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Thermal Conductance of Multilayered Metallic Sheets

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An experimental investigation was conducted to determine the thermal conductivity, the overall thermal conductance, and the thermal contact conductance between layers of stacked aluminum alloy 3004, 5042, and 5182 sheet. Tests were conducted for aluminum sample thicknesses of 0.0305–0.3074 cm (0.012–0.121 in.), mean junction temperatures of 79.5 and 165.5°C (175 and 330°F), and contact pressures of 0.689–10.34 MPa (100–1500 psi). The overall thermal conductance increased with increasing contact pressure and increasing temperature. It decreased as the number of aluminum layers was increased. The experimental data were used to derive thermal contact conductance between layers of stacked aluminum sheet. From these derived values, a correlation for the thermal contact conductance was developed. The resulting expressions are presented as a function of dimensionless parameters for the layer material, apparent contact pressure, and mean junction temperature.

Nomenclature

A = apparent contact area
H = Vickers hardness
h_c = thermal contact conductance
k = thermal conductivity
P = pressure
Q = heat flux
R_c = thermal contact resistance
T = temperature
t = thickness
β = coefficient of linear expansion
ΔT = temperature difference
ε = porosity

Subscripts

c = contacts
l = layers
m = microhardness
01 = one layer
03 = three layers
05 = five layers
07 = seven layers

Introduction

THERE have been numerous investigations of heat transfer across metallic surfaces in contact and some investigations of selected interstitial materials for thermal isolation and thermal enhancement.[1] However, there have been few investigations of the thermal contact conductance of layered metal sheets.[2] Mazur et al.[3] explored different methods for rapid cooling of coils of hot-rolled strip steel to ensure high-sheet quality. Typical rolling processes result in an exit temperature of 840–930°C with coiling at temperatures of 550–700°C. Natural cooling of these coils has been estimated to take from 3–8 days.

In their analysis, Mazur et al.[3] assumed that heat was lost primarily in the axial direction of the coil. The degree of contact between layers was assumed to be on the order of 3%, and the thermal contact conductance was not addressed except in terms of the interstitial gas between layers. Results of the analysis indicated that when the coil was immersed in water the inner and outer wraps cooled an order of magnitude faster than the central laps of the coil. Disparities in the rate of inner and outer wrap cooling lead to a considerable difference in mechanical properties and microstructure over the length of a hot rolled strip. The thermal properties are also affected by the rolling and cooling process.

Heat conduction through multilayered metal supports used as insulators for cryogenic liquid storage vessels was investigated experimentally by Mikesell and Scott.[4] Stainless steel 302-, 304-, and Monel disks 2.54-cm diam and 0.002–0.043-cm thick were stacked between brass endplates. Some tests included perforated disks, high vacuum grease, or Teflon® sheets, and others used manganese dioxide dust. The relatively high thermal resistance of the multilayered supports was caused by the numerous contacts between the individual plates. A stack of untreated stainless steel 304 plates (0.002-cm thick) was the best insulator per unit length of all the materials tested, over the temperature range between liquid hydrogen and liquid nitrogen. At 6.894 MPa (1000 psi), the thermal resistance was found to be 50 times greater than that for a solid sample of the same material. The results further indicated that the resistance per unit length of a stack varied approximately as the inverse square root of the plate thickness.

Thomas and Probert[5] conducted an experimental investigation to verify the results of Mikesell and Scott.[4] They measured from 51 up to 600 contacts of thin layers of selected steels, brass, and phenolic laminates with thicknesses from 0.056 to 0.672 mm. Apparent contact pressures ranged up to 0.5 MPa, with a temperature range of 72–296 K. They found that there are no significant differences between the results from stacks of different numbers of contacts and justified the assumption of a constant conductance per contact. The thermal contact conductance was shown to be proportional to the applied load raised to a power between 0.5–1. By plotting the quotient of the thermal conductivity of the stack components and the thermal conductance per unit area per unit

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length vs thickness of the layers, a minimum for the total conductance of the stack was determined. The resulting curve was the result of two competing mechanisms: 1) the decrease of conductance with the number of contacts per unit length; and 2) the decrease of conductance per contact with thickness of the bulk material. Thomas and Probert[5] concluded that low thermal conductance per stack length could be obtained by using rough surfaces, high E-modulus, very thin layers, and high-surface hardness.

