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Electrical contact resistance and its relationship to hardness*

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Studies have been made of the electrical resistance at the contact between a silicon carbide indenter and various metals. It has been found that reproducible results can be obtained if the contact under load is subjected to a low-energy condenser discharge prior to the measurement of the resistance. After this pre-test operation, the electrical resistance is inversely proportional to the length of the diagonal of the indentation, as observed under a microscope. This allows one to define a hardness value, from the contact resistance measurement, that correlates well with the Vickers hardness. It is shown that the technique can be adapted to the continuous study of hardness under load for viscoelastic non-conducting materials.

1. Introduction

A method for determining the hardness of certain materials from measurements of the thermal contact resistance has recently been described [1, 2]. However, the method is really satisfactory only when the thermal conductivity of the material under test is very high. It becomes insensitive when poor conductors of heat are tested, since thermal losses then tend to predominate over heat transfer across the contact and, even for a metal, it is necessary to apply a correction involving its thermal conductivity, which must, therefore, be known or determined in a separate experiment.

It will be appreciated that these difficulties might be overcome if the electrical resistance between a conducting indenter and a metallic sample were measured, instead of the thermal resistance. It would be easy to ensure that all the electrical current passed through the contact region and the electrical resistivity of the metal would not need to be known, if its value were much less than that of the indenter material. When two semi-infinite solids of resistivity ϱ_1 and ϱ_2 make contact over a circular area of radius r, the electrical resistance between them is equal to $(\varrho_1 + \varrho_2)/4r$ [3]. Thus, if $\varrho_1 \gg \varrho_2$, the resistance becomes equal to $\varrho_1/4r$, so that the resistivity of only one of the two materials need be known.

The disadvantage of using an electrical measurement to determine the contact area is that it is much more likely to be affected by oxide layers and other surface contaminants than is a thermal measurement. Also, of course, in neither case is there any assurance that the real area of contact is going to be at all close to the apparent area, as observed under a microscope. Nevertheless, it does seem that under some circumstances it is possible to achieve intimate electrical contact between two solid conductors [4]. We have, therefore, carried out an investigation of the electrical contact resistance between an indenter made from a hard, electrically conducting material and a number of metals.

We selected silicon carbide as the indenter material, since it is second only to diamond in the Moh's scale of hardness and, being a semiconductor, its electrical resistivity can be much higher than any metallic value while, at the same time, not being so great that resistance measurements are made difficult. We do not believe that our indenters have been made from samples of SiC with the most suitable properties but, nevertheless, our results seem to offer good prospects for the determination of hardness from the electrical contact resistance.

2. Experimental methods

The experiments were carried out using a Zwick hardness testing machine Type Z3 2A. This machine is normally used for the performance of Vickers hardness tests, using loads of up to 10 kg. In our electrical measurements, leads were attached to the indenter and to the metallic test samples, the latter being electrically insulated from the rest of the machine.

In the Vickers test, the indenter consists of a diamond pyramid having an angle of 136° between opposite faces. In our work, the diamond indenter was replaced by one of a number made from hot-pressed, high-density silicon carbide, originally supplied by the National Bureau of Standards in bar form. The indenters were either of the standard Vickers shape or were conical with a half-angle of 60°. The results were qualitatively similar for all the indenters but the data that are presented here refer specifically to one of the standard pyramidal shape, with well-polished faces, that was made from a particular bar of SiC. All the measurements with the indenter were carried out at a temperature of 300 K.

The electrical resistance between the indenter and the metal sample was determined by observing the potential drop, using a multi-range digital voltmeter,

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TABLE I Samples used in the measurements

Sample no.	Material	Vickers hardness ($kg\,mm^{-2}$)
G1	Gold	63
C1	Copper	88
B1	Brass	131
A1	Aluminium	140
S1	Steel	148
S2	Steel	330
S3	Steel	594
S4	Steel	654
S5	Steel	718

for various values of the current. It was established that the only significant voltage occurred in the region of the contact between the two materials. Provision was later made for the discharge of a condenser through the contact, as will be described shortly.

Table I lists the samples that were studied, together with their Vickers hardness numbers, as determined using a diamond indenter. The surfaces of the samples were polished, as is normal for hardness testing, and degreased, but no special cleaning procedure was necessary.

