

Electrical Contact Resistance between Metallic Surfaces Subjected to Various Treatments

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with a certain probability due to the so-called tunnel-effect. Sommerfeld and Bethe⁽⁴⁾, and Holm and Kirchstein⁽⁵⁾, and others computed this probability, from which the transition resistance was derived.

From Holm and Meissner's experiment made at room temperature and at the boiling points of liquid nitrogen, hydrogen and helium, it can be inferred that the transition resistance is almost independent of temperatures. Basing on a few assumptions, we can estimate the contact area and the thickness of the transition layer. Moreover, using the relation between the contact resistance and the load applied to the contact point, it is also possible to discuss the surface state of a metal in contact. In the present paper, physical properties of the contact resistance have been studied and by means of these experimental results, discussions have been attempted on the contact resistance subjected to various surface treatments.

II. Apparatus and procedures

Two rods of tungsten are pressed together crosswise at right angle. One end of each rod is connected with current terminals and the other ends with potential ones as shown in Fig. 1. The potential difference at the contact and the current across it are measured by a potentiometer, and the ratio of the two gives a contact resistance under test. As measured values of the contact resistance scatter over a considerable region because of the surface conditions, three kinds of standard resistances, 0.1, 0.01 and 0.001 Ω , are employed. The measuring apparatus is schematically shown in Fig. 2. Loads

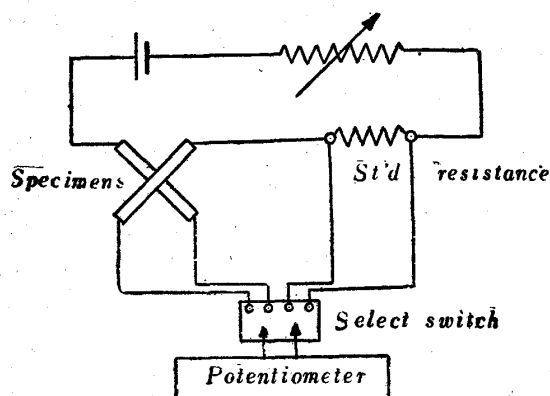


Fig. 1. Measuring circuit for contact resistance.

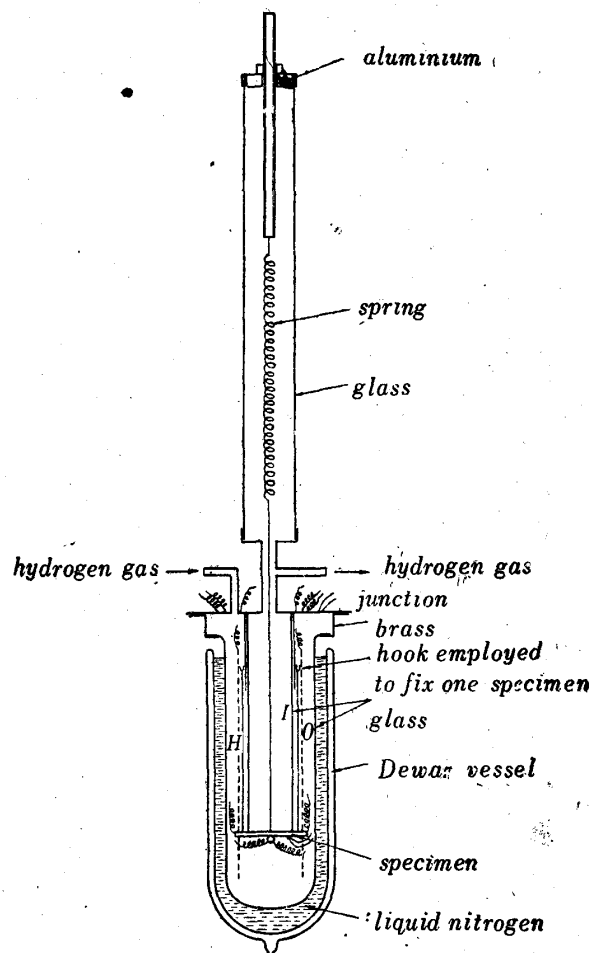


Fig. 2. The apparatus schematically drawn for measuring electrical contact resistance.

(4) A. Sommerfeld and H. Bethe, Handb. d. Phys., 24/2 Kap. 3 Ziff. 21 S. 446.

