Int. J. Heat Mass Transfer. Vol. 9, pp. 791–801. Pergamon Press 1966. Printed in Great Britain

HEAT TRANSFER AT THE INTERFACE OF DISSIMILAR METALS—THE INFLUENCE OF THERMAL STRAIN

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(*Received* 16 *July* 1965 *and in revised form* 20 *January* 1966)

Abstract—Several investigations have revealed that the thermal contact resistance is influenced by the direction of heat flow in contacts between dissimilar metals. Attempts to explain this phenomenon from a microscopic approach have not been successful. Employing the macroscopic model which the author recently proposed, it is revealed that thermal strain can be the source of a pronounced directional effect. Experimental results are given for several combinations of metals which vividly demonstrate these influences. It is seen that the thermal contact resistance for an interface between dissimilar metals is strongly dependent upon the heat flux. Furthermore, the directional effect vanishes if the heat flux approaches zero.

NOMENCLATURE

a, radius of a contact area [in];
b, radius of constriction region [in];
d, equivalent flatness deviation (see Fig. 1) [in];
E, modulus of elasticity [lb_f/in^2];
h, interface conductance, $h = (1/A_a R)$ [Btu/h ft^2 degF];
k, thermal conductivity [Btu/h ft degF];
L, length of specimen [in];
p, contact pressure [lb_f/in^2];
q, rate of heat flow [Btu/h];
R, resistance [degF h/Btu];
R^*, dimensionless resistance (see equation 4);
ΔT, a temperature difference [degF];
x, constriction ratio, $x = a/b$;
α, coefficient of linear expansion [in/in degF];
ζ, elastic conformity modulus, $(p_a/E_m) \times (b/d_t)$.

Subscripts
1, region or specimen 1;
2, region or specimen 2;
12, direction from metal or region 1 to region 2;
21, direction from metal or region 2 to region 1;
a, apparent contact area;
L, macroscopic constrictions or contact regions;
m, a harmonic mean value;
o, film resistance;
s, microscopic constrictions or contact areas.

1. INTRODUCTION

A CONSIDERABLE effort has been expended in recent years in an endeavor to understand the nature of the resistance to heat flow caused by the interface between metallic members in contact. The recent surge of interest in this problem arose in the thermal design of space vehicles.

A comprehensive review of the literature on thermal contact resistance and a detailed discussion of the mechanism of heat transfer at an interface was given in earlier publications [1, 2]. It was also demonstrated in these references that for many surfaces commonly encountered in engineering practice, macroscopic influences appear to be dominant when compared with microscopic effects if thick surface films are not present. Since previous studies emphasized microscopic effects and neglected macroscopic influences, little was learned about the true nature of the thermal contact resistance. References [1] and [2] gave a restrictive analysis based on a new macroscopic model for the prediction of the thermal contact resistance for similar metallic members in contact in a vacuum environment. Heat transfer at the interface of dissimilar metals will now be considered. Specifically, the dependence of the thermal contact resistance on the direction of heat flow at such an interface will be analyzed.

The dependence of the thermal contact resistance on the direction of heat flow at an interface between dissimilar metals was first reported by Barzelay *et al.* [3]. They found that in some instances the thermal contact resistance for heat flow from steel to aluminum was over five times higher than when the heat flowed in the other direction. Motivated by Barzelay's results, Rogers [4] performed a more detailed experimental study of dissimilar metallic interfaces. His results showed that the contact resistance for an interface in air was approximately 20 per cent higher when heat flowed from steel to aluminum than when it flowed in the other direction. The numerical difference between the values of the contact resistance for an interface in vacuum remained approximately the same, but the percentage difference rose to 100 per cent. Rogers found little or no directional effect for chromel–alumel and copper–steel interfaces. He suggested that the effect could be associated with the mechanism of conduction at the "points" of metallic contact. Williams [5] attributed this phenomenon to surface contamination, and Moon and Keeler [6] applied the theory of heat conduction in the solid state to explain this asymmetric behaviour. Powell *et al.* [7] did not find any directional effect for an aluminum–steel interface or for several other interfaces formed by dissimilar metals which they recently tested. They attributed the lack of a directional effect to the small contact area used in their experiments. Their measurements were made with a thermal comparator.

It is thus seen that the directional effect is a confusing phenomenon. Barzelay attributed it to warping, whereas Rogers claimed that his results made Barzelay's explanation seem unacceptable. Others are studying the physics of heat conduction across the "actual" contact areas. At the same time, some data has shown no directional effect. It is not possible to explain or account for the presence of a directional effect with the microscopic models presented in the literature (see references [1, 2] for a discussion of these models). Let us now consider this phenomenon employing the macroscopic model presented in reference [1].

