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EXPERIMENTS ON THE TEMPERATURE COEFFICIENT OF STATIC FRICTION

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ABSTRACT. Angles of repose of metals have been measured under controlled vacuum conditions.

Preliminary measurements were made at room temperature in air. As it was found that vibrations tended to reduce the angle of repose, they were eliminated. Naked metal surfaces were obtained for aluminium and cadmium by cleaning by volatilization in a high vacuum. Interesting results were found with a steel slider when a deposit of volatilized aluminium had formed on steel crutches.

Experiments on cadmium cleaned by volatilization at various temperatures at which the whole friction chamber was baked out were carried out in the range from + 176° c. to —100° c. The results, in spite of the inevitable fluctuations of individual values at any particular temperature, clearly show a general drift with temperature, and are a first instalment towards an approach to the thermodynamical criterion for the fundamental mechanism of friction between *naked* metal surfaces. A conservative analysis of the results of measurements between —100° c. and +100° c. leads to a temperature coefficient of the angle of repose $d\bar{\alpha}/dt = -3{\cdot}5 \times 10^{-2}$ degrees, while a bolder interpolation would raise this numerical value by a factor of about two ($d\bar{\alpha}/dt = -8 \times 10^{-2}$ degrees). Above about + 100° c, the angle of repose of naked cadmium increased with rising temperature.

§ 1. INTRODUCTION

In the work described below, measurements have been made of the angle of repose of metals under controlled vacuum conditions. With cadmium, where cleaning by volatilization from the surfaces was possible, the measurements have been extended to cover a wide range of temperatures from + 176° c. to − 100° c., and a temperature coefficient of static friction * of very good reproducibility has been derived for the range of temperatures from + 100° c. to − 100° c.

§ 2. THE SIGNIFICANCE OF A TEMPERATURE COEFFICIENT OF SOLID FRICTION

Solid friction (between naked surfaces) must arise at the small irregularities of the surfaces in contact, which can suffer both *elastic deformation* and *abrasion.*

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* It is of fundamental importance, as Dr. F. E. Simon, F.R.S., suggested some time ago, to determine whether such a temperature coefficient of friction between naked solids exists.

The existence of the temperature coefficient is a criterion for deformation as an essential part of the mechanism for the loss of energy by solid friction. In the case of deformation, the energy is dissipated to some extent by means of the heat conductivity of the materials; in the case of pure abrasion the only heat loss is the latent heat of vaporization. Over a wide range of temperatures, from the melting point of a solid down to the neighbourhood of the absolute zero, both the adiabatic compression energy and the thermal conductivity exhibit a marked dependence upon temperature. Therefore, the energy loss which is perceived as friction should exhibit a measurable temperature coefficient, if deformation of the surface irregularities is the elementary mechanism of solid friction. On the other hand, the latent heat of vaporization has only a very slight temperature coefficient below the melting point of a material, and if abrasion of molecules (even monatomic) from the irregularities of the surfaces in contact were the predominant action in solid friction, virtual independence of temperature could be expected. There is reason to believe that the force of friction between naked *metal* surfaces is a function of the temperature only, over a wide range of velocities of sliding, and therefore the variation of static friction with temperature should indicate directly the temperature coefficient of the energy loss by solid friction during a given displacement.

§ 3. EXPERIMENTAL

Method

A cylindrical metal rod resting on two pairs of V-shaped (90°) metal crutches (Shaw and Leavey, 1930) was free to travel to and fro between two buffers when the apparatus was tilted in either direction to the horizontal. Shaw and Leavey's apparatus, the great virtue of which was that an unlimited number of observations could be made without opening the friction chamber, had to be disconnected from the vacuum pump before the angle of repose could be measured, the atmosphere of residual gas being at a pressure certainly not less than 10^{-2} to 10^{-1} mm. Hg. The present apparatus was designed to remain connected with a high-vacuum pump (about 10^{-6} mm. Hg) throughout the operations of baking out and of making measurements. This involves turning the apparatus upside down * so as to separate the slider and crutches while baking out, and tilting it in either direction up to 90° to the horizontal to measure the angle of repose. Also it was to remain vacuum-tight, whilst its temperature was varied between +450° c. and that of liquid air.

