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A Survey of the Thermal Conductance of Metallic Contacts

By

H. Y. Wong

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- By -

H. Y. Wong

Foreword

The Addendum cites papers which have been published since the survey was written; the majority of these consist of translations of previous work published in foreign countries, summaries of work, experimental reports or contract reports. A large proportion is the study of contact conductance in vacuo (in this case heat transfer through the fluid gap is treated in a free molecular regime instead of in a continuum regime). In other words, the work represents substantial gains in the practical field but little in the field of fundamentals.

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* Replaces A.R.C.26 715.

1. Introduction

The problem of thermal conductance of metallic contacts has become increasingly a problem of considerable significance in many practices of engineering and has received a great deal of attention in recent years. Theoretical and experimental studies have yielded valuable data which provide an insight into the complexity of the problem and a better understanding for future development. Although the problem has existed in almost all branches of engineering for some time, any serious study made is probably due to Jacobs and Starr (1) who carried out their investigation with the object of providing data for the design of cryogenic apparatus. In the course of their investigation into the problem of resisting welding, Kouwenhoven, Tampico and Sackett (2,3,4) brought forward a number of valuable points contributory to the investigation of the thermal contact problem. Since the problem of electric contacts has been under thorough study for a much longer time, any findings therefrom must have great bearing on the allied problem of thermal contacts. For this reason the classical work of Holm's (5) can be considered as relevant. Whether or not the electric contact equations can be applied also to thermal contacts will be discussed later, the presence of the thermal contact problem during an electric contact is clearly shown in the application of electrical welding. Some good work from Kouwenhoven and Potter (6) shows their interest in both these problems. Apart from welding, the demand for a better knowledge in other fields is equally strong. Keller (7) measured the heat transfer in strip coil annealing when heat was supplied radially to the coils. Brunot and Buckland (8) who were interested in the application of the problem to components of electrical equipment, measured the thermal resistance between laminated steel blocks and between cold rolled steel blocks. In order to study the resistance to the dissipation of combustion heat from aircraft engines, Weills and Ryder (9), at about the same time, made a much more general approach to the problem with the intention that any results thus obtained could be applied to other branches of engineering. The same problem exists between machined parts of a heat plant and specifically at the root of gas turbine blades. This was investigated by Dyban, Kondak and Shvets (10). In foundry practice the freezing rate depends on the contact resistance between casting and mold. Owing to shrinkage, the resistance is liable to increase thus slowing down the freezing rate. Based on dimensionless parameters, Harvey and Edsall gave an analytical prediction (11).

The search for a better understanding of the problem of thermal contact conductance will continue to extend with progress in science and technology, but the urgent demand in the fields of aeronautical engineering and nuclear engineering has kindled a general interest and given an impetus to recent advances. In the design of aircraft for supersonic speed flight, the thermal stresses produced by aerodynamic heating may cause buckling, flutter, loss of stiffness or other effects detrimental to the functioning of the aircraft. The prediction of thermal stresses depends on a knowledge of the temperature distribution which is often hampered by the uncertainty of the contact resistance in the structure. In order to obtain a more realistic solution, large schemes of experiments on actual joint samples have also been conducted (12-21). In the design of a nuclear reactor, on the other hand, not only does the accurate prediction of the thermal contact resistance lead to the safe design of the plant, but also any reduction in the contact resistance between fuel and shield will yield a greater quantity of heat extraction. Unfortunately the problem is complicated by the variable contact conditions during burn-up when fission gas is being released. Because of the properties of the fuel and the geometry of contact, special considerations such as avoiding oxidation of the fuel and providing cylindrical surface contact to represent the true condition of fuels in rod form have to be given during experiments (22-32).

/Parallel

Parallel with the progress in experimental studies useful theoretical studies have also been advanced (33-41, 70). Some of the work has been fittingly summarized by Putnaerglis, Wheeler and Kanokawa (26,42,43). In space environments, the thermal contact resistance can be greatly increased due to the reduction of applied contact pressure and interfacial fluid pressure, as reported by Fried and Costello (44). The investigation carried out at low temperatures by Berman and Mate at Oxford for the design of mechanical heat switches provides useful information for cryogenic applications (45,46).

2. Mechanism of Contact Heat Transfer

In a solid body the condition of heat flow follows the law of conduction. When the body is cut into two halves, however carefully the process may be carried out, the two sections will never fit together again and the heat flow will experience a discontinuity at the joint where there is a sudden temperature drop (47). Two pieces of metal would form a perfect joint only if the surfaces of contact were perfectly smooth and clean. Unfortunately a perfectly smooth surface is not feasible in practice, from the microscopic point of view. There are irregularities present even on very carefully prepared surfaces, so that when two bodies are brought into contact, only the summits of some of the irregularities are in actual contact whilst the rest of the two surfaces are separated by a gap filled with fluid. Furthermore, the intimacy of metallic contact is greatly influenced by the presence of surface films which under normal conditions are difficult to avoid (48). Hence the flow of heat at the interface will be forced to take up different modes of transfer dictated by the conditions at the interface. As the contact conditions are subject to alteration during heating, the modes of heat transfer are therefore affected, preventing the forming of accurate predictions. For the purpose of discussion, let us assume in broad terms that there are three modes of heat transfer.

1. Heat transfer by conduction through actual contact.

   Owing to the thermal conductivities of metals being much higher than those of fluids, the lines of heat flow will converge towards the contact spots giving rise to a contact resistance. In the event of the actual contact of two irregularities being prevented by the presence of a tarnish film, this can still be regarded as a contact spot, but the contact resistance is now increased because of the lower thermal conductivity of tarnish films compared with that of metals. The total contact resistance is denoted as R_c .

2. Heat transfer through interfacial gas. (If the fluid is a gas)

   If the distance between the two surfaces is small, convective heat transfer becomes unimportant and heat transfer can be considered as by means of conduction. At the solid-gas interface there is a temperature drop, the effect of which is specified in terms of the accommodation coefficient. When the surfaces are covered with tarnish films, the fluid resistance will consist of the resistance due to the temperature jump, the conduction resistance of the films and the conduction resistance of the fluid. We denote the total resistance as R_f .

/3.

3. Heat transfer by direct radiation

Radiation heat transfer will take place between two surfaces of different temperatures. The quantity of heat transferred in this way depends on the absolute values of the temperatures and the surface emissivities. Although hot gases may also emit radiant energy, this is really insignificant. Let the resistance to radiation be denoted as R_r.

If we assume that there are three separate paths for the contact heat flow, we see that the total resistance of the interface can be expressed as

$$\frac{1}{R_T} = \frac{1}{R_c} + \frac{1}{R_f} + \frac{1}{R_r}$$

where R_T is the total contact resistance of the interface.