(5) R. Holm and B. Kirchstein, Phys. Zs., 36 (1935), 882.

extending from 10 to 100 g are applied to the contact point by the force of the spring of a piano wire, the stress in which is measured by a cathetometer with an accuracy of 0.2 g. To effect the contact pressure, a tungsten rod is fixed at the lowest part of the inner glass cylinder *I*, and the other is pulled by the spring mentioned above. Temperatures of specimens are changed by a constantan heater *H* from the boiling point of liquid air up to room temperature with a moderate rate. Temperatures are measured by a copper-constantan thermocouple which is firmly bound to the specimen. Whole apparatus is included in the outer glass cylinder *O* closed at the lower end, and hydrogen gas is introduced in order to protect the contact surface from congelment of water when the cylinder *O* is immersed in liquid air.

The measured values of contact resistance had scattered extensively even under the same contact pressure and temperature, so that the conditions were controlled by giving small mechanical vibration to one end of the fixed specimen. Thus, it seems likely that the contact area is increased to a constant value and the extraneous layer at the contact is removed in some measure.

The tungsten specimens, 2 mm in diameter, which had been obtained from Tohoku Metal Industry Co., were cut about 5 cm in length and the same specimens were always dealt with throughout the experiment. Three kinds of surface treatments, mechanical polishing, electrolytic polishing and electrolytic etching, were examined. Mechanical polishing surface was finished with "00000" grade emery paper. Electrolytic polishing operation was carried out in a bath which was made of 0.5 N caustic soda solution; electrolysis was carried out with the specimen as anode and a carbon rod as cathode, at a current density of 4 to 5 amp/cm² and a potential difference of 6 to 8 volts. A specimen was immersed, for about half a minute, till a beautiful and glossy surface appeared. Electrolytic etching was also done in the same solution at a potential difference of 1.5 to 1.7 volts and a current density of 3 amp/cm² for about 20 seconds. Then a fine crystalline structure could be observed with the aid of a microscope. The electrolyte is influenced so sensitively by its previous history that a new solution was used in need of unifying the conditions. After the surface treatment, the specimen was washed in pure alcohol and the contact resistance was measured immediately. In case benzol was used for rinsing, the surface seemed to be coated with a thin film, for the contact resistance appeared to be very high.

III. Experimental results

(1) Influence of the time in contact

As soon as two tungsten rods are brought into contact with each other, a considerable high contact resistance appears, but continues to decrease till it approaches nearly a constant value after some time. In Fig. 3, the contact resistance *R* is plotted against the time in contact *T*, both ordinate and abscissa being taken in logarithmic scales. Roughly speaking, log *R* decreases linearly with log *T* at first, attaining gradually to a constant value. But, it is experienced often that the

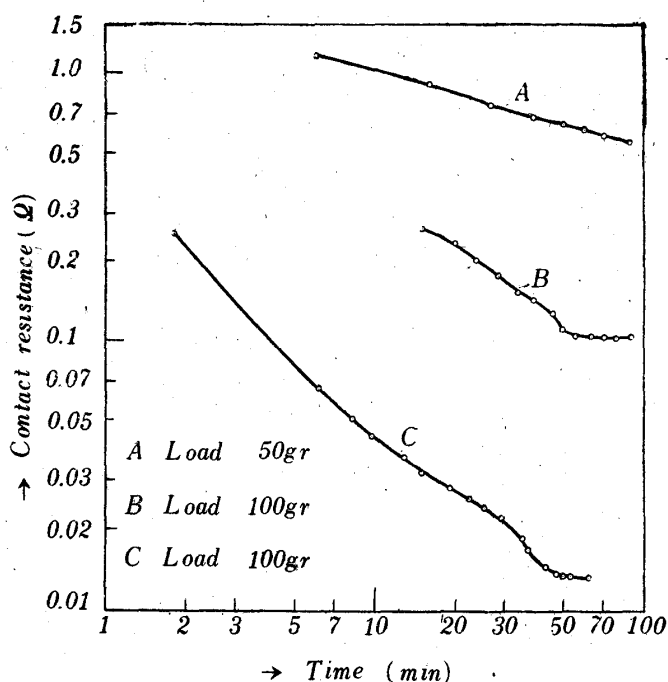


Fig. 3. Contact resistance versus time in contact.

