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A Survey of Contact Resistance Theory for Nominally Clean Surfaces

Abstract: While the theory of electrical contact resistance is, for the most part, well known, it is difficult to apply directly to the prediction of experimental results since, in general, the theory involves microscopic parameters beyond the control of the investigator. Recent measurements of contact resistance as a function of the applied contact load, carried out under specified conditions, have yielded results which are in excellent agreement with the general theory. In contrast, however, to a number of previous publications, the results indicate that the contact area is determined completely by the applied load and an effective plastic yield pressure. Under conditions where contact wipe and vibration are held to a practical minimum, the contact area can be specified in terms of a plastic yielding mechanism down to pressures as low as 0.1 gram. In this region the bulk of the contact resistance is seen to be attributable, for nominally clean contacts, to an absorbed gaseous monolayer approximately two angstroms thick.

Theory

Electrical contact resistance between two metallic bodies in physical contact under a given total load is comprised of two distinct components usually termed *constriction* or metallic resistance and *film* resistance.[1]

Constriction resistance is a direct consequence of the voltage gradient produced by current flowing from one contact to the other through the narrow or constricted regions of actual contact. Film resistance is developed when surface films are present to impede the flow of current. In the experiments to be described, in which only thin films are evident, electrons penetrate the film by the mechanism of "tunneling." Here the film resistivity is independent of the composition of the film.

In general, the total measured contact resistance will be determined by certain physical parameters of the contact material, by the applied load which determines the magnitude of the area of contact, by the thickness of the surface film, and by the micro-topography of the contact surfaces. Of these, it is the topography of the actual area contact which is most difficult to ascertain and which, in fact, is seldom known with any degree of accuracy. Nevertheless, in order to permit mathematical calculation, it is necessary to assume a geometrical configuration. R. Holm,[1] to whom most of the general theory of contact resistance is attributable, has calculated the special case in which it is assumed that the actual contact areas may be approximated by elliptical areas of semiaxes α and β. Letting $\beta = a/\gamma$ and $\alpha = a\gamma$ (such that the contact area, $\pi\alpha\beta$ is equal in magnitude to a circular area, πa^2), the constriction resistance, R_c of n independent contact spots is given by

$$R_c = \frac{\rho}{2 \sum_{i=1}^{n} \dfrac{a_i}{f(\gamma_i)}} \qquad (1)$$

where ρ is the resistivity of the contact material, a_i is the area of and $f(\gamma_i)$ a calculable function of the ith constriction. Figure 1 shows $f(\gamma)$ as a function of γ, graphically indicating the manner in which the constriction resistance decreases with increasing eccentricity of the contact area. While in principle, a knowledge of the quantities involved in Eq. (1) should allow an approximation of the constriction resistance, in practice, a, γ, and n which are determined by the actual topography of the mating surfaces are known only in a limited number of rather special instances. It is therefore impossible to utilize Eq. (1) without first making some simplifying assumptions. For the purpose of discussion it is convenient to assume that all n contact spots have the same

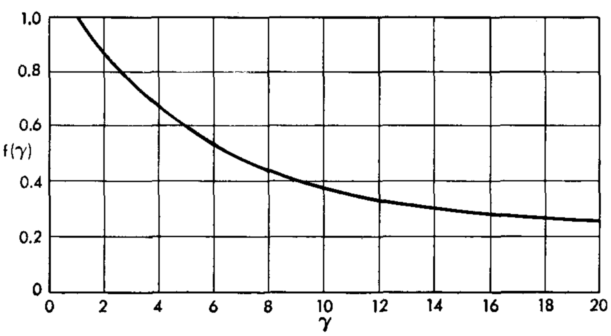

Figure 1

$f(\gamma)$ as a function of γ, where the eccentricity is given by $(\gamma^4-1)^{\frac{1}{2}}/\gamma^2$.

