EFFECT OF FOILS UPON JOINT RESISTANCE: EVIDENCE OF OPTIMUM THICKNESS

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Abstract

Results are presented of a series of experiments made to determine the effect of metallic foils upon the joint resistance of an interface formed by the mechanical contact of a lathe turned surface and an optically flat surface. The foils tested were lead, tin, aluminum, and copper. The thickness ranged from 10 to 500μ. The test specimens were Armco iron. The mechanical pressure ranged from 20 to 100 kg/cm^2, and measurements were made during the first loading and unloading cycles. All data were obtained under atmospheric conditions. Test results show that there is an optimum foil thickness defined as that thickness which yields the minimum joint resistance. The ratio of optimum thickness to rms surface roughness is about 2 for lead and tin and about 0.48-0.58 for aluminum and 0.68 for copper. It is proposed that a better way of ranking the foil material is by means of the ratio of the thermal conductivity to the material hardness; the larger this ratio, the greater will be the reduction in the bare joint resistance.

Nomenclature

A_a = apparent or nominal contact area
H = foil hardness, kg/mm^2
k = thermal conductivity, w/cm°C
P_a = apparent contact pressure, kg/cm^2
Q = heat flow rate, w
R = thermal resistance, °C cm^2/w
R^* = R_m/R_b

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T = temperature, ^{o}C
t = foil thickness, μ

Subscripts

a = apparent
b = bare joint
F = foil
g = gas
j = joint
ℓ = first loading cycle
m = minimum
o = optimum
u = first unloading cycle
v = Vickers hardness
x = location along specimen

Greek Symbols

σ = surface roughness, rms
σ' = surface slope, rms

Introduction

It has been known for some time that the thermal contact resistance of a bare joint can be decreased considerably by inserting a metallic foil between the contacting members.[1-12] This effect has been observed for joints in air [1-3,8] and for joints placed in a vacuum.[4,6,7,10-12] The presence of foils is most effective in reducing the bare joint resistance when the contact pressure is low and the joint is in a vacuum. Many foils have been tested: soft materials such as indium and lead as well as hard materials, such as gold and copper. The soft materials usually have low thermal conductivity while the hard materials have high thermal conductivity. In these tests the foil thickness ranged from 25 to 150μ.

Brunot and Buckland[1] tested AISI M27 steel under atmospheric conditions with steel and aluminum shims as well as aluminum foil inserted in the joint. They concluded that a shim can be used to reduce the bare joint resistance provided the shim is softer than the contacting members. Barzelay et al.[2,3] ran atmospheric tests on aluminum 2024-T6 and T3 with aluminum and brass shims. They also showed that shims are effective provided they are softer than the contacting members. Fried and Costello[4] conducted vacuum tests with lead foil placed between magnesium AZ31 members and aluminum foil inserted between aluminum 2024-T3 members. In both cases the foils substantially reduced the bare joint resistance. Jansson[5] also

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ran vacuum tests to determine the effect of indium,lead, aluminum and gold foils upon the bare joint resistance of beryllium joints having a surface roughness of 125 rms and aluminum joints having a rms surface roughness of 70μ in. The indium, aluminum and gold foils were 25μ thick while the lead foil thickness was about 37.5μ. Jansson concluded that the ranking of the metallic foils could be accomplished by stating that the reduction of bare joint resistance is inversely proportional to the hardness of the foil material. Cunnington[6] conducted vacuum tests with indium foil inserted between aluminum 6061-T6 joints and magnesium AZ31 joints. Koh and John[7] inserted copper, aluminum, lead and indium foils of varying thickness between mild steel specimens which had been lathe turned to a rms surface roughness of 170 to 210μ in. All tests were conducted under atmospheric conditions. The apparent contact pressure ranged from about zero to 7 kg/cm^2. They observed that at a contact pressure of 4.1 kg/cm^2, both aluminum and copper foils had an optimum thickness of about 25.6μ. For a foil thickness of 100μ or greater, little or no decrease in joint resistance was observed. They did not report the optimum thickness for lead and indium foils. They concluded that there exists an optimum foil thickness which provides a maximum reduction in resistance. Furthermore, they stated that "in the selection of interfacial metallic foil materials to reduce the thermal resistance, softness of foil material should be the primary consideration, not the thermal conductivity of the foil". Fry[8] ran vacuum tests with lathe turned stainless steel 416 specimens having a rms surface roughness of 10 to 32μ in. All tests were performed at a contact pressure of 34.8 kg/cm^2. He used one thickness of each foil, and the foils were indium, tin, gold and aluminum having thickness of 120, 100, 500 and 25μ. Getty and Tatro[9] conducted tests in vacuum using aluminum specimens and tin, aluminum and copper foils. They conducted three sets of tests with rms surface roughness of 300μ in., 140-200μ in. and 8μ in., respectively. The contact pressures were fixed at 0.5, 1.18 and 2.15 kg/cm^2, respectively, for all foils. The foil thicknesses were 90, 50 and 38.6μ, for tin, copper and aluminum, respectively. Fletcher et al.[10] in their vacuum tests reported that bare joint resistance of aluminum 2024 specimens can be reduced greatly by means of indium, lead or gold foils. They ranked indium before lead, and gold next.

