for which the coefficient of friction was considerably lower than that reported for static friction.

Friction and Load

Steel Surfaces—With polished steel surfaces the lubricants could be divided into two classes. (*a*) Those for which the value of μ_K was constant with load, or increased slightly with increasing load. Examples are given in Table XI.

TABLE XI—AMONTONS'S LAW. MILD STEEL SURFACES

Load gm	Octane μ_K	Tetradecane μ_K	Cetyl iodide μ_K	Ethyl palmitate μ_K	Bayonne oil μ_K
10·8	0·250	0·086	0·081	0·064	0·130
38·5	0·250	0·094	0·088	0·080	0·118
95·7	—	0·099	—	0·075	0·122

(*b*) Those for which the value of μ_K decreased markedly with increasing load. Examples are given in Table XII.

TABLE XII—SHOWING DECREASE OF μ_K WITH INCREASING LOAD
MILD STEEL SURFACES

Load gm	Octyl alcohol	Heptylic acid	Oleic acid	Rape oil
10·8	0·105	0·080	0·124	0·140
14·0	0·090	—	—	—
22·0	0·083	—	—	—
22·3	0·082	—	—	—
38·5	0·064	0·072	0·093	0·110
41·7	0·061	—	—	—
95·7	0·053	0·064	0·071	0·091

The curve of μ_K against load for octyl alcohol on steel in fig. 8 shows that μ_K approached a minimum with the highest load used. The examples in Table XI

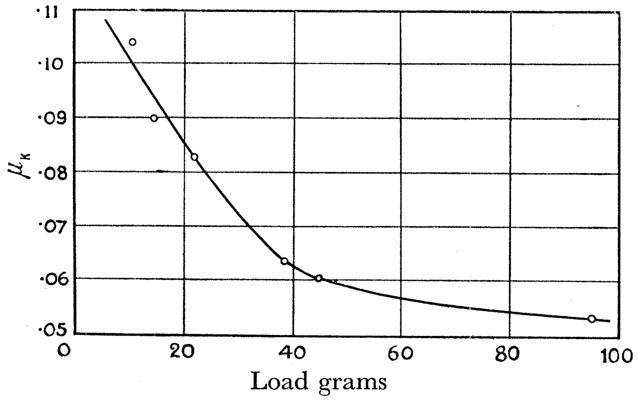

FIG. 8—Octyl alcohol on steel μ_K/load curve

and Table XII show that the change in μ_K with load could not be correlated with the polarity of the molecules of the lubricant. Table XIII shows that the change in μ_K with load cannot be correlated with the viscosity of the lubricant.

TABLE XIII—SHOWING THAT THE RELATION BETWEEN μ_K AND LOAD IS NOT CONNECTED WITH VISCOSITY OF LUBRICANT

Lubricant	Viscosity in centi-poises	Decrease in μ_K from 10·8 gm load to 95·7 gm load
Octyl alcohol	8·92	0·052
Oleic acid	—	0·053
Sperm oil	43	0·033
Olive oil	100	0·051
Rape oil	110	0·049
Bayonne oil	165	0·007
Tetradecane	2·22	—0·013

Mixtures of Lubricants on Steel Surfaces—If a dilute solution of oleic acid in octane or of palmitic acid in medicinal paraffin oil is placed on a steel surface, the acid will be adsorbed on the surface. Table XIV shows that the decrease in μ_K with increasing load, observed with pure oleic acid was not observed with the film formed by its adsorption from octane, although the friction was considerably less than with pure octane. A solution of palmitic acid in paraffin oil shows a decrease in μ_K with increasing load.

TABLE XIV—MIXTURES OF LUBRICANTS ON STEEL SURFACES

Lubricant	Load 10·8 gm μ_K	 38·5 gm μ_K	 95·7 gm μ_K
Octane	0·250	0·250	—
2% oleic acid in octane	0·190	0·192	0·196
5% oleic acid in octane	0·171	0·164	—
Oleic acid	0·164	0·093	0·071
Paraffin oil	0·189	0·148	0·132
1% palmitic acid in paraffin oil	0·153	0·113	0·099
Palmitic acid	—	0·084	—

Effect of the Nature of the Surfaces—The dependence of μ_K on the load proved to be quite different for the same lubricant on different surfaces. Thus for octyl alcohol and heptylic acid on polished glass surfaces the values of μ_K were respectively 0·259 and 0·216 and were independent of load, whereas on steel surfaces μ_K was markedly dependent upon the load. See fig. 8 for oleic acid on steel. The behaviour of oleic acid on steel and glass surfaces is also shown in Table XV. In both cases there is a decrease in μ_K with load but the effect is greater with the steel surfaces.