a *and* γ. In this case the expression for R_c reduces to

$$R_c = \frac{\rho f(\gamma)}{2na} \tag{2}$$

The film resistance, R_f, due to electrons tunneling through thin surface barriers has also been calculated by Holm,[2,3] and may be written as

$$R_f = \frac{\sigma}{\pi a^2} = \frac{10^{-22} \quad A^2}{\pi a^2 \, (1 + A\psi)} \, e^{A\psi} \tag{3}$$

$$\text{where } A = 7.32 \times 10^5 s \left(1 - \frac{7.2}{s\phi}\right)$$

$$\text{and } \psi = 1.265 \times 10^{-6} \left(\phi - \frac{10}{s}\right)$$

Here ϕ is the electron work function in electron volts; s, the film thickness in angstrom units; σ, the film resistivity in ohm-cm and πa^2, the area of the film. Figure 2 shows σ graphically as a function of the thickness for a number of representative work functions.

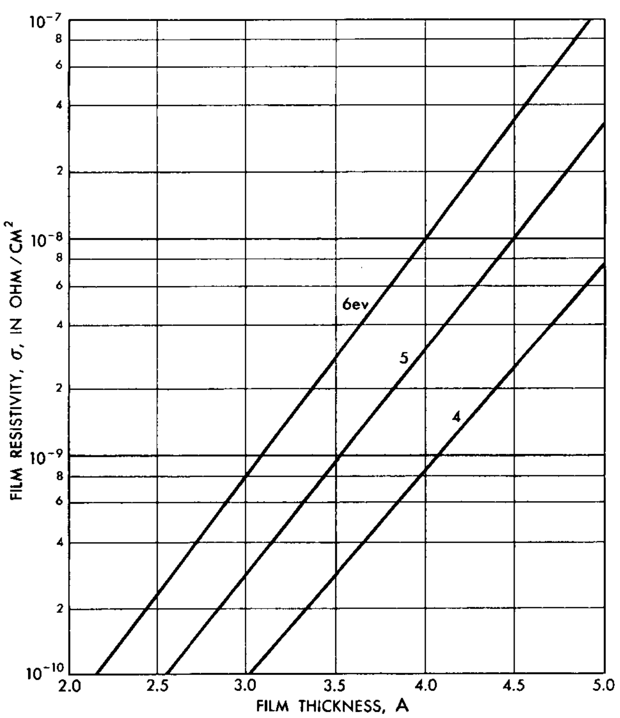

Figure 2

The film resistivity, σ, in ohm-cm as a function of the film thickness for a number of representative work functions.

The total contact resistance is obviously obtained by adding in series the constriction and film resistance of each contact spot and summing to obtain the parallel resistance of all contact spots. If we assume the simple geometrical configuration used in obtaining Eq. (2), the film resistance for n contact spots is

$$R_f = \frac{\sigma}{n\pi a^2} \tag{4}$$

It is now possible to discuss the manner in which Eqs. (2) and (4) would be expected to vary with the applied contact load. Holm,[4] for example, has discussed the formation of contact spots in terms of the yielding of the contact members under an applied load. It is assumed that under relatively light loads (e.g., less than 100 grams) the contact yielding is purely elastic, in which case the area of contact may be calculated with the aid of formulas first given by Hertz.[5] For crossed wire contacts of radius, r, the radius of the area of contact is given to a good approximation for most metals as

$$a \cong 1.11 \sqrt[3]{\frac{Lr}{E}} \tag{5}$$

where L is the applied load and E the modulus of elasticity.

Under increasing loads, plastic yielding soon begins to occur, at which time the area of contact is obtained by assuming that the total load divided by the total area of contact is equal to the average hardness of the specimen. Designating what we shall term the average "effective yield pressure" by the symbol p, we have

$$\pi a^2 = \frac{L}{p} \tag{6}$$

Under these assumptions, it would be anticipated that under relatively light contact loads the constriction resistance would vary inversely with the third power and the film resistance inversely with the two-thirds power of the applied load. Under greater loads the constriction resistance would be expected to vary inversely as the half power and the film resistance inversely as the first power of the applied load.