Since the available experimental data were more useful qualitatively than quantitatively, an experimental program was initiated to obtain basic contact resistance data for an optically flat surface contacting a lathe turned surface having a predetermined surface geometry. The foils and their thicknesses were chosen such that a wide range of material hardness, thermal conductivity and foil thickness could be tested. The specimens chosen were Armco iron and the foils chosen were lead, tin, aluminum and copper. The static contact pressure ranged from 20 to 100 kg/cm^2, which is representative of many aerospace contacts. Both first loading and unloading test data were obtained. All tests were conducted under atmospheric conditions.

Test Program

Test Equipment, Specimens, and Foils

The test program was carried out in a conventional thermal contact resistance test apparatus.[11] Axial forces were applied directly to the test specimens by means of a dead-weight loading mechanism. The force was measured by means of a calibrated load cell located near the heat sink so that it would not be influenced by the heat flow rate through the system. The static apparent contact pressure was increased from 20 to 100 kg/cm^2 by increments of 20 kg/cm^2 and then decreased from 100 to 20 kg/cm^2 by the same increments. The heat flow rate through the joint was supplied by passing a steady stream of hot water through a large copper block which acted as a constant temperature heat source. The heat was removed at the base of the system through a water-cooled aluminum heat sink. Guard blocks distributed the heat such that it flowed axially through the test specimens. The temperature distribution within the test specimens as well as the heat flow rate across the joint were monitored by 8 copper-constantan thermocouples (4 per specimen) located along the centerline of the specimens. The thermocouples were spaced 9.9 mm apart starting at 2.8 mm from the test surface, and force fitted into individual holes in the test specimens. Additional thermocouples were placed on the guard blocks and near the heat source and sink to monitor their temperatures. The average heat flux across the joint was about 3 w/cm^2 for all tests. Radiation and convection losses from the test specimens were calculated to be negligible.

The test specimens were Armco iron rods 25.4 mm in diameter by 38 mm long. All plane surfaces were lapped. One test surface was made optically flat while the other face was lathe turned such that a continuous spiral was produced. The sawtooth profile of the turned surface had a peak-to-valley height of 90μ and a peak-to-peak span of 180μ. The slope of the surface roughness was 45° and the rms roughness was 52μ. Profilometer measurements of the turned surface were made

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Table 1 Hardness and conductivity of foils

Material	Hardness[12,13] kg/mm^2	Conductivity[13] w/cm$^\circ$C
Lead	4.0	0.35
Tin	5.3	0.60
Armco Iron	100.0	0.72
Aluminum	27.0	2.04
Copper	80.0	3.84

The foil thickness ranged from 10 to 500μ. If the required thickness were not available, a foil of larger thickness was rolled to that required and annealed prior to the testing.

Test Procedure

In order to preserve the same surfaces for the entire test program the following test procedure was followed: the thickest, softest foil was tested first and the thinnest, hardest foil was tested last. Loading and unloading test data were obtained for each material and each thickness. At the conclusion of each test the surface of the turned specimen was examined by means of a profilometer to see whether it had changed. The foil thickness sequence was 500, 100, 50, 25 and 10μ, and the foil material sequence was lead, tin, aluminum and finally copper for each thickness. The very last test was made with the joint bare. A final profilometer reading was taken at the conclusion of the bare joint unloading test.

Data Reduction

Thermocouple measurements were recorded after each loading when the entire test assembly had reached thermal equilibrium. Values of thermocouple emf vs position along both specimens were inputs to a computer program that performed a least-

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squares straight-line fit of the data, then extrapolating to the nominal interface to give the temperature difference across the joint ΔT_j, which is a manifestation of the joint resistance. The thermal joint resistance was determined by means of

$$R_j = \Delta T_j/(Q/A_a) \qquad (1)$$

where the average heat flux across the joint is calculated from

$$Q/A_a = (k_1\Delta T_1/\Delta x_1 + k_2\Delta T_2/\Delta x_2)/2 \qquad (2)$$

The thermal conductivity, k_1, the temperature difference between adjacent thermocouples, ΔT_1, and the distance between adjacent thermocouples, Δx_1, all refer to one of the two specimens. The subscript 2 refers to the other specimen.

