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HEAT TRANSFER AT THE INTERFACE OF STAINLESS STEEL AND ALUMINUM—THE INFLUENCE OF SURFACE CONDITIONS ON THE DIRECTIONAL EFFECT

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Abstract—Recent investigators have reported that the magnitude of interface conductance of certain dissimilar metals is dependent on heat flow direction. In the present paper, previous conflicting results concerning this directional effect in stainless steel–aluminum interfaces are resolved by showing the directional effect phenomenon to be dependent upon interface surface conditions, i.e. flatness and roughness. Experimental evidence which demonstrates this dependency is given, and models to explain the phenomenon are presented.

NOMENCLATURE

A,	cross sectional area [in^2];
AL,	aluminum;
H,	interface conductance [Btu/h ft^2 degF];
K,	thermal conductivity [Btu/h ft degF];
P,	contact pressure [lb/in^2];
Q'',	heat flux [Btu/h ft^2];
R,	interface thermal resistance [degF h/Btu];
SS,	stainless steel;
T,	temperature [degF];
ΔT,	temperature difference [degF];
Δx,	distance between temperature measurements [in];
α,	coefficient of linear expansion [in/in degF];
ε,	emissivity.

Subscripts

1,	region 1, specimen 1;
2,	region 2, specimen 2;
I, II, III, IV, V, VI,	thermocouple locations or temperatures;
US,	upper specimen;
LS,	lower specimen;
IF,	interface;
TS,	test specimen.

1. INTRODUCTION

AT THE interface of any two metals in contact there is encountered a temperature drop, ΔT. This temperature drop, due to interface imperfections which prevent a perfect matching of the surfaces, is associated with the interface contact resistance, R. The interface conductance, a reciprocal function of the contact resistance, is used more often in the literature. The interface conductance, H, is defined by:

$$H = \frac{1}{RA} = \frac{Q''}{\Delta T}. \tag{1}$$

Ideally, the temperature drop across an interface is zero, and this value is used in many engineering problems. There are certain applications, though, such as the design of space

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vehicles, where a high degree of accuracy is required in determining the temperature distribution. In these cases, accurate knowledge of the nature of interface conductance becomes a critical design factor.

Recent investigations, many of them in support of space vehicle design projects, have been carried out to determine the nature of interface conductance of certain metal to metal joints, the metals being stainless steel, aluminum and aluminum alloy. One of the most interesting phenomena that has been observed in these investigations is the dependency of interface conductance on the direction of heat flow at the interface of dissimilar metals.

This paper is concerned with a study of this directional effect. It is shown that the divergent results of various investigators can be explained in terms of the two surface parameters surface flatness and surface roughness. Clausing and Chao [1] have pointed out that the increased resistance to heat transfer at the interface of two metals can be considered to be made up of a macroscopic resistance, a microscopic resistance, and, if appropriate, a film resistance. The two surface parameters of flatness and roughness enter into these resistances in a direct way. The degree of surface flatness determines the ability of two surfaces to match so that for very flat surfaces one would expect a lower macroscopic resistance than for non-flat surfaces. In the latter case only a small portion of the surfaces may be in macroscopic contact so that the heat-transfer resistance would be high. The surface roughness will affect the microscopic resistance since the ability of surfaces to make contact on a microscopic basis will be dependent on the height of the largest roughness elements.

Clausing and Chao [1] have studied the effects of macroscopic resistance on the interface conductance for various pairs of similar metals in contact and have obtained good agreement between theory and experiment for surfaces which will be categorized later in this paper as *spherical cap surfaces*. For their flatter surfaces the agreement is not good. Yovanovich and Fenech [2] have studied the interface conductance for "nominally-flat, rough surfaces". They obtained good agreement between their theory and experiment for this type of surface. For the nominally flat, rough surface one may presume that the microscopic resistance is controlling. This should be the case since essentially the whole of the surface area is in macroscopic contact, i.e. there is contact over the whole area and not just at the meeting of two spherical caps. The data of this paper substantiate this view.

The first quantitative report of the directional effect was that of Barzelay *et al.* [3]. They found that the interface conductance of an aluminum–stainless steel interface was greater when the heat flow was in the aluminum to stainless steel direction.

More recently, however, Clausing [4], using a more sophisticated test apparatus, has observed a directional effect such that the interface conductance is greater when heat flows in the stainless steel to aluminum direction. Thus both the existence and nature of the directional effect are confusing phenomena which recent investigators have not been able to totally explain.

In 1955 Barzelay *et al.* [3] observed and measured experimentally a heat flux directional effect on a stainless steel–aluminum interface. This effect was such that, at low contact pressures (5 lb/in^2) the interface conductance had only a slight directional dependence but as the contact pressure increased, the directional effect increased. Also, at high pressures (400 lb/in^2) the magnitude of directional effect increased with increasing heat flux. The interface conductance was always higher for heat flow in the aluminum to stainless steel direction. Details of these results and information regarding the interfaces used are given in later sections. Barzelay *et al.* suggested that thermal warping of the stainless steel interface was the cause of the directional effect.

Rogers [5], who in 1960 performed a more specific study of directional effects in dissimilar metals, found a slightly different trend. His in vacuum data show that at a constant pressure of 122 lb/in^2 the interface conductance is about 100 per cent higher when heat flows in the aluminum to stainless steel direction than when it flows in the opposite direction. He also found this effect to be constant with varying mean interface temperature.