Measurements by Holm[4] and more recently by Kappler, Ruchardt, and Schlater[6] appear to confirm this general approach. It is, however, possible to show that the experimental results obtained by these authors is consistent with an interpretation which assumes that plastic yielding is responsible for determining the area of contact at all contact loads. Holm, for example, has himself pointed out the fact that from the microscopic standpoint the contact surfaces are relatively rough and that the mating of surfaces inevitably takes place at a small number of surface asperities which would be expected to yield plastically under the applied load.[7] Under these circumstances the application of Eq. (5) becomes meaningless. Even allowing for the fact that elastic yielding does occur, there is no feasible method of assigning a suitable value to the quantity r in Eq. (5), since r would correspond not to the macroscopic indenter radius but to the radius of the surface asperities.

This may be seen from the fact that the observed contact resistance between flat plates (where r macroscopically approaches infinity) is not noticeably different from the contact resistance between fine wires (where r macroscopically approaches zero). It would appear, therefore, that the use of Eq. (5) to justify the decreased slope of the resistance load curves at light loads is highly questionable.

It is possible, moreover, to justify this decreased slope in a manner which is in accord with the known facts. Accordingly assume that for all practical surfaces, plastic yielding of the surface asperities is the mechanism by which the actual areas of contact are formed. Under this assumption Eqs. (2) and (4), with the use of Eq. (6), become

$$R_c = \frac{\rho p^{\frac{1}{2}}\pi^{\frac{1}{2}}}{2n^{\frac{1}{2}}L^{\frac{1}{2}}} f(\gamma) \tag{7}$$

$$R_f = \frac{\sigma p}{L} \tag{8}$$

It is obvious, at this point, that because of the approximations which have been introduced regarding the geometry of the area of contact, the total resistance as given by the sum of Eqs. (7) and (8) will be correct only with regard to the order of magnitude. It will be necessary therefore to take sufficient experimental data to obtain results which are representative of average values for n and γ. It is, nevertheless, instructive to inquire into the manner in which Eqs. (7) and (8) might be used to determine the average resistance characteristics of crossed wire contacts.

At relatively high contact loads (e.g., greater than 100 grams) deformation of the contact surfaces is large and it is reasonable to expect plastic deformation will have obliterated most of the surface asperities to the extent that the contact load will be concentrated largely in one spot. Under these conditions the number of contact spots, n, will be equal to one, and for crossed circular wires, the elliptical form factor, γ, will be roughly equal to one. Hence R_c will vary inversely as the half power and R_f inversely as the first power of the applied load.

At lighter loads, however, a number of effects will occur such as to reduce the resistance/load curve slopes to a value less than that indicated above:

1. The average pressure at the contact spots will occasionally be less than the average effective yield pressure by virtue of a fortuitous mating of the contact surfaces in an area larger than would normally be formed by plastic yielding.

2. The effective yield pressure could be lower at light loads than at heavy loads where a certain amount of work hardening of the contacts is expected to take place.

3. At light loads, the actual areas of contact might be expected to lie along surface scratches or abrasions leading to a form factor, γ, less than unity.

4. Lateral contact motion (induced, for example, by microscopic vibration or smear) tends to smear out the area of contact into an elliptical shape lowering γ. Likewise the plowing together of surface asperities not only tends to eliminate some of the film resistance, but would be expected to increase substantially the area of contact.[8]

5. At light loads the surface roughness is more likely to result in a greater number of contact spots, n.

6. In any practical measuring device, momentary overloading of the contacts will produce a hysteresis effect resulting in a lowering of the contact resistance. (Under purely elastic deformation this would not be expected to occur.)

7. Plastic flow or creep of the contact material under pressures less than the average effective yield pressure would tend to produce a resistance decrease with time.