The amount of heat which can flow along each path depends on the resistance of all three paths. For example

$$Q_c = Q \left[\frac{R_f R_r}{R_c R_f + R_c R_r + R_r R_f} \right]$$

$$Q_f = Q \left[\frac{R_c R_r}{R_c R_f + R_c R_r + R_r R_f} \right]$$

$$Q_r = Q \left[\frac{R_c R_f}{R_c R_f + R_c R_r + R_r R_f} \right]$$

where Q_c, Q_f, Q_r are the amount of heat flow through the contact path, fluid path and radiation path respectively. Q is the total amount of heat flow through the interface. Strictly speaking all three modes of heat transfer are inter-dependent and this is due to the fact that the resistance of each path is sensitive to the amount of heat flowing through it.

For simplicity of calculation, the three modes of heat transfer are usually treated as independent.

/3.

3. Metallic Contact Conductance

3.1 Contact area

Only if the actual contact area is of a reasonable size compared with the apparent area of contact, dominant flow of heat across the interface will certainly be attracted through the metallic contact spots, as the thermal conductivity of metals is very much higher than that of a gas. Keller (7) reported from his experiment that 95-98% of conductance was due to air films and only 2-5% to actual metallic contacts. We may well suspect that the actual contact area in his experiment must be remarkably small. This is not surprising as on a normal contact surface the actual contact area is but a very small fraction of the apparent area of contact. Bowden and Tabor (49) showed that for a load of 2 kg. acting on a flat area of 20 sq. cm of steel, the area of intimate contact was only 1/100,000 th of the apparent area. This indicates that the local contact pressure can be very high, being sufficient to cause local plastic flow. They confirmed that this does in fact happen even at a very low load. Hence it is reasonable to assume that except for a very smooth surface under a very small load, the occurrence of purely elastic deformation is unlikely. If the applied load causes a local mean pressure equal to about 1.1 times the elastic limit of the material, we have the onset of plastic flow. As the load is increased, the mean pressure increases until it is about 3 times the elastic limit of the material (i.e. the softer of the two materials), when we have the fully plastic flow. If the load is further increased, the area of contact will increase but the mean pressure will remain equal to 3 times the elastic limit which may increase during the process of work hardening, a consequence of plastic deformation (50). Since the surface of most materials is, to a certain extent, work hardened owing to manufacturing processes, we may assume the total load-bearing area, which is the sum of all actual contact areas, to be taken as

$$A_c = \frac{W}{P_m} .$$

where W is the applied load and P_m the mean yield pressure. For full work-hardening, P_m is the Meyer hardness value (51). This total contact area A_c is made up from the sum of a large number of small contact areas over the whole surface of contact. To know the number and the distribution is essential for the determination of the contact conductance.

3.2 Constriction resistance

When uniform current flow occurs in a solid body, the current density is uniform everywhere because of uniform resistance of the body. The flow lines run parallel to each other. As the flow lines approach the contact region they are attracted toward paths of least resistance and this usually occurs at the metallic contact points, resulting in their convergence towards those points. The constriction of current flow through narrow passages gives rise therefore to a resistance termed as constriction resistance. If the two contact surfaces are perfectly clean, the contact members will adhere as if they were welded at the spots. In this case the constriction resistance applies to both electric and thermal contacts (5). Such a close relationship between the two problems has been advantageously used by a number of workers (4,25,33,35,37,38,45,46,48,51) either in formulating a contact theory for a single contact model or in predicting the number and size of the contact spots.

/In

In general, the size of the contact spots is very small compared with the distance separating them. Thus Holm's simple expression of constriction resistance is frequently applied in computations, i.e.

$$R = \frac{1}{2a\ k} = \frac{1}{C}$$

where a is the radius of the contact spot, k the conductivity and C is the conductance. For interface materials with different thermal conductivities the harmonic mean value is used and k is replaced by k_s, i.e.

$$k_s = \frac{2\ k_1 k_2}{k_1 + k_2}$$

Roess (51) calculated the contact conductance of heat flow through a right circular cylinder with a symmetrical constriction, on the assumption that there was no heat transfer through the fluid between the surfaces and that the heat flux at the metallic contact at a distance x from the centre was given by $q/2\,\pi a\sqrt{a^2 - x^2}$ where q is the quantity of heat flow per unit time.

The contact conductance equation which he obtained takes the following form

$$C = 2a\ k_s \left[1 - 1.4093\left(\frac{a}{r}\right) + 0.2959\left(\frac{a}{r}\right)^3 + 0.0525\left(\frac{a}{r}\right)^5 + \ldots\right]^{-1}$$

where k_s is the thermal conductivity of the solid and r the radius of the cylinder. By reason of a/r generally being small, Laming considered the first two terms should be adequate and he used

$$C = 2a\ k_s \left[1 - 1.41\left(\frac{a}{r}\right)\right]^{-1}$$

Karush (39) considered that the temperature distribution was disturbed by the constriction of the flow and that it could be represented by a harmonic function which vanished at a distance from the contact region. The contact resistance equation he calculated is

$$R = \frac{2r}{k_s}\ f\left(\frac{a}{r}\right)$$

for two identical spots in contact with zero plug length, where k_s is the thermal conductivity of the material. For small a/r ratio, the function

$f\left(\frac{a}{r}\right)$ becomes

$$f\left(\frac{a}{r}\right) = \frac{8\ a}{3\pi r}$$

/∴ C

$$\therefore \quad C \; = \; \text{conductance} \; = \; \frac{1}{R} \; = \; \frac{3\pi \; k_s}{16a} \; \pi \, a^2 \; = \; 1.85 \; a \; k_s$$

Cetinkale and Fishenden (33) carried out one of the first thorough analyses in which they considered the simultaneous existence both of solid and fluid conductances. A dividing flow line separates the lines of flow so that on one side of it the amount of heat is transferred by solid conductance and on the other side by fluid conductance. The flow lines for solid conductance converge towards the contact spot giving rise to the constriction resistance.

The equation for solid conductance takes the form

$$C_s \; = \; \frac{\pi \; a \; k_s}{\tan^{-1}\left[(r_d - a)/a\right]}$$

where $r_d = r\sqrt{1 - \dfrac{C_f}{C_T}}$ (radius from the centre of the cylinder to the dividing flow line at a distance from the contact region. C_f and C_T are fluid conductance and total conductance respectively)

It can be seen that the link between solid conductance and fluid conductance lies in the ratio r_d/r . The direct determination of this ratio is made complicated by the number of boundary conditions to be satisfied. For this reason, they resorted to the relaxation method. When fluid conductance is ignored and a is assumed to be very small compared with r , the above conductance equation becomes

$$C_s \; = \; 2 \; a \; k_s$$

which is Holm's equation.