2. THEORETICAL MODEL

Figure 1 represents the simplified model of the contacting members which was employed in the analysis of the mechanism of thermal contact resistance in reference [1]. It will be briefly described.

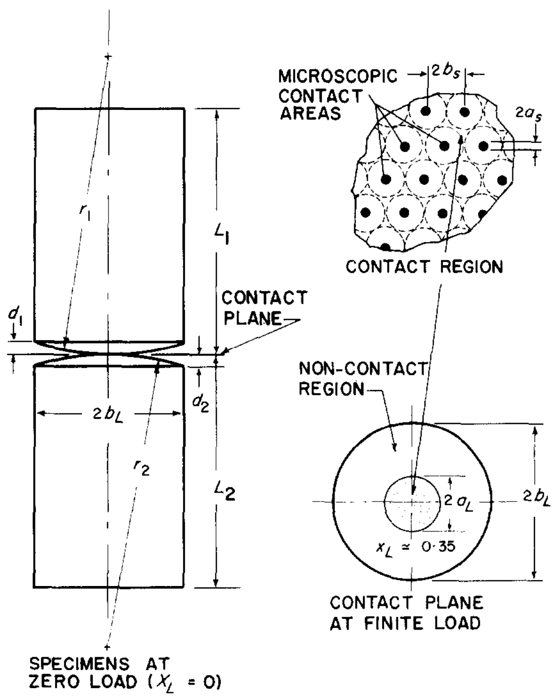

FIG. 1. Model of contact surface.

In the analysis the apparent contact area was conceived to be divided into two regions: the *contact region* and the *noncontact region*. The noncontact region was defined as the portion of the interface which contained few or no microscopic contact areas. The contact region (referred to as the macroscopic contact area) is the portion of the interface where the density of the micro-contacts is high. In the absence of a conducting fluid, the flow of heat is first constricted to the macroscopic contact areas; it is then further constricted to the microscopic contact areas within this macroscopic area; and finally it must flow through the surface films. The total contact resistance for an interface in the absence of an interstitial material such as air could be thought of as the sum of three resistances in series: the macroscopic constriction resistance R_L, the microscopic constriction resistance R_s, and the film resistance R_o, i.e.†

$$R_t = R_L + R_s + R_o. \tag{1}$$

It was established in reference [1] that in the absence of thick surface films the macroscopic constrictions have a commanding influence for many surfaces commonly encountered in engineering practice. Thus, the subscripts are dropped and the macroscopic constriction resistance is assumed to be equal to R_t and is represented by the symbol R.

The contact resistance which might be more appropriately called the constriction resistance is defined by:

$$R = \frac{\Delta T}{q} = \frac{1}{hA_a} \tag{2}$$

where ΔT is the additional temperature drop due to the presence of the interface, A_a the apparent contact area, q the rate of heat flow, and h the interface conductance.

The macroscopic contact area in the simplified model proposed was assumed to consist of a single circular contact area of radius a whose center coincides with that of the apparent contact area of radius b (see Fig. 1). The size of the macroscopic contact area is governed by the elastic deformation of the contacting members. The flatness deviation or waviness which gives rise to this resistance was simulated by spherical caps on the end surfaces of the cylindrical contacting members. The length of the cylindrical contacting members, L, was assumed to be large compared with the radius b. The heat flux and the stress was assumed to be uniform and normal to the interface at a distance sufficiently removed from the interface.

The determination of the additional temperature drop due to the presence of a constriction consists of two parts: (i) given the load, what is the macroscopic contact area? and (ii) given the macroscopic contact area, what is the constriction resistance? Once the constriction resistance is known, the additional temperature drop due to the presence of the interface can be easily calculated. For the model employed, it is sufficient to determine the constriction ratio $x(= a/b)$ for the solution of Part (i). This ratio was found in terms of the equivalent flatness deviation $d_t(= d_1 + d_2)$, the apparent contact pressure p_a, and the harmonic mean modulus of elasticity E_m as:

$$x = 1{\cdot}285 \left[\frac{p_a}{E_m}\ \frac{b}{d_t}\right]^{\frac{1}{3}}, \quad \begin{Bmatrix} L/b > 2{\cdot}0 \\ x \quad < 0{\cdot}65 \end{Bmatrix} \tag{3}$$

The dimensionless group $(p_a/E_m)(b/d_t)$ was designated by ζ and called the elastic conformity modulus. It is a measure of the conformity of the mating surfaces under load.