3. Experimental results

3.1. Electrical resistivity of hot-pressed silicon carbide

As mentioned in the Introduction, it is desirable that the electrical resistivity ϱ of the indenter should be much greater than that of any of the metals that might be tested. Fig. 1 shows our observed values for ϱ, over the temperature range 300 to 450 K, obtained using a four-contact technique on a rectangular bar. The resistivity at 300 K is 0.37 Ω m, whereas metals and metallic alloys have resistivities in the range 10^{-8} to

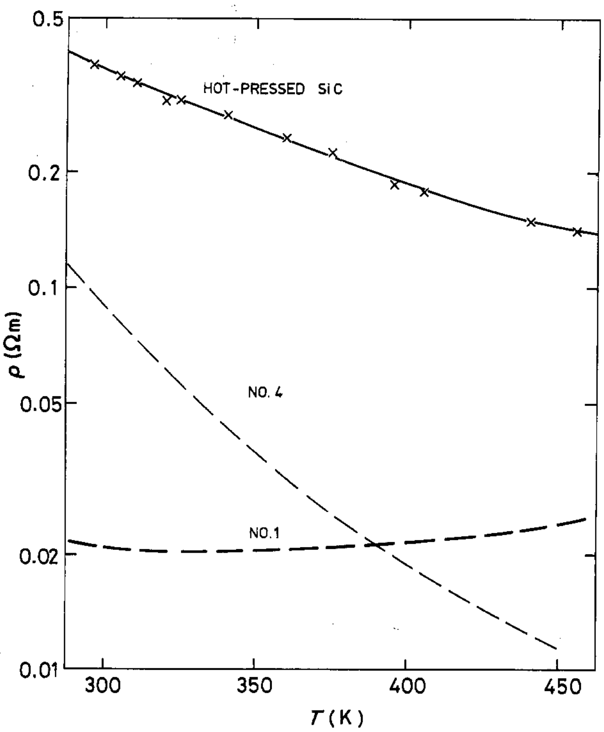

Figure 1 Electrical resistivity plotted against temperature for the silicon carbide material used in the indenter. Also shown are the data for two of the crystalline samples measured by Burgemeister *et al.* [5].

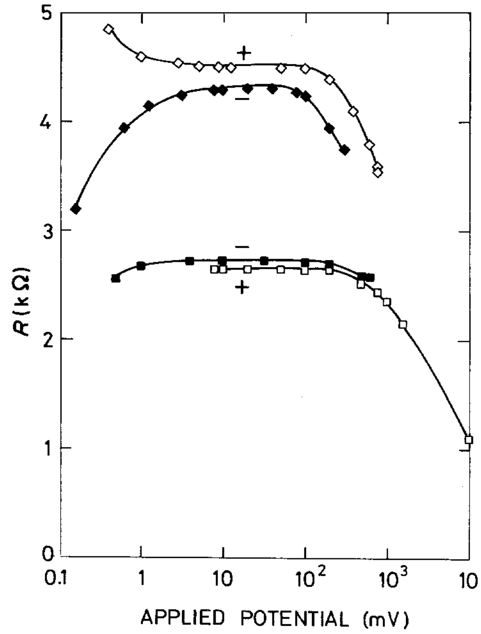

Figure 2 Plot of electrical resistance between indenter and a steel sample against applied voltage, (♦, ◊) before and (■, □) after condenser discharge. Load = 0.2 kg. The positive and negative signs indicate the polarity of the SiC during the resistance measurement.

$10^{-6}\,\Omega$ m. Thus, our required condition is easily satisfied.

Fig. 1 also shows the variation of electrical resistivity with temperature for two of the crystalline samples that were studied by Burgmeister *et al.* [5]. It is noted that whereas the negative temperature coefficient of the resistivity $-(d\varrho/dT)/\varrho$ for the hot-pressed SiC is less than for the crystalline sample No. 4, it still has the relatively high value of $6.9 \times 10^{-3}\,K^{-1}$. However, the crystalline sample No. 1 has almost zero temperature coefficient and its electrical resistivity is still several orders of magnitude greater than that of a metal. Thus, an indenter made from material similar to Burgemeister's sample No. 1 would have the important additional advantage of virtual temperature independence.