TABLE XV—VARIATION OF μ_K WITH LOAD ON DIFFERENT SURFACES
LUBRICANT OLEIC ACID

Load gm	Steel μ_K	Glass μ_K
10·8	0·124	0·110
38·5	0·093	0·086
95·7	0·071	0·084

Conclusion—These experiments indicate that for one class of lubricants and surfaces AMONTONS's Law holds for boundary lubrication and μ_K is approximately independent of load. For another class μ_K decreases with increasing load, this effect can be very marked (*e.g.*, for octyl alcohol on steel μ_K decreased by 50% on increasing the load by a factor of 9). The dependence of μ_K upon the load cannot be correlated with the viscosity of the lubricant nor the polarity of its molecules. No satisfactory physical explanation of this has been obtained and further investigation is necessary.

Absence of Latent Period for Kinetic Friction

The work of HARDY and DOUBLEDAY* has shown that for static friction with lubricants composed of polar molecules there is a " latent period." These investigators found that, after the addition of lubricant to a surface a considerable period of time must elapse before the coefficient of static friction reached its equilibrium value. This latent period was as great as 60 minutes with an acid and 40 minutes with an alcohol and was explained as the time necessary for the lubricant to become adsorbed and oriented on the surface. An extensive series of measurements, a few of which are given in Table XVI, failed to show this effect for kinetic friction.

TABLE XVI—ABSENCE OF A LATENT PERIOD

	Steel Surfaces				Glass Surfaces
Time after application of lubricant	Octyl alcohol μ_K	Octane μ_K	Rape oil μ_K	2% Oleic acid in octane μ_K	Pelargonic acid μ_K
5 seconds	0·080	0·237	0·110	0·190	0·205
5 minutes	0·090	—	0·113	0·188	0·222
10 "	0·079	0·268	—	0·198	—
15 "	0·075	—	0·112	0·196	0·220
30 "	0·083	0·248	—	0·186	0·210
40 "	0·081	0·256	0·114	—	—
50 "	0·076	—	—	—	—

The first readings in Table XVI represent the shortest time, after the addition of the lubricant, at which it was possible to measure the friction. There was no

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* ' Proc. Roy. Soc.,' A, vol. 104, p. 25 (1923).

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evidence for a latent period greater than five seconds. It was stated by Hardy and Doubleday that the latent period was reduced by mechanical agitation of the slider in the pool of lubricant. Agitation of the same sort would be effected more efficiently by running the surfaces together at the speeds used here, and it appears that the latent period for kinetic friction is reduced to a time which is too short for measurement.

Dependence of Kinetic Friction on Chemical Constitution of the Lubricant

Hardy and Bircumshaw* have shown that the static friction bears a very simple relation to the chemical composition of the lubricant. For each homologous series of hydrocarbons, alcohols, and acids the coefficient of static friction on steel and on glass surfaces was observed to decrease in a linear manner with increasing molecular weight of the lubricant and to fall to zero at high molecular weights.

In figs. 9, 10, and 11 the coefficient of kinetic friction is plotted against the molecular weight for a series of paraffins, alcohols, and acids on surfaces of glass and steel.

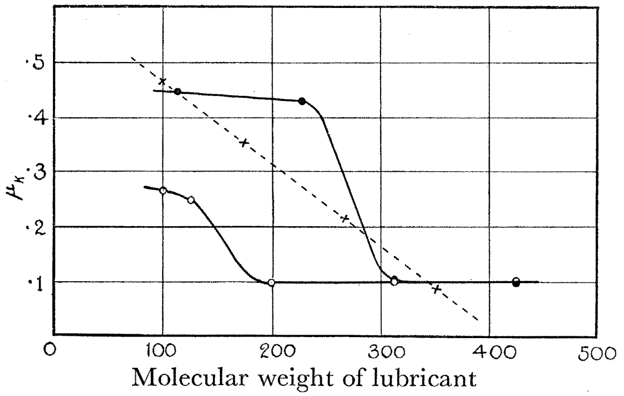

Fig. 9— ● Paraffin on glass, ○ paraffin on steel, × Hardy static friction on steel