Test Results and Discussion

Test Results

An examination of the data shows clearly that metallic foils such as lead, tin, aluminum and copper significantly reduce the bare joint resistance for foil thicknesses ranging from 10 to 500μ. It was noted that neither the thickest nor the thinnest foil, irrespective of the material used, has the greatest effect upon the bare joint resistance. The maximum reduction occurs at some intermediate foil thickness. There is evidence of plastic deformation of the foil because the joint resistance for the unloading cycle is less than the joint resistance for the loading cycle at corresponding contact pressures. This is true for all foil materials and foil thicknesses. It was noted that the softer foils yield a lower joint resistance than the harder foils. The greatest reduction of joint resistance for a constant foil thickness occurs with tin, then lead, followed by aluminum and then copper. This is true for all contact pressures for both loading and unloading cycles. This is made more evident when the first loading and first unloading test results are cross plotted as joint resistance versus foil thickness with contact pressure as a parameter, Figs. 1-8.

Tin Foil

Figure 1 shows the loading joint resistance as a function of the thickness of tin foil. It can be seen that the resistance decreases sharply as the foil thickness increases. The resistance seems to be minimum for all contact pressures when the foil thickness is 100μ or about 2 times the rms roughness

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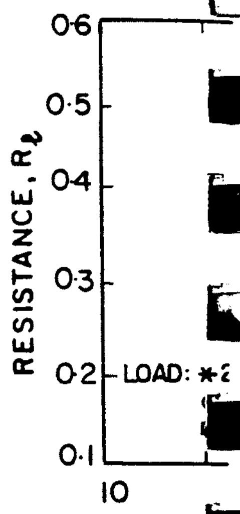

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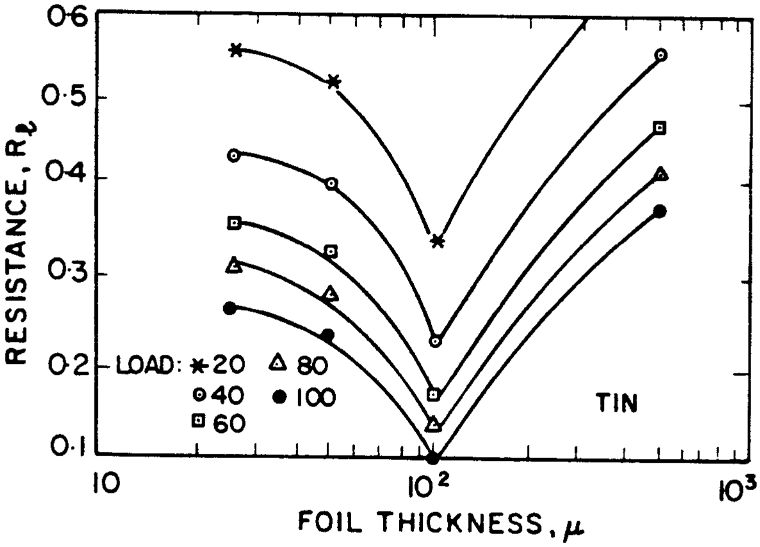


Fig. 1 Loading resistance with tin.

of the turned surface. Any further increase in foil thickness results in a higher joint resistance. The minimum joint resistance decreases as the contact pressure increases. At a constant pressure of 100 kg/cm^2, the minimum resistance is 0.10°C cm^2/w compared with 2.20°C cm^2/w, the corresponding bare joint resistance. At a contact pressure of 20 kg/cm^2, the minimum resistance is 0.34 compared with 4.16 the corresponding bare joint resistance during loading. The reduction in both cases is considerable. In Fig. 5 we see the unloading resistance versus the contact pressure. With the exception of the maximum load, the joint resistance is less than the corresponding resistance during the loading cycle. The rate of change of resistance with foil thickness is much greater than observed during the loading cycle. There is no question that the optimum foil thickness is 100μ.

Lead Foil

Loading joint resistance vs lead foil thickness is shown in Fig. 2. The effect of foil thickness in this case is not so pronounced when the thickness is less than 100μ for all contact pressures. This suggests that the deformation of lead foil which is softer than tin foil is different from the latter. It appears that the minimum resistance occurs when the foil thickness is about 100μ similar to the tin foil. The minimum resistances are 0.68 and 0.14°C cm^2/w for contact pressures of 20 and 100 kg/cm^2, respectively. These minimum