A numerical solution of the mixed boundary valued thermal problem [8] gave the dimensionless constriction resistance R^*, for two regions of radius b in contact, as the following function of the constriction ratio

$$R^* = \frac{k_m R A_a}{b} = \frac{k_m}{hb} = 2[10^{f(x)}],$$

$$\begin{Bmatrix} L/b \ > 0{\cdot}8 \\ 0{\cdot}16 < x \ < 0{\cdot}84 \end{Bmatrix} \tag{4}$$

† In the use of this equation, it must be remembered that these resistances are not independent.

where k_m $[= 2k_1 k_2/(k_1 + k_2)]$ is the harmonic mean thermal conductivity, and

$$f(x) = [1{\cdot}39839 - 7{\cdot}44698\,x + 19{\cdot}9303\,x^2 - 38{\cdot}5897\,x^3 + 38{\cdot}6553\,x^4 - 16{\cdot}6247\,x^5] \quad (5)$$

This is the solution to the problem of Part (ii). The constriction resistance in terms of the elastic conformity modulus can now be determined by substituting equation (3) into (4) which gives:

$$R^* = \phi(\zeta), \qquad \left\{\begin{matrix} L/b > 2{\cdot}0 \\ \zeta \; < 0{\cdot}14 \end{matrix}\right\} \qquad (6)$$

where

$$\phi(\zeta) = 2\{10^{f[1.285(\xi)^{1/3}]}\}$$

Excellent agreement was found between experimental results and the theoretical prediction of equation (6) for contacts between similar metallic members. In this case $k_m = k_1 = k_2$ and $E_m = E_1 = E_2$. Many apparent discrepancies which previously existed in the literature could also be explained with this model. A discussion of these is given in reference [1]. A close examination of the model shows that equation (6) is applicable to contacts between dissimilar interfaces if thermal strain causes a negligible change in the contact areas. Thermal strain and its influences on both the microscopic and macroscopic contact areas will now be considered.

The formation of the microscopic contact areas is usually attributed to plastic deformation between contacting asperities. This means that the thermal stresses caused by microscopic constrictions† are probably small in comparison to the local mechanical stresses which were responsible for the plastic deformation; consequently, it is reasonable to expect that the influence of temperature gradients on the microscopic contact areas is small. On the other hand, the mechanical stresses and accompanying strains which cause the formation of the macroscopic contact areas are usually small, since thermal contact resistance is a major problem only if the loads between the contacting surfaces are small, and since the flatness deviations of realistic surfaces are not large. It would thus appear that in some instances thermal strain would influence the size of the macroscopic contact area and consequently the macroscopic constriction resistance.

It can be seen from the results presented in reference [1] that relative strains of only a few microinches in a direction perpendicular to the plane of the interface could appreciably influence the macroscopic contact area. The reader can easily verify, by considering the simple problem of the linear expansion of a rod, that thermal strains of this magnitude could have been present in many of the specimens employed in obtaining the data reported in the literature. It can also be easily shown that strains parallel to the plane of the interface cause a negligible change in the macroscopic constriction.

If it is assumed that one end of the two contacting members is unrestrained, i.e. that the load exerted between the contacting members is constant and not affected by the longitudinal expansion or contraction of the contacting members, thermal strain affects the macroscopic constriction resistance only when temperature gradients parallel to the plane of contact are present. Such gradients will result if: (i) macroscopic constrictions to the heat flow across the interface are present, or (ii) the thermal boundary conditions caused by the environment permit heat flow through the boundaries perpendicular to the plane of contact. These two sources of strain will be considered separately.

2.1 *Thermal strain resulting from macroscopic constrictions*

Consider the physical model of the contacting

† This discussion excludes the thermal strains due to a change in the temperature level of the regions. These strains would cause a relative motion between the contacting surfaces which would cause a change in the microscopic contact areas. However, these changes would occur in all joints, and although they add considerable complication to a microscopic deformation model, they cannot account for a directional effect.

members shown in Fig. 1, i.e. two cylindrical isotropic, homogeneous regions of length L and identical radius b. It will be assumed momentarily that the coefficient of linear expansion of region 2 is zero.