As a result of one or more of the above effects a typical $\ln R_c/\ln L$ plot would be expected to possess characteristics similar to the curve shown in Fig. 3. At loads above 100 grams the curve has a slope of roughly -0.5. In the region below 100 grams the slope begins to fall off to a value in the neighborhood of -0.3. The plot shown in Fig. 3 is, in fact, typical of data collected by numerous investigators.[4,6] Such data have, however, generally been interpreted as an indication of the validity of Eq. (5).

Experimental method

In order to verify the preceding interpretation it is necessary to avoid, insofar as is possible, the effects which tend to lower the contact resistance at the lighter loads. Under these circumstances it might be expected that the experimental results will be in general accord with Eqs. (7) and (8). To this end the following experimental procedures were adopted:

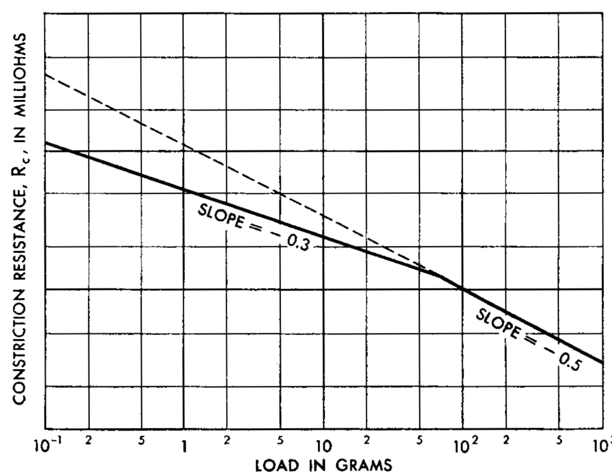

Figure 3
Typical plot for $\ln R_c/\ln L$.

1. Contact wipe and vibration were held to a practical minimum.

2. Momentary overloading of the contacts was avoided by the use of magnetically-actuated loading devices.

3. Measurements were made as soon after the application of the applied load as was feasible.

All of the measurements were carried out on crossed wire contacts rigidly mounted in such a manner that the load could be varied smoothly and continuously by the adjustment of a current. For loads of from 0.1 to 10 grams a modified Weston meter movement was used as the actuating device,* while a device similar to that employed by Kappler et al[6] was used to obtain loads of from 10 to 1000 grams. Vibration and wipe were simply kept to a practical laboratory minimum. In order to prevent unwanted heating effects the contact voltage, as read on a standard microvoltmeter, was never allowed to exceed 50 microvolts. Actually, readings in the two different load ranges were taken independently by different observers and the averaged data plotted on one curve. In each case this procedure led to a smooth, continuous curve.

The contact wires were cleaned by a number of common methods with no attempted control of the surface finish. In the load range from 0.1 to 10 grams the experiments were carried out in a vacuum system at a pressure slightly less than one micron. In this load range where film resistance becomes dominant it is found that almost all wires cleaned in air initially show some sign of contact contamination. This contamination is readily removed, however, by subjecting the contacts to a series of short anode arcs,[9] or by allowing the contacts to bridge on closure at a voltage less than 10 volts.[10]

The fact that cleaning in this manner alters the condition of the surface presumably accounts for the fact that the initial surface finish of the contacts was not apparent in measurements at light loads. At higher loads, the contact yielding is sufficient to prevent initial surface finish from producing a noticeable effect on the measurements.

