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HEAT TRANSFER AT THE INTERFACE OF DISSIMILAR METALS*

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Abstract—One investigation into the resistance to heat flow at the interface of metals in contact revealed that when the metals were dissimilar the resistance depended upon the direction of heat flow. This note presents further results which confirm the existence of the phenomenon and which indicate that the effect could be associated with the mechanism of conduction at the points of metallic contact.

Résumé—Une recherche sur la résistance thermique de la surface de contact de deux metaux a révélée que, lorsque les métaux sont différents, la résistance dépend du sens du flux de chaleur. Cet article présente des résultats obtenus par la suite qui confirment l'existence de ce phénomène et indiquent que cet effet peut être associé au mécanisme de conduction aux points de contact métallique.

Zusammenfassung—Eine Untersuchung über den Wärmeleitwiderstand an der Kontaktfläche zwischen zwei Metallen ergab, dass bei ungleichartigen Metallen der Widerstand von der Richtung des Wärmestroms abhing. Diese Arbeit bringt weitere Ergebnisse, die diese Erscheinung bestätigen und ihn mit dem Leitungsmechanismus an den metallischen Kontaktstellen in Verbindung bringen.

Аннотация—В статье приводятся результаты экспериментальных исследований по определению контактного термического сопротивления на границе раздела соприкасающихся металлов. Автор обнаружил, что величина контактного сопротивления при неоднородных металлах зависит от направления теплового потока. Указывается, что этот эффект можно ассоциировать с механизмом проводимости в точках соприкосновения контактных металлических поверхностей.

1. INTRODUCTION

ALL metal surfaces, even when flat, highly polished and under pressure, show appreciable contact resistance to heat flow. Little work has been done to determine this resistance until recently, when interest has been aroused by such problems as kinetic heating of rocket structures, nuclear fuel element canning and turbine blade cooling. References [1] to [10] represent the major portion of the work done in this field.

In [1] and [2] Barzelay *et al.* reported a comprehensive investigation into the effects of heat flow, mean interface temperature, interface pressure, surface condition and sandwich material on the thermal conductance of a series of aircraft joints of 75S–T6 aluminium alloy, and of A.I.S.I. type 416 stainless steel. As a side issue they noted in [1] that when steel and aluminium specimens were in contact the conductance depended upon the direction of heat flow, the conductance from aluminium to steel being appreciably larger than that from steel to aluminium. Previous workers do not seem to have investigated the effect of heat flow direction upon the conductance at the interface of dissimilar metals, and it was suggested that further work would be of interest. This note describes tests on several dissimilar metals and some of the results confirm the existence of the directional effect.

All the tests in [1] were performed in air at atmospheric pressure, and in order to effect the

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reversal of heat flow direction the specimens had to be inverted. Since the conductance is very sensitive to changes in contact configuration it was decided to design the apparatus with a heating element and cooling coil at each end of the experimental column to avoid any disturbance of the specimens. Furthermore, the apparatus was assembled in a vacuum chamber so that the heat flow due to conduction in the air film could be virtually eliminated. Thus only radiation and conduction at the points of metallic contact would remain as possible sources of the directional effect if this was still observed under vacuum.