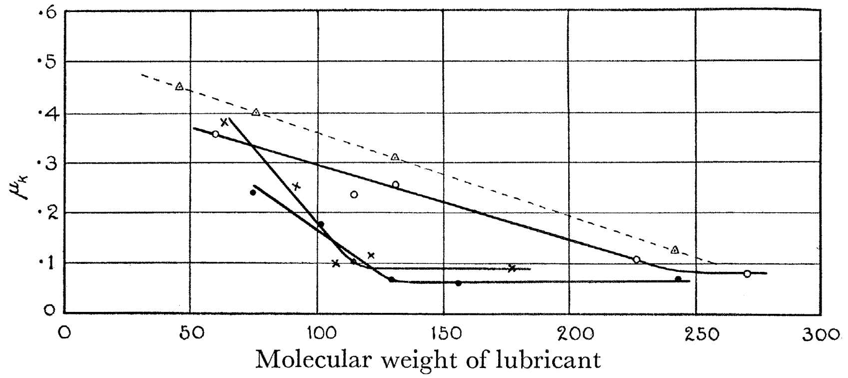

Fig. 10— ○ Alcohol on glass, × alcohol on steel, ● alcohol on nickel, △ Hardy static friction on steel

A load of 38·5 gm was used throughout these experiments. The analogous results for static friction obtained by Hardy and his co-workers on steel surfaces are shown

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* 'Proc. Roy. Soc.,' A, vol. 118, p. 607 (1928).

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in the dotted curve on each figure. The results for kinetic friction bear a general resemblance to those found by HARDY for static friction in that the coefficient of kinetic friction decreased with increasing molecular weight of the lubricant. Over the first part of the curve (at low molecular weights) the relation was approximately (though only approximately) linear. For each case, however, a minimum value for μ_K was reached and the kinetic friction was then constant and independent of further increase in the molecular weight of the lubricant. The length of the carbon chain at which μ_K reached the minimum value depended upon the chemical series of the lubricant and on the nature of the surface (see Table XVII).

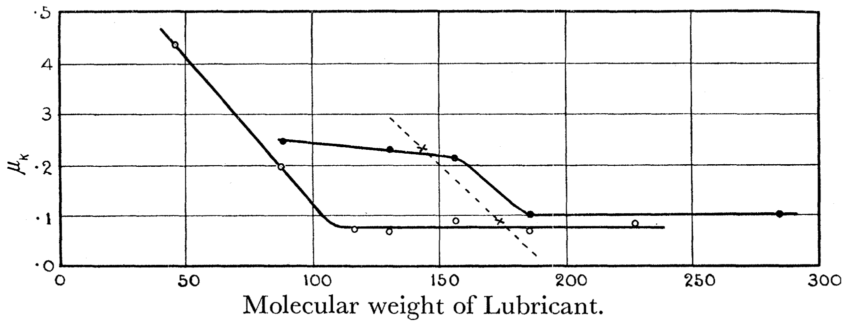

FIG. 11—● Acids on glass, o acids on steel, x HARDY static friction on steel

TABLE XVII—LENGTH OF CARBON CHAIN AT WHICH μ_K ATTAINS CONSTANT MINIMUM

	Glass	Steel	Nickel
Paraffins	C_{22}	C_{14}	
Acids	C_{11}	C_6	—
Alcohols	C_{16}	C_8	C_7

The curves obtained on the glass surface all resemble one another in that the initial slope of the curve, for low molecular weights, is at first small and is followed by a sudden decrease in the friction to the minimum value. It may be noted that with paraffins up to C_{16} on a glass surface the value of μ_K is about 0·43 which is actually slightly higher than that found for unlubricated glass ($\mu = 0{\cdot}40$).

On the metal surfaces, steel and nickel, the initial slope of the curve is steeper and for each homologous series the minimum value of the friction is reached at a lower molecular weight than is the case on glass. The high values of μ_K obtained with the short chain acids on steel (*e.g.*, formic acid) are probably due to some extent to corrosion of the surface. Even heptylic acid left on the surface for long periods (24 hours) formed dull grey corrosion patches: on this corroded surface with heptylic acid as a lubricant μ_K was equal to 0·26 which was three times as great as that obtained with a fresh surface.

A microscopic examination of the polished surfaces after a run again showed that some abrasion had taken place. This abrasion was less with lubricants of high molecular weight but even under the best lubricating conditions ($\mu = 0 \cdot 053$) some abrasion was always observed. This indicates that the effects of sliding are not confined to the surface films of adsorbed lubricant but penetrate deeper so that atoms or particles of the underlying metal are torn off during the process. It will be noted that the value of the coefficient of kinetic friction is considerably smaller than the coefficient of static friction measured by HARDY under similar conditions. (μ_K is usually one-third to one-half μ_S.) It is assumed that in static friction the frictional effects are confined to the primary adsorbed layers of lubricant.

