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HEAT TRANSFER AT THE INTERFACE OF DISSIMILAR MATERIALS: EVIDENCE OF THERMAL-COMPARATOR EXPERIMENTS

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Abstract—A recent publication has drawn attention to a marked directional dependence of the heat flow at the interface of certain contacting metals, and considers the effect to be associated with the mechanism of conduction at the points of metallic contact.

The effect is now investigated in terms of the reading of a thermal comparator having initial temperatures both above and below that of the test sample. No such directional difference is found in this way for the metal combinations for which the effect had previously been reported, namely steel and aluminium, and steel and aluminium alloy, nor is any difference found for the combinations of a metal (steel) with either a semiconductor (germanium) or an electrical insulator (a ceramic material based on soapstone), for which it is to be expected that differences in the heat conduction mechanism would be more pronounced.

It is concluded that the use of the thermal comparator for thermal conductivity determinations is not complicated by any such directional effect.

INTRODUCTION

ROGERS [1] has recently described experiments, made in the Mechanical Engineering Department of the University of Bristol, which supported an earlier investigation by Barzelay *et al.* [2] and indicated that under certain circumstances the resistance to heat flow at the interface of dissimilar metals can depend on the direction of heat flow. The work at Bristol showed the interface conductance to be 20 per cent higher from aluminium or aluminium alloy to steel than from steel to aluminium or aluminium alloy. Under vacuum conditions the directional difference remained about the same, but owing to the removal of the air conduction component, the percentage difference rose to about 100 per cent. It was concluded "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".

The results and conclusions were of particular interest in connexion with comparative thermal-conductivity determinations being made at the National Physical Laboratory by means of the thermal comparator [3, 4], shown in Fig. 1.

The thermal comparator is a simple device which measures the transfer of heat to or from a small metal sphere following contact with a test surface at a fixed difference in temperature. The rate of change in temperature of the sphere is observed, and, so far as heat conduction by the solids is concerned, this has been shown [5] to depend only on the thermal conductivities of the two materials, the initial temperature difference and the effective radius of contact. The conclusions of Rogers would appear to require the inclusion of an additional controlling mechanism.

It therefore seemed important to ascertain whether there was any evidence for the presence of a complicating effect of this nature in measurements involving the use of the thermal comparator. These measurements are described and have failed to reveal any directional effect of the order reported by Rogers.

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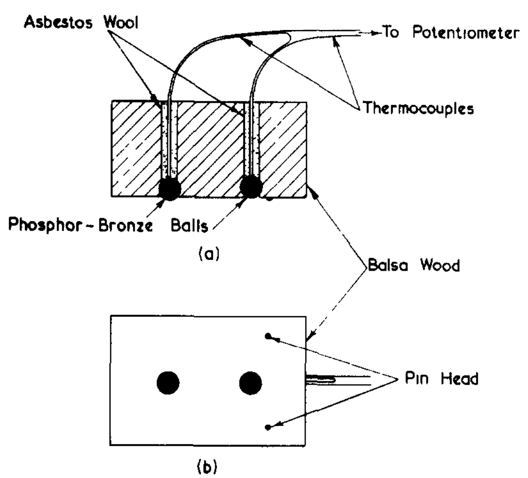

FIG. 1. Diagram of thermal comparator.

DESCRIPTION OF THE THERMAL COMPARATOR

The thermal comparator used for these experiments consisted of two steel balls $\frac{1}{8}$ in in dia., mounted in a block of balsa wood. The balls were about $\frac{1}{2}$ in apart, and one ball and two studs formed an equilateral triangle of about $\frac{3}{4}$ in side, which provided a three-point contact on a plane surface and ensured that the other ball just failed to make contact. A thermocouple composed of 36 s.w.g. nickel–chromium alloy and constantan wires was welded to the top of each ball and these thermocouples were connected in opposition. The weight of this thermal comparator was 3·1 g, but for most tests a steel weight was added to give increased stability, and under these conditions the total weight was 102 g. The main change from the thermal comparator previously used is seen to be the replacement of phosphor-bronze by steel balls.

EXPERIMENTS WITH ALUMINIUM ALLOY

A disk of aluminium alloy, 3·8 in in dia. and 2·15 in thick was used for the first tests. The plane surfaces of the disk had been finished to a surface roughness of CLA value of about 8 μin. Tests were made in the normal way with the warmed comparator applied to the aluminium alloy, for which condition the heat flow would be from steel to aluminium alloy.

In conducting this test the thermal comparator was placed on a large steel block in a temperature-controlled oven and allowed to attain an equilibrium temperature given by a thermocouple attached to the block.

The aluminium alloy was at room temperature and its temperature was also indicated by means of an attached thermocouple.