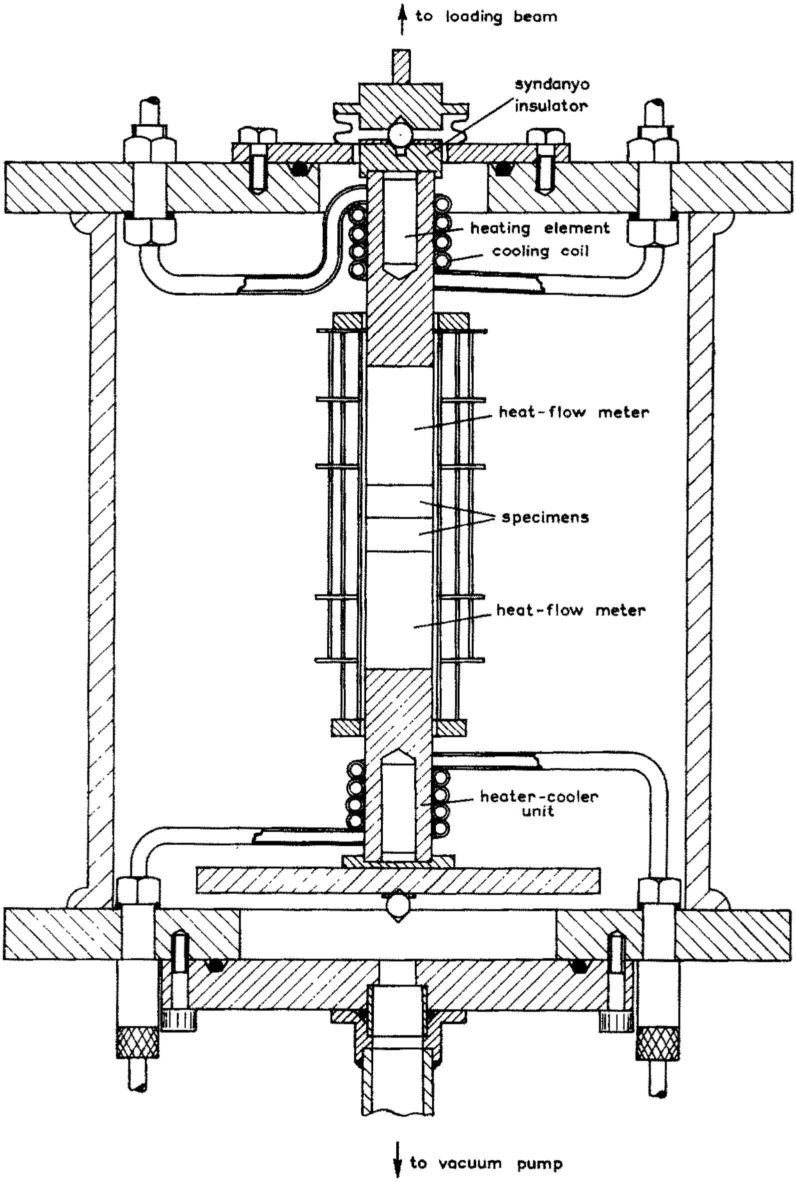

FIG. 1.

2. DESCRIPTION OF APPARATUS

Figure 1 shows the experimental column in a vacuum chamber formed by a glass cylinder with ground ends sandwiched between brass plates. A two-stage pump enabled a vacuum of about 0·02 mm Hg to be achieved.

Three vertical "Syndanyo" rods making line contact only located the column of specimens, heat-flow meters and heater–cooler units, and insulation against radial heat losses was provided by a series of concentric aluminium shields. The column was supported kinematically on the lower brass plate and a pivoted loading beam transmitted an axial force to the column via flexible bellows and a spherical bearing.

Each heater–cooler unit was constructed by cementing a 180 W heating element into a copper cylinder, to the outer surface of which was soldered a copper coil fed with cooling water from a constant head reservoir. The heat flow was measured by noting the temperature difference between thermocouples a known distance apart in aluminium bars on each side of the specimen pair, these bars being referred to as "heat-flow meters". All the specimens, 1 in. dia. × 0·5 in. thick, were machined with a diamond-tipped tool to give a surface roughness of 2–19 μ in. (average over a gauge length of $\frac{5}{16}$ in. on a Talysurf). The specimens were parallel to within 0·0003 in.

Temperatures were measured by thermocouples of 36 s.w.g. copper–constantan "insuglass" wire, cemented into holes (no. 56 drill) with Devcon F aluminium putty. E.m.f.'s were measured with a Tinsley portable potentiometer and the temperatures were accurate to within 0·5°C. Special care was taken to drill the thermocouple holes perpendicularly to the axes of the specimens and heat-flow meters so that the location of the junctions would be known accurately. To check the uniformity of heat flow three thermocouples were placed at different radii in the measuring planes nearest to the heater–cooler units. The degree of non-uniformity between the temperatures from the co-planar thermocouples was always less than 5 per cent of the mean value. Radial heat losses were such that the two heat-flow meter readings were within ±5 per cent of their mean value at maximum heat flow, but for most of the tests agreement was better than ±3 per cent.