(2) Effect of the load applied to the contact spot

It is difficult to detect the relationship between the contact resistance and the applied load with regard to one and the same contact point by varying the amount

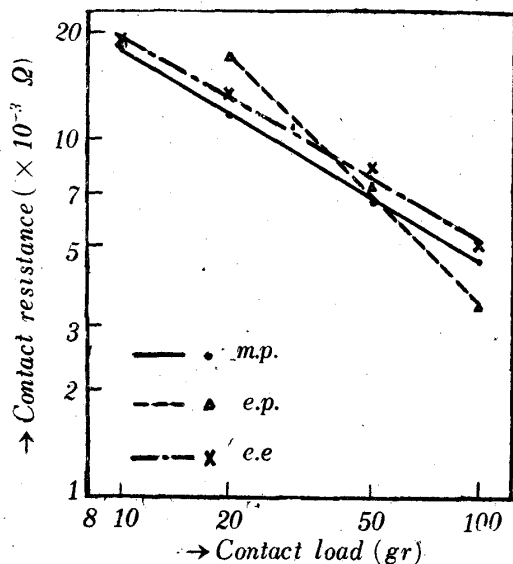


Fig. 4. Electrical contact resistance versus contact load on some surfaces. m. p. designates mechanical polished, e. p. electrolytic polished and e. e. electrolytic etched surface.

contact resistance, after having attained nearly a constant value, happens to decrease again to some extent. This phenomena might be caused by a vibration from outside, whose possible effect would give rise to the displacement of the contact point or the removal of the transient surface. In order to eliminate these disturbing phenomena and to get reproducible results, an artificial settlement was imposed on the contact point by giving a mechanical vibration to the specimen.

of load, because the smoothly polished surface is liable to be displaced during the loading operation. Owing to the surface roughness and to the lack of reproducibility of other conditions, even under the same load the contact resistance hardly settles down to the same value. Therefore, for convenience' sake, the average values of the contact resistance measured immediately after the surface treatment under some loads are shown in Fig. 4. It is indicated that as the load becomes heavier the contact resistance falls to a low value, and, moreover, that $\log R$ is proportional to $\log P$ for every kind of surface, where P is the load applied to the contact spot. These results can be represented by the following equations:

$$R_{e.p.} = 0.34 P^{-1.00} \quad (\text{electrolytically polished surface}), \quad (1)$$

$$R_{m.p.} = 0.07 P^{-0.60} \quad (\text{mechanically polished one}), \quad (2)$$

$$R_{e.e.} = 0.07 P^{-0.57} \quad (\text{electrolytically etched one}). \quad (3)$$

One can also see from Fig. 4 that the straight line just mentioned, corresponding to the electrolytic polishing, crosses with the ones, corresponding to the other treatments, with a steeper gradient than the others. Therefore, in the case of the heavy load, the contact resistance for the electrolytically polished surface is lower than the others. And in the case of the light load, the lower contact resistance appears for the mechanically polished surface. On the other hand, the contact resistance for the electrolytically etched surface has relatively high values and a moderate slope.

(3) Validity of the Ohm's law

It is also found that Ohm's law is valid for the contact resistance at ordinary temperature and boiling point of liquid nitrogen when the current is kept in the order of 0.001 to 0.1 amp.

(4) Dependence on temperatures

Holm and Meissner²⁾ measured the contact resistance at room temperature and at the boiling point of liquid nitrogen, hydrogen and helium, and Went⁽³⁾ measured for molybdenum at liquid oxygen temperature. Following them, we carried out continuously the measurements at temperatures ranging from the boiling point of liquid air up to room temperature. The reading of the potential difference at the contact, however, was susceptibly influenced by a slight external vibration, and in order to prevent any disturbance during measurements, the heating rate was obliged to make fairly great. Hence, it was unavoidable that the accuracy of temperature reading was limited within about $\pm 1^\circ\text{C}$. Figs. 5 and 6 show the results obtained with the loads of 20 g and 100 g, which depicts linear relationships against temperatures, viz.,