Rogers found no directional effect for chromel–alumel and copper–stainless steel interfaces. He concluded that the directional effect might be caused by the conduction mechanism at the interface contact points.

Powell *et al.* [6] showed by use of a thermal comparator, which makes use of the point contact of a small radius ($\frac{1}{4}$ in) steel ball, that there was no directional effect in the point contact of aluminum and steel. Their tests were made at contact pressures of 400; 1350; and 22 700 lb/in^2. They concluded that the directional effect occurred only when the contact area is large and was due to some effect which changes the interface configuration. They suggested that it might be thermal warping.

In 1966, Clausing [4] reported a directional effect that was quite different from those reported previously. His data show that over a contact pressure range of 0 to 800 lb/in^2 (determined by the present authors from his non-dimensional results) the interface conductance for heat flow in the stainless steel to aluminum direction was three times greater than when the heat flowed in the opposite direction. He also observed that the magnitude of the directional effect varied as the heat flux magnitude.

Clausing also observed a directional effect in a magnesium stainless steel interface. This was very similar to the effect observed for an aluminum–stainless steel interface and the interface conductance was greater when the heat flowed in the stainless steel to magnesium direction.

Clausing showed that the directional effects he observed were due to thermal strain as will be considered in the next section.

2. ANALYSIS

Clausing has presented an analysis of the interface conductance directional effect exhibited by dissimilar metals in contact over a smooth symmetrical area. Because of the importance of his model to the present work, it will be presented in detail. In his model he considers, [4]:

> . . . the physical model of the contacting 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. 1 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. 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 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.

Thus the interface conductance is a function of heat flow direction such that when heat flows

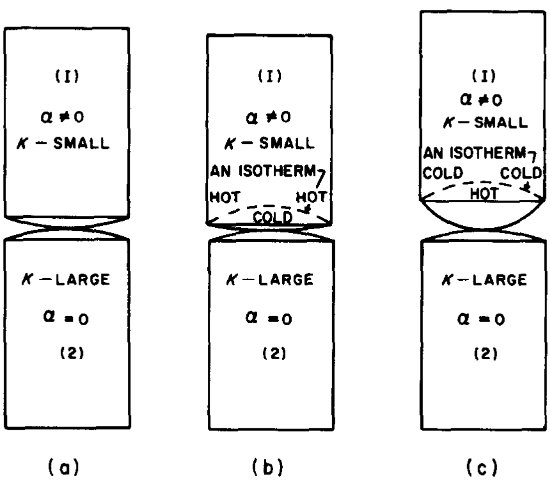

FIG. 1. Geometric effects of thermal strain resulting from a macroscopic constriction, after Clausing [4]: (a) geometry for no heat flow; (b) geometry for heat flow from 1 to 2; (c) geometry for heat flow from 2 to 1.

from the region of low thermal conductivity to that of high thermal conductivity the interface conductance is higher than when the heat flow is in the opposite direction.

Clausing's model is seen to depend upon the existence of interface surfaces which can be considered as smooth *contacting spherical caps* or smooth contacting toruses. In this paper this model will be called the spherical cap model or model *A*.

Let us now consider an alternative model resulting from the type of interface that would be the normal result of machine grinding to a fine finish (surface roughness 16–32 μin RMS). This type of surface would be *flat* over a major portion of its area with a random array of small grooves or discontinuities. For such a surface a measuring instrument would see deviations in flatness over the surface which would be caused solely by the *local* deviation in height due to local roughness and there would be no cumulative flatness deviation [Fig. 5(b) defines such a surface]. For an interface of surfaces of this type, the following physical model will be analyzed.

Consider the section of two contacting members of equal cross sectional area shown in Fig. 2. In the microscopic section chosen the material in the upper region (1) is of low thermal conductivity and has a smooth interface. The material in the lower region (2) is of high thermal conductivity and has a discontinuity at the interface.

If the heat flow is in the 1–2 direction, the portion of region (1) opposite the discontinuity will be at a higher temperature than the surrounding interface area. Thus this portion will expand into the discontinuity as shown in Fig. 2(b). If the heat flow is in the opposite direction, the portion of region (1) opposite the discontinuity will be at a lower temperature than the surrounding interface area. Thus this portion will contract as shown in Fig. 2(c).

For this section, with the discontinuity in the high conductivity material, the changes in contact area due to heat flow are small.

If a microscopic section is chosen with a discontinuity in the low thermal conductivity material, region (1), and a smooth interface in the high conductivity material, region (2), the physical model will be as shown in Fig. 3(a).

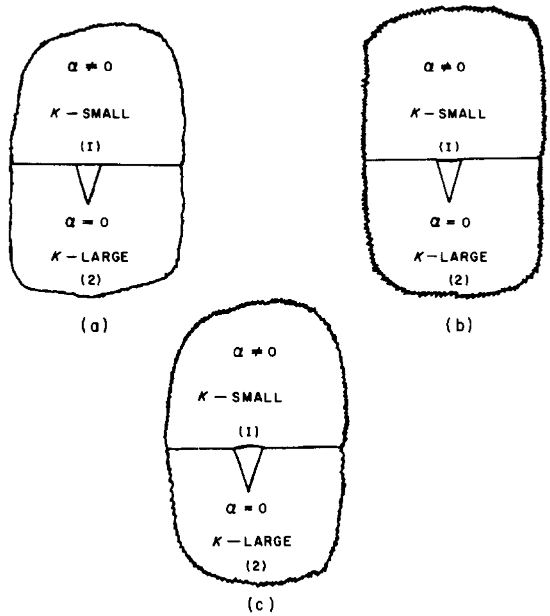

FIG. 2. Geometric effects of thermal strain resulting from a discontinuity in the material of high thermal conductivity: (a) geometry for no heat flow; (b) geometry for heat flow from 1 to 2; (c) geometry for heat flow from 2 to 1.