Roberts[6] modeled the stators of large high-voltage machines using a line source method, developed for anisotropic materials, to determine the thermal conductivity of sheet steel laminations and high-voltage winding insulation. The thermal conductivity of these stator core materials was determined to be a function of the following: 1) individual lamination thickness; 2) type and thickness of the interlaminar insulation; 3) surface finish of the lamination, i.e., whether hot or cold rolled; and 4) pressure under which the laminations were clamped. Results were presented for three different sheet steel lamination materials as a function of the clamping pressure.

In an investigation of the heat flow across stacks of steel laminations, Williams[7] determined that the effective thermal conductivity of enameled steel laminations used in the stator cores of large turbogenerators depended on the fluid trapped between the laminations. Tests conducted in an air environment were adjusted for other environments with a simple mathematical model. Tests at other conditions confirmed that such an approach was reasonable. Experimental data were presented for stacks of 2.3% silicon steel in helium, air, and vacuum environments. The investigation was extended by Williams[8] to explore the effect of changing the profiles of the contacting surfaces on the thermal resistance of a stack of laminations. Three different roughness values were used [R_A = center line average (c.l.a.) 0.76–1.02 μm (30–40 μin.), R_B = c.l.a. 1.14–1.40 μm (45–55 μin.), R_C = c.l.a. 0.08–0.10 μm (3–4 μin.)]. The results of the investigation generally supported the mathematical model developed for adjustment of results in an air environment to other conditions.

Al-Astrabadi et al.[9] conducted an analysis of previously published experimental data for the thermal contact conductance of multilayered stacks of different materials using dimensionless values. Contact pressure was divided by surface hardness, and contact conductance was nondimensionalized with the layer thickness and thermal conductivity of the bulk material. A relationship was developed such that conductance was proportional to the load raised to the power of 0.58. A correlation coefficient of 0.96 showed relatively narrow scatter in the data.

The total stack conductance of one-, three-, five-, and six-layer stacks of Si-steel laminations, in air at atmospheric and reduced pressure, was measured by O'Callaghan et al.[10] They observed that high pressure caused increasing conductance per contact because of increasing contact area by flattening surface protuberances. The characteristics of the data were quantitatively independent for both environmental conditions and differed by a factor of about 25 for decreasing contact pressure. The thermal conductance of the lamination-to-lamination interface was independent of the number of layers and approached asymptotically a constant value with increasing axial load. Radial heat losses were estimated to be smaller than 5%.

Veziroglu et al.[11] developed a theory for the steady-state thermal conductance of stacks of thin metallic sheets. The theory covers a pressure range from 0.69 Pa (10^{-4} psi) to 6.9 $\times$ 10^7 Pa (10^4 psi) for increasing and decreasing load. The predictions compared well with test measurements of stainless steel, brass, and transformer core steel for several different interstitial fluids.

The thermal contact conductance of multilayered electrically insulated sheets was experimentally investigated by Sheffield et al.[12] Selected lamination materials were investigated in a vacuum environment over a wide range of contact pressures. The results of the experimental tests were analyzed, and a correlation was developed for prediction of the effective thermal conductivity. This simple correlation was used for predicting the overall heat transfer of stacks of electrically insulated, thin electrical steel sheets.

Assuming that the contact interfaces in a stack of coated laminations are composed of a number of similar contact elements, Sheffield et al.[13] solved the Laplace equation for one contact. The boundary conditions were chosen for one circular contact with the interstitial gap filled with a fluid. Comparisons of this theory with earlier theories and experimental data showed satisfactory agreement.

One of the main objectives of Luu et al.[14] was to investigate multilayer insulation consisting of numerous layers of thin radiation shields separated by crinkles formed on the shields or by spacer materials. A semiempirical model based on the temperature jump theory was developed using experimental results from the multilayered insulation specimens. The model was used to evaluate the relative contributions of gas conduction, solid conduction, and radiation as a function of environmental pressure. They found that at pressures lower than 7.6 $\times$ 10^{-3} Torr, where the mean free path of gas molecules was much larger than the space between the layers (free molecule regime), convection was negligible. Radiation also was neglected. They concluded that solid conduction was particularly important at low pressures.