Fenech and Rohsenow (36) presented a mathematical analysis for an ideal contact spot similar to the one used by Cetinkale and Fisheneen. In spite of the complicated boundary conditions to be satisfied, they have succeeded in obtaining a direct solution after making some simplifying assumptions. The heat transfer coefficient for solid conductance alone is given by

$$k_c \; = \; \frac{2.4 \; ^{\varepsilon}/r}{(1 - \varepsilon^2)\left[1 \; - \; \dfrac{k_f}{\delta_1 + \delta_2}\left(\dfrac{\delta_1}{k_1} + \dfrac{\delta_2}{k_2}\right)\right]\left[\dfrac{2.4\;\delta_1/a + 1}{k_1} + \dfrac{2.4\;\delta_2/a + 1}{k_2}\right]}$$

where $\varepsilon = \dfrac{a}{r}$ and δ_1 , δ_2 are respective heights of the fluid space.

When a is small compared with r and when the fluid is absent, the solid conductance may be expressed by

$$C \; = \; \frac{2.4 \; \pi \; a \; k}{2.4 \; \delta/a \; + \; 2}$$

/where

where $\delta = \delta_1 + \delta_2$

If δ is of the same order as a , C assumes a value very much the same as the Holm's value.

It may be concluded therefore that Holm's expression for the constriction resistance gives a good approximation. Hence by means of electrical resistance measurements, the number and size of the contact spots can be obtained. For n spots, we have the contact resistance

$$R = \frac{1}{2akn}$$

also

$$A_c = n \pi a^2 = \frac{W}{P_m}$$

Therefore

$$n = \frac{\pi P_m}{4 k^2 R^2 W}$$

and

$$a = \frac{2 k W R}{\pi P_m}$$

3.3 Surface roughness

It must be admitted from the start that up to the present no one standard parameter can adequately define the roughness of a surface to satisfy the requirements of a thermal contact problem. This has been realised by many investigators (6,13,30,36,40,42,53,54). Standards for surface roughness used by most countries are either the Mean Line system or the Envelope system.

In the mean line system, the roughness of a surface is defined either by the centre line average values or the root mean square values, and the usual technique of measurement is by means of a stylus equipment in conjunction with an electrical integrating meter to indicate the value over a sample length. In the Envelope system, no reliable instrument has yet been designed for the measurement. The main object of all these standards is to give a reasonable classification of a surface texture for industrial purposes. Users for academic purposes are warned of their limitation (55,56). Olsen (57) made a close study of the various standards employed by different countries, pointing out that the true measurements of any surface should be three-dimensional. The difficulty involved in making such measurements, however, lies in the transformation of the various definitions into a two-dimensional plane. Machined surfaces would have ridges and waviness, but ground, polished and lapped surfaces would only have dimples and humps. Other types of surfaces may have irregularities distributed at random. When two surfaces are pressed together metallic contacts are set up but the manner in which these are established is often arbitrary. With the same pair of surfaces there may be an infinite number of matching configurations

/although

although the net results may not always be of a wide range. The variation of matching configuration for flat and smooth surfaces is smaller than for rough surfaces. On the other hand, the establishment of metallic contact between rough surfaces is more definite at higher contact pressures and this in turn produces more consistent results. Thus it is clear that the size and distribution of metallic contacts between two surfaces depends both on the roughness of the surfaces and the applied pressure.

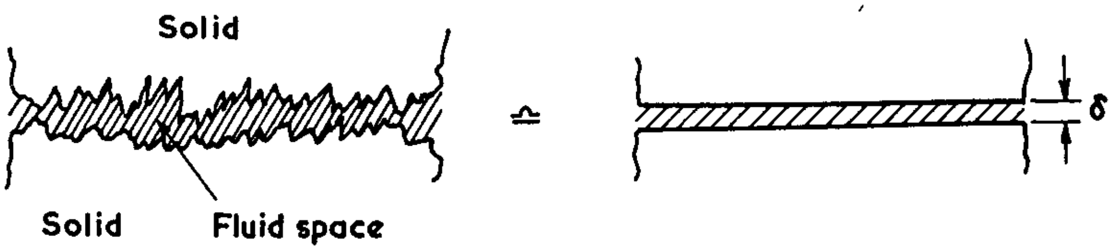
To meet the requirements of a thermal contact problem, the complete definition of surface roughness will require a number of parameters, the larger the number the more precise the definition. Yet too large a number of parameters will certainly make the problem much more involved and perhaps unsolvable. This can be regarded as the most difficult part of the whole problem. Any accurate prediction of the sizes, number and distribution of the contact areas may never be possible unless the surfaces are specially prepared to produce a controlled texture. Controlled surfaces to give a more defined contact configuration have been used by many investigators (6,8,30,34,36,40,54). In this way, the mechanism of heat transfer at the interface can be more positively examined. There is a definite relationship between the contact conductance and the areas of contact. A roughness parameter together with the applied pressure, however, can only, at best, provide a qualitative indication of the nature of heat transfer through the joint. This may also explain the reason why there were conflicting conclusions when contact conductance was treated as a function of roughness parameter and applied pressure.

4. Fluid Conductance

If the distance between two contact surfaces is less than the mean free path of the gas molecules heat transfer can be considered as by means of free molecular conduction. At any rate, if the Gashof No. is below 10^3, convective heat transfer can be assumed to be unimportant (58). The amount of heat transferred across the fluid space by conduction therefore depends largely on the thermal conductivity of the fluid. If the fluid thermal conductivity value is higher than that of the metal we can expect most of the flow lines to be attracted towards the fluid region. The convergence of the flow lines will similarly give rise to a constriction resistance. But since the fluid covers a much greater space the nett resistance of the interface is expected to be less than the normal resistance of the metal for the whole cross-sectional area. If the interfacial fluid is a gas as in most cases, the gain in occupying a large surface area is off-set by the lower thermal conductivity of the gas itself when compared with that of the metal. Thus the thickness of the fluid layer becomes also an important factor.

Owing to the irregularities on the contact surfaces, the thickness of the fluid layer varies from point to point, and so long as the roughness of the surface can not be successfully defined, the variation of the fluid thickness will not be accurately determined. One way of overcoming this difficulty is to take sample lengths of the two surface profiles and take measurements to give the equivalent fluid height on the assumption that the three-dimensional space can be reasonably represented by the two-dimensional profiles.