3.2. Resistance as a function of applied voltage

The upper curves in Fig. 2 show typical behaviour of the electrical contact resistance, as measured over a wide range of applied voltage. The features that are apparent are (i) a small difference in resistance according to whether the indenter is positive or negative with respect to the metal, (ii) an increase or decrease of resistance, according to the polarity, at low voltages, and (iii) a substantial decrease at high voltages. Fig. 2 applies specifically for a sample of steel, with a load of 0.2 kg applied to the indenter, but it was invariably found that the plateau region included measurements at an applied potential difference of 10 mV, whatever the test metal or the load. For this reason, our observations were normally carried out with this value for the applied voltage. The behaviour at very low voltages, including the effect of polarity, may be indicative of interfacial barrier effects, while the trend at high temperatures could be due to Joule heating.

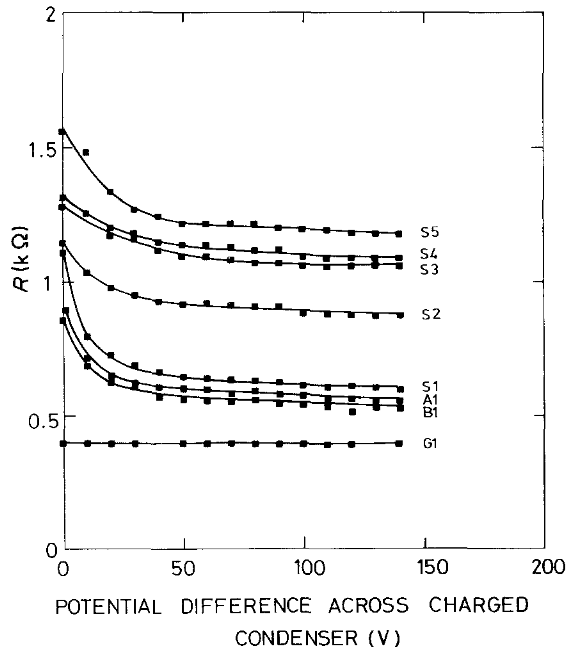

Figure 3 Electrical resistance after condenser discharge, as a function of the voltage on the condenser, for various samples. Load = 1.0 kg.

The value for the resistance at a given load was not at first found to be particularly reproducible. However, it was observed that less variable results were obtained after the electric current was switched off and on while the load was applied. This led to an investigation of the effect of discharging a condenser through the contact and the development of a beneficial pre-test procedure. The lower curves in Fig. 2 were obtained after the discharge of a 15 nF condenser that had been charged to 100 V. After the discharge, the resistance was much lower and more reproducible, and it no longer depended significantly on the polarity of the indenter with respect to the sample.

It must be emphasised that the energy in the discharge is of the order of only 100 μJ and there is no question of any adhesion between the surfaces. It is possible that the discharge is effective in removing surface contaminants, since neither the indenter nor the metal had been subject to elaborate cleaning techniques.

Fig. 3 shows how the resistance of the contact fell, as the voltage on the 15 nF condenser was increased, for a variety of samples. There was little or no change for the gold sample G1, but in all the other cases there was a significant effect. It was apparent that little further reduction of resistance occurred after the condenser voltage reached 100 V. Thus, a discharge from the condenser at this voltage was adopted as a standard pre-test operation. There is, of course, no reason why the capacitance of 15 nF should be better than any other value, and further studies could be made on the optimization of the discharge.

3.3. Relation between the resistance and the size of the indentation

We have seen that the resistance for a plane circular contact of radius r should be proportional to $1/r$. The contact between the indenter and the sample, however, has a square profile and is non-planar. Nevertheless, we would still expect the resistance to depend inversely on the linear dimensions of the indentation, and we select as a parameter the length d of the diagonal, as observed with a microscope. It is, of course, this quantity that is used in definition of the Vickers hardness H_V in the relation

$$H_V = \frac{1.8544}{d^2} L \qquad (1)$$

This implies that the Vickers hardness is the ratio of the load L to the pyramidal contact area. Hardness values are usually expressed in kg mm^{-2}.

If there is a geometric similarity between all the contacts, for different loads and samples, we expect that the resistance R should be proportional to $1/d$. We have, therefore, plotted R against $1/d$ in Fig. 4 for a typical steel sample. Before the pre-test operation the results were rather scattered, but afterwards all the results followed a straight line through the origin quite closely. It does seem, then, that the contact resistance is inversely proportional to the length of the diagonal across the indentation, provided that a suitable testing procedure is adopted.