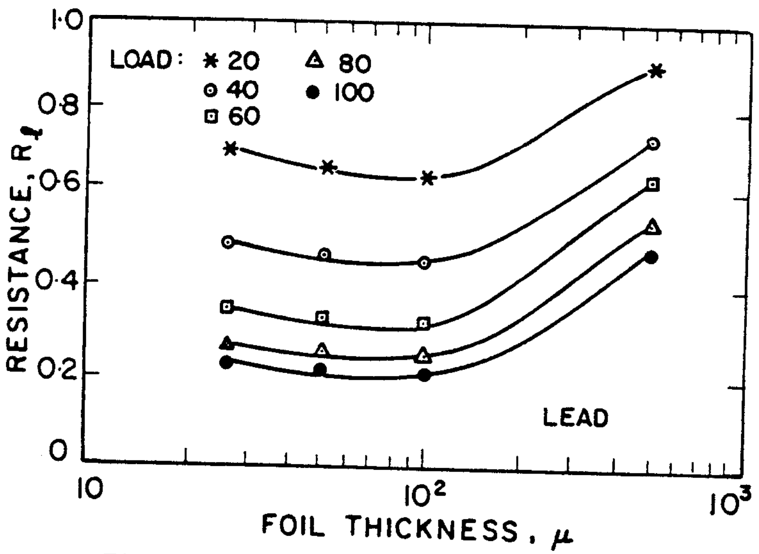
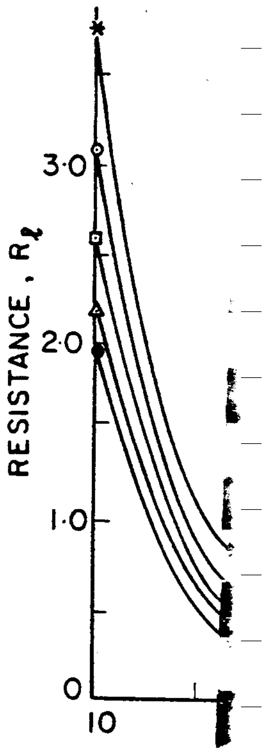


Fig. 2 Loading resistance with lead.

resistances are greater than the minimum resistances obtained with tin foils. Here, as observed with the tin foils, the resistance is inferior to the first loading resistance except at the maximum contact pressure, Fig. 6. The optimum foil thickness is clearly 100μ.

Aluminum Foil

In Fig. 3 we see first loading joint resistance vs aluminum foil thickness, and its effect is quite evident. There is a sharp decrease in the resistance as the thickness is increased beyond 10μ. At about 25 to 30μ, the joint resistance goes through a minimum and then begins to increase with increasing thickness. The rate of increase with thickness in this case is far less than observed when either tin or lead foils are used. The minimum resistances are greater than the minimum resistances obtained with either tin or lead foils. Aluminum foils are therefore inferior to both tin and lead. It appears that the optimum foil thickness is slightly dependent upon the contact pressure. The deformation of the aluminum foil must be quite different from the deformation of tin or lead foils. The first unloading effects are shown plotted in Fig. 7, and the trends are similar to those of the first loading cycle. The deformation of the aluminum foils must be partly plastic because all the resistances are inferior to corresponding loading resistances. The optimum thickness is the same as the first loading cycle.



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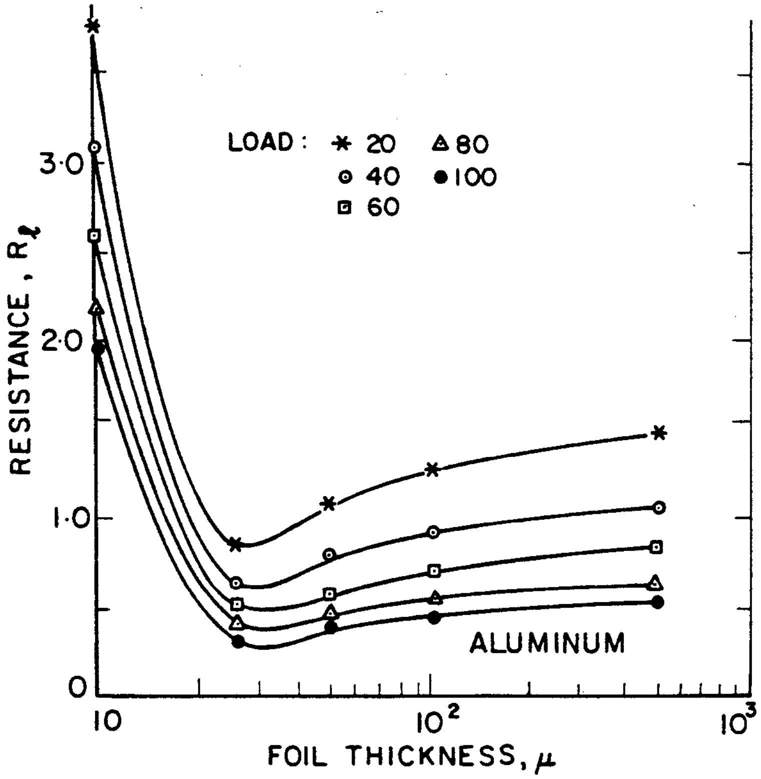

Fig. 3 Loading resistance with aluminum.