Experimental results

Figure 4 shows typical data taken in a series of measurements carried out with palladium contacts in the load range from 0.1 to 10 grams. Comparison of the data taken before and after cleaning illustrates the manner in which an anode arc may be used to clean the surface. Figure 4 also gives some indication of the statistical variations between individual runs. In a number of instances data were taken under both increasing and decreasing contact loading. The results of such measurements, while not shown in the figure in all cases, showed an almost complete hysteresis effect indicating that plastic yielding does occur at loads as low as 0.1 gram. It might be pointed out that at light loads a

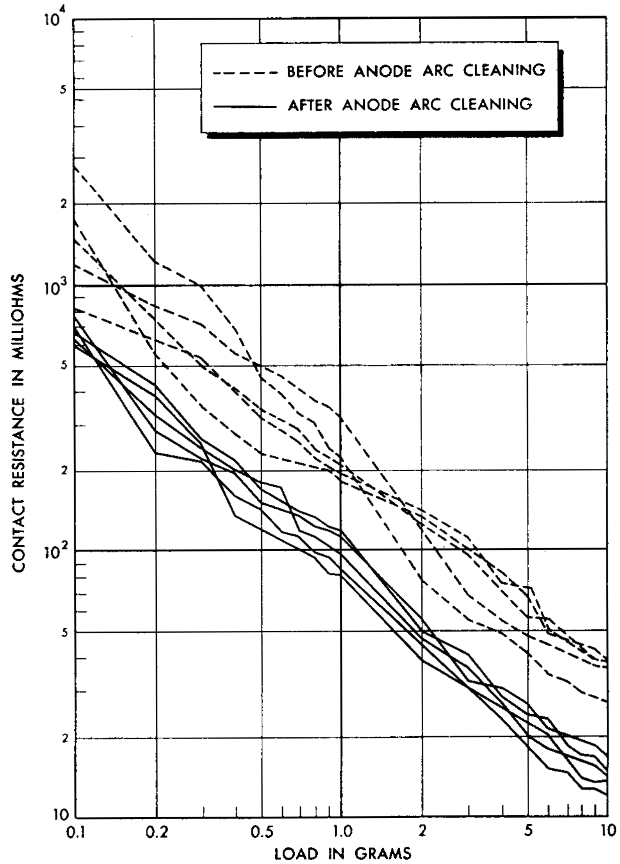

Figure 4

Contact resistance of palladium contacts in milliohms as a function of the applied load in grams. (Data were taken with contacts which had been cleaned in air and held in vacuum for one week, and with contacts which were cleaned by a series of anode arcs.)

noticeable drop in resistance occurs with time following the initial application of force. This is taken as an indication of plastic flow at pressures near or below the average yield pressure coupled with a certain amount of unavoidable contact vibration.

The results of averaging over several dozen individual runs are shown in Figs. 5(a), (b), (c), and (d). In all cases it is possible to separate the curves of measured resistance versus load into two components having slopes of -1.0 and -0.5 corresponding respectively to a film and a constriction resistance.

The component curve for the constriction resistance in conjunction with the measured value of the resistivity may be used to calculate the effective yield pressure (here, both n and γ are arbitrarily set equal to one). In turn the calculated value of p along with the component curve for R_f may be used to calculate the film resistivity, σ. Finally, using Fig. 2 and the tabulated value of the work function, it is possible to obtain the film thickness, s. In each case, s turns out to be of the order of 2A and is taken as evidence of the existence

*Supplied by the Weston Corporation as an ASTM contact tester.