/Sketch



δ = equivalent fluid height

This approach has been used by a number of investigators (33-38). Cetinkale and Fishenden (33) determined the value of δ from the arithmetic mean value of the profile β by putting

$$\delta = \varepsilon \beta$$

where ε is a constant which was calculated from the relationship

$$\delta = k_f/u$$

where u is the heat transfer coefficient through the fluid measured during contact at zero pressure and k_f is the fluid thermal conductivity. They found from specimens of ground surfaces that the equivalent fluid height δ is a linear function of the centre line average value β giving ε a value of 0.61.

Laming (40) on the other hand, pointed out the unreliability of measuring fluid conductance at zero pressure owing to the complications presented by the presence of any tarnish film on the surface. From his machined surface specimens he found that the zero load conductances were considerably larger than calculation would indicate using a simple gap parameter.

Alternatively, if tests are conducted in vacuum and with other types of gases, some information on the value of the equivalent fluid height may be obtained. The results of such tests may also facilitate the study of the significance of the fluid conductance in the contact conductance of the interface as a whole. This was in fact carried out by Laming and others (6,9,24,25,29, 30,33,54,59).

Assuming for the moment that the equivalent fluid height value can be successfully obtained, and assuming that the heat transfer through the fluid space is essentially linear (i.e. the heat transfer through the solid contact has no effect on that through the fluid) we may obtain the fluid conductance as

$$C_f = \frac{k_f}{\delta}$$

The assumption of linear heat transfer through fluid is valid if the fluid gap is small compared with the size of the solid contact area. If this is not so, the influence of the solid conductance cannot be altogether ignored. Fenech and Rohsenow (36) included the coupling condition in their analysis and derived the fluid conductance as

/C_f =

$$C_f = \frac{\dfrac{k_f}{\delta_1 + \delta_2}\left[(1-\epsilon^2)\left(\dfrac{2.4\ \delta_1/a+1}{k_1} + \dfrac{2.4\ \delta_2/a+1}{k_2}\right) + 1.1\ \epsilon\ f(\epsilon)\left(\dfrac{1}{k_1} + \dfrac{1}{k_2}\right)\right]}{(1-\epsilon^2)\left[1 - \dfrac{k_f}{\delta_1+\delta_2}\left(\dfrac{\delta_1}{k_1} + \dfrac{\delta_2}{k_2}\right)\right]\left[\dfrac{2.4\ \delta_1/a+1}{k_1} + \dfrac{2.4\ \delta_2/a+1}{k_2}\right]}$$

where $f(\epsilon)$ is a function of ϵ and has a value near to unity for $\epsilon < 0.1$. If we take $\epsilon \ll 1$, $\delta_1 \ll a$, $\delta_2 \ll a$, $k_f \ll k$ this equation can be reduced to a simple expression

$$C_f \simeq \frac{k_f}{\delta_1 + \delta_2}$$

To determine δ_1 and δ_2 they used a graphical method taking into account the three-dimensional nature of the fluid space.

For those investigators who used specimens with controlled surface texture, the value of δ could be readily obtained. Rapier, Jones and McIntosh idealized the surface profile in their calculation (30).

If the fluid is a gas, the accommodation effect will cause a temperature jump at the solid-gas interface.

$$T_{solid} - T_{gas} = \ell \frac{\partial T}{\partial n}$$

where ℓ is equivalent to a temperature jump distance and $\dfrac{\partial T}{\partial n}$ the temperature gradient normal to the wall. To include this effect, extra distance is added to the equivalent fluid height δ (33). This distance is a function of the gas properties and the accommodation function (60). For the effects on both faces we have

$$\ell = \ell_1 + \ell_2 = \frac{a_1 + a_2 - a_1 a_2}{a_1 a_2}\ \frac{4}{\gamma + 1}\ \frac{k_f\ \lambda}{\mu\ C_v}$$

where λ is the mean free path, μ the coefficient of viscosity, C_v the specific heat for constant volume and γ the ratio of specific heats. Hence the equation of fluid conductance becomes

$$C_f = \frac{k_f}{\delta + \ell}$$

In general, metal surfaces are covered with a layer of contaminating film which offers additional resistance to the heat flow. This can be computed from

$$R_0 = \frac{1}{C_0} = \frac{\delta_0}{k_0}$$

/where

where δ_0 is the thickness and k_0 the thermal conductivity of the film (41).

Now the total fluid conductance takes the form

$$C_f' = \frac{C_f C_0}{C_f + C_0}$$

Usually the values of δ_0 and k_0 are not easy to measure. In this case the use of different gases may give an indirect answer.

We consider the thermal conductivities of gases being independent of gas pressure. This is not the case when the pressure is very low, so low that the mean free path of the molecules is larger than the boundaries confining them. Under this condition, the molecules transport heat across the interface at a single bound. There is no temperature gradient and the whole gas is at a uniform temperature. This is called free molecular conduction. In space environment where any heat transfer has to take place either in vacuum or in rarefied gases, free molecular conduction, although with a low heat transmitting efficiency, has to be reckoned with and it can be expressed by (44,60)

$$C_m = \frac{a_1 a_2}{a_1 + a_2 - a_1 a_2} \left(\frac{\gamma + 1}{\gamma - 1}\right)\left(\frac{R_g}{8\pi}\right)^{\frac{1}{2}} \frac{p}{\sqrt{M T}}$$

where p is the pressure of gas, R_g the universal gas constant, T the absolute temperature, a_1 and a_2 the accommodation coefficients and M the molecular weight. Fried and Costello's investigation in this field provides valuable information on a thermal contact joint problem which will be encountered in space vehicles.

5. Heat Conductance by Radiation

Jacobs and Starr (1) found that the conductance of the interface was approximately the same when the surfaces were just touching or separated and concluded that this was entirely due to radiation but the quantity was negligibly small. When the two surfaces are pressed together under a higher pressure where heat transfer through metallic channels prevails, it is expected that the heat transferred by radiation will be reduced. Unless the interface temperature is very high, this mode of heat transfer represented by

$$q = \sigma \frac{E_1 E_2}{E_1 + E_2 - E_1 E_2} (T_1^4 - T_2^4)$$

σ - Stefan-Boltzmann's constant

where T_1 and T_2 are the temperatures and E_1 and E_2 are the emissivities of the surfaces 1 and 2 respectively, is rather insignificant. Fenech and Rohsenow showed that even for a mean interface temperature as high as 1100°F, the amount of heat transferred by radiation is still less than 1% of the total quantity.