The friction mechanism is enclosed in a metal tube with one solid end and with a head (*h*, figure 1) bolted to a flange at the other end. The vacuum-tight joint is achieved by inserting two concentric washers of diamond-shaped cross-section, made of copper and invar respectively. At the higher temperatures the copper washer maintains the seal, and below room temperature the invar washer.

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* The sliding rod rests on two Pyrex tubes instead of on the crutches during the baking-out process.

The sliding rod (5 cm. long) and the crutches were 3·17 mm. diameter, and the surfaces were finished on 0000-emery paper flooded with paraffin.

The movement of the rod is limited to 3·5 mm. by a rigid copper buffer (*b*, figure 1) at each end. When the rod makes contact with one of the buffers, *b*, it closes an electric circuit which ignites a neon lamp to indicate that sliding has taken place.

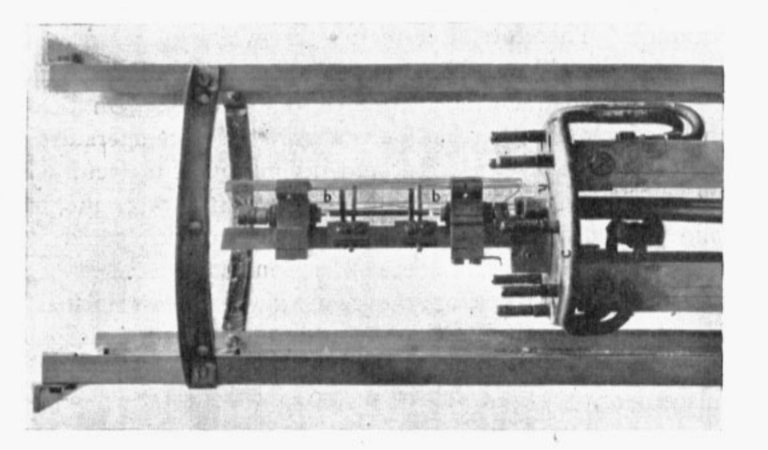

Figure 1. View of friction device.

The temperature of the friction elements is varied by heat conduction and radiation. The cylinder which encloses the friction chamber is double-walled with an open copper pipe of helical shape between the walls (figure 2), and a heating coil is wound on the outer copper cylinder. Temperatures below atmospheric are attained when a cooling agent is passed through the pipe C, which is brazed on to the head *h*, and through the helical copper pipe (figure 2). This arrangement leads to a temperature gradient along the triangular bar supporting the crutches inside the friction chamber. The end of the bar secured to the head *h* assumes a slightly lower temperature than the opposite end. The electric heating coil produces a similar gradient at temperatures above atmospheric. When metal was volatilized in the friction chamber, the amount of condensed metal

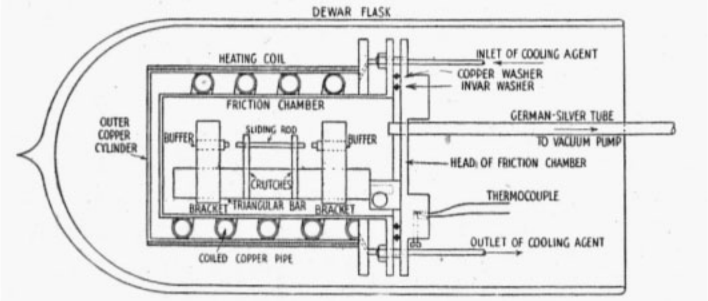

Figure 2. Apparatus.

was always largest on the inside of the head. The measured temperatures were those of the head *h*, and were taken with a copper-constantan thermocouple. Since the primary object of the experiments was to show whether a temperature coefficient exists, it was sufficient to measure temperature changes at one end of the gradient.

Measurements at room temperature

Preliminary experiments were carried out in air with a rod and crutches made of a steel containing 1·2 to 1·5 % C, 0·35 % (max.) Mn. External vibrations were apt to diminish the measured angles of repose, and their effect was practically eliminated by suitable alterations. With a visible rust layer on the surface, no sliding took place, even at a tilting angle of 90° ($\mu = \infty$). After the rust had been removed, and the friction chamber baked out at 450° c. at a pressure of about 10^{-6} mm. Hg with the slider out of contact with the crutches, an angle of repose α of 51° ($\mu = 0{\cdot}9$; it follows from the geometry of the crutches supporting the rod that $\mu\sqrt{2} = \tan\alpha$) was measured, which gradually decreased and finally settled down between about 38° ($\mu = 0{\cdot}5_5$) and 42° ($\mu = 0{\cdot}6$).*