$$R = R_0 (1 + \alpha t) , \tag{4}$$

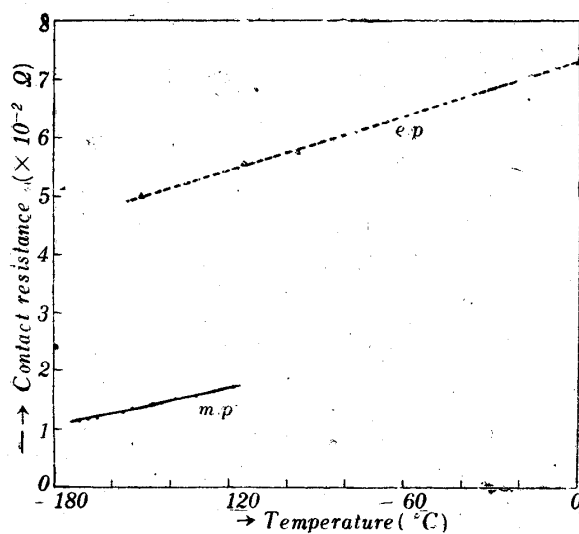


Fig. 5. Electrical contact resistance versus temperature at load 20 g.

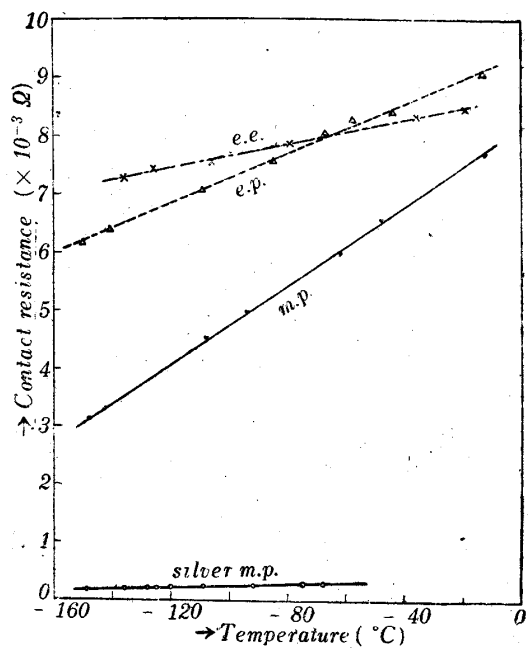


Fig. 6. Electrical contact resistance versus temperature at load 100 g.

where R and R_0 are the contact resistance at measured temperature and 0°C , respectively, t temperature ($^\circ\text{C}$), and α the temperature coefficient which is listed in Table I. This relation is similar to the dependence of the specific resistance of bulk metal on temperature, except that the temperature coefficient of the contact resistance is smaller than that of the specific resistance of bulk tungsten. In Figs. 5 and 6 and Table I, the said relations for the mechanically polished and electrolytically polished and etched surfaces are, respectively, denoted by m. p., e. p. and e. e. Figs. 5 and 6 correspond to the loads of 20 g and 100 g, respectively. From these results we see that the temperature coefficient depends on the surface treatment and the applied load. For the surface treated in the same way, the temperature coefficient with the heavy load ($P=100$ g) is greater than that with the light load ($P=20$ g). And as against the same load, the curve for the mechanically polished surface has the largest slope, followed by the electrolytically polished one. For the purpose of comparison, the similar result obtained for a mechanically polished specimen of silver, 2 mm in diameter, is also shown in Fig. 6 with the load of 100 g.

IV. Discussion of the results

(1) Decrease of the contact resistance with the lapse of time

As outlined before, when two metals come in contact with each other, the contact resistance decreases continuously till it attains a constant value. These results will be explained as follows: notwithstanding the contact area being estimated to be the order of 10^{-6} to 10^{-8} cm^2 as referred to below, the surface seems to be finely irregular even in such a small area; let two surfaces come into contact with each other at some projecting points, and contact load per unit area should surpass the yield point of tungsten so that a projecting point flows into some indentation and the contact area will rapidly enlarge, and as the contact area becomes larger, the contact resistance will result in a smaller value. Therefore, the contact resistance will decrease with the lapse of time.

(2) Contact resistance according to surface treatments

(a) Correlation with the applied load

When two metals come in contact with each other, a recession will be produced, owing partly to the elastic deformation and partly to the plastic one; its dimension will depend on the mechanical property of the metal and the applied load. Taking into account the flow of projecting points as a result of the plastic deformation but leaving the elastic deformation out of consideration due to its smallness, it may be assumed that a circular contact spot will result, whose radius a ($a \ll$ radius of the specimen) is given by

$$a = \sqrt{\frac{P}{\pi f}}, \quad (5)$$

in which f is the yield point of the metal under investigation.