If heat flows in the 2–1 direction, the interface portion of region (1) around the discontinuity will be at a lower temperature than the surrounding interface area. Thus this portion will contract slightly, decreasing the contacting area in the section as shown in Fig. 3(b).

If heat flows in the direction 1–2, the interface portion of region (1) around the discontinuity will be at a higher temperature than the surrounding interface area. Thus this portion will expand locally causing a ridge which lifts the entire interface as shown in Fig. 3(c). This is not an equilibrium condition, though, since the ridge will now be colder and tend to contract. Since it also cannot return to the condition in Fig. 3(a), the section must reach an equilibrium condition as shown in Fig. 3(d). This final equilibrium position will be a function of both the interface

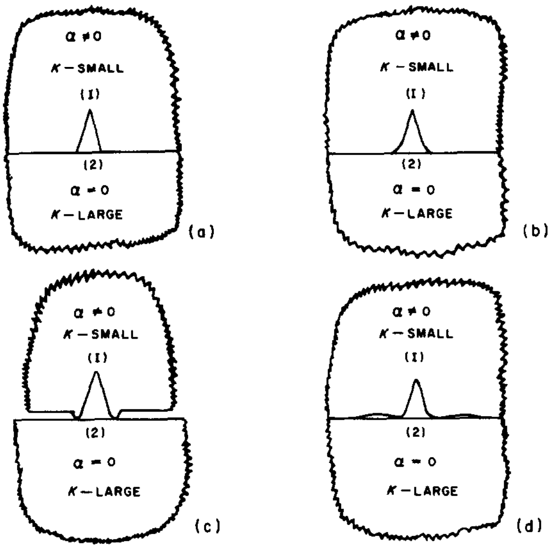

FIG. 3. Geometric effects of thermal strain resulting from a discontinuity in the material of low thermal conductivity: (a) geometry for no heat flow; (b) geometry for heat flow from 2 to 1; (c) geometry with non-equilibrium heat flow from 1 to 2; (d) geometry for equilibrium heat flow from 1 to 2.

pressure and the heat flux and will be such that there will be a large loss in contacting area.

It can then be seen that for this type of section, with the discontinuity in the low conductivity material, the interface conductance will be highest when heat flows *from the material of high conductivity to that of low conductivity*, i.e. in the 2–1 direction for the section selected. On the other hand, with the discontinuity in the high conductivity material, there was very little change in contacting area due to heat flux and thus no cause for a directional effect.

The macroscopic surface of a test specimen is made up on a microscopic basis of many small regions, as described in Figs. 2 and 3, which can be analyzed in the manner just completed. Thus, in many respects the model just described is an extension of Clausing's macroscopic spherical cap idea applied to a microscopic model of the surface.

It can thus be seen that for dissimilar metals which have reasonably flat machined surfaces, as described above, the interface conductance will be highest when heat flows from the metal of high thermal conductivity to that of low thermal conductivity. This model will be called the *flat rough model* or model *B*.

For certain dissimilar metals in contact, the directional effect can now be predicted if the interface conditions are known to match the conditions in the two physical models presented. In many respects the models can be considered to exhibit a dominant macroscopic resistance (spherical cap model) or a dominant microscopic resistance (flat rough model).

Approach to the problem

Directional effects in the interface conductance of stainless steel–aluminum interfaces have been quantitatively measured by Clausing [4] and Barzelay *et al.* [3]. The directional effect observed by Clausing was quite different from that observed by Barzelay *et al.* An analysis of the problem has shown, considering the test specimens used in each investigation, that the effect that each investigator observed could have been qualitatively predicted.

The test specimens used by Barzelay *et al.*, were 3-in dia. stainless steel with a machined surface roughness of 30 μin RMS and aluminum alloy with a machined surface roughness of 65 μin RMS. They did not specify the flatness of their individual specimens but did specify the machining process and gave an average value for flatness of 200 μin.* Their flatness to diameter ratio is thus 67 μin/in.

Clausing used 1-in dia. specimens with a spherical cap (specimen flatness approx: 90 μin) and a surface roughness of 4 μin RMS. His specimens fit the smooth spherical model, model *A*. It will be seen that the Barzelay *et al.* models give results characteristic of model *B*.

An experimental investigation has been performed with test specimens which fit both models *A* and *B*. The results show quantitatively

* In [1] a value of 800 μin, presumably the total of the two interface surfaces, is given.

that the different directional effects predicted by the analysis of both models are valid.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The test apparatus has been previously described in detail in the report of Young [7]; only a brief description will be given here.

All tests were run in a vacuum chamber at an ambient pressure of less than 5×10^{-5} torr. Pressure measurements were made with a Vacuum Industries Inc. Discharge Vacuum Gauge Model 700.

A schematic representation of the test column is given in Fig. 4 and nomenclature for thermocouple location is established by this figure. The mechanical load in the test column was measured by strain gauges on the support columns and a BLH Strain Indicator. The load was developed by spring forces.