Williams and Malik[15] developed a model to predict the heat flow through stacks of coated laminations. The test specimens had thicknesses of up to 635 μm and coating thicknesses of up to 12.7 μm. Oxides, enamel, magnesium, and phosphates were the coating materials used. The tests were conducted in helium, air, and vacuum conditions. The model relied on the separation of the components of contact conduction attributable to the solid contacts and to the interface fluid. The model was found to be useful for predicting the contact heat transfer behavior for any environmental gaseous condition when the results under normal atmospheric and vacuum conditions had been determined.

These experimental and theoretical investigations have provided a better understanding of the heat transfer occurring in selected layered materials. The majority of these investigations, however, have involved coated and uncoated sheet steel in varying thicknesses and numbers of layers. A few of these studies have included other materials, but none has investigated the use of layered aluminum materials. The use of layered hard materials may result in a high thermal resistance, depending upon the number of layers. Some softer materials, however, may provide equally high thermal resistance for some applications. The present investigation is directed toward measurement of the interfacial resistance of selected aluminum materials.

Experimental Program

An experimental investigation was conducted to determine the thermal conductivity of and thermal contact conductance between rolled aluminum alloys. The thermal contact conductance samples were machined from sheets of aluminum alloys 3004, 5042, and 5182. To examine the effect of processing history on the thermal contact conductance, the aluminum sheets were taken from two different stages in the rolling process. The thermal conductivities were not measured at these stages in the process because the sample sizes were too thin to provide accurate and precise results. The thermal conductivity samples were machined from thicker plates of each alloy. The overall test program for the thermal contact conductance measurements is provided in Table 1.

Experimental Test Facility

The experimental test facility, which is shown in Fig. 1, has been used for numerous investigations of thermal contact conductance and thermal conductivity. The facility consists of a

Table 1 Aluminum sample surface characteristics

Material aluminum alloy	Thickness	Vickers microhardness, kg/mm^2		Surface roughness RMS, µm	Surface roughness CLA, µm	Asperity slope RMS	Asperity slope ARITH	Surface waviness ARITH, µm	Surface waviness MAX, µm
3004	3.036 ± 0.013 mm	67	Side 1	16.0	13.0	0.049	0.035	23	120
	(0.116 ± 0.0005 in.)		Side 2	17.0	12.5	0.051	0.037	18	103
3004	0.305 ± 0.013 mm	91	Side 1	22.5	18.0	0.080	0.060	109	457
	(0.012 ± 0.0005 in.)		Side 2	23.5	18.5	0.087	0.064	87	395
5042	2.896 ± 0.013 mm	66	Side 1	16.0	11.0	0.055	0.036	14	142
	(0.114 ± 0.0005 in.)		Side 2	20.0	15.5	0.081	0.055	26	138
5042	0.457 ± 0.013 mm	101	Side 1	22.5	18.5	0.078	0.057	18	129
	(0.018 ± 0.0005 in.)		Side 2	22.5	18.0	0.075	0.055	30	146
5182	3.056 ± 0.013 mm	67	Side 1	21.5	16.5	0.068	0.046	51	223
	(0.120 ± 0.0005 in.)		Side 2	23.0	17.5	0.055	0.037	31	168
5182	0.305 ± 0.013 mm	103	Side 1	21.0	16.5	0.095	0.069	28	134
	(0.012 ± 0.0005 in.)		Side 2	19.5	15.5	0.088	0.065	16	99