It can be seen from Fig. 2 that if heat is flowing from region 1 to region 2, i.e. in the direction 1–2, the portion of region 1 near the macroscopic contact area is cold relative to the rest of the member. Thus, this portion contracts, which causes the formation of a larger macroscopic contact area than that which is predicted if only the mechanical stresses are considered (see Fig. 2). If the direction of heat flow is reversed, the portion of region 1 near the macroscopic contact is hot relative to the remainder of the member. In this case, the thermal strain causes a smaller macroscopic contact area than that which is predicted from the mechanical stresses. Thus, it is seen that if the heat is flowing in the direction 1–2, the thermal strain causes a *decrease* in the macroscopic constriction resistance, whereas if it is flowing in the direction 2–1, the thermal strain causes an *increase* in the macroscopic constriction resistance. *The thermal contact resistance thus becomes a function of the direction of heat flow.*

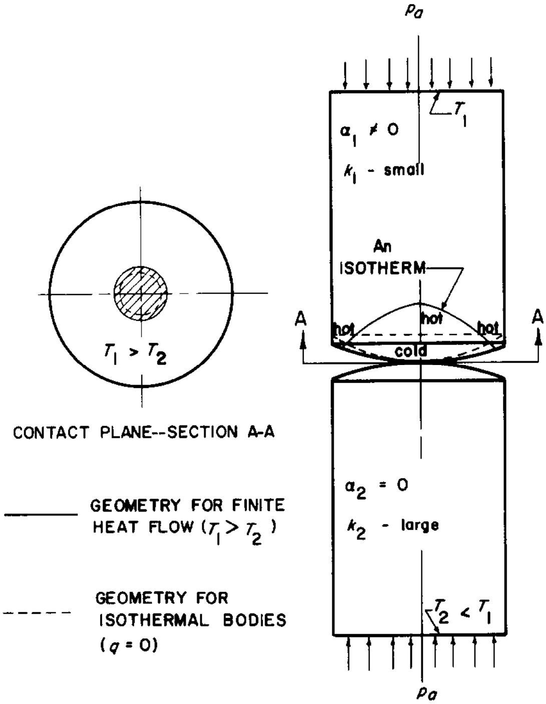

FIG. 2. Geometric effects of thermal strain resulting from a macroscopic constriction.

The geometry of the contacting members will obviously influence the size of the macroscopic contact area and the manner in which the size of this area varies with the mechanical load. However, the trend of the directional effect is seen to be independent of the geometry of the contacting surfaces. For example, consider the case when the heat is flowing in the direction 1–2. The portion of region 1 near the macroscopic contact area will be cold relative to the surrounding portion of the region. The thermal strain for this case will cause the macroscopic contact area to grow whether the upper contacting surface is concave or convex. (The lower surface could also be either concave or convex.)

The amount of thermal strain which occurs is a function of the coefficient of linear expansion α, the modulus of elasticity E, Poisson's ratio ν, and the magnitude of the temperature gradients. Thus the influence of thermal strain is dependent on the heat flux and the thermal conductivity of the material. If the heat flux is small and the thermal conductivity is large, the *influences of thermal strain would vanish.*

Now consider a contact formed between two identical materials where both the upper and lower regions have the same coefficient of linear expansion. If the material properties are independent of temperature, the thermal strains perpendicular to the interface which occur in the regions as a consequence of macroscopic constrictions are complementary; thus the macroscopic contact area is approximately the same as that present in the absence of thermal strain. Since the variation of the material properties with temperature is not large, the neglect of the effect of thermal strain due to macroscopic constrictions should not cause much discrepancy between the theoretical predictions and the experimental results for contacts between identical materials. Dependency of material properties on temperature will not cause a directional effect in contacts between identical materials as long as the specimen's geometries and the imposed boundary conditions are identical.

When dissimilar metals are in contact, a pronounced directional effect is frequently experienced as is witnessed by the experimental results. A pronounced effect, however, is only experienced at higher heat fluxes. For very low rates of heat flow, the direction dependency is small and equation (6) can be used to predict the constriction resistance.

2.2 *Thermal strain due to the thermal environment*

The importance of small temperature gradients due to heat flow through the boundaries perpendicular to the plane of the interface has not been realized, probably because the importance of slight macroscopic nonconformities of the mating surfaces was previously not realized. However, gradients as small as 1 degF in a direction parallel to the plane of the interface may cause an appreciable change in the macroscopic constriction resistance. These gradients could arise, for example, from small amounts of radiant heat exchange with the environment or from thermal shunting. Thermal shunting would occur if an alignment device or an insulating material were in contact with the specimens as, for example, in Rogers' apparatus [4]. Gradients in a direction parallel to the plane of the interface would be most likely to occur in poor conductors, e.g. stainless steel, since a small heat flux causes a much larger gradient in a poor conductor. Figure 3 gives an exaggerated representation of the effect of a small radial gradient on a previously flat surface for the cylindrical geometry employed in reference [1]. It is seen that in this case the thermal strain may be beneficial or detrimental depending on the original geometry of surfaces and on the sign of the radial heat flux. For the geometry employed in the present investigation, the effect was small but always detrimental since the specimens were losing heat by radiation to the chamber walls in all cases.