Fig. 5 shows R plotted against $1/d$ for all the samples listed in Table I, at loads between 0.2 and 10 kg. A single straight line of slope 0.083 Ω m satisfies

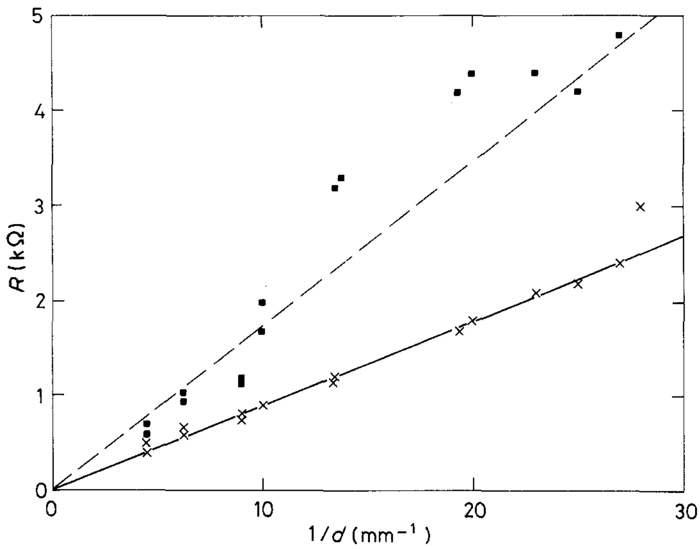

Figure 4 Electrical resistance plotted against reciprocal of the observed diagonal of the indentation for a typical steel sample, (■) before and (X) after condenser discharge.

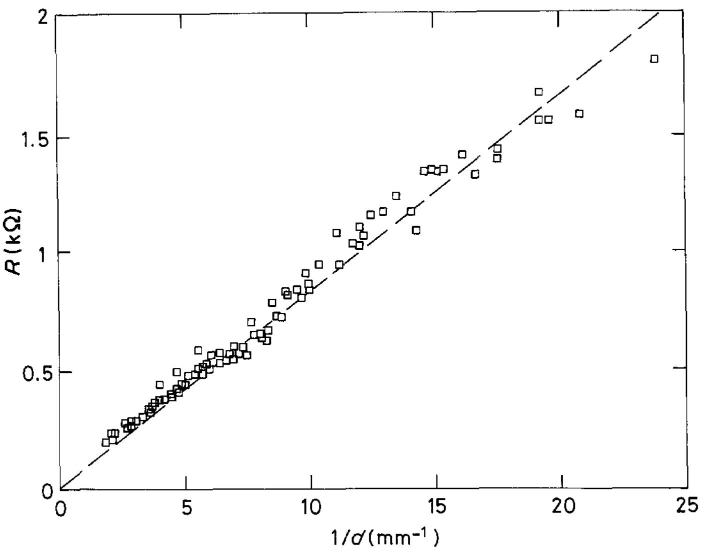

Figure 5 Plot of electrical resistance against reciprocal of the diagonal for all the samples studied for loads between 0.2 and 10 kg.

all the data with a standard deviation of less than 10%. We call this slope the indenter constant C. It is concluded that the measured contact resistance can be employed to predict the length of the diagonal of the indentation for a given load and, thus, the hardness of the metal.

3.4. Hardness measurement

Knowing the indenter constant C, as defined above, we may specify a hardness value H_R from the resistance measurement as

$$H_R = \frac{1.8544}{C^2} R^2 L \tag{2}$$

There is no reason why the Vickers hardness should be dependent on the load but, in case there should be any load-dependent effect, H_R has been plotted against the Vickers hardness in Fig. 6, for the nine samples specified in Table I, using the particular load of 1 kg. The broken line in Fig. 6 represents the plot $H_R = H_V$ and it is clear that all the experimental results correspond closely with this condition. The largest discrepancy, for the very soft gold sample, could be due to the fact that the indentation has reached a width that is becoming comparable with the width of the indenter.

4. Application to viscoelastic materials

The method of hardness testing that has been described is, of course, only suitable for good electrical conductors. However, we have found that the technique can be adapted for use with electrical insulators if they are coated with a conducting material. This is of some significance, since it means that microhardness tests on ceramics and glass may also be possible by this method and, in addition, continuous time-dependent hardness measurements under load can be made on viscoelastic materials.