It is a matter of considerable experimental difficulty to remove the last traces of adsorbed matter and oxide films from a metal surface, and it is considered that *volatilization* from the metal surface in a high vacuum is the most reliable means of obtaining naked surfaces. But even in this case, the surfaces can be preserved free from a continuous layer of contamination for a limited period of time only. Perfect cleaning was obtained with a sliding rod of aluminium † which was partly volatilized during the baking-out process. When the temperature measured at the head, i.e. at the end of the gradient, where it had its lowest value, was 260° c., aluminium vapour condensed on the inside of the head and in its neighbourhood, while the rate of volatilization increased towards the far end of the aluminium rod, which, at about 10^{-6} mm. Hg, showed on the steel crutches angles of repose between 68°·5 ($\mu = 1{\cdot}8$) and 54° ($\mu = 1$). On opening the friction chamber, this rod was found to have acquired a coarse dendritic surface during volatilization, and to have slid on a deposit of aluminium on the steel crutches. This is an indication that even the far end of the crutches was at a temperature below the volatilization point of aluminium. The sliding rod had been baked out while resting on the Pyrex tubes, and had been heated by radiation from the wall of the chamber. Without cleaning the crutches, the aluminium rod was replaced by the steel rod previously used. The chamber was evacuated again, and appreciably smaller angles of repose between 26° and 28° ($\mu = 0{\cdot}35$) were found. Repolishing the rod and crutches with 0000-emery until they acquired

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* Fogg and Hunwicks (1940), with the Deeley machine modified by substituting three steel balls for the three flat pegs, measured coefficients of static friction between 0·56 and 0·60, when they resorted to the drastic method of removing the contaminated surfaces completely by abrasion with "0000 blue back" emery paper, and of performing their measurements immediately after such removal in order to keep re-contamination from atmospheric sources as small as possible.

† The aluminium was reasonably pure, containing 0·16 % Si, 0·28 % Fe and traces of Mg and Mn.

a bright appearance (the crutches with the aluminium deposit had a dull appearance prior to repolishing), further *reduced* the angles to between 18° and 22° ($\mu = 0{\cdot}2$ to $0{\cdot}3$). To prove that the reduction of the angle of repose was due to the deposit itself as a mechanical aid, the friction chamber was baked out for many days, and the gradual increase of the angle of repose was noted until angles between 36° and 38° were reached again, when this experiment was discontinued.

The volatilization point of both friction elements was approached in the case of a cadmium rod on cadmium crutches. After such cleaning by volatilization, the mean value of the angle of repose when measured at room temperature was about 43° ($\mu = 0{\cdot}6$ to $0{\cdot}7$). Since individual measurements showed wide fluctuations * even when the friction chamber with the cadmium specimens had been baked out at 250° c., a large number of readings were taken at room temperature. The mean values of the angles of repose obtained by tilting the friction chamber in one direction were not always found to coincide with the mean values obtained by tilting the chamber in the opposite direction. Table 1 contains these mean values $\bar{\alpha}_1$ and $\bar{\alpha}_2$, and the width of the bands of fluctuations (extreme values of α_1 and α_2). All the measured angles lie between 34°·5 and 57°·0 and the mean values between 42°·2 and 43°·6. It is obvious from table 1 that the individual values α_1 and α_2 are not distributed evenly between the extreme values.

Table 1

Baking-out temps. (°c.)	Observed min. and max. values of the angle of repose		Mean values				
	α_1	α_2	$\bar{\alpha}_2$	No. of observations	$\bar{\alpha}_2$	No. of observations	$\frac{\bar{\alpha}_1+\bar{\alpha}_2}{2}$
160	36·5–52·5	38·5–47·0	41·7	16	42·8	15	42·2
	37·0–52·0	39·0–52·0	41·5	16	42·7	15	42·7
	42·5–53·5	34·5–57·0	45·4	11	41·9	12	43·6
	38·5–51·0	40·5–47·5	42·8	13	43·2	13	43·0
228	44·0–48·0	38·0–45·0	45·4	8	40·9	8	43·2

As an example of a soft material of appreciably higher volatilization point, a copper rod was used on copper crutches. When the chamber was evacuated, but not baked out, an angle of repose of about 43°·5 ($\mu = 0{\cdot}7$) was measured at 21° c. The friction chamber was then baked out, and the angle of repose was measured, as it cooled down to room temperature. After standing for three days, a pressure of a few millimetres Hg had built up in the chamber. Upon its re-evacuation to $9{\cdot}6 \times 10^{-4}$ mm. Hg, an angle of repose of 62°·5 ($\mu = 1{\cdot}3_5$) was measured at 20° c., which settled down to about 41°·4 ($\mu = 0{\cdot}6$) as the vacuum further improved.