An experiment consisted of reading both thermocouples, noting the "zero" differential e.m.f. as the thermal comparator is placed gently on the plane surface of the aluminium alloy, and finally noting the differential e.m.f. 10 s later.

This experiment was repeated for various initial excess temperatures of the thermal comparator and the results obtained are indicated by means of crosses in the upper portion of Fig. 2.

The conditions were then reversed so that the heat transfer was from aluminium alloy to steel. The large disk of aluminium alloy was warmed in the oven, removed and wrapped in cotton wool, except for the exposed surface area. The thermal comparator was placed on the block of steel and the initial temperatures of the aluminium alloy and thermal comparator measured by thermocouples. The thermal comparator was then gently placed on the plane surface of the aluminium alloy and 10 s later the differential e.m.f. was noted as before.

These measurements were repeated at intervals as the aluminium alloy slowly cooled, and the results obtained are indicated by the ringed points in the upper portion of Fig. 2.

The two types of points will be seen to lie within ± 7 per cent of the straight line drawn to pass through the origin and to be reasonably evenly distributed about the line. The results do not give any support for Roger's claim that the heat transfer from the aluminium alloy to steel (ringed points) is 20 per cent greater than the heat transfer from steel to aluminium alloy (crosses).

Rogers' experiments were stated to have been conducted under a load of 122 lb/in^2 and those of Barzelay *et al.* at loads of about 5–425 lb/in^2.

Williams [6], in discussing Rogers' results, stated that he would be more convinced of the existence of a direction-conscious surface thermal potential barrier if the effects were found for:

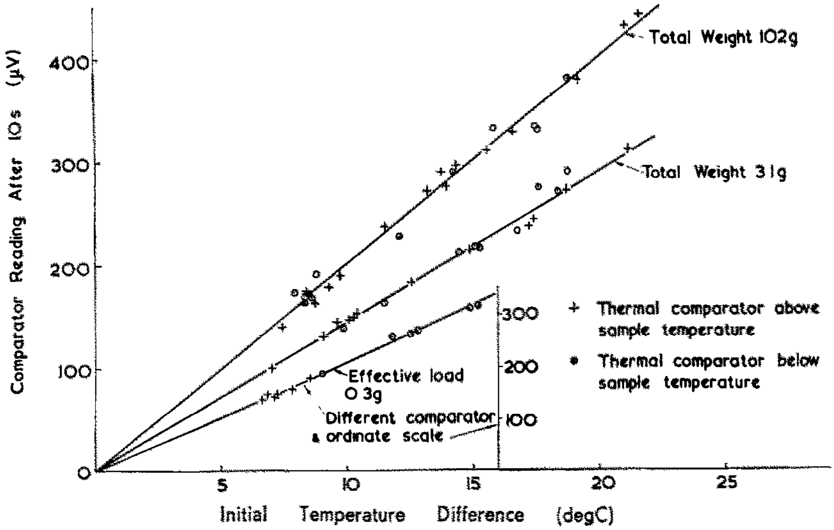

FIG. 2. Thermal comparator measurement on sample of aluminium alloy.

(a) a much higher contact pressure,
(b) a specified contact geometry,
(c) a controlled film thickness.

The present tests were made using the loaded thermal comparator, for which the load on the contacting ball was 34 g (0·075 lb). The assumption, that the whole of the heat transfer takes place through the solids at their point of contact, leads, according to Clark, to a contact area of $8{\cdot}6 \times 10^{-6}$ in^2 and hence to a load of 22 700 lb/in^2. This satisfies condition (a), but revealed no effect, and suggests that the experiment should be repeated with smaller loads.

It is believed that the contact geometry of a sphere on a plane tends to fulfil condition (b). In a subsequent set of experiments the unloaded comparator was used, thus applying a load of about 1 g, equivalent to about 1350 lb/in^2. Finally, another comparator was used, this being counter-balanced to give an effective load of only 0·3 g.

These results are shown in the lower portion of Fig. 2. They are seen to be closely similar to those with the heavier loading and again show no directional effect. The thermal comparator is unlikely to be used with a smaller effective load and it would seem that this device is normally operated at a considerably greater load per unit area than has been used in reported heat-transfer investigations.

EXPERIMENTS WITH ALUMINIUM

Since Rogers had also reported differences of the order of 20 per cent for commercial aluminium, it was thought desirable to make similar measurements for a test surface of 99 per cent aluminium. The plane surface of a disk of 99 per cent aluminium, lapped to a roughness of CLA value of about 15 μin, was used.

The experimental points obtained for similar tests with the loaded thermal comparator on this surface are plotted in Fig. 3 and these are seen to be uniformly distributed about the upper straight line. Again there is no evidence for any directional dependence.