Cetinkate and Fishenden (33) incorporated the radiation term into the fluid conductance so that in the absence of any interfial fluid the conductance by radiation became the whole amount of fluid conductance. A majority of workers ignored radiation in their investigation

6. Effects on Thermal Conductance

There are a good number of factors which can have considerable influence on the thermal conductance of a contact joint. We shall now consider a few important ones.

6.1 The effect of surface films

A metal surface is usually covered by a tarnish layer of film, owing to either physical adsorption or chemical reaction. It is a compound of the metal itself and some constituents of the surrounding atmosphere. An oxide film is being the most common one on a metal surface. The film is sometimes relatively thick and visible such as in the case of a blackened silver; in other cases it may only be a few atoms thick and invisible, as in the case of aluminium. Bowden and Tabor (48) found that adherence and friction can be greatly reduced with the presence of the tarnish films on the surface and pointed out that it is clearly impossible under ordinary atmospheric conditions to produce surfaces which are really clean. The only effective way to remove them is to apply high temperature in high vacuum.

When two surfaces are brought together, only the surface films are in contact. Since the material of the film usually possesses different properties from those of the underlying metal, it presents a major difficulty in contact problems, both electrical and thermal.

It is well known that there is a close relationship between the thermal conductivity and electrical resistivity by the Wiedermann-Franz-Lorenz law and the use of electrical measurement for the solution of a thermal problem may seem to be a most convenient approach. This has been found, however, to be unsuitable with the thermal contact problem (4,10,25,33,35,36,44,45,46,61). In an electric contact the resistance can be considered to consist of the constriction resistance and film resistance in series whilst in a thermal contact, the resistance consists of solid contact constriction resistance, fluid and film resistance as well as radiation resistance to be connected as if in series and in parallel as explained in Section 2 of this paper. Even if both the fluid and radiation resistances were assumed to be absent, we still have the surface films to contend with. Any tarnish film may have a very high resistance to electricity but not so much to heat. As a result, the contact conditions presented by electrical measurements may not fit entirely into the thermal aspect. For example, if surface films are present, the number of contact areas determined by electrical resistance measurement will not include all those which are not entirely metallic contact points but separated only by a film layer. These points are still potential thermal contact points. The condition of these films around each contact point, whether metal-metal with films around it or metal-film-metal, must vary considerably under different local contact pressures. The situation may be further aggrevated by temperature and time. Hence the likely error of applying an electrical measurement to a thermal contact problem based on the constriction concept may not be easily compensated by taking an extra term to include the film electrical resistance as used by Holm (5) and suggested by Fenech and Rohsenow (36).

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In the case of fluid conductance, surface films will increase the fluid resistance. Since the thickness and the thermal conductivity can not be readily known, their effect may have to be treated with the interfacial fluid as a whole.

If the pressure on the contact points is increased the surface films, usually rather brittle, may be penetrated by the tip of the irregularities to allow metallic contacts to be established. The increase in metallic contact conductance is thus expected. This may explain the fact that rough surfaces are more responsive to pressure than smooth surface.

The significance of tarnish films at the interface has been clearly revealed by those investigators on nuclear fuel and can problems. Uranium is very prone to oxidation. A thin layer of oxide film may increase the thermal contact resistance many times. Special studies on the effect of oxide films have been made, and valuable information produced (22,23,24,25,27,29,31).

6.2 The effect of applied pressure

The effect of applied pressure on the contact conductance is the most noticeable of all parameters, especially at low pressure level. This could be due first to the increasing number of contact points and to the change of deformations of the engaging irregularities from elastic to plastic. (For elastic deformation the area of contact is proportional to the 2/3 power of the applied load; for plastic deformation, it is proportional to the load). During this initial stage, the closing of the fluid gap under pressure is much more pronounced. As the pressure is further increased, the matching configuration is gradually settled, the major change then being the increase in size of the contact areas. Boeschoten and Held (25) made a study of the size and number of contact points. They estimated from their experiment that the number of contact points at a pressure of 75 kg./sq.cm was twice as many as that at 35 kg./sq.cm, while the size of each spot remained practically the same, and concluded that the contact pressure had not much influence on the size of the contact spots but on their number. They found also the size of the spots was not affected by the type of material used to form the joint. Ascoli and Germagnoli (24) showed that above a contact pressure of about 100 kg./sq.cm the size of the contact spots increased linearly with the contact pressure. The pressure range quoted may not have great significance, but merely gives an indication of an increasing number of contact spots with pressure at a low pressure level. At a higher pressure level, as most of the peaks of the irregularities have already engaged in contact, the number may not increase much. Owing to the progress of work-hardening the size of the spots may not grow indefinitely as the applied load would suggest. This could account for the phenomenon reported by Kouwenhoven and Potter (6) that the contact resistance decreased with applied pressure in a manner which was essentially exponential. Such behaviour is supported by the findings of Barzelay et al and Miller (59). All these give reason to suppose that the number and size of contact spots depend very much on the surface roughness, the applied pressure and the process of work-hardening of the material. In this aspect, a better knowledge is needed for a more accurate prediction to be made possible.

For very flat and smooth surfaces in contact, the effect of pressure is less marked (3). This is because the areas of actual contact, which may be large initially, and the fluid gap will not be substantially changed by pressure. On the other hand, any lack of pressure may encourage surface films to dominate the situation and to cause the joint to behave in an erratic manner.

The influence of pressure on the reduction of contact resistance is now a generally accepted fact. But the magnitude of the exerting pressure on a practical contact joint may be impossible to know. Hence measurements of thermal conductance may often have to be carried out under the actual operating conditions. Barzelay and his colleagues at Syracuse University have carried out testing on a wide range of aircraft joints and produced very useful information (17,18,20). The interfacial pressure of an aircraft skin lapped joint is usually unknown. Coulbert and Liu (12) made a study of the thermal resistance of such joints by means of the Mach-Zehnder interferometer which is based on the principle of light interference and the fact that the refractive index of a fluid varies with its density. The testing of joints composed of very thin sheets requires a special technique. The pressure dependent behaviour of such joints was clearly reported by Bernard (61). In the case of cylindrical uranium rods cladded with thin cans as generally used in a nuclear reactor, the contact pressure in operation is not known owing to varying conditions during burnup. Hence measurements of the contact resistance can only be obtained from experiments carried out under operating conditions which again require special experimental technique. The valuable work by Brutto, Casagrande and Perona (28) is another example. A similar problem occurs in interference fit finned tubes. The heat transfer capacity depends on the contact pressure between fin and tube. Owing to differential expansion between fins and tubes at elevated temperatures, complete relaxation of contact pressure may introduce an additional contact resistance. Gardner and Carnaros (62) obtained test data and derived a theoretical method for predicting the interface resistance.