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* It would appear plausible to suppose that minute evolutions of gas might cause such fluctuations in the work with *naked* metal surfaces.

The results at room temperature are summarized in table 2.

Table 2

Sliding rod	Crutches	Remarks	Angle of repose	Coefficient of static friction
Steel	Steel	At atmospheric pressure with visible layer of rust on surfaces	>90°	∞
Steel	Steel	Baked out	51°	0·9
Steel	Steel	Final values, a few days after baking out	38°–42°	$0{\cdot}5_5$–0·6
Copper	Copper	Before baking out	43°·5	0·7
Copper	Copper	At $9{\cdot}6\times10^{-4}$ mm. Hg	62°·5	$1{\cdot}3_5$
Copper	Copper	Pressure $\ll 9{\cdot}6\times10^{-4}$ mm. Hg	41°·4	0·6
Aluminium	Deposit of aluminium on steel crutches	Baked out and volatilized	54°–68°·5	1–1·8
Steel	Ditto	—	26°–28°	$0{\cdot}3_5$
Steel	Ditto	Rod and crutches repolished with 0000-emery	18°–22°	0·2–0·3
Steel	Ditto	Baked out for many days	36°–38°	
Cadmium	Cadmium	Baked out and volatilized	34°·5–57°	0·5–1·1

§ 4. THE TEMPERATURE COEFFICIENT

On general grounds, solid friction cannot assume a finite value in the close neighbourhood of the absolute zero of temperature, where entropy changes tend to vanish. At room temperature, solid friction assumes an appreciable finite value as the above-described experiments show. When the temperature of the surface of the lower-melting friction-element reaches the melting point, the force of friction between non-porous solids assumes a very small value because then the molten surface layers act as a lubricant, as indicated by the low values observed with ice at temperatures near its melting point (Jacob, 1912; Bowden and Hughes, 1939). From the absolute zero of temperature to the melting point the sign of the temperature coefficient of solid friction would thus change at least once, although no prediction could be made about either the existence or the sign of a temperature coefficient in the intermediate range of temperatures.

Cadmium, which can be cleaned easily by volatilization *in vacuo* at a temperature at which the whole friction chamber can be baked out, was chosen for measurements between +176° c. and −100° c. The results clearly show a trend with temperature in spite of considerable fluctuations * of individual values (figures 3 *a* and 3 *b*). The angle of repose of cadmium is found to increase with falling

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* The crosses and circles in the diagrams indicate the mean values, whereas the range of individual values is represented by the vertical lines at the various temperatures. The positions of the crosses and circles on the vertical lines demonstrate that the individual values are not distributed evenly between the extreme values at any given temperature.