It is well known that the convergence resistance R_c at the contact surface with radius a can be expressed with the following formula:

$$R_c = \frac{\rho}{2a}, \quad (6)$$

where ρ is the specific resistance of the specimen.

As the transition resistance R_t is inversely proportional to the contact area, we define it in terms of σ , which is named "specific transition resistance", by the next formula

$$R_t = \frac{\sigma}{\pi a^2}. \quad (7)$$

As already mentioned in the introduction, the total contact resistance is given by the sum of the convergence resistance and the transition resistance, therefore,

$$R = R_c + R_t = \frac{\rho}{2a} + \frac{\sigma}{\pi a^2}. \quad (8)$$

Substituting Eq. (5) in Eq. (8), one obtains

$$R = \frac{\rho}{2} \left(\frac{\pi f}{P} \right)^{\frac{1}{2}} + \frac{\sigma f}{P}. \quad (9)$$

From Eq. (9) we can directly infer that the contact resistance becomes smaller, as the applied load becomes larger. The contact resistance must be proportional to $P^{-0.5}$, if the convergence resistance only exists, while it must be proportional to P^{-1} , if the transition resistance is dominant. In Eqs. (2) and (3), we have seen that the contact resistance varies in proportion to $P^{-0.60}$ and $P^{-0.57}$, when the surfaces are subjected to mechanical polishing and electrolytic etching, respectively, so it seems that the convergence resistance predominates over the transition resistance; but when the surface is polished electrolytically, the said resistance varies as P^{-1} as indicated in Eq. (1), and this fact suggests us that the transition resistance is the dominant factor. Therefore, it would not be too far-fetched hypothesis to suppose that the oxide layer, which has been yielded during an electrolytic polishing process, is fairly stable and difficult of being peeled off in spite of loading.

(b) Influence of surface conditions

It is found from Eqs. (6) and (7) that the convergence resistance is inversely proportional to a and the transition resistance to a^2 ; and then as the contact radius becomes smaller, the transition resistance becomes comparatively higher than the convergence resistance. A small contact radius implies a light load from Eq. (5), so that the transition resistance predominates under the light load.

Electrolytically polished surface shows a more beautiful and glossy appearance than other kinds of surfaces, when observed under a microscope as well as with an unaided eye, while it is well known from electron diffraction research that it is covered with a very thin film of oxidized metal, which behaves as a stable and protective layer. On the other hand, it seems that Beilby layer which has been produced by a mechanical polishing process would be a certain amorphous and perhaps oxidized layer; when the surface is examined under a microscope it is very rough and uneven compared with the electrolytically polished one.

In Fig. 4, under the heavy load of 100 g, the contact resistance for the electrolytically polished surface is the lowest among those for three kinds of treatments. When

specimens which have the smooth surface come into contact with each other, the contact area is deemed to be considerably large; then the low contact resistance will ensue for the electrolytically polished surface. If that is the case, it is incomprehensible why the contact resistance for the electrolytically polished surface in the case of the light load is considerably high. It seems to us, however, that the electrolytically polished surface is so smooth that the contact spot is displaced from point to point by giving the vibration, so that it will not give rise to a significant increase of the contact area at a certain point. Moreover, a light load applied to the contact spot would not be sufficient to remove the tenacious oxide layer at that spot, whereas the mechanically polished surface is so rough that it will hardly slide. Then its contact area with the light load would become relatively large due to the given vibrations. Therefore, the contact resistance of the light load for the mechanically polished surface will be smaller than that for the electrolytically polished one.

(3) The effect of temperature

In the introduction it was already mentioned, basing on Holm and Meissner's result, that it is not likely that the transition resistance depends on temperatures. If one is allowed to make an assumption* that the contact radius remains constant with temperature as it is plausible because of the linear relationship between the contact resistance and temperature (Figs. 5 and 6), the specific transition resistance σ and the contact radius a can readily be estimated from Eq. (8) by measuring the specific resistance of the specimen ρ .

By taking account of the image force and assuming a suitable potential barrier on the boundary surface, Holm and Kirchstein⁽⁵⁾ found that the said resistance σ can be given by the following equation:

$$\frac{1}{\sigma} = \frac{8\pi m}{h^3} \frac{1 + A \sqrt{\varphi - \frac{e^2}{d} \ln 2}}{A^2} \exp\left(-A \sqrt{\varphi - \frac{e^2}{d} \ln 2}\right), \quad (10)$$

where

$$A = 1.15 \frac{\pi^2}{h} d \sqrt{2m} \left(1 - \frac{e^2}{2d\varphi}\right),$$

e and m are the charge and mass of electron, φ the work function of tungsten which is hardly influenced by temperature (ca. 4.54 eV), h Planck's constant and d the contact distance, viz., the thickness of the intermediate layer at the contact. Then, by putting the numerical values in Eq. (10), we can compute d from σ . The temperature coefficient, the contact radius, the contact distance, the transition resistance and the specific transition resistance obtained in this way are tabulated in Table I.