This source of thermal strain could also give rise to a directional effect in contacts between dissimilar metals. For example, for a stainless steel–aluminum interface, the heat flow in the stainless specimen would cause the largest gradients; thus geometry changes due to thermal

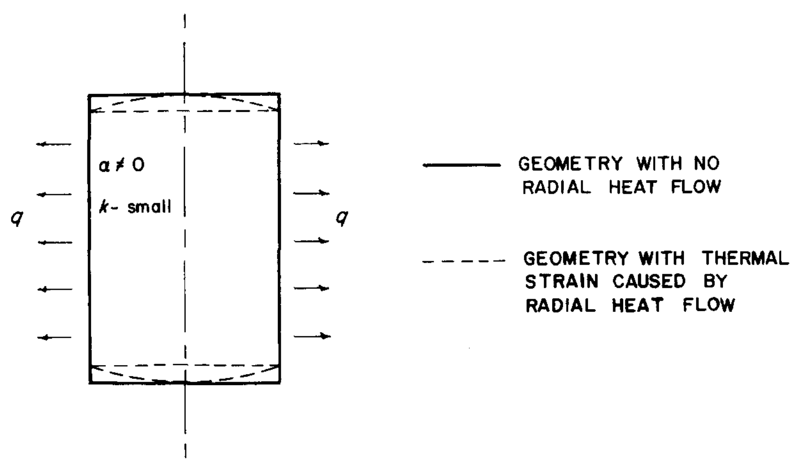

FIG. 3. Geometrical effects of thermal strain caused by radial heat flow.

strain in this specimen would have the greatest influence on the macroscopic contact area. Since the temperature level of the stainless steel specimen and therefore the amount of heat it exchanges with its environment would normally vary considerably with the direction of heat flow, a directional effect would result. The influence of these gradients is presently being studied in greater detail.

3. THE EXPERIMENTAL APPARATUS AND PROCEDURE

All measurements of the contact resistance were made in a vacuum chamber at an ambient pressure of about 10^{-5} mmHg. A schematic representation of the test column is given in Fig. 4. The test specimens consisted of two cylinders of 1 inch dia. and $2\frac{3}{4}$ inches long. The test column was made symmetrical with respect to the test interface; thus, a combination heat source–heat sink was located at both ends of the specimen set. This enabled the reversal of the direction of heat flow without disturbing the test interface. No substance was in contact with the highly polished cylindrical surfaces of the specimens; thus, the only heat loss from these surfaces was that caused by a small amount of thermal radiation. Five calibrated No. 30 gauge copper–constantan thermocouples were installed in each specimen to determine the axial temperature gradients. The thermocouples were placed into 0·046 in dia. holes drilled $\frac{5}{8}$ in deep, and small pieces of lead foil were tamped around the junction. The hole was filled with lead to a depth of approximately $\frac{3}{8}$ in. The remaining portion was filled with epoxy. The load was applied by means of a dead-weight lever-arm system; thus, the load exerted between the contacting members was constant and not affected by the longitudinal expansion or contraction of the test column.

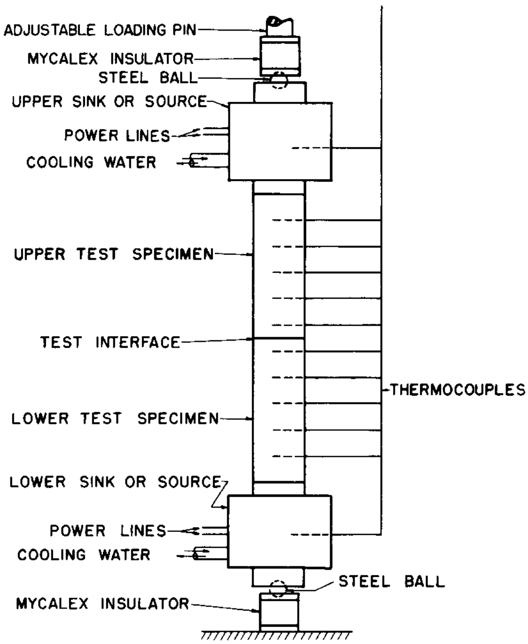

FIG. 4. Schematic representation of test column.