Copper Foil

The effect of copper foils, the hardest material used, can be seen in Fig. 4. As with the other three materials used, the joint resistance first decreases with increasing foil thickness, goes through a minimum value corresponding to the optimum foil thickness, then increases rather sharply for thicknesses greater than the optimum. This trend is observed at all contact pressures, being most evident at the lowest contact pressure. The optimum thickness appears to be about 30-40μ depending slightly upon the contact pressure. This trend was also observed when aluminum foils were used. The deformation of copper foils appears to be different from that of the other foils. Copper is inferior to aluminum, lead and tin. In Fig. 8 we see the cross plot of first unloading resistance vs the contact pressure. The trend is similar to that already described. The optimum thickness is seen to be 40μ.

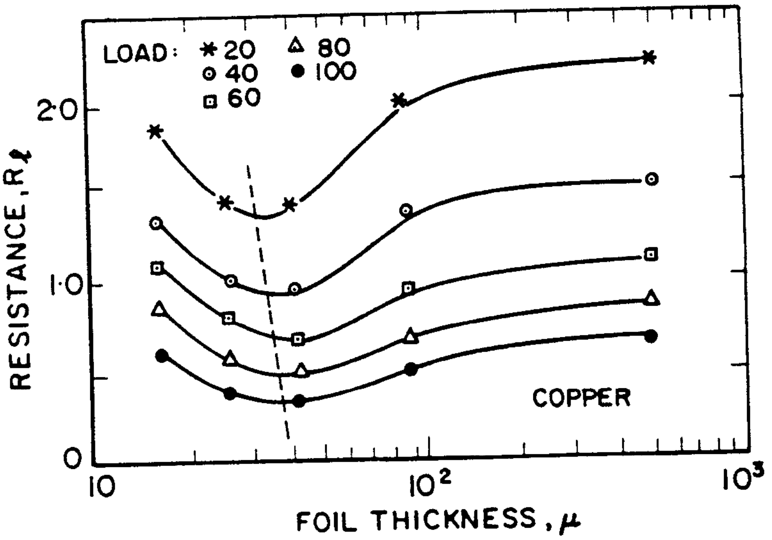

Fig. 4 Loading resistance with copper.

Discussion

The minimum joint resistance corresponding to the optimum foil thickness as determined by means of Figs. 1-4, are divided by the bare joint resistance for the first loading cycle and these are presented in Table 2 for all foils used.

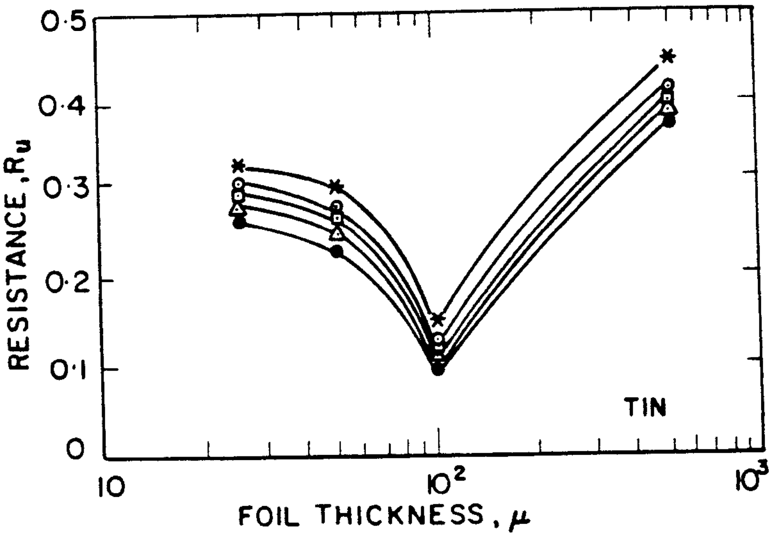

Fig. 5 Unloading resistance with tin.

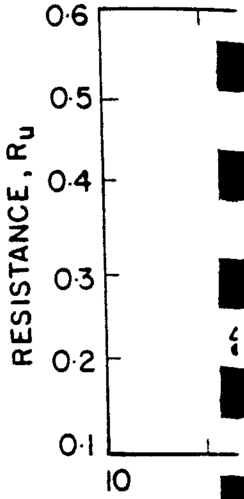

Fig. 6 Un

Table 2 Minimum res

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Tin	0.08
Lead	0.163
Aluminum	0.20
Copper	0.32

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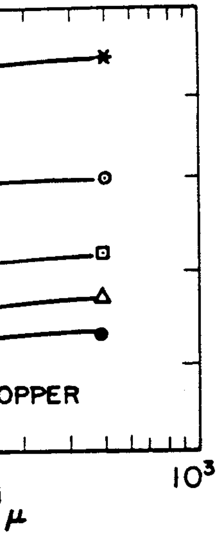