The test column was symmetric with respect to the test interface. A source-sink was at each end of the test column, thus enabling heat flow in either direction. When used as a heat source, the source-sink was capable of maintaining a temperature of 400°F. When used as a heat-sink, the temperature was maintained at 80°F.

The heat flow meters were ALCOA 6063-T5 aluminum cylinders 1-in diameter and 2-in long. Temperature measurements were made by three No. 28 gauge premium grade Chromel–P/Alumel thermocouples soldered in holes $\frac{1}{2}$ in apart. The thermocouple wire was calibrated at the ice point and atmospheric water boiling points. Although data was taken at temperatures above the latter point, the agreement at that point with the NBS 561 tables was excellent and there should be no appreciable error in using the thermocouples to moderately higher temperatures.

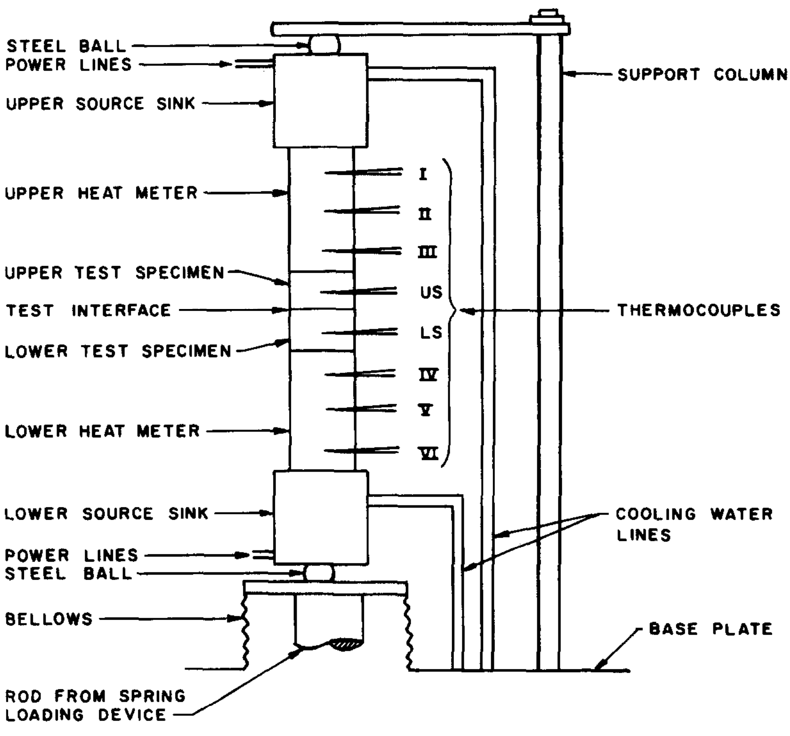

FIG. 4. Test column and supporting structure.

Test specimens

The test specimen materials used were 6063-T5 aluminum and stainless steel Type 316. The specimens "as received" were $1 \pm 0{\cdot}001$-in long and $1 \pm 0{\cdot}001$-in dia. The faces were parallel to within $\pm 0{\cdot}001$ in. A No. 56 drill hole, $\frac{9}{16}$-in deep was drilled $0{\cdot}500 \pm 0{\cdot}001$ in from the test surface. The aluminum specimens had a surface roughness of 32 μin RMS and the stainless steel specimens had a surface roughness of 24 μin RMS; further, the roughness was uniform over the entire surface. The flatness of the specimens as measured was dependent only upon the surface roughness [see Fig. 5(a)]. Thus the flatness, as defined in Fig. 5(b), is near perfect, i.e. no cumulative deviation exists and only local changes in flatness, due to roughness, occur. Thus the measured flatnesses were 32 μ in for the aluminum and 24 μin for the stainless steel. Flatness and surface roughness measurements were made using a Moore Products Pneumatic comparator gauge for flatness measurements and a Profilometer for surface roughness measurements. Surface roughness measurements were also made by comparison with General Electric "Standard Roughness Specimens".

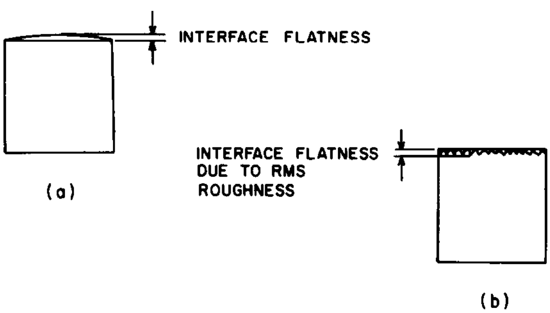

FIG. 5. Test specimen nomenclature. (a) Flatness definition; (b) flat–rough specimen where the RMS roughness is the sole cause of a non-flat surface.

The specimens were tested in the following conditions: (1) as received; (2) after light polishing; (3) after buffing; (4) after hand lapping.

Light polishing consisted of lightly polishing, by hand, the "as received" specimens with jeweller's rouge and Brasso. This process had no measurable effect on the stainless steel specimens, but reduced the surface roughness of the aluminum specimens to 24 μin RMS and increased the flatness deviation to 50 μin.

Buffing consisted of buffing the "light polished" specimens on an electric cloth buffing wheel using jeweller's rouge as the abrasive. This process reduced the surface finish of both specimens to 16 μin RMS.