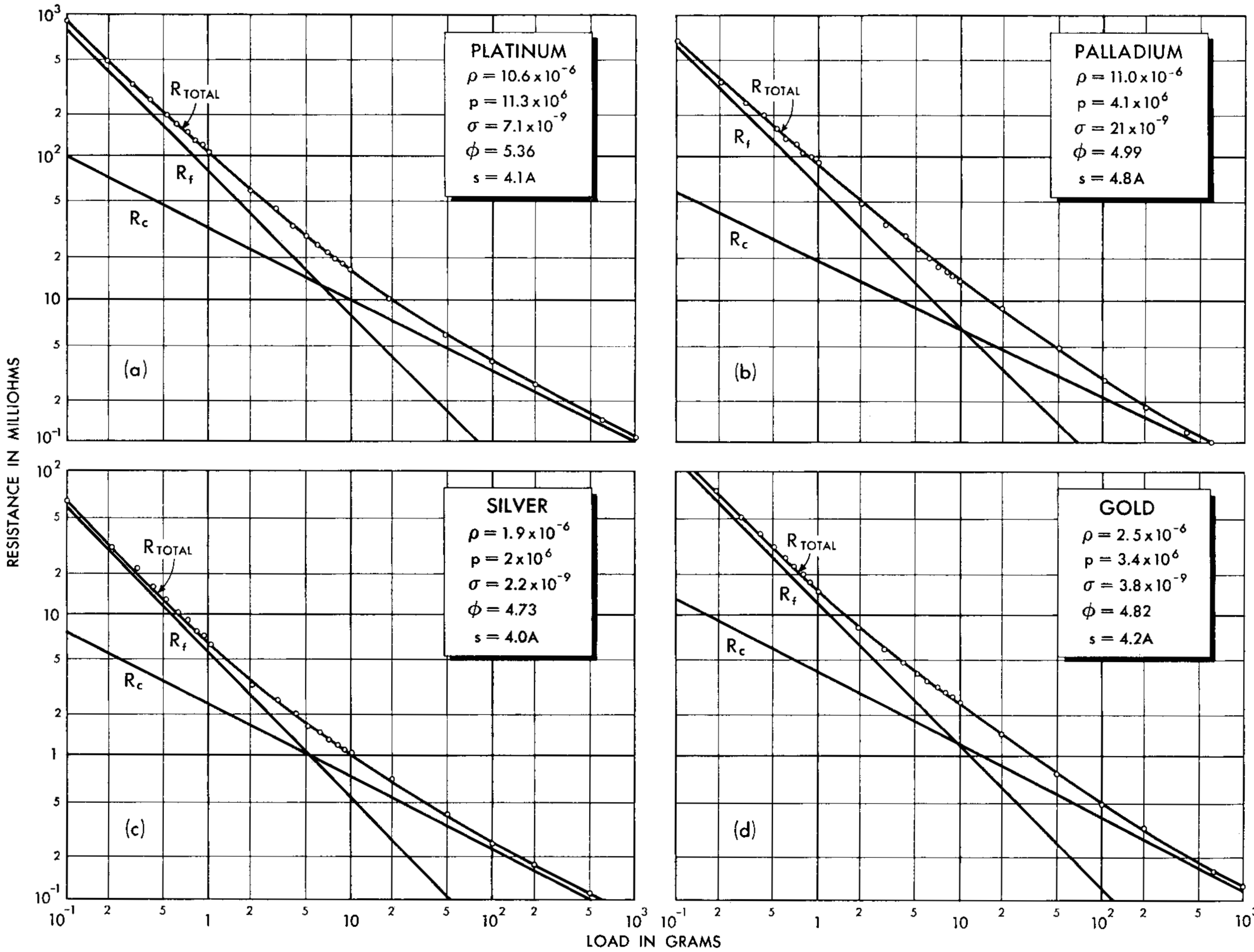

Figure 5

Curves of contact resistance versus load for the contacts: (a) platinum, (b) palladium, (c) silver, (d) gold.

of a monolayer of absorbed gas molecules on each contact surface. This is, in fact, in good agreement with expectations.[11]

Conclusions

The results of measurements carried out under controlled conditions indicate that the area of contact can be written as a function of an effective yield pressure over the load range from 0.1 to 1000 grams. Under this assumption the constriction resistance varies inversely as the half power and the film resistance inversely as the first power of the applied load. These expectations may be verified by experimental measurements on nominally clean contacts under relatively vibration-free conditions. The effect of contact vibration and wipe is such as to generally lower the contact resistance, particularly under a light load. Nominally clean contacts show evidence of being covered with a rather tightly bound monolayer of absorbed gas molecules approximately 2A thick.

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