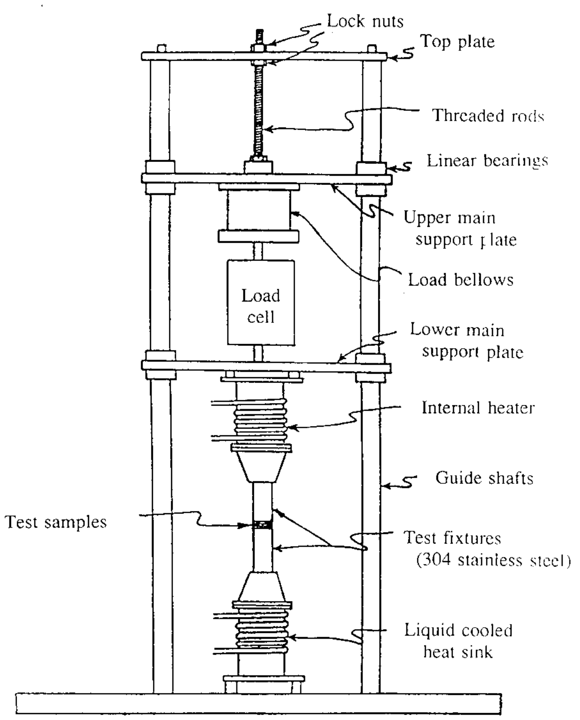

Fig. 1 Experimental test facility.

vertical column composed of a guard heater, a heat source, two stainless steel 304 heat fluxmeters 2.54-cm (1.0-in.) diam, a heat sink, a load cell, and a gas bellows. The thermal conductivity of the two heat fluxmeters was calibrated utilizing an electrolytic iron standard. The stacks of aluminum test disks were placed between the two stainless steel heat fluxmeters. A 8.90-kN (2000-lb) load cell was used to measure the axial force on the test samples. The load cell calibration was checked before the test series was initiated. The heat source was a 600-W resistance heater positioned at the base of the upper heat fluxmeter. A radiation shield composed of aluminum and asbestos was placed around the heat fluxmeters and aluminum samples to minimize radial radiative heat losses.

The thermal conductance test facility was operated in a vacuum environment to minimize the effects of any junction interstitial fluids on the thermal measurements and to minimize convective losses. A vacuum of 5×10^{-5} Torr or greater was maintained using an ALCATEL 2300 C roughing pump in series with an NRC VHJ-6 oil diffusion pump. Four NRC model 531 thermocouple gauges, in conjunction with two Bayerd Alpert ionization gauge tubes and controller, were used to monitor the vacuum level.

To determine the total thermal contact conductance of the stacks of aluminum, four Chromel-Alumel glass-braid sheathed thermocouples (type K, AWG 30, 480°C maximum temperature) were located along the centerline of each of the heat fluxmeters. These thermocouples were packed into number-56 drilled holes using Omegatherm 201 high thermal conductivity filled silicone paste. Each thermocouple was wrapped around the sample and held in place with high-temperature cement. This technique reduces conduction heat losses from the temperature measurement area of the sample. The thermocouples were connected to a HP 3497A data acquisition control unit and a HP 87 terminal. The reference temperature for the thermocouples was provided internally by the HP data acquisition system.

Sample Preparation

The thermal conductivity samples were machined to 2.54-cm (1.00-in.) diam by 2.54-cm (1.00-in.) long. Once the test samples had been machined to a smooth finish, a series of three thermocouple holes were drilled (no. 56 drill) to the centerline in the radial direction at 0.635-cm (0.25-in.) intervals.

The thermal contact conductance samples were prepared from aluminum sheet with an as-rolled finish. Each sample was machined to 2.54-cm (1.00-in.) diam at rolled thicknesses. A representative sample of each material was sent to Sheffield Measurements Laboratory in Dayton, Ohio, where the surface parameters were measured, including the RMS surface roughness, the average surface roughness (CLA), the RMS asperity slope, the average asperity slope, and the arithmetic and maximum surface waviness. The sample thicknesses and surface parameters are shown in Table 1. A more detailed description of the surface parameters and their measurements is given by Amstutz[16] and Zipin.[17]

Thermal Conductivity

The thermal conductivity measurements were made in a standard cut-bar test facility. This apparatus, manufactured by the Dynatech Corporation, was designed for thermal conductivity measurements at vacuum conditions. The facility is composed of a heat sink, which is cooled by a constant temperature bath with a controllable temperature; two cylindrical heat flux meters, 2.54-cm (1.00-in.) diam and 10.16-cm (4.00-in.) long, instrumented with thermocouples to assess the temperature gradient, and a heat source. The stainless steel 304 heat flux meters were calibrated using a National Bureau of Standards Electrolytic Iron sample[18] to determine their temperature-dependent thermal conductivity.