(a) Contact area

It is of interest to study the relation between the real contact area and the apparent one. If we calculate the contact area from Eq. (5) by assuming the plastic deformation, we would get $a = 2.06 \times 10^{-3}$ cm at $P = 100$ g and $a = 9.20 \times 10^{-4}$ cm

* This assumption is not strictly right. The yield point (and then the hardness) of the metal is the function of temperature, so that from Eq. (5) the contact area is also obliged to vary with temperature.

Table I.

Specimen	Surface treatment	Load (g)	Temp. coef. ($\times 10^{-3}$)	Contact radius ($\times 10^{-4}$ cm)	Contact distance (Å)	Spec. trans. resis. ($\times 10^{-9} \Omega / \text{cm}^2$)	Trans. resis. ($\times 10^{-3} \Omega$)	Contact resis. at 0°C ($\times 10^{-3} \Omega$)
W	m.p.	100	4.1	3.58	3.48	0.27	0.69	8.16
		20	3.5	1.12	3.41	0.23	5.80	29.1
	e.p.	100	2.3	5.30	4.70	4.50	4.50	9.45
		20	2.1	0.75	3.88	0.67	38.2	73.1
	e.e.	100	1.2	11.0	5.50	23.0	6.30	8.69
	Ag	m.p.	100	3.8	20.3	3.50	0.54	0.042

at $P = 20$ g, using $f = 75$ kg/mm². When the elastic deformation only is assumed, one can use the following equation that was obtained by Hertz⁽⁶⁾ and discussed by Bowden and Tabor:⁽⁷⁾

$$a = 1.1 \left(\frac{Pr}{E} \right)^{\frac{1}{3}} \quad (11)$$

in which r is the radius of the specimen, about 1 mm, and Young's modulus E is 3.62×10^6 kg/cm². Putting these numerical values in Eq. (11), we have $a = 1.53 \times 10^{-3}$ cm and $a = 9.03 \times 10^{-4}$ cm for 100 g and 20 g, respectively.

All real contact radii shown in Table I are smaller than either of these corresponding two values. Although we could not measure the apparent contact area for each load under the microscope, owing to the light load and the hard metal, we may say that it is nearly the same order as the above-mentioned ones. Then the real contact will perhaps be smaller than the apparent one. We obtain, however, $a = 1.06 \times 10^{-3}$ cm in silver, by assuming the plastic deformation, while contact area measured is to be $a = 2.03 \times 10^{-3}$ cm for the load of 100 g. Therefore, these results are inconsistent with one another; with tungsten the real contact area is smaller than the apparent one, while with silver the former is larger than the latter. It is conceivable that tungsten is a hard metal so that the flow of projecting points is difficult to take place in contrast with silver and the real contact area of tungsten does not become so large, while the contact part of silver flows comparatively easily and the real contact area will attain to the same order of magnitude as the apparent one.

(b) Contact distance

As mentioned previously, any surface treatments will give rise to a certain oxide layer which acts as a potential barrier. The thickness of this intermediate layer between two specimens should be represented as a contact distance in Table I. These data suggest that two or three oxygen atoms lie between two surfaces under discussion.

(6) H. Hertz, J. reine angew. Math., 92 (1881) 156 (or in his collected works)

(7) F. P. Bowden and D. Tabor, Proc. Roy. Soc., 169 (1939), 391

(c) Correlation between surface conditions and temperature coefficients

The temperature coefficient of the contact resistance is closely dependent on the surface conditions as shown in Figs. 4 and 5 and Table I. From Eq. (4), we get

$$\frac{R - R_0}{R_0} = \alpha t \quad (12)$$

For the sake of convenience in comparing the temperature coefficient, a plot of $(R - R_0)/R_0$ as a function of temperature t is shown in Fig. 7, using Eq. (12).