The specimen's test surfaces were lapped on a lapping machine. They were further lapped by hand in order to decrease the surface roughness and in some cases to alter the flatness. Spherical surfaces with flatness deviations varying from a few microinches to several hundred microinches were obtained in this manner. The flatness deviations were determined by optical measurements. Optical measurements also showed that the surfaces were relatively spherical. The surface roughness was determined from the irregularity of the fringes and was always about 4 μin.

The data were reduced with an IBM 7094 digital computer which enabled many fine corrections and resulted in high, consistent accuracy. The curvature in the temperature gradients in the specimens caused by the variation in the thermal conductivity and radiation heat losses was removed before the gradients were extrapolated to the test interface. The gradients were determined from the corrected thermocouple readings by a first degree least squares polynomial approximation.

The sink temperature was fixed at approximately 50°F. The total temperature drop across the specimens varied with the type of test, but was never greater than 360 degF. The temperature drop across the test interface varied between 2·8 and 185 degF.

4. EXPERIMENTAL RESULTS

Figure 5 gives a comparison of the experimental results of a stainless steel–aluminum interface which was studied. This interface had a total equivalent flatness deviation of 180 μin, and the specimens had surface roughnesses of approximately 4 μin. The dimensionless coordinates employed permit the correlation of experimental data with different materials, flatness deviations and loads on a single plot. They also account for the variations with temperature of E_m and k_m which now are the harmonic means based on the values for aluminum and stainless steel. The theoretical curve which is given in Fig. 5 does not include the effects of thermal strain. Thus, when the heat flowed from the stainless steel to the aluminum, the resistance was generally lower than the predicted values due to the enlargement of the macroscopic contact area by thermal strain as discussed in Section 2.1. When the heat flowed from the aluminum to the stainless steel, the thermal contact resistance was greater than the theoretical predictions. These results indicate that the thermal strain due to the macroscopic constriction was dominant. This was expected since the specimen surfaces were highly polished; therefore, the heat loss by radiation was small.

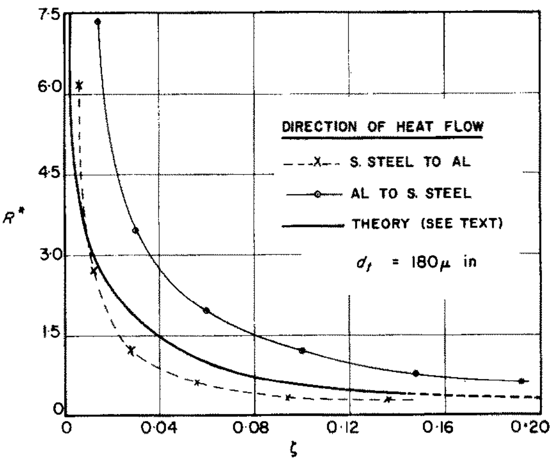

FIG. 5. Comparison between experimental results for stainless steel–aluminum interface and theoretical predictions which neglect thermal strain effects.

The data given in Fig. 5 were taken with a constant temperature drop across the test column of approximately 350 degF; thus, when the resistance of the interface changed, the heat flux was changed. Of course, the contact resistance is highly dependent on the heat flux for this combination of dissimilar metals and it must be considered in using these data.

It is seen that a single conductance or resistance versus pressure curve is no longer sufficient to describe a given interface between dissimilar metals even in the absence of hysteresis-like variations. If the heat-flow rate is employed as a parameter, a family of curves would result. If the thermal strain is due only to the macroscopic constriction and if microscopic effects are unimportant, the theoretical curve given in Fig. 5 would represent the limiting case of zero heat flux.

The curves given in Fig. 6 show the variation of the contact resistance with heat flux at constant load for this stainless steel–aluminum interface. The three curves given are for contact pressures of 44·6, 86·9, and 157 lb/in^2. The arrows on the curves indicate the order in which the data were taken. During a given series of tests, the contact pressure was held constant while the heat flow rate was varied from some maximum value to a value near zero. The direction of heat flow was then reversed and the heat-flow rate was again increased.