EXPERIMENTS WITH A SEMICONDUCTOR AND AN INSULATOR

Having confirmed that the reading of the thermal comparator is not directionally dependent for the two cases cited by Rogers—steel and aluminium or aluminium alloy—it was thought of interest to use the thermal-comparator method for tests on a semiconducting material and an electrical insulator. In the former, almost all the heat flow takes place by phonon or lattice waves,

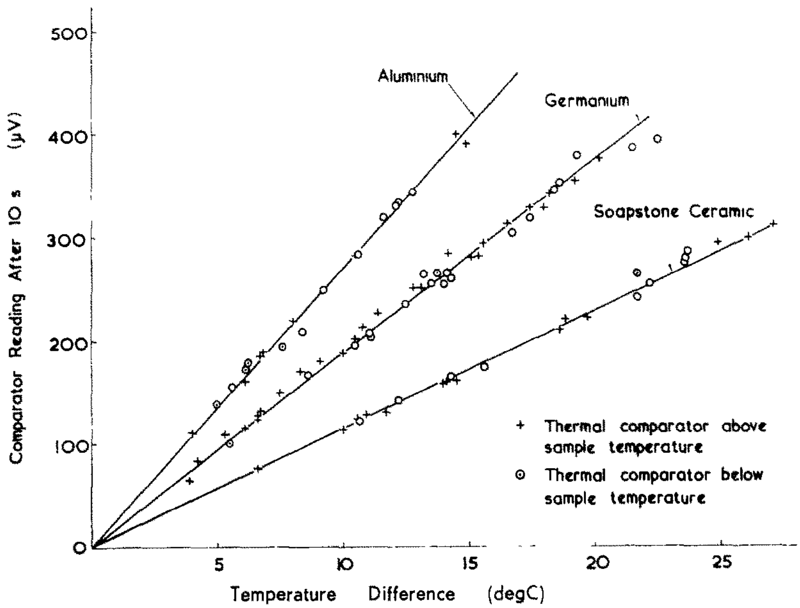

FIG. 3. Thermal comparator measurements on various materials.

and only a very small proportion by electrons, whilst in the latter there can be no electronic conduction of heat. Thus, when the warm thermal comparator is used, the heat will flow from steel, for which the bulk of the heat flow occurs by means of electrons, to another material in which there is little or no heat flow by electrons but the major portion or entire heat flow is by phonons. On the other hand, when the thermal comparator is cooler than the test material the conditions will be reversed and the heat flow with phonons predominent will become one with electrons predominent.

The semiconductor chosen for these tests was a slice of germanium with a plane ground surface of CLA value of about 40 μin and the electrical insulator a block of ceramic material based on soapstone that had been lapped on the upper surface to a CLA value of about 100 μin.

The results for these two samples are also plotted in Fig. 3. In neither case is there any evidence that the resistance to heat flow is a function of flow direction.

THERMAL CONDUCTIVITY OF GERMANIUM

The samples for which results are plotted in Fig. 3 all had fairly similar surface finishes, hence their relative thermal conductivities are indicated by the varying slopes of the lines. The thermal conductivities of the 99 per cent aluminium and the ceramic material were known to be 2·26 and 0·0288 J cm/cm^2 s degC respectively, but that of the germanium sample had not been measured previously.

Earlier work [3] has shown that with phosphor-bronze balls the thermal comparator reading is proportional to the square root of the thermal conductivity, λ, for thermal conductivity values ranging from aluminium down to high-alloy steel (0·107 J cm/cm^2 s degC). Fig. 4 shows the results of Fig. 3 plotted in this way and includes additional measurements made on high-alloy steel and Armco iron.

As found previously, the point for the ceramic material is again displaced from the line fitting the higher conductivity results. The thermal comparator reading for the germanium sample indicates a thermal conductivity of 0·58 J cm/cm^2 s degC, which agrees well with the room temperature value of about 0·6 J cm/cm^2 s degC quoted by Slack and Glasbrener [7].

CONCLUSIONS

The thermal-comparator method has been

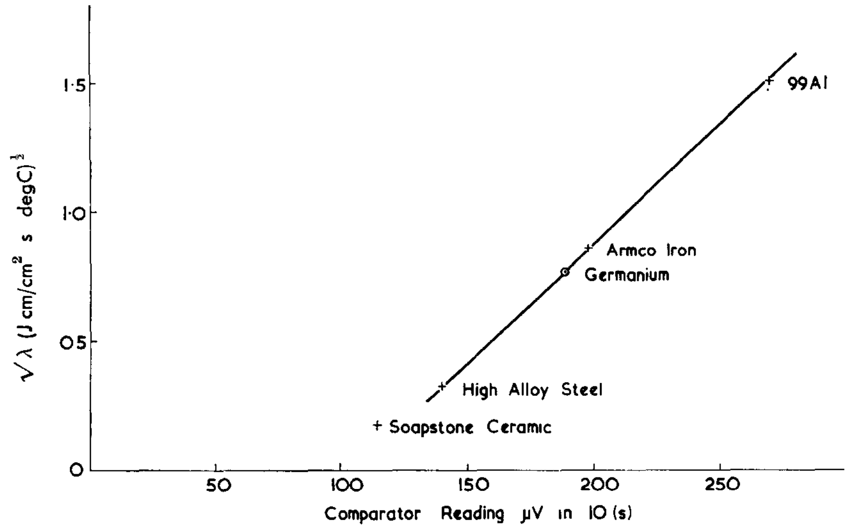

FIG. 4. Thermal comparator reading against $\sqrt{\lambda}$ to estimate the thermal conductivity of germanium.