In order to compare the minimum friction obtained with the different series and surfaces, it is necessary to take into consideration the fact that, with alcohols and acids on steel, the coefficient of friction decreased with increase in load. Table XII shows that the minimum value of kinetic friction ($\mu_K = 0 \cdot 053$) was obtained with octyl alcohol as a lubricant between heavily loaded steel surfaces. A comparison is made in Table XVIII of the lowest values of μ_K obtained by increasing the load between the surfaces and the molecular weight of the lubricant.

TABLE XVIII—MINIMUM μ_K OBTAINED WITH HEAVY LOAD ON SURFACES, AND HIGH MOLECULAR WEIGHT OF LUBRICANT

	Steel	Glass
Paraffins	0·098	0·099
Alcohols	0·053	0·079
Acids	0·063	0·104

The minimum friction for acids and alcohols is lower on steel than on glass and for the paraffins is the same on both surfaces. The minimum friction for the alcohols is lower than for the acids and paraffins on the same surface.

Friction between Dissimilar Lubricated Surfaces

HARDY and DOUBLEDAY* have formulated the Mean Value rule for static friction between dissimilar surfaces. When the opposed surfaces were of different materials (*e.g.*, glass/steel) the observed coefficient of static friction lay half-way between the two values obtained when the surfaces were of the same material. For example, the static friction between lubricated surfaces of glass/steel was found to be equal to the mean of the two values for glass/glass and steel/steel.

The observed value for the coefficient of kinetic friction between dissimilar surfaces of steel/glass and steel/nickel with a variety of lubricants is shown in Table XIX.

It will be seen that the value of the friction between dissimilar lubricated surfaces depends upon the manner in which they are used. A spherical contact of steel on a moving glass surface gives a value different from that obtained with a glass contact on a moving steel surface. This is shown in the last two columns of the table : the

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* ' Proc. Roy. Soc., A, vol. 104, p. 25 (1923).

substance used as the spherical contact is named first. A similar effect has been described earlier for the dry friction of dissimilar surfaces.

TABLE XIX—KINETIC FRICTION BETWEEN DISSIMILAR LUBRICATED SURFACES

Lubricant	Load gm	Steel/steel	Glass/glass	Mean calculated	Steel/glass observed	Glass/steel observed
Octyl alcohol	10·8	0·105	0·259	0·182	0·109	0·117
,,	38·5	0·068	0·259	0·164	0·076	—
Pelargonic acid	10·8	0·099	0·213	0·156	0·119	0·094
Hexadecane	10·8	0·100	0·430	0·265	0·106	0·204
,,	38·5	0·106	0·447	0·277	0·092	0·263
3-in-1 oil	10·8	0·108	0·116	0·112	0·108	—

Lubricant	Load gm	Nickel/nickel	Steel/steel	Mean calculated	Nickel/steel observed	Steel/nickel observed
Octyl alcohol	10·8	0·130	0·105	0·118	—	0·115
,,	38·5	0·102	0·068	0·085	—	0·079
Triolein	10·8	0·169	0·128	0·149	0·178	0·124
,,	38·5	—	—	—	—	—
Tetradecane	38·5	0·197	0·087	0·142	0·200	0·088

An examination of the last three columns shows little evidence for a mean value rule for kinetic friction. The friction of dissimilar surfaces usually lies between the two values given by each substance, but it is not numerically equal to the mean. For steel and glass surfaces it is usually lower than the mean value.

Effect of Load on the Friction of Various Oils

The coefficients of friction with a variety of lubricants on steel surfaces with different loads are given in Table XX.

TABLE XX—ORDER OF EFFICIENCY AS LUBRICANTS

Load 10·8 gm	μ_K	Load 95·7 gm	μ_K
3-in-1 oil	0·108	Oleic acid	0·071
Oleic acid	0·124	3-in-1 oil	0·084
Tri-olein	0·128	Rape oil	0·091
Bayonne oil	0·130	Sperm oil	0·106
Sperm oil	0·138	Tri-olein	0·110
Rape oil	0·140	Olive oil	0·112
Olive oil	0·164	Bayonne oil	0·123
Paraffin oil	0·189	Paraffin	0·132

The relative efficiency of the various oils in reducing the friction depends upon the load between the surfaces. The fact that oleic acid gives less friction than triolein is consistent with the observation that a fatty acid is more effective than a glyceride oil in increasing the lubricating efficiency of a mineral oil.

We are greatly indebted to the late Sir WILLIAM HARDY for his interest and encouragement in the work, to the Commissioners of the Exhibition of 1851 for an Overseas Scholarship (to W. G. B.) and to the Lubrication Research Committee of the Department of Scientific and Industrial Research for a grant for apparatus (to F. P. B.).