3. TEST PROCEDURE

Values of the interface temperature drop Δt and mean interface temperature t_m were obtained by extrapolating the temperature gradient in the specimens: Fig. 2 shows the type of temperature distribution in the column. The temperature

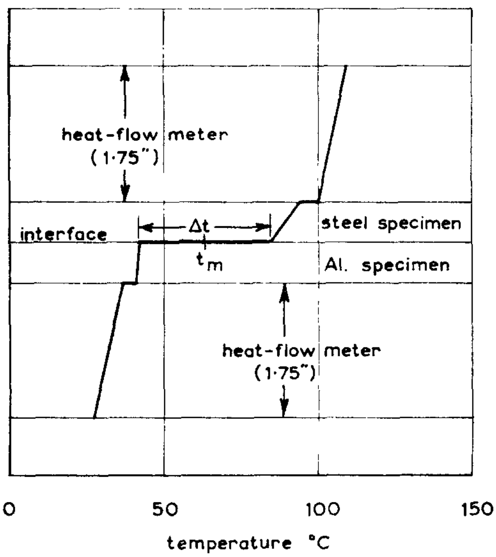

FIG. 2. Typical temperature distribution in column.

drops across all interfaces other than that of the specimen pair were minimized by shims of aluminium foil. The interface conductance h is defined by $h = q/\Delta t$, where q is the heat flow per unit area determined from the mean of the two heat-flow meter readings. h was determined over a range of mean interface temperature t_m for both directions of heat flow, with a constant interface pressure of 122 lb/in². The instrumentation was checked by testing a pair of specimens of the same material (commercially pure aluminium), when no change in the value of h was observed on reversing the direction of heat flow.

On assembly, the specimen surfaces were cleaned with trichlorethylene and ether. After an initial heating period of 2 hr with maximum heat flow the heat input was adjusted to give the required value of t_m. A settling period of 1 hr was used for each subsequent change of heat flow; repeat tests after all-night settling periods showed that 1 hr was sufficient. Heat flows ranging from 2000 to 16,000 chu/ft^{2}hr gave interface temperature drops ranging from 6° to 73°C, at mean interface temperatures between 40° and 140°C.

4. RESULTS

Specimens 1

Steel (Vibrac V 30 EN 25 T) and commercially pure aluminium. From the results in Fig. 3 it may be seen that, in atmospheric air, h was approximately 20 per cent higher for the Al $\rightarrow$ St direction than for the St $\rightarrow$ Al direction. Under vacuum, the numerical difference between the values of h was much the same but, since the values were lower, the percentage difference rose to about 100 per cent. The magnitude of the contribution to the conductance provided by the air film is worth noting.

This test, and a few others not reported in detail here, indicated that the directional effect was not eliminated by evacuation and all subsequent results are for tests in air.

Specimens 2

Steel (12/14 Chrome steel EN 56 C) with a composition similar to the American A.I.S.I. type 416, and an aluminium alloy with a composition closely resembling the American 75S–T6. The values of h were slightly lower than the corresponding values in Fig. 3, but again the values for the Al $\rightarrow$ St direction were about 20 per cent higher than those for the St $\rightarrow$ Al direction. The curves were as well defined as those in Fig. 3.

Specimens 3

T1 alloy (chromel) and T2 alloy (alumel). This specimen pair, chosen for its very large difference in thermoelectric potential, was then tested to see whether the directional effect was associated with thermoelectric phenomena. The results exhibited more scatter, however, and showed no directional effect that was clearly outside the margin of experimental error. The values of h lay between 275 and 500 chu/ft^{2}hr°C over a 45° to 95°C range of t_m.