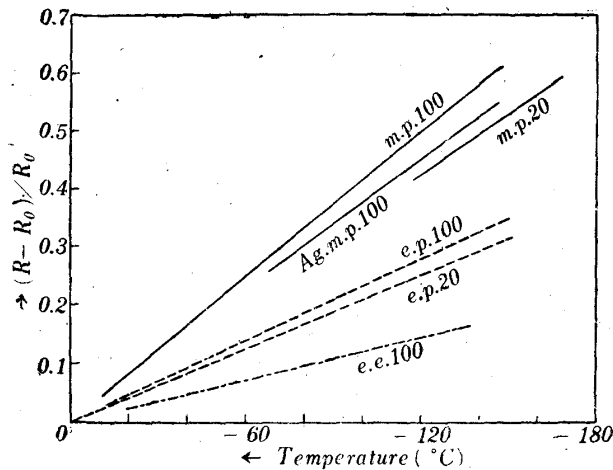


Fig. 7. Relations between ratio of contact resistances at measured temperatures to ones at 0°C and temperatures for various surface treatments.

As already mentioned, the temperature coefficient with the light load is smaller than that with the heavy one for the same polished surface. If there is only the convergence resistance in presence, it is plausible from Eq. (8) that the temperature coefficient is 4.4×10^{-3} which is equal to that of the specific resistance of tungsten. The fact that the slope for the heavy load is slightly steep implies the small-

ness of the transition resistance. It seems that though the transition resistance depends on both the contact area and the contact distance which is derived from the specific transition resistance, its effective factor is not the contact distance but principally the contact radius as we can see from Table I. It is clear that the larger contact radius or the heavier load entails the lower transition resistance.

Moreover, with the same load the temperature coefficient for the mechanically polished surface is particularly large, followed by that for the electrolytically polished one. The fact that the gradient for the mechanically polished surface is very steep suggests the low transition resistance. In the case of silver which has the mechanically polished surface, the temperature coefficient of the specific resistance is found to be 4.1×10^{-3} and that of the contact resistance to be 3.8×10^{-3} . Nevertheless, in the case of load 100 g in Fig. 3, the contact resistance for the mechanically polished surface is higher than that of the electrolytically polished one. This would be caused by the roughness of the surface, the contact area being very small as shown in Table I. On the other hand, the electrolytically polished surface is so smooth that the contact area is relatively large and then the contact resistance is very low with the load of 100 g. But with the light load of 20 g the contact radius is very small. When the load is light, the contact point on the smooth electrolytically treated surface is liable to be displaced from point to point, and as a result it hardly brings about a flow there. Therefore, the contact radius would be very small.

As for the electrolytically etched surface, it is incomprehensible that in spite of its large contact area, as shown in Table I, the contact resistance is fairly high. But

the result that the temperature coefficient is not so large would imply that the transition resistance is more prevailing for this surface. Considering that the contact distance is great on this surface, the comparatively thick layer of oxide will be developed. The fact that the slope of the resistance versus load curve is not large enough, however, appears to be incompatible with the above explanation that such a surface is covered with the thick oxide layer.

Summary

(1) Electrical contact resistance between two tungsten rods, which are placed cross-wise and pressed together with a pressure between 10 to 100 g, is investigated over the temperature range from room temperature down to the boiling point of liquid nitrogen.

(2) The contact resistance is measured, by means of a potentiometer, from the potential difference at the contact and the current across it.

(3) Three kinds of surface treatments, mechanical polishing, electrolytic polishing and etching, are examined by measuring the contact resistance.

(4) The contact resistance continues to decrease with the lapse of time till it approaches nearly a constant value as shown in Fig. 2. It is occasionally observed that the contact resistance, after having attained nearly a constant value, happens to decrease again to some extent.

(5) The average values of the contact resistance are measured under some loads immediately after surface treatments. The result obtained is that $\log R$ is proportional to $\log P$ for every kind of surface as shown in Fig. 3, where R is the contact resistance and P is the applied load.

(6) Ohm's law is valid for the contact resistance in the case of a weak current at every temperature under examination.

(7) The contact resistance is proportional to temperature for some surface treatments and loads, and consists of two kinds of resistance; the convergence resistance and the transition one which is independent of temperature. By assuming that the contact area would not vary with temperature, the specific transition resistance, the contact distance and the contact radius are computed.

(8) Some explanatory discussion is attempted on the relation between the contact resistance and the surface condition on the basis of the experimental results.