Hand lapping consisted of hand lapping the "buffed" specimens on a microflat using 600 W Emery cloth followed by Crocous cloth. This resulted in a surface finish of less than 5 μin RMS. The specimens were then buffed to a high polish.

Prior to installation in the test column, all specimens were cleaned with Acetone and/or alcohol.

Experimental procedure

The test apparatus is designed so that the test column can be installed with a small compressive loading due to spring forces created in the bellows. This causes a small interface pressure ($\Delta P \approx 5$ lb/in^2) which is considered as the zero loading pressure for all tests.

After installation of the test column, the ambient pressure was reduced to at least 5×10^{-5} torr before testing was initiated.

For the various data points in each run, power was set on a heat source, cooling water was valved through the opposite source sink, and a load was set. Equilibrium was reached in 4–5 h. Thermocouple and load readings were taken after waiting at least 5 h.

The heat flow direction was reversed in such a manner that no more than three consecutive data points were taken with heat flow in the same direction.

Temperature readings were taken on a Leeds and Northrup mV potentiometer model 8686.

The heat flux through each heat meter was calculated using equation (2). The thermal conductivity was evaluated at the middle thermocouple temperature and the average temperature drop across the three thermocouples was used. Thus:

$$Q'' = 24 \times K_{\text{at } T_{II}} \times \frac{(T_I - T_{III})}{2} \frac{\text{Btu}}{\text{h ft}^2} \quad (2)$$

The test column heat flux was computed as the arithmetic average of the heat flux calculated in the heat meters.

The difference in heat flux measured through the two meters was usually less than 5 per cent. For a few data points the difference was as high as 10 per cent.

The interface temperature in each specimen was calculated using equation (3). For the aluminum specimens the thermal conductivity was evaluated at the thermocouple reading temperature since there is only a small temperature change across the aluminum specimen. For the stainless steel specimens the thermal conductivity was calculated at $(T_{TS} + T_{IF}t)/2$ where $T_{IF}t$ was the first approximation of the interface temperature. This was necessary since the temperature drop across the stainless steel was appreciable.

$$T_{IF} = T_{TS} \pm \frac{Q''\Delta x}{K}. \quad (3)$$

The interface temperature drop ΔT_{IF} was calculated as the difference in the interface temperatures of the two specimens. The mean interface temperature was calculated as the average of the interface temperatures. The interface conductance was calculated using equation (1).

The temperature dependency of the thermal conductivity of the aluminum and stainless steel was taken from [8, 9], respectively.

The apparent area, i.e. the cross sectional area of the test column, was always considered as the heat flow area for heat flux calculations and as the contact area for pressure calculations.

RESULTS

Precision of data

The possible sources of error encountered in this investigation were due to either uncertainty of the measured data or faulty experimental technique. In addition, radial heat losses might be considered a source of error since a large radial loss at the interface would cause a warping and distortion of the interface surface. This would change the experimental results and thus might prove to give misleading data. These gradients would be greatest in the low conductivity material (stainless steel in this investigation).

Radial heat losses could only have been due to radiation since the ambient atmosphere was 5×10^{-5} torr. Radiation heat losses in the stainless steel were calculated on the basis of $\epsilon = 0{\cdot}18$ (stainless steel [10]) and found to be less than 1 per cent of the axial heat flow, which results in a radial temperature difference from center line to edge, due to radiation losses, of less than 0·1 degF. The surface of the test column was polished to minimize radial heat losses.

An uncertainty analysis made in the manner of Kline and McClintock [11] shows the uncertainty of the measured H to be from 5 to 12 per cent, depending upon the magnitude of the interface temperature drop ΔT_{IF}.

Error in experimental technique could be due to misalignment of the test specimens or to the presence of foreign material on the test specimen interfaces. The test specimens were considered misaligned when the center of the actual contacting area did not coincide with the test column centerline. Thus, misalignment could occur if the specimens were non-flat, such as with non-symmetrical spherical caps. Caution was used to prevent these errors. It was discovered in an early run that misalignment did not affect the directional effect but did reduce the magnitude of the conductance (see Fig. 8).

Thus the only significant source of error was the uncertainty of measured data.

The uncertainty in pressure measurements was estimated using a system of dead weights to be as high as 10 per cent for low pressures (0–150 lb/in^2). No check was made at high pressures but it is felt that the same amount of error is likely.

To investigate sources of error in the temperature measurements tests were run at high pressure with the stainless steel–aluminum test interface filled with vacuum grease to minimize contact resistance. Under these conditions the temperatures measured in the test specimens and extrapolated to the interface were found to closely agree. The effect of the vacuum grease should be to increase the interface conductance by approximately an order of magnitude [1] and thus to reduce the temperature drop across the interface to a small value. The uncertainty in temperature measurements is estimated to be 1 per cent, worst case, for an individual temperature measurement and 5 per cent, worst case, for the temperature drop across the interface.

Vacuum grease was also used between the non-test interfaces to reduce the temperature drop across these to a negligibly small value. These surfaces were in an "as received" condition with a uniform roughness and a flat surface. Thus, there should be no effect of the aluminum–stainless steel and aluminum–aluminum heat meter to test specimen interface on the actual test interface.