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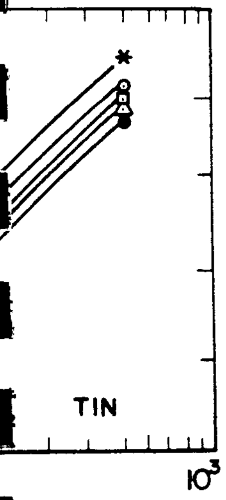

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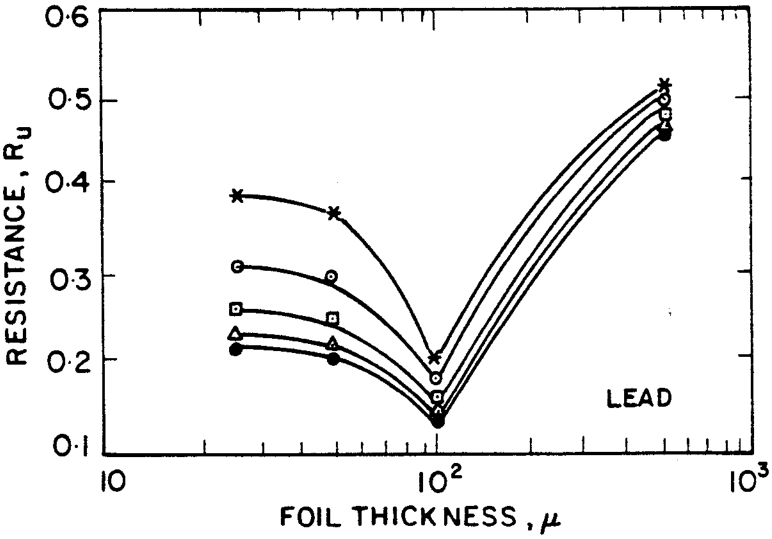

Fig. 6 Unloading resistance with lead.

Table 2 Minimum resistance with foils to bare joint resistance

Material	Apparent contact pressure				
	20	40	60	80	100
Tin	0.082	0.071	0.063	0.055	0.046
Lead	0.163	0.139	0.116	0.088	0.064
Aluminum	0.204	0.195	0.182	0.167	0.145
Copper	0.324	0.284	0.254	0.218	0.182

Table 2 does not include the very slight dependence of optimum foil thickness upon contact pressure which is discernible with aluminum and copper foils. Table 2 does show clearly that for all contact pressures tin is superior to lead; lead is superior to aluminum; and aluminum is superior to copper. This ranking of the foil material does not agree with the ranking proposed by Jansson[5] and Koh and John.[7] They would have put lead ahead of tin, and copper ahead of aluminum, based upon material hardness only. Other parameters are clearly needed to explain what has been observed. These parameters must come from an analysis of the mechanical interaction of two solids separated

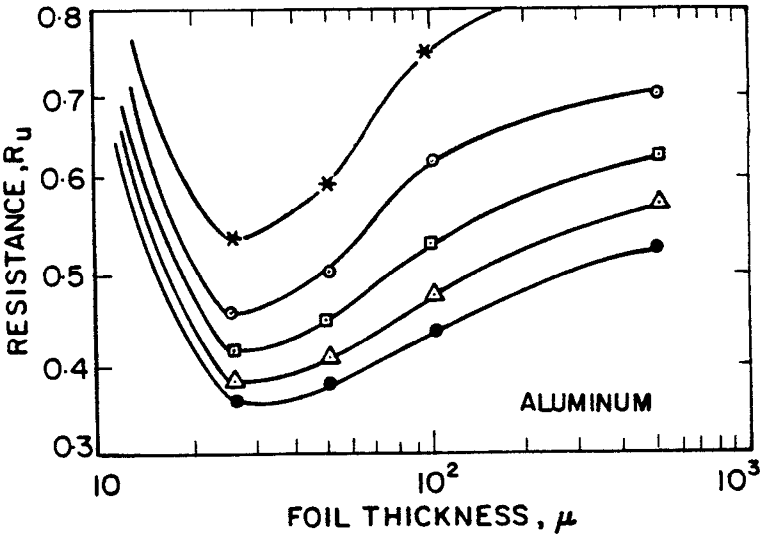

Fig. 7 Unloading resistance with aluminum.

by a metallic foil, and the steady heat transfer across such a joint.