We have carried out some preliminary tests on

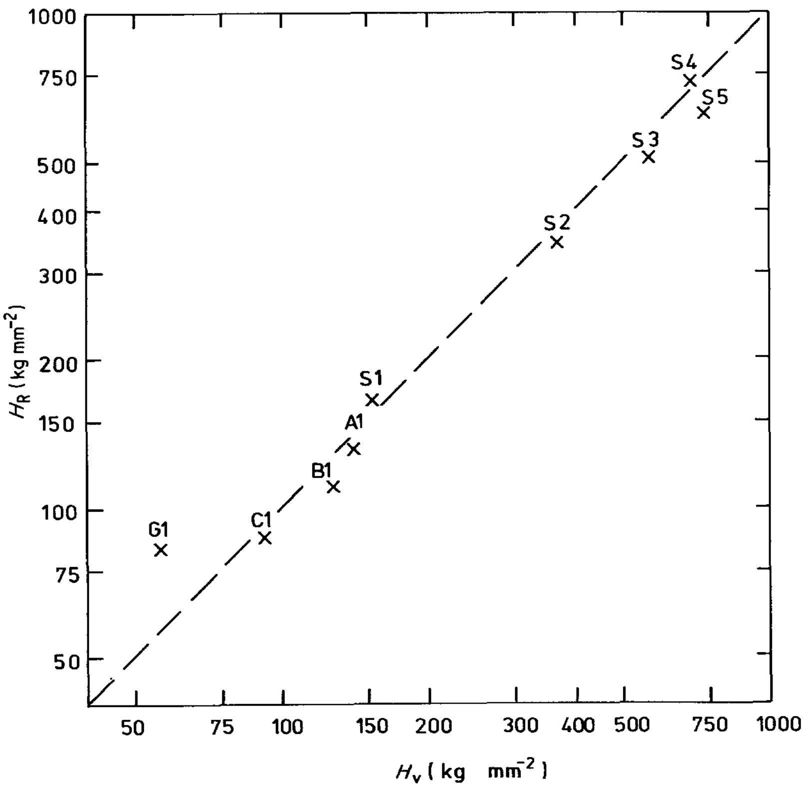

Figure 6 Comparison of hardness determined from resistance measurements with the conventionally measured Vickers hardness for different metals. Load = 1.0 kg.