It is seen in these figures that as the heat flux approaches zero, the directional effect vanishes. This was to be expected since the thermal strain resulting from the macroscopic constriction approaches zero as the heat flow rate approaches zero, and also the small radial heat loss from the specimen surfaces was virtually eliminated. The heat loss from the specimen surfaces was due to thermal radiation. The sink temperature was fixed at approximately 50°F; the chamber temperature was

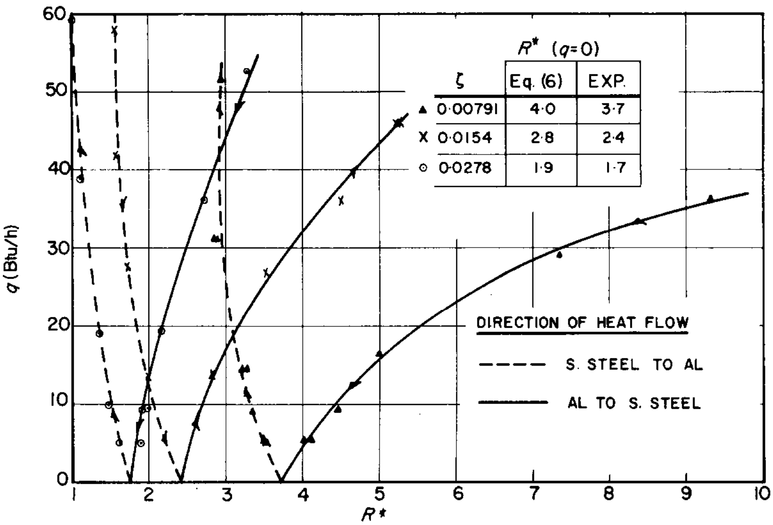

FIG. 6. The influences of the rate of heat flow, direction of heat flow, and contact pressure: Stainless steel–aluminum interface (d_t = 180 μin).

approximately 75°F; and the source temperature varied with the rate of heat flow from approximately 100°F to 400°F.

Since the specimen surfaces were polished to reduce the radiation heat loss, the thermal strain due to the macroscopic constriction caused the dominant directional effect. However, it is believed that the influence of the thermal strain due to the radiation heat losses can also be seen. For example, the change in the dimensionless resistance R^* with the rate of heat flow q, i.e. dR^*/dq, is either positive or negative depending on the direction of heat flow; however, d^2R^*/dq^2 is always positive. The fact that d^2R^*/dq^2 is always positive is probably due to the radiation heat losses. Figure 6 also shows that for the case when heat flowed from stainless steel to aluminum, dR^*/dq approached zero for large values of q. Perhaps if q were sufficiently large, the thermal strain due to heat losses would dominate, and dR^*/dq would be positive.

A comparison is given in Fig. 6 between the experimental values extrapolated to zero heat flow and the theoretical prediction of equation (6). The two values agree to within approximately 10 per cent. This is believed excellent considering the nature of the problem. It is seen that the theoretical predictions are larger than the experimentally measured resistances. This is probably a consequence of an increase in the conformity of the specimens during the test series due to the creep of the aluminum specimen. Flatness measurements taken after completion of the test series showed the aluminum specimen had a "hole" at the center portion of its surface which was approximately 6 μin deep.

Another series of tests were made, identical to those previously described except that the aluminum specimen was replaced by a magnesium specimen. These results are presented in Fig. 7. The general trends and the signs of dR^*/dq and d^2R^*/dq^2 are the same as those experienced before the magnesium was substituted for the aluminum. The agreement between the theoretically predicted resistances and the extrapolated experimental values for zero heat flow was not as good as previously experienced. This undoubtedly was due to the large amount of creep which took place in the magnesium specimen during the test series; thus, the conformity of the surfaces improved and the predicted resistances were too large.

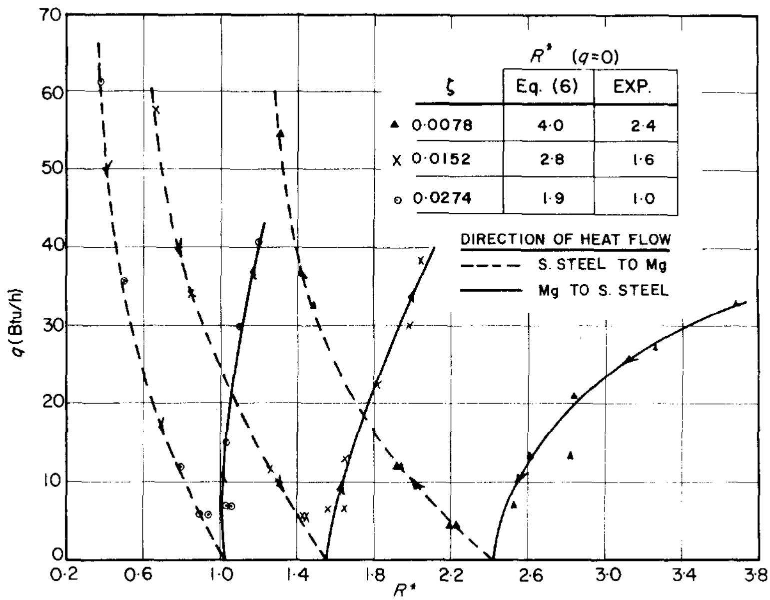

FIG. 7. The influences of the rate of heat flow, direction of heat flow, and contact pressure: Stainless steel–magnesium interface (d_t = 250 μin).