This thermal contact resistance problem is, at the moment, much too difficult to resolve because the mechanical problem, consisting of the penetration of the hard rough surface into a soft foil, cannot be solved, and its results are required for the equally difficult heat conduction problem. One cannot

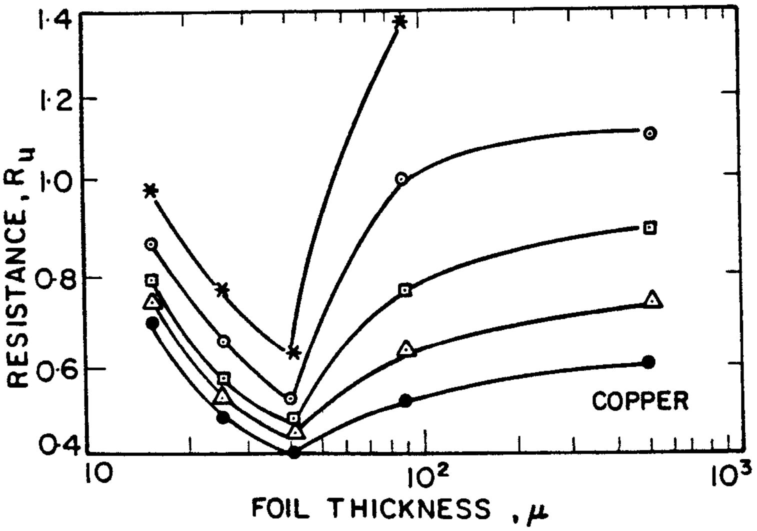

Fig. 8 Unloading resistance with copper.

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location of the dividing heat flow line relative to the two planes of symmetry will depend upon the total resistances of the heat flow paths. The total resistance of the metal contact path consists of at least three constriction resistances in series: constriction resistance in one solid (R_{11}), resistance in the foil (R_{F1}) and constriction resistance in the second solid (R_{12}). There is probably some resistance to heat transfer at the interfaces between the foil and the two solids. If the contact pressure is substantial and the surfaces are smooth, as they are in this study, these resistances should be negligible. The total resistance of the gas (air) path consists of at least four constriction resistances. The constriction resistance in one solid (R_{21}), the resistance of the gas layer (R_g), foil resistance (R_{F2}) and the constriction resistance of the second solid (R_{22}). The total resistance of the heat channel is therefore

$$1/R = 1/R_1 + 1/R_2 \tag{3}$$

where

$$R_1 = R_{11} + R_{F1} + R_{12} \tag{4}$$

and

$$R_2 = R_{21} + R_g + R_{F2} + R_{22} \tag{5}$$

The total resistance of the joint will depend upon the number of typical channels per unit area of contact surface.

Since each of the component resistances depends upon the foil thickness and hardness, the penetration, as well as several other parameters, it is obvious that this problem cannot be resolved at present. However, one can qualitatively explain what is happening as the foil thickness increases from zero thickness to a very large thickness.

For a fixed contact pressure, R_{11}, R_{12}, R_{21}, R_{22} and R_g will decrease with increasing foil thickness because the rough surface will penetrate the foil and so decrease the constriction resistance. Of these five resistances, R_{11}, R_{12} and R_g will be influenced greatly by the increase in foil thickness. It is obvious that R_{F1} and R_{F2}, the foil resistances, will increase with increasing foil thickness. From zero thickness to the optimum thickness, the changes in R_{11}, R_{12}, and R_g will dominate the joint resistance and it will decrease with increasing foil thickness. For foil thickness greater than the optimum thickness, the changes in R_{11}, R_{12}, R_{21}, R_{22} and R_g will be minimal while changes in R_{F1} and R_{F2} will be a maximum and so the joint resistance will increase. The qualitative explanation will have to suffice because a detailed knowledge of the mechanical interaction of a turned surface with an optically flat surface separated by a metallic foil is presently not

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available. If this information were available, then one could predict the contact geometry which is an essential ingredient for predicting the component resistances which determine the joint resistance. One can, however, write the total joint resistance with metallic foils in the following functional form:

$$R_j = f(k_i, H_i, E_i, \nu_i, \sigma, \sigma', t, P_a) \qquad (6)$$

where k_i, H_i, E_i, and ν_i are the thermal and physical properties of the contacting members, the foil and the gas gap; σ, σ' and t are the geometric parameters of the joint; and P_a is the mechanical force on the joint. Some of the parameters are much more important than others. For most aerospace applications, and for the joint under consideration, a good approximation for Eq. (6) is the following:

$$R_j = f(k_F, H_F, \sigma, \sigma', t, P_a) \qquad (7)$$

where only the foil thermal, physical and geometric parameters are considered along with the geometric parameters of the lathe turned surface.

Since it is still not possible to take into consideration the geometry of the joint, it will be assumed that if the joint under investigation is an adequate model of most turned surfaces, then an empirical correlation can be obtained to relate the minimum joint resistance with metallic foils to the corresponding bare joint resistance. This is accomplished by normalizing the minimum resistance. The normalized minimum resistance corresponding to the optimum foil thickness is defined as the ratio of the minimum resistance to the corresponding bare joint resistance. Only the first loading cycle will be considered. Normalized resistances of the four foils tested are plotted vs the apparent contact pressure in Fig. 10.