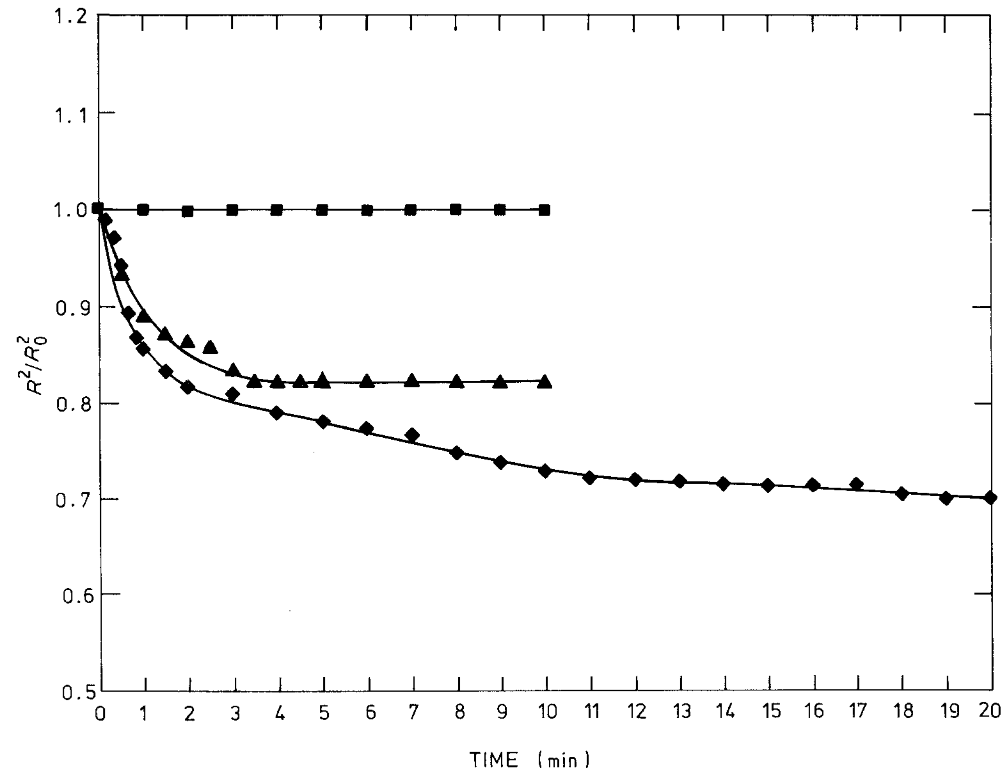

Figure 7 Variation of relative hardness (proportional to the square of the resistance) with time, for indentations on (♦) metallized Perspex, (▲) CR–39 and (■) gold.

samples of Perspex (polymethyl methacrylate) and Cr–39 (diallyl diglycol carbonate) coated with gold. Continuous chart recordings, showing the variation with time of the resistance under constant load, were used to calculate relative hardness values (proportional to R^2 for a given load) as shown in Fig. 7. R_0 is the resistance at zero time. It is seen that, whereas for gold the resistance is time-independent, it takes several minutes with CR–39 and Perspex before constant values are approached. Clearly, important information about the time-dependent mechanical properties of these materials is thus made available by a comparatively simple technique, much less time-consuming than the equivalent optical microscope method [6].

5. Discussion of results

If the contact were plane and circular, the indenter constant C would be equal to $\varrho/2$, d then being taken to be the diameter of the circle, and the assumption being made that the two surfaces touch at all points [3]. In practice, we would expect the indenter constant to be somewhat greater than $\varrho/2$, because a square of diagonal d occupies less area than a circle of diameter d and there is extra resistance associated with the part of the pyramid lying within the indentation. The indenter constant would also be made larger by any imperfection in the contact between the surfaces. In fact, the observed value for the indenter constant is no more than $0.083\,\Omega\,\mathrm{m}$ whereas $\varrho/2$ is $0.185\,\Omega\,\mathrm{m}$.

A possible explanation that we can see for this discrepancy is that the resistivity of the SiC near the tip of the indenter may be of lower resistivity than the value measured on the rectangular bar from which the indenter was cut. We found the bar to be quite uniform on a macroscopic scale, but it is possible that it was microscopically inhomogeneous. There is some evidence for this, in that a different indenter constant was obtained when the SiC was reground and repolished. It has also been suggested to us that the resistivity of SiC may be stress-dependent. However, we found no difference between the values of the indenter constant when employing samples of very different hardness, in spite of the different pressures involved. Thus, we do not think that stress-dependence of the resistivity is important in this work. Whatever the reason for the discrepancy, the indenter constant is obviously of the same order as the predicted value which suggests that the surfaces must be in intimate electrical contact with one another, at least after the pre-test operation.

6. Conclusions

It appears that a hardness test based on the measurement of electrical resistance is now feasible. Such a test could be performed rapidly either in the laboratory or in the field. It is clearly an advantage that the hardness test is carried out under load, since this obviates difficulties due to the change of shape of the indentation that often accompanies recovery, after the load is removed. Also, it would be a simple matter to perform the test for a specific depth of penetration rather than a specific load, and this might well lead to more reproducible results. The technique could be applied by means of an attachment to an existing indentation hardness tester, and the retention of the Vickers pyramidal geometry would make calibration very simple. The possibility of obtaining continuous measurements on viscoelastic materials is a most attractive feature of the technique.

We realise, of course, that a much wider range of metals would have to be tested before the method could be adopted for general use. Also, further work should undoubtedly be carried out using indenters made from samples of SiC having close to zero temperature coefficient of the resistivity, and further studies of the condenser discharge procedure are called for. It would certainly be worthwhile to carry out an examination of the indented surface with a scanning electron microscope, after the discharge, with a view to discovering whether or not local melting of asperities might have recurred. It is possible that the discharge has a similar effect to that of a vibrating tuning fork, as mentioned by Bowden and Tabor [4]. We have, in fact, ourselves observed a reduction of the electrical resistance on applying sonic vibrations to the contact, though we find the condenser discharge to be simpler to use and more reproducible in its results.

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