Some comments concerning the size of test samples are appropriate. The length to radius ratio is 2. Jeng [12] has noted that for a ratio of length to radius greater than 0·8 the microscopic constriction resistance should be independent of length. Thus, the heat flow away from the interface should be one-dimensional. For the flat–rough test specimens the resistance is dominated by microscopic considerations and it is felt that the thermocouples were reading in a region of one-dimensional heat flow. For the spherical cap specimens the macroscopic resistance is controlling and the heat flow must go through the area of macroscopic contact which lies on the axial center line of the specimens. In this case, if the flow were not one-dimensional at the thermocouple, the thermocouple in both the stainless steel and aluminum specimens could be reading differently than the corresponding reading for one-dimensional flow. The stainless steel specimen would be more seriously affected; however, the effect is essentially independent of the heat flow direction and the effect on interface resistance would be the same for either direction. Thus the magnitude of the interface conductance might be affected but the trends in the directional effect are not changed. As a last comment on accuracy, results with the same specimens were found to be reproducible, within the given limits of uncertainty, for different runs made under similar test conditions. Further, all measured trends were repeatable.

Effect of polishing

Figure 6 shows the effect of light polishing on the directional effect. The interface conductances shown in Fig. 6(a) are for specimens in an "as received" condition, i.e. they were machine ground to the surface roughness and flatness shown. In Fig. 6(b) the interface conductance for the same specimen pair with lightly polished interfaces is shown. The surface conditions of the aluminum interface changed in that the flatness deviation increased but there was no appreciable change in the stainless steel interface. Since the flatness was essentially equal to the surface roughness these specimens are considered to be flat–rough. The conductance is higher for heat flow in the aluminum to stainless steel direction.

Comparing Figs. 6(a) and 6(b) it is seen that the polishing reduced the interface conductance but had no effect on the directional effect. The decrease in conductance was expected since the polishing technique used slightly reduced the flatness of the aluminum specimen. No change in the directional effect was expected since in both cases the interface surfaces resembled model *B*, i.e. flat–rough.

Effect of buffing and lapping

The interface conductances for a specimen pair were measured: first in the "as received" condition, Fig. 7(a), then, after high speed buffing, Fig. 7(b), and finally, after hand lapping, Fig. 7(c). The fact that the magnitude of inter-

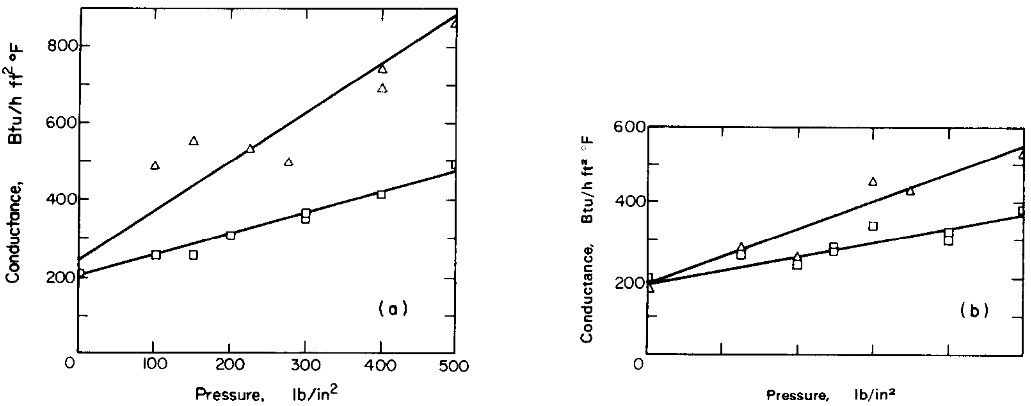

FIG. 6. Effect of polishing on the directional effect: (a) as received conditions; (b) lightly polished specimens, flat-rough conditions in both a and b; (μ = μin).

	Heat flow direction	Finish *AL*	Finish *SS*	Flatness *AL*	Flatness *SS*	Q'' average (Btu/h ft² × 100)	Mean interface temperature (°F)	Interface ΔT (°F)
(a) □	*SS*→*AL*	32	24	32	24	100→120	125→140	25→55
△	*AL*→*SS*	μ	μ	μ	μ	99→125	216→250	14→52
(b) □	*SS*→*AL*	24	24	50	24	115→130	125→150	34→67
△	*AL*→*SS*	μ	μ	μ	μ	99→115	215→245	21→63

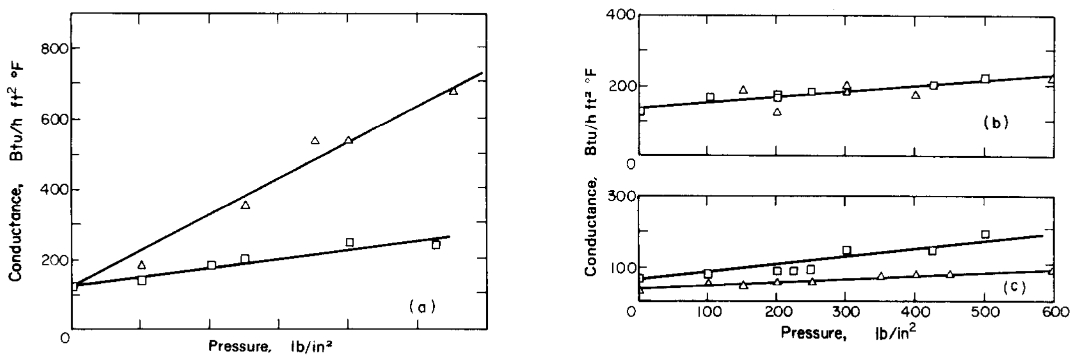

FIG. 7. Reversal of the direction for greater conductance, caused by buffing and lapping. (a) Flat rough model, as received conditions; (b) after high speed buffing; (c) after hand lapping, spherical cap model; (μ = μin).