6.3 The effect of increasing temperature

When the mean temperature of the interface is raised, the thermal conductance will increase also. This phenomenon has been observed by most investigators (1,2,10,13,14,15,27,33).

The change of temperature generally causes a change in the properties of the materials. In most metals there is a reduction in strength at a rise in temperature. The yield strength of aluminium alloy will fall very rapidly at a temperature of between 150 - 200°C whilst that of steel will not be seriously affected until the temperature has reached a value of 250 - 300°C. The rise in temperature is also responsible for a decrease in the hardness of the metal, owing to the thermal movement of the atoms, the process of which was explained by Holm (5) as atomic diffusion. Through the increase of atomic diffusion with rising temperature, there is a decrease in hardness in the part, which is due to work-hardening. Work-hardening may be completely removed if the temperature exceeds a certain critical value called softening temperature. It follows that the direct consequence of a temperature rise at the interface is an increase in contact areas. Since the process of atomic diffusion is a function of temperature and time, the contact areas will increase, though slowly, with time. To account for this change in hardness, Cetinkale and Fishenden (33) used an equation derived from Van Liempt's theory (63), such as

$$H = H_0 \left[1 - \omega \left(\frac{T'}{T} \log_e \tau' + 35 \frac{T'}{T} - 29.8 \right) \right]$$

where T is the temperature at which ω, a constant of the metal, is determined. H and H_0 are the Meyer hardnesses at temperature T' for τ' hours and 1/180 hour application of load respectively.

/A rise

A rise in temperature also affects the part of heat transfer due to fluid conductance. If the fluid is a gas we expect the thermal conductivity of the interfacial gas to increase with temperature since the thermal conductivity of a gas is proportional to the coefficient of viscosity which, in turn, is proportioned to the square root of the absolution temperature. Combining equations (66a),(126b) and (157) in reference (60) by Kennar, we have

$$k_g = \frac{9\gamma - 5}{2\sqrt{2\pi}} C_v \rho \lambda \sqrt{\frac{\sigma T}{m}}$$

where σ is the Boltzmann constant, m the mass of the gas molecule, λ the mean free path, C_v the specific heat and T the absolute temperature. With this expression the increase in fluid conductance for a rise in temperature can be estimated. Dyban, Kondak and Shvets (10) reported a large proportion of heat flux was transmitted through gas slits in their experiment and commented that the heat flow across the interface might become redistributed and this could reduce the loss due to constriction. An interdependence between different modes of heat transfer is explained.

The effect of temperature on surface films is much more difficult to assess. Normally an oxide film grows with the increase of temperature. But if the temperature is really high enough it may be boiled off from the surface.

In certain cases an increase of temperature may lead to a higher contact pressure as a result of the thermal expansion of the parts. This was pointed out by Fenech and Roshenow and observed by Barzelay and his co-workers in the testing of structural joints. (13,14,34).

6.4 Effect of heating time

As described in Section 6.3, the hardness of a metal decreases with increasing temperature and time. Even at room temperature the process of atomic diffusion continues though very slowly (5). Cetinkale and Fishenden (33) carried out experiments with the use of a Rockwell hardness testing machine and found the following expression

$$H = H_0 \left[1 - \omega \log_e 180\, \tau\right] \qquad 24 \text{ hr.} < \tau < \frac{1}{180} \text{ hr.}$$

Since in a thermal contact problem, temperature is always associated with time, the expression for hardness quoted in Section 6.3 is more appropriate.

An increase of contact conductance with time is now to be expected. This has been observed by Barzelay, Tong, Holloway (14) and Skipper and Wooton (27). Boeschoten reported an improvement of contact conductance after the application of pressure over a long period (22). A pressure of 25 atmospheres was applied for a week and the improvement was found to be about 75%.

If heating is carried out in air, an oxide film over the metal surface will grow with time. Holm and others (5) made extended observations and found that at temperatures above 600°C the thickness of the films increased proportion-

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ally to the square of time (termed parabolic law) while at lower temperatures there was a slight deviation.

7. Contact Joints under Transient Heating

In the design of aircraft structures where aerodynamic heating is generated during supersonic flight, a knowledge of the temperature distribution within the structure is of considerable importance. Unless the speed and altitude of the aircraft are maintained constant for a substantial period, heating is of a transient nature. In order to obtain realistic data of the thermal conductance through joints of current constructure used in aircraft structures under such a condition, Barzelay and Holloway (17,18,20) carried out an intensive testing programme and were able to reveal the complexity of the problem. They found that the interface conductance varied widely from specimen to specimen and even from one test run to another in the same specimen. Fabricated specimens possess different characteristics from each other and the contact pressure varies according to the process of rivetting. As a matter of fact the local contact pressure actually varies with distance from the rivet. Consequently, interface conductance becomes a function of location as well, and the usual definition of the thermal contact conductance does not seem to have its full meaning in this respect. On the other hand, it may not be possible to determine the local contact conductance in order to work out an average value for the whole joint. Apart from this, the occurrence of warping of the contacting parts is on a much larger scale, especially with thin plates. As the temperature distribution varies with time, all the other governing factors will vary with time as well and the change of contact conditions will take place continuously during the whole period of heating. Even if we wish, it may not be possible to determine the relationship between each governing factor and time over the whole period of heating as the cause and effect are closely interrelated, hence all factors are, in varying degree, interdependent. This is a non-linear problem of a very complex nature which is not yet fully understood.

Theoretical studies have exhibited the importance of a contact joint thermal resistance in influencing the thermal stress distribution in the structures. Barber, Weiner and Boley (21) in their analysis, assumed the temperature drop at the interface to be proportional to the heat flow and idealized the structure so that the heat flow was one-dimensional. They showed that for pulses of short duration of heating, even a contact resistance of small magnitude would produce a considerable effect on the temperature distribution. Griffith and Miltonberger (16) carried out their investigation with the purpose of determining the effects of joint conductance on the temperature and the thermal stresses in skin-stiffener structures for different aerodynamic heating conditions. Their analysis was carried out in non-dimensional form with the aid of an electronic differential analyzer for the solution of the simultaneous differential equations. The joint conductance was included in the Biot No. used as the joint conductivity parameter, thus the effect of the joint conductance could be studied from the solutions according to a geometrical configuration of the joint assembly and a heat input rate. Pohle, Lardner and French (64) investigated the temperature distribution in a built-up structure in the form of an I-section composed of cover plates and a web. For analysis, the section was idealized to give one-dimensional heat flow and the contact geometry was assumed according to an idealized model. From experimental evidence, the temperature drop at the junction was taken proportional to the rate of change of the temperature at the web face (assuming heat flow to be from flange to web). Their results showed that the temperature drop at the interface was approximately a constant, irrespective of time. This would not be so if it was taken to be proportional to the heat flux as assumed by Barker, Weiner and Boley.