SUMMARY

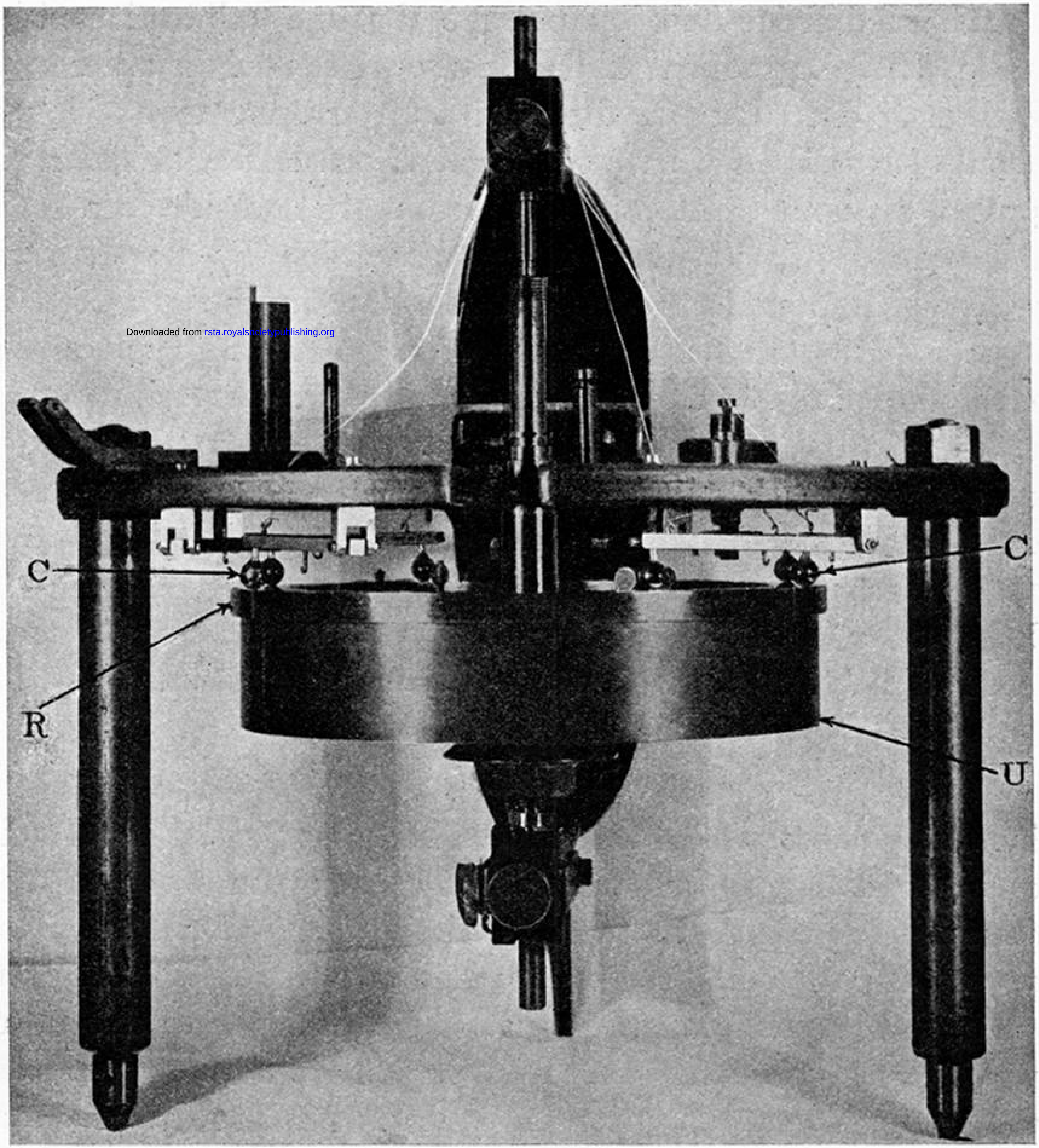
A method is described for the measurement of kinetic friction between highly polished surfaces. With unlubricated surfaces the coefficient of kinetic friction μ_K is independent of the load, of the area of contact and of the velocity. The presence of contaminating films on the surface can give apparent deviations from these relationships.

With lubricated surfaces a transition from " fluid lubrication " to " boundary lubrication " is shown and in the latter state μ_K is again independent of the velocity and of the area of contact. With some lubricants μ_K decreases with increasing load, with others it is constant.

No " latent period " was found for kinetic friction.

The effect of chemical composition on μ_K is investigated for homologous series of hydrocarbons, alcohols and acids.

Kinetic friction measurements between dissimilar surfaces show no evidence for a mean value rule.



IG. 1—U, hollow metal flywheel. R, annular ring forming lower friction surface. C, C, stationary rubbing contacts