used to investigate the suggestion that the thermal resistance at the interface of certain dissimilar materials, e.g. steel and aluminium or aluminium alloy, can vary according to the direction of heat flow. Neither for these materials nor with steel and germanium and steel and an electrical insulating material is there any indication of an effect of this kind. It follows from this that the use of the thermal comparator for thermal conductivity determinations is not complicated by any directional effect. Nor do the present experiments give any support for Rogers' explanation in terms of differences in the mechanism of heat conduction at the points of contact. The absence of any directional effect when the contacting area is small rather suggests that it may occur only when metals are in contact over a large area. In this case, the explanation proposed by Barzelay *et al.* and elaborated by Wheeler [8], when discussing their experiments, seems more likely. These workers attributed the effect to thermal warping due to local temperature differences. Such an effect would be greater in the poorer conducting steel and thus could explain both the greater heat flow from aluminium to steel, and also the greater dependence on pressure which Barzelay *et al.* found for this direction of flow.

ACKNOWLEDGEMENTS

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Résumé—Une publication récente a attiré l'attention sur l'influence marquée de la direction du flux de chaleur à l'interface de certains métaux en contact et considère que cet effet est associé au mécanisme de conduction aux points de contact métallique.

L'effet est étudié en fonction des indications d'un comparateur thermique ayant des températures initiales inférieure et supérieure à celle de l'échantillon. Aucune différence due au sens du flux n'a été mise en évidence de cette façon pour des métaux pour lesquels on avait précédemment noté un effet: acier-aluminium, acier-alliage d'aluminium, pas plus que pour des combinaisons d'un métal (acier) avec un semi-conducteur (germanium) ou un isolant électrique (céramique à base de stéatite) pour lesquelles on pourrait s'attendre à ce que les différences dans le mécanisme de conduction thermique soient plus importantes.

On en conclut que l'usage du comparateur thermique pour les déterminations de conductivité thermique évite les erreurs dues à un tel phénomène directionnel.

Zusammenfassung—Eine kürzlich erschienene Veröffentlichung beschrieb eine ausgeprägte Richtungsabhängigkeit des Wärmeflusses an der Trennfläche zwischen verschiedenen sich berührenden Materialien und befasst sich mit den Auswirkungen dieser Erscheinung auf die Punkte metallischer Verbindung. Der Effekt wurde nun mit einem Vergleichskörper nachgeprüft, wobei dieser sowohl höhere als auch niedrigere Anfangstemperaturen als das Probestück besass. Dabei zeigte sich keine Richtungsabhängigkeit für die Metallkombinationen, für die eine solche erwähnt wurde, nämlich Stahl und Aluminium bzw. Stahl und Aluminiumlegierung. Auch bei Verbindungen von Metall (Stahl) mit einem Halbleiter (Germanium) oder einem elektrischen Isolator (einem Keramikmaterial, auf der Grundlage von Seifenstein) konnte keine Richtungsabhängigkeit des Wärmestromes bemerkt werden; dabei wären für letztere Materialien ausgeprägtere Unterschiede im Mechanismus der Wärmeleitung zu erwarten. Die Bestimmung der Wärmeleitfähigkeit mit dem Vergleichskörper wird also nicht durch irgendwelche Richtungseinflüsse erschwert.

Аннотация—В предыдущей статье уделялось внимание исследованию влияния направления теплового потока на границе раздела некоторых соприкасающихся металлов и рассматривалось, какое влияние оказывает механизм теплопроводности в точках соприкосновения металлов.

В данной статье это влияние исследуется на основе показаний термического компаратора, начальные температуры которого могут быть как выше, так и ниже температуры исследуемого образца. Этим путём не найдена разность направлений для сочетаний металлов, влияние которых анализировалось раньше, а именно сталь и алюминий, сплав стали и алюминия. Не найдена также разность для сочетания металла (сталь) или с полупроводником (германий) или с электроизолятором (керамический материал, основанный на стеатите), для которых полагают, что разности в механизме теплопроводности могут быть явные.

Доказано, что использование термического компаратора для определения коэффициента теплопроводности не осложняется каким-либо направленным эффектом.