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In view of the complicated nature of the problem, their results agreed well with measurements in spite of the simplified assumptions and idealizations introduced in their analysis.

8. Thermal Contact at Low Temperatures

Cryogenic engineering has been widely applied in many fields in recent years and the problem of thermal contacts at very low temperatures has received increasing attention. Jacobs and Starr (1) were concerned with its application to cryogenic apparatus and carried out experiments to measure the thermal conductance between pairs of copper, silver and gold plates at room temperature and at liquid air temperature. Berman and Mate (45,46) in the study of the problem of thermal switches for low temperature work provided a better understanding of this rarely explored subject.

The physical properties of materials at very low temperatures differ greatly from those commonly encountered. Thus the manner of heat transfer across an interface at low temperatures will appear somewhat different from those at elevated temperatures. For example, the thermal conductivity of most pure metals increases greatly at low temperature and has a maximum value which may be many times the room temperature value. The state of the interfacial fluid may be changed from gaseous to liquid if the temperature and gas pressure are appropriate for the transition. In that case, the fluid conductance will increase considerably. If the interfacial fluid is in a gaseous state we may expect the thermal conductivity of the gas to decrease with a decreasing temperature. Besides it has been known that gases tend to be absorbed on to the surface of a solid and the quantity of absorption increases greatly when the temperature is lowered towards a value at which the gas will normally condense. This is the phenomenon which causes the failure of thermal switches at low temperature as described by Jacobs and Starr (1).

The electrical resistances of most pure metals are extremely small at low temperature and this affects calculations of constriction resistance. Holm (5) found that the constriction resistance at low temperature (4.2°K) is only 1/6th that at room temperature, but the high resistance due to surface films may make the constriction resistance value rather insignificant. On the other hand, the contact thermal conductance may increase a great deal owing to the increase in thermal conductivity of both metal and fluid at low temperature. Under such circumstances the Wiedemann-Franz-Lorenz law is totally inapplicable. This was observed by Berman (45). One most interesting point discovered by him is that the thermal contact conductance is proportional to T^{2} irrespective of the type of materials which form the contact. The temperature at which experiments were carried out by Berman and Mate was around liquid helium temperature.

9. Heat Transfer at the Interface of Dissimilar Metals

Apart from other factors discussed above, the direction of heat flow under certain circumstances may have an effect on the contact resistance of dissimilar metals. Barzeley et al (13,14) were the first to notice this phenomenon. They found that the thermal conductance of an aluminium alloy-stainless steel assembly was several times greater when the heat flowed from aluminium alloy to stainless steel than it was when it was from the opposite direction. They explained that this could be due to the warping of the stainless steel which has a lower thermal conductivity value. Their alternative explanation was that if the

/aluminium

aluminium alloy was put on the hotter side of the interface owing to release of its residual stresses at an elevated temperature it could also cause a change in the matching configuration. Wheeler (26) elaborated the possibility of this hypothesis with diagrams.

Miller (59) is another investigator in the problem of thermal contact who reported that the thermal resistance was higher for two different metals than for two identical ones, but he did not mention any directional effect.

With a specially designed apparatus Rogers (65) set out to investigate the problem and obtained some interesting results which confirmed the existence of a directional effect between aluminium or aluminium alloy and steel but not between chromel-alumel, copper-steel and aluminium - mica - steel interfaces. He concluded that the mechanism of conduction at the contact points could be the associating factor. Williams (66) in discussing Rogers' results, suggested, however, that the effect might be due to a direct result of surface contamination. His thinking on this point was connected with the influence on actual metallic contacts but not with it being a potential barrier. He also suggested the possibility of the change of metal hardness at elevated temperatures.

With the aid of the thermal comparator, a simple ingenious device invented by them at NPL, Powell, Tye and Jolliffe (67) took up the investigation. The thermal comparator method is the measurement of the heat transfer to and from a small metal ball (in this case a steel ball) following contact with a test surface at a fixed temperature difference. This is the reason why steel always appears as one of the two materials forming assembly joints in their experiments. With the four pairs of dissimilar materials they investigated, i.e. steel-aluminium, steel-aluminium alloy, steel-germanium and steel-soapstone, there was not any indication of the directional effect. Perhaps Powell et al may be correct in remarking that the thermal comparator method, owing to the small area of contact, might not be suitable for detecting the directional effect of heat flow. Indeed, in this method the contact geometry is clearly defined and will remain more or less unchanged during measurement. This means also that the contact area will not be affected by warping or any differential expansion between the metals. It may be affected by the change of material hardness but the test temperature was too low to be of any significance. In this method the contact pressure is very high, which could repress the influence of the surface films, and therefore the potential barrier. If the contact area or the surface film or both are truly the causes of the thermal directional effect, we have reason to think that the thermal comparator method is really unique in respect of it being unaffected by any thermal directional effect.

The possibility of a thermal directional effect due to the presence of a potential barrier was investigated by Moon and Keller (68). Most surface films are semi-conductors which are considered potential barriers between the contact members. The thermal movement of electrons of high energy levels is sufficient to allow them to pass through the barriers and the work functions together with the temperature govern the transition. According to the principles of quantum mechanics, they calculated the transmission of electrons across such a potential barrier as the electronic contribution to heat transfer. The directional effect was considered due to the difference in transition of electrons from both directions. Based on assumed values for the work functions and for the ratio of actual to apparent contact area, they computed a result which compared well with Rogers' result from the aluminium-steel assembly. One may still be puzzled, however, by the evidence from Rogers that the steel-copper assembly result gave no indication of such a directional effect. This may be because with the aluminium oxide the work function for electric transition from metal

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to the semi-conductor is larger than that responsible for an oxide film over steel or stainless steel, whereas, between copper and steel, the difference of the two work functions may be too small to show any appreciable effect. Although the nature of potential barriers between dissimilar metal during thermal contact is still not clearly understood, Moon and Keller's theory has at least provided an incentive to further investigation.