Specimens 4

Copper (commercially pure) and steel (Vibrac). In Ref. [1] it was suggested that, since the temperature is not completely uniform over the cross-section, thermal stress or stress relief might cause the material of low thermal conductivity (i.e. the steel) to warp and so change the contact configuration. This warping would be more severe the higher the temperature and thus would be different for the two directions of heat flow.

The results from the T1–T2 specimen pair could support this hypothesis: these alloys have very similar thermal conductivities and no definite directional effect was observed. It is difficult to see, however, why the slight change in contact configuration should consistently lead to a decrease in h, when the heat flow changed to the St $\rightarrow$ Al direction, and not sometimes to an improvement in the matching of the surfaces and so to an increase in h. Furthermore, if this be the explanation, h would be expected to decrease with increase of t_m when the heat was flowing in the St $\rightarrow$ Al direction, because an increase of t_m implies a higher heat flow and hence is associated with an increase in the average temperature of the steel specimen. In fact, as shown by Fig. 3, there is a slight increase in h with increase in t_m.

In an attempt to check the suggestion, however, specimens 4, differing still more in thermal conductivity than steel and aluminium, were tested. The results for the copper–steel pair were rather scattered, like those for the T1–T2 pair. h lay between 750 and 850 chu/ft^{2}hr°C over a 45° to 90°C range of t_m, and there was only a slight indication of an increased h when the heat flow was from the good to the poor conductor. The warping explanation, therefore, seems unacceptable.

If, on the other hand, the cause of the directional effect is associated in some way with the metallic contacts this experiment would not refute the possibility because the copper would rapidly acquire an oxide film which might effectively eliminate direct contact between the metals. One possibility is that there might be a contact potential across the interface which inhibits the diffusion of electrons in one direction while assisting it in the other.

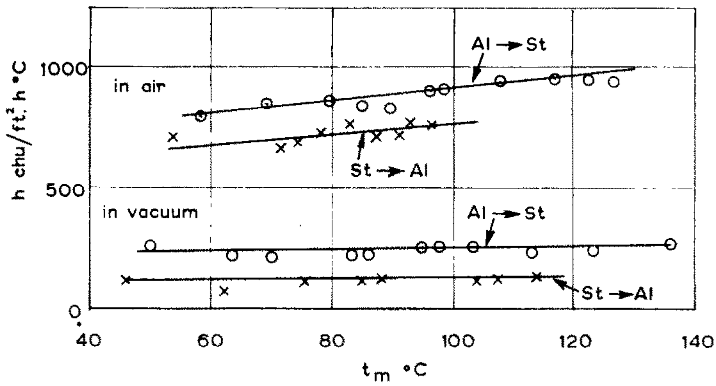

FIG. 3. Variation of conductance with mean interface temperature. Specimens 1.

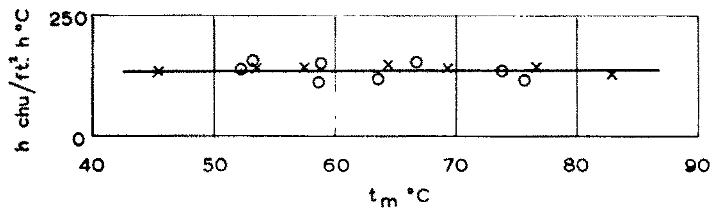

FIG. 4. Variation of conductance with mean interface temperature. Specimens 5.

Specimens 5

Specimens 1 but with a shim of mica between them. The results in Fig. 4 show that the directional effect is eliminated.

5. CONCLUSIONS

This note presents a few results which support the suggestion in [1] that under certain circumstances the resistance to heat flow at the interface of dissimilar metals can depend upon the direction of heat flow. The results indicate that the effect could be associated with the mechanism of conduction at the points of metallic contact, e.g. when metals having different values of the work function are in contact a potential barrier is created which might reduce the drift of free electrons in one direction and increase it in the other.

Comments from those specializing in the physics of conduction in metals would be welcome.

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