	Heat flow direction	Finish *AL*	Finish *SS*	Flatness *AL*	Flatness *SS*	Q'' average (Btu/h ft² × 100)	Mean interface temperature (°F)	Interface ΔT(°F)
(a) □	*SS*→*AL*	32	24	32	24	85→120	125→157	38→79
△	*AL*→*SS*	μ	μ	μ	μ	100→145	245→277	18→79
(b) □	*SS*→*AL*	12	16	100	50	106→132	140→190	58→86
△	*AL*→*SS*	μ	μ	μ	μ	92→105	235→250	43→70
(c) □	*SS*→*AL*	5	5	300	230	97→141	155→207	66→158
△	*AL*→*SS*	μ	μ	μ	μ	53→99	238→274	94→156

face conductance decreased in successive runs was due to the polishing and lapping techniques which reduced the flatness.

By comparing Figs. 7(a) and (c), it can be seen that the *directional effect did reverse itself* as the surface conditions changed from flat rough (model *B*) to a spherical cap (model *A*). Figure 7(b), which shows no directional effect, indicates that the buffing resulted in an interface surface condition which is neither model *A* nor model *B*, but presumably somewhere in between. This data is considered to verify the existence of the need for a model(s) which includes the effects of both flatness and roughness.

Effect of orientation

The sensitivity of the measurement of interface conductance to changes in orientation of the test specimens is shown in Fig. 8. The specimen pair used in run No. 8 was the same pair used in run No. 7 and fitted the spherical cap model. When run No. 7 was completed, the test specimen pair was rotated in such a manner that the same surfaces formed the interface while the test specimens changed position in the test column. During run No. 7, the test specimens were observed to be misaligned. The specimens were positioned to a better alignment for run No. 8. Note that here the conductance is greater for heat flow in the stainless steel to aluminum direction.

Comparing the results, it is seen that measurements of the directional effect were not sensitive to changes in orientation of the specimen pair. Thus, changes in alignment or test column position did not effect the directional effect. However, quantitative measurements of the interface conductance are sensitive to changes in orientation.

Effect of surface conditions

Figures 6 and 7(a) show interface conductances for interface surfaces which had a surface roughness of 24–32 μin RMS and a measured flatness of 24–50 μin. These surfaces clearly fit model *B*. It is seen in these figures that the interface conductance is higher when *heat flows in the aluminum to stainless steel direction.* The analysis of model *B* predicted this directional effect. Thus both the analysis and the experimental results agree such that for interfaces of dissimilar metals with a flat rough interface the conductance is greater when heat flows from the metal of high conductivity (aluminum) to that of low conductivity (stainless steel).

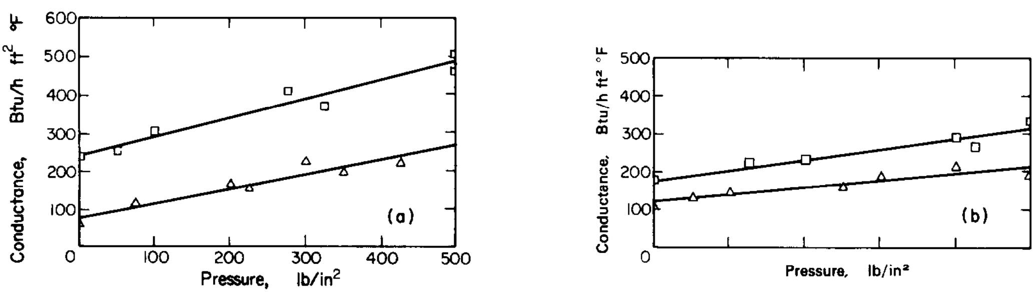

FIG. 8. Effect of orientation on the interface conductance, spherical cap type specimens. (a) run number 7; (b) run number 8; (μ = μin).

		Heat flow direction	Finish *AL*	Finish *SS*	Flatness *AL*	Flatness *SS*	Q'' average (Btu/hft² × 100)	Mean interface temperature (°F)	Interface *T* (°F)
(a)	□	*SS*→*AL*	5	5	2000	1250	98→113	121→135	21→44
	Δ	*AL*→*SS*	μ	μ	μ	μ	85→118	225→268	48→135
(b)	□	*SS*→*AL*	5	5	2000	1250	90→100	120→135	31→52
	Δ	*AL*→*SS*	μ	μ	μ	μ	88→116	227→260	50→80

The directional effect shown in Figs 6 and 7(a) agree qualitatively with the observations of Barzelay *et al.* [3] who also used specimens fitting model *B*. The quantitative difference between the two experiments is expected since they performed their tests at atmospheric conditions, at higher heat rates and with specimens that had a greater surface roughness.

Figures 7(c) and 8 show interface conductances for interface surfaces which have a surface roughness of 5 μin RMS and flatness of 230–2000 μin. These interface surfaces fit model *A*. The interface conductances shown in Figs. 6(a) and 8(c) are higher when heat flows in *the stainless steel to aluminum direction*. Clausing [4], using model *A* and test specimens fitting model *A*, predicted and measured this type of directional effect.