It can be seen that the normalized resistance decreases linearly with the pressure for the four foils. The slope for tin and copper foils are the same, whereas the slope for lead foils is greater, and the slope for aluminum foils is smaller. Work hardening of the foil during compression would explain the smaller slope for aluminum foils. There is no explanation for the larger slope for lead foils.

The normalized resistance as a function of the foil material and the contact pressure can be expressed in the following way:

$$\ln R^* = C + mP_a \qquad (8)$$

where C and m are determined from the test results and are given in Table 3.

Table 3 Constants for Eq. (8)

Material	C	m
Tin	-2.30	-0.0074
Lead	-1.60	-0.0100
Aluminum	-1.46	-0.0042
Copper	-0.98	-0.0072

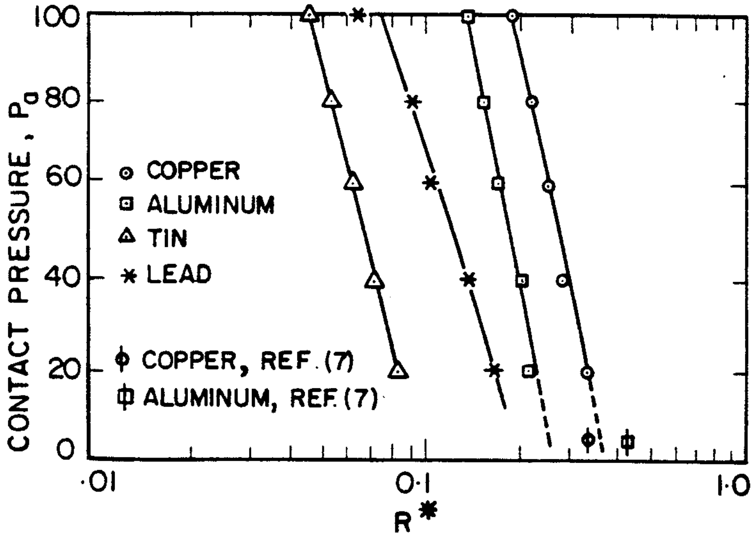

Fig. 10 Dimensionless minimum resistance to bare joint resistance.

It is further assumed that the parameter C is a function of the properties of the foil such as the thermal conductivity and the hardness, while m depends upon the geometry of the lathe turned specimen and the mode of penetration. The absolute value of m based upon the test results lies between 0.004 and 0.01, with 0.0072 being a good average for the four foils tested. The absolute value of C was plotted against the parameter k/H_v, based upon the foil only, and it was found that

$$\ln|C| = 2.75 + (0.92)\ln(k/H_v) \qquad (9)$$

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is a good fit to all the test data. The normalized minimum resistance can be written as

$$R^* = 1/\exp\{0.0072P_a + 15.5(k/H_v)^{0.92}\} \qquad (10)$$

The validity of Eqs. (9) and (10) was verified by means of the test data of Koh and John[7] the only available data dealing with optimum foil thickness. Koh and John found that $R^* = 0.425$ and 0.340 when aluminum and copper foils, respectively, were used with an apparent contact pressure of 4.1 kg/cm^2. These values are indicated in Fig. 10. They did not report optimum foil thicknesses for indium or lead, the other foils tested. It can be seen in Fig. 10 that $R^* = 0.340$ for copper agrees very well with the data of this investigation. The value of $R^* = 0.425$, however, lies well above the aluminum data of this investigation. This large difference could be attributed to the difference in hardness of the aluminum foils used by Koh and John, and those used in this investigation. If one takes their thermal conductivity data ($k = 2.05$ w/cm°C) and the highest value of the aluminum hardness ($H_v = 50$ kg/mm^2) reported by them, one can calculate $|C| = 0.842$ by means of Eq. (9). With this absolute value of C, one can, by means of Eq. (10), predict $R^* = 0.415$ at a contact pressure of 4.1 kg/cm^2. This agrees very well with the value of 0.425 observed by Koh and John. No other investigators reported optimum foil thickness data.

Conclusions

This investigation has led to following several conclusions regarding the effect of metallic foils on joint resistance. There is an optimum foil thickness for both soft and hard foils. The optimum thickness is observed for both first loading and first unloading cycles. For soft foils the optimum thickness is the same for both unloading cycles, apparently independent of contact pressure. For hard foils the optimum thickness is the same for both loading cycles; however, this thickness appears to be slightly dependent upon contact pressure. Experimental data indicates that a better method of ranking the effectiveness of the foils is by means of the parameter (k/H_v) based upon the foil properties only. Empirical expressions are developed for predicting the maximum reduction of bare joint resistance when foils of optimum thickness are utilized. These empirical expressions can be used successfully to predict results observed by others.

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