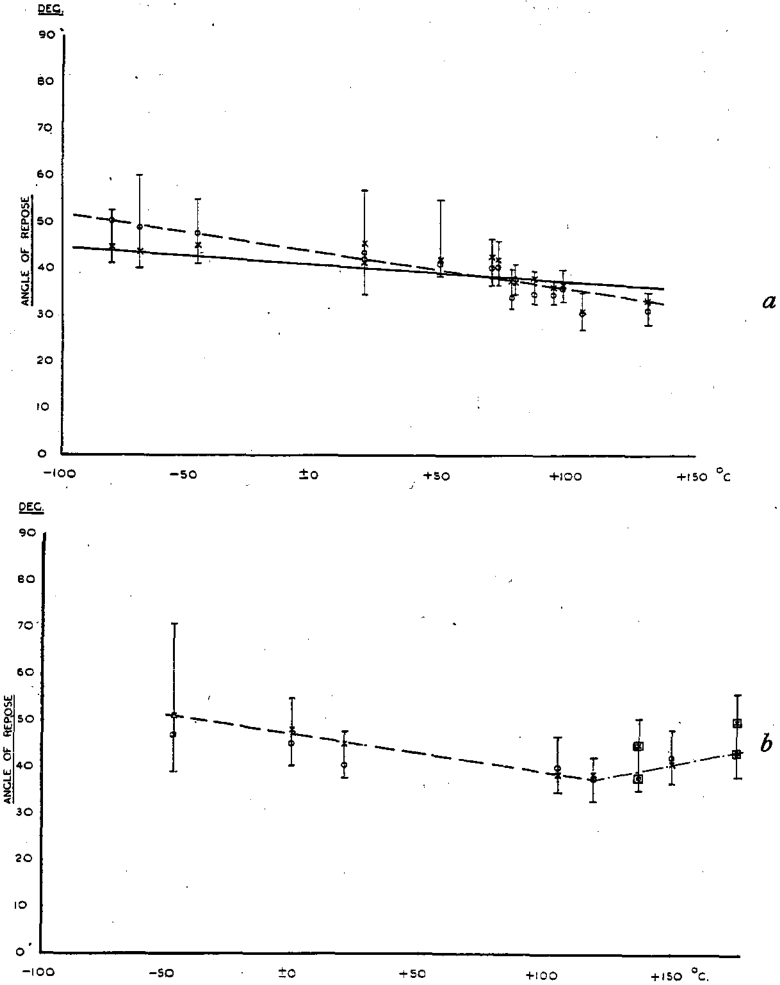

Figure 3. Angles of repose of cadmium on cadmium at various temperatures. The crosses and circles indicate the mean values of the critical angles obtained by tilting the friction chamber in opposite directions, whereas the range of individual values is represented by the vertical lines.

a. After friction chamber had been baked out at +160° c.

b. After friction chamber had been baked out at +228° c. The results at +137° c. and +176° c. were obtained in a separate series of experiments when the chamber had been baked out at +250°.

temperature in the range from +100° c. to −100° c. (table 3). Figure 3 *a* was obtained after the friction chamber had been baked out at 160° c. The plotted curves are arbitrary interpolations which indicate that even a conservative analysis of the results (full line, figure 3 *a*) shows a general drift in the direction suggested.

The dotted line was inserted with the intention of demonstrationg that a bolder interpolation would raise the numerical value of the temperature coefficient by a factor of about two. The reproducibility of the results was checked by measuring some further points * in the neighbourhood of temperatures at which measurements had been taken previously. The values found at 94° c. ($\bar{\alpha}_1 = 36^\circ\cdot 3$; $\bar{\alpha}_2 = 34\cdot 4^\circ$) agree satisfactorily with those found previously at 97°·3 c. ($\bar{\alpha}_1 = 36^\circ\cdot 6$; $\bar{\alpha}_2 = 35^\circ\cdot 8$), those at 78°·5 c. ($\bar{\alpha}_1 = 37^\circ\cdot 4$; $\bar{\alpha}_2 = 37^\circ\cdot 8$) with those at 77° c. ($\bar{\alpha}_1 = 37^\circ\cdot 6$; $\bar{\alpha}_2 = 33^\circ\cdot 8$), those at 69°·5 c. ($\bar{\alpha}_1 = 42^\circ\cdot 7$; $\bar{\alpha}_2 = 40^\circ\cdot 3$) with those at 72° c. ($\bar{\alpha}_1 = 42^\circ\cdot 0$; $\bar{\alpha}_2 = 40^\circ\cdot 2$), and those at 19° c. ($\bar{\alpha}_1 = 45^\circ\cdot 4$; $\bar{\alpha}_2 = 41^\circ\cdot 9$) with the other values obtained at room temperature (see table 1).