10. Hysteresis Phenomenon

When a joint is loaded progressively and then unloaded, the thermal conductance of the joint upon increasing load is not reproducible upon decreasing load. The values of conductance during unloading are always higher than those during loading. This phenomenon has been observed by many investigators (9,10,33, 35,36). Holm (5) found that the same phenomenon occurs in electric contacts and considered the cause being due to cold welding. As the load is increasing, the surface films at contact points will gradually be broken down to allow for base metal contact to be established. The adherence of these points, as the result of cold welding, will remain in firm contact even when the load is being reduced, giving rise to a relatively larger area of contact hence a higher conductance. Fenech and Rohsenow (36) on the other hand, suggested that this was due to the elastic deformation of the bulk of material in the sublayers and thus bringing the two surfaces closer together. We may well suppose that, whatsoever the cause, the surface contact condition, after a high load is applied, has been considerably improved. The hysteresis phenomenon indicates an irreversible process. When pressure is being increased for the first time, deformations of the contact points are elastic and then plastic if the magnitude of the contact pressure exceeds the elastic limit of the material. When the load is reduced, recovery of deformation will take place only in the elastic domain so that the variation of the contact area is proportional to $W^{2/3}$ whereas during plastic deformation the variation of the contact area is proportional to W. The recovery of area during elastic unloading is therefore smaller than the formation of the contact area during plastic loading. This may explain the reason why contact conductance is always larger during unloading. As plastic deformation plays an important part in cold welding and as the deformation in the bulk material is the direct result of the applied surface pressure, it may not be too unreasonable to suggest that they all have some contribution towards creating the hysteresis phenomenon.

11. Improvement of Contact Conductance

Recent advances in thermal contact research have provided not only a better understanding of the mechanism of heat transfer across a contact joint, but also a clear indication of the lines along which any improvements of a contact joint conductance can be made. This may be regarded as invaluable for practical applications. The most significant factor for such a purpose is the increase of applied pressure to achieve a better metallic contact especially if the surface is rough. Kouwenhoven and Tampeco (3) sprinkled the contact surface of the specimens uniformly with fine steel filings of the same material. Under an increasing pressure they observed that the contact resistance (electrical) was lowered to one-tenth of the initial values. The explanation is rather simple in this case. A larger metallic area of contact is promoted when the steel particles penetrate the surface films under high local concentrations of pressure. A rough surface without any projecting particles will produce similar results. The reduction of the fluid gap under pressure also improves matters, perhaps to a lesser degree. There are opinions, however, suggesting that the fluid gap is the primary path of heat transfer. This is true under certain circumstances and any means of improving the value of k_f/δ will certainly be rewarding.

Filling the fluid gap between the fuel element and the can in a nuclear reactor with a high thermal conductivity gas such as helium, which although is primarily for preventing oxidation and for facilitating the leak detection, can be considered to fulfil this requirement.

With smooth surfaces, the significance of applied pressure is not so marked. Improvement of contact conductance may be achieved by the insertion of a softer material with a high thermal conductivity at the interface. A good number of investigators have used shims of soft materials such as aluminium, lead and copper etc. and have found a remarkable improvement when pressure was applied (8,9,10,13,14,44,59). In spite of another interface being created by the presence of another piece of material, the thermal conductance value can still be expected to increase provided the shim is not too thick. The improvement of conductance in this case is largely brought about by the increase in actual contact areas. Materials with a low yielding strength are quite ready to deform under pressure, the greater the pressure the larger the actual contact area until the void space is filled up, this being an extreme limit, in which case the resistance of the tarnish films between the surfaces together with a certain amount of constriction resistance are the only resistances of the contact joint.

In some engineering practices where the insertion of separate pieces of soft metal foils may not be possible, other methods to give a similar effect have therefore been introduced. Boesehoten (22), suggested the use of liquid lining of low-melting alloys (to be effective, the melting point has to be lower than the interface temperature). For use in a nuclear reactor this material should possess a low neutron absorption character. Ascoli and Germagnoli (22,23) used another technique. They sprayed a coat of aluminium on the uranium surface and their report was most encouraging.

12. Concluding Remarks

Considerable progress in heat transfer through metallic contact joints has been achieved in recent years, giving a better understanding of the problem where the state of heat flow is steady. In the transient state, valuable studies have been made which reveal the complexity of the problem. The changing character of a contact joint during transient heating hampers reasonable prediction. The uncertainties of the matching configuration are caused by a large number of factors which vary with time. Thus they are interrelated and the significance of each of them can not be easily investigated. Any fruitful study of the problem, at this stage, would only be achieved, seemingly, if the number of governing variables could be reduced to a minimum. The uncertainty of the matching condition of an interface, whether in the state of steady or transient heat flow, may remain for some time until the roughness of a surface can be meaningfully defined. In the meantime, our studies can only be carried out with controlled contact surfaces or with approximations.

The properties of surface films and their behaviour at the interface have been studied intensively in the electrical field, but not so much from the thermal aspect. The presence of surface films may render two otherwise physically identical joints to behave quite differently from each other. A knowledge of the thickness and the thermal conductivity of a surface film would be valuable. The nature of these films acting as potential barriers at the interface of dissimilar metals is not clearly understood. A better knowledge of this may be desirable for further investigation into the cause of the thermal directional effects.

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Our knowledge of thermal conductance at low temperature has been limited to the liquid helium temperature region. The behaviour of a thermal contact along the temperature scale from room temperature downward may be of interest both from a practical and from an academic point of view.

From the engineering design viewpoint, a correlation of all the experimental data in a common form should be valuable. This is not an easy task as the data have been presented in different ways under different experimental conditions. Graff (69) has made a very good attempt at presenting some selected data in diagrammatic forms for design purposes. Where generalisations cannot be applied, such as in aircraft structural joints, design data may only be obtained from tests of specific samples. Reasonable experience has been gained for improving the heat transfer ability of a contact joint. This may be regarded as being of considerable practical value.

/List of Symbols

List of Symbols

A	area of contact
C	conductance (either thermal or electrical)
R	resistance (" " ")
Q	quantity of heat flow
W	applied load
P_m	mean yield pressure
T	absolute temperature
H	Meyer hardness
E	emissivity
M	molecular weight
R_g	universal gas constant
a	radius of contact spot, also accommodation coefficient
r	radius of a model cylinder
k	thermal conductivity
k_s	conductivity, harmonic mean value
h	coefficient of heat transfer
ℓ	temperature jump distance
m	mass of molecule
n	number of contact areas
q	quantity of heat flow per unit time
u	heat transfer coefficient at zero pressure
ε	a/r
δ	average fluid height
λ	mean free path

/C_v

C_v	specific heat for constant volume
γ	ratio of specific heats
ε	a constant
β	centre line average value
μ	coefficient of viscosity
τ	time

Subscripts:

c	metallic contact
f	fluid
r	radiation
1	solid 1 or surface 1
2	solid 2 or surface 2
o	surface film
T	total
g	gas

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