Evidence of the influence of creep on the contact resistance for magnesium interfaces is also given in reference [1].

From Figs. 6 and 7, it can be seen that for both interfaces at the higher rates of heat flow a variation in the contact resistance of approximately 300 per cent occurred with the reversal of the direction of heat flow. The directional trend which was found in this investigation for the stainless steel–aluminum interface is opposite to that found by Barzelay *et al.* [3], and Rogers [4]. This is believed to be a consequence of the dominance of the thermal strain due to the thermal environment in their experimental results which indirectly caused the variation in the macroscopic constriction with the direction of heat flow in contrast to that resulting directly from the macroscopic constriction which dominated the present results. There is strong evidence, however, that macroscopic constrictions were present and that variations in these constrictions were the source of the directional effect. For example, Barzelay *et al.* [3] reported the presence of large radial gradients when the resistance of the interface was large. When the direction of heat flow was reversed, the large radial gradients disappeared and the thermal contact resistance was considerably smaller. Rogers [4] had an alignment device in contact with the test specimens. Powell's [7] failure to detect a directional effect was probably due to a combination of the geometry and the small rate of heat flow employed; thus, thermal strain was not of importance. A more complete explanation of the experimental results in the literature cannot be given without more information on the test conditions and procedures.

5. CONCLUSIONS

Evidence has been given to demonstrate that thermal strain due to macroscopic influences can cause a pronounced directional effect in contacts between dissimilar metals. On the other hand, the experimental results showed that the directional influence will vanish if the thermal strain can be made sufficiently small. The proposed model was also found to be capable of predicting the thermal contact resistance for interfaces between dissimilar metals if the effects of thermal strain were not of importance.

ACKNOWLEDGEMENT

The author gratefully acknowledges the financial support of the National Aeronautics and Space Administration in sponsoring this work (Research Grant NsG 242 Supplement No. 2).

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Résumé—Plusiers études ont mis en évidence que la résistance thermique de contact entre deux métaux différents est influencée par la direction du flux de chaleur. Des tentations d'explication du phénomène d'un point de vue microscopique n'ont pas été couronnées de succès. Si l'on utilise le modèle macroscopique que l'auteur a proposé récemment, on montre que la déformation thermique peut provoquer un effet directionnel notable. On expose les résultats expérimentaux pour plusieurs combinaisons de métaux pour lesquels cet effet est important. On voit que la résistance thermique de contact pour une interface entre des métaux différents dépend fortement du flux de chaleur. De plus, l'effet de la direction disparait lorsque le flux de chaleur tend vers zéro.

Zusammenfassung—Verschiedene Untersuchungen haben gezeigt, dass der thermische Kontaktwiderstand zwischen nichtgleichen Metallen von der Richtung des Wärmestroms in den Kontakten beeinflusst wird. Versuche, dieses Phänomen mit einer mikroskopischen Betrachtung zu klären, waren nicht erfolgreich. Mit Hilfe des makroskopischen Modells, wie es der Autor kürzlich vorschlug, wird deutlich, dass eine thermische Spannung die Quelle eines ausgeprägten Richtungseffekts sein kann. Versuchsergebnisse werden für verschiedene Metallkombinationen wiedergegeben; sie zeigen augenscheinlich diese Einflüsse. Man bemerkt, dass der thermische Kontaktwiderstand für die Trennfläche zwischen zwei ungleichen Metallen stark vom Wärmestrom abhängt. Weiterhin verschwindet der Richtungseffekt bei Annäherung des Wärmestroms an Null.

Аннотация—В нескольких исследованиях была обнаружена зависимость термосопротивления контакта различных металлов от направления теплового потока. Попытки объяснить это явление с микроскопической точки зрения не удались. Предложенная автором макроскопическая модель позволяет связать это явление с термической деформацией. Влияние последней отчетливо видно по результатам экспериментов с несколькими комбинациями металлов. Далее, очевидно, что термосопротивление контакта различных металлов сильно зависит от плотности теплового потока. При стремящейся к нулю плотности теплового потока влияние направления последнего исчезает.