Table 3

Baking-out temperatures (°c.)	Mean values of the angle of repose	Temperature coefficients		Remarks
		$\frac{d\bar{\alpha}}{dt}$	$\frac{d\mu}{dt}$	
160	$\bar{\alpha}_{-100^\circ \text{c.}} = 44^\circ\cdot 5$ $\bar{\alpha}_{+100^\circ \text{c.}} = 37^\circ\cdot 5$	$-3\cdot 5\times 10^{-2}$	$-7\cdot 5\times 10^{-4}$	Full line of figure 3 *a*
	$\bar{\alpha}_{-100^\circ \text{c.}} = 52^\circ$ $\bar{\alpha}_{+100^\circ \text{c.}} = 36^\circ$	-8×10^{-2}	$-19\cdot 5\times 10^{-4}$	Dotted line of figure 3 *a*
228	$\bar{\alpha}_{-50^\circ \text{c.}} = 51^\circ\cdot 25$ $\bar{\alpha}_{+100^\circ \text{c.}} = 39^\circ\cdot 25$	-8×10^{-2}	$-20\cdot 2\times 10^{-4}$	Dotted line of figure 3 *b*

In spite of the fluctuations of individual values it seems reasonable to derive from these results a conservative *lower* limit for the temperature coefficient of cadmium by extrapolating along the full line of figure 3 *a* from −100° c. to +100° c., with the result that $d\bar{\alpha}/dt = -(3\cdot 5\times 10^{-2})$ degrees per +1° c. and $d\mu/dt = -7\cdot 5\times 10^{-4}$ per 1° c. (table 3). If the extrapolation were taken along the dotted line, a higher temperature coefficient $d\bar{\alpha}/dt = -(8\times 10^{-2})$ degrees per +1° c., would be derived. From figure 3 *b*, which summarizes independent results obtained when the friction chamber had been baked out at 228° c., a temperature coefficient $d\bar{\alpha}/dt = -(8\times 10^{-2})$ degrees per +1° c. would follow as the result of an interpolation in the range from −50° c. to +100° c. This is in good agreement with the result deduced from figure 3 *a*. It appears that above +100° c. the angle of repose increases again, as the result obtained at +150° c. suggests. Observations made at +137° c. and +176° c. in a *separate* series of experiments when the friction chamber had been baked out at 250° c. fit very well with the results obtained at +150° c. and support the view that the curve of figure 3 *b* rises between about +100° c. and +200° c. The following values were found at +137° c.: $\bar{\alpha}_1 = 45^\circ\cdot 3$; $\bar{\alpha}_2 = 38^\circ\cdot 2$ (with a range of fluctuations of $\bar{\alpha}_1$ between 40°·5 and 51°·0 and of α_2 between 35°·5 and 49°·0), and at +176° c.:

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* These points are also shown in figure 3 *a*.

$\bar{\alpha}_1 = 50°{\cdot}2$, $\bar{\alpha}_2 = 43°{\cdot}7$ (with a range of fluctuations of α_1 between $44°{\cdot}0$ and $56°{\cdot}5$ and of α_2 between $38°{\cdot}5$ and $55°{\cdot}5$).

It is apparent from some preliminary measurements with a sliding rod of copper on copper crutches that, in this case of a soft metal "cleaned" *in vacuo* at a temperature below its volatilization point, the dependence of friction upon temperature is much less conspicuous than that of cadmium. The angles measured at room temperature almost coincide with those measured for cadmium. Up to about 100° c. the values for copper remain nearly independent of temperature. As the temperature is still further increased, they show a tendency to rise.

§ 5. DISCUSSION

In the experiments described above, the coefficients of static friction of metals, which while out of contact were baked out in a high vacuum, were found to be somewhere between, say, 0·5 and 1·8. These results were obtained with steel on steel, with aluminium on steel carrying a deposit of volatilized aluminium, with copper on copper, and with cadmium on cadmium. The existence of a negative temperature coefficient was established with friction elements of cadmium in the range from −100° c. to +100° c. Above +100° c. the sign of the temperature coefficient appears to change. The trend of the angle of repose with temperature is apparent even when the wide bands of fluctuating values are plotted at the various temperatures. It might be thought that measurements with very soft materials like cadmium, in which deformation in the neighbourhood of points of contact is certain to occur on account of the inevitable stress concentration there, would yield little information as to the nature of friction, since the plastic properties of cadmium depend on temperature. However, no noticeable temperature coefficient of friction could be expected, even though the plastic properties of cadmium do depend on temperature, if abrasion alone were responsible for the elementary mechanism of friction. The fact that these properties and the coefficient of friction both depend on temperature, is an argument in favour of the essential part played by deformation in the mechanism of solid friction. The reason why cadmium was chosen for these experiments is that cadmium can be cleaned by volatilization *in vacuo* at a temperature at which the whole friction chamber can be baked out.

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