Effect of pressure

The results in Figs. 7(c) and 8 show little or no directional effect at low pressures. Reference [3] also shows little or no directional effect at low contact pressures. At higher contact pressures, [3] shows an increased directional effect; the present results also show an increase in directional effect with pressure. In each of these cases the surface conditions were those prescribed by model *B*.

For the specimens with model *A* interfaces (smooth spherical cap) pressure had no effect on the magnitude of the directional effect (see Figs. 7(c) and 8). Clausing, also using specimens with model *A* interfaces, found no change in directional effects with pressure.

Discussion

The test specimens used in this investigation were machined to represent model *A* in the "hand lapped" condition and model *B* in the "as received" condition. The lightly polished specimens also represented model *B* since their interface surface conditions were only slightly altered. The buffed specimen pair represented neither model *A* nor model *B*.

When model *A* specimens were used, the directional effect observed was that predicted and observed by Clausing. Thus his investigation is verified and extended to include smooth specimens with flatnesses of 90–2000 μin.

When model *B* specimens were used, the directional effect observed was that predicted in the present analysis for flat rough surfaces. Barzelay *et al.* used model *B* specimens and observed the same directional effect. Clausing [4] has suggested that this directional effect might have been due to radial heat losses. This possibility was eliminated in this investigation since minimal radial heat losses were experienced and still directional effects opposite to those of Clausing's were observed.

Moon and Keeler [13] have suggested that directional effects could be caused by oxide layers on the interface. This investigation has not eliminated this possible cause of directional effects but has shown that the oxide layer effect is small compared with the effects of surface flatness and roughness.

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REFERENCES

1. A. M. Clausing and B. T. Chao, Thermal contact resistance in a vacuum environment, *J. Heat Transfer* **87**, 243–251 (1965).
2. M. M. Yovanovich and H. Fenech, Thermal contact conductance of a nominally-flat, rough surface in a vacuum environment, AIAA paper 66–42 (1966).
3. M. E. Barzelay, K. E. Tong and G. F. Holloway, Effect of pressure on thermal conductance of contact joints, NACA TN 3295 (1955).
4. A. M. Clausing, Heat transfer at the interface of dissimilar metals—the influence of thermal strain, *Int. J. Heat Mass Transfer* **9**, 791–801 (1966).
5. F. F. C. Rogers, Heat transfer at the interface of dissimilar metals, *Int. J. Heat Mass Transfer* **2**, 150–154 (1961).
6. R. W. Powell, R. P. Tye and B. W. Jollife, Heat

transfer at the interface of dissimilar materials: evidence of thermal-comparator experiments, *Int. J. Heat Mass Transfer* **5**, 897–902 (1962).
7. R. K. Young, Experimental aspects of directional effects of interface thermal conductance between aluminum and stainless steel, Master's report, Aerospace and Mechanical Engineering Department University of Arizona (1966).
8. H. C. Perkins. Personal correspondence with R. P. Pingatore of Aluminum Company of America, Los Angeles, Calif. (May 1966).
9. J. Metolick, Jr., Thermal conductivity and electrical resistivity of type B16 stainless steel from 0 to 1800 F, NACA CR 54151 BATT-7096 (1965).
10. J. A. Wiebelt, *Engineering Radiation Heat Transfer*. Holt, Rinehart and Winston, New York (1966).
11. S. J. Kline and F. A. McClintock, The description of uncertainties in single sample experiments, *Mech. Engng* **75**, 3 (1953).
12. D. R. Jeng, Thermal contact resistance in vacuum, *J. Heat Transfer* **89**, 275–276 (1967).
13. J. S. Moon and R. N. Keeler, A theoretical consideration of effects in heat flow at the interface of dissimilar metals, *Int. J. Heat Mass Transfer* **5**, 967–971 (1962).

Résumé—Des chersheurs ont exposé récemment que le grandeur de la conductance de l'interface de certains métaux différents dépend de la direction du flux de chaleur. Dans cet article, la contradiction entre les résultats antérieurs concernant cet effet directionnel pour les interfaces acier-inoxydable–aluminium est résolue en montrant que le phénomène de cet effet directionnel dépend des conditions de surface de l'interface, c'est-à-dire de la planéité et de la rugosité. On donne la démonstration expérimentale de cette dépendance et l'on présente des modèles pour expliquer le phénomène.

Zusammenfassung—In neuerer Zeit wurde berichtet, dass die Grösse des Kontaktwiderstandes ungleicher Metalle von der Richtung des Wärmestromes abhängt. In dieser Arbeit werden frühere Widersprüche in den Ergebnissen hinsichtlich des Richtungseinflusses bei Stainless Steel–Aluminium-Kontakten geklärt, indem gezeigt wird, dass Richtungseffekte von der Oberfächenbeschaffenheit d. h. Flachheit und Rauhigkeit, abhängen.

Der experimentelle Nachweis für diese Abhängigkeit wird gebracht und Modelle, die das Phänomen erklären, werden angegeben.

Аннотация—В недавно опубликованных работах сообщалось, что величина теплопроводности на границе раздела некоторых неоднородных металлов зависит от направления теплового потока. В данной статье ранее опубликованные противоречивые результаты о влянии направления потока на границе раздела: нержавеющая сталь–алюминий разрешаются с помощью учета зависимости влияния направления потока от условий поверхности границы раздела, т.е. от плостностности и шероховатости. Эта зависимость подтверждается экспериментальными данными. Приводятся модели для объяснения этого явления.