The experimental thermal conductivity measurements of the aluminum alloys 3004, 5042, and 5182 were made at vacuum conditions of less than 10^{-5} Torr. The instrumented thermal conductivity sample of each material was inserted between the heat flux meters using heat transfer grease to minimize the thermal resistance of the junction. An axial load was then placed on the vertical column, and the sample was aligned to assure that the surfaces would remain in contact when the chamber was evacuated to a level of 10^{-5} Torr or lower. Radiation shields were used to minimize radiative heat losses to the surrounding chamber. The chamber was evacuated, the heat source and sink temperatures were set, and the heaters were activated. Data were taken when the temperature of the test samples did not vary more than 0.2°C over a 45-min period.

The resulting thermal conductivity values have been previously reported[2] and correlations for the thermal conductivity were derived from the data as follows:

Aluminum Alloy 3004 $k = 147.76 + 0.15469T$

$(280\ K < T < 420\ K)$

Aluminum Alloy 5042 $k = 124.26 + 0.088136T$

$(280\ K < T < 420\ K)$

Aluminum Alloy 5182 $k = 94.231 + 0.1279T$

$(280\ K < T < 420\ K)$

where k is in W/m-K and T is in Kelvin. These thermal conductivity values were used in the determination of all contact conductances in this investigation. The uncertainty associated with the thermal conductivity measurements was determined using the method of Kline and McClintock.[19] The uncertainties include the location of the thermocouple holes, the measurement of the temperature, and determination of the axial heat flux. Based on these measurements, the uncertainty in the thermal conductivity was calculated to be ±5% at higher heat flux levels and ±7% at lower heat flux levels.

Microhardness Measurements

The surfaces of the rolled sheet consist of a large number of aligned asperities which contribute to the measured surface roughness noted in Table 1. When the surfaces are placed in contact and the apparent contact pressure is increased, more asperities come in contact. The increased contact area results in an increase in the overall thermal contact conductance at the junction. Since the harder asperities penetrate the softer surface, the microhardness for the contacting surfaces is important.[20]

The Vickers microhardness is an important parameter to measure when evaluating thermal contact conductance. Kang[21] provides an excellent summary of the importance of microhardness in thermal contact conductance and has described the measurement procedures. The present Vickers microhardness measurements were made using a Micromet automatic microhardness tester. Five different load settings were used, and readings were obtained at five different locations for each load. A pyrimidal indentor with a 136-deg angle between opposite faces and a 148-deg angle between opposite edges was used. A microscope was used to measure the indentation size after the load had been applied for 15 s. Results of the microhardness tests also are presented in Table 1. Initial tests were conducted on the thicker aluminum alloy 3004 samples to determine if the Vickers microhardness was dependent on the sample measurement side, sample measurement face location, or face orientation. No dependence on sample side or location was found. As a result, the remainder of the tests were conducted at the center of one side on each sample.

Fluxmeter Calibration

In order to determine the heat flux in the upper and lower heat fluxmeters, the temperature-dependent thermal conductivity of stainless steel 304 was needed. For this purpose, a cylindrical test sample (2.54-cm diam) was machined from electrolytic iron and inserted between the upper and lower stainless steel heat fluxmeters. Thermal grease was used to minimize the contact resistance at the interfaces. The thermal conductivity of the electrolytic iron sample was provided by NBS/NIST.[18] Three thermocouples were used to measure the temperatures along the centerline of the iron sample. Thermal gradients in the fluxmeters and iron sample were determined using a linear least-squares fit of the measured temperatures.

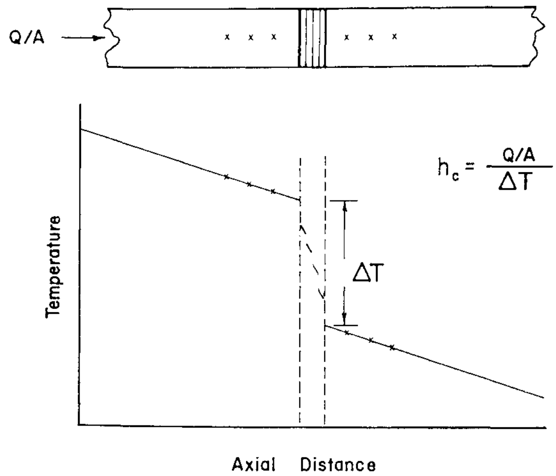

Fig. 2 Schematic of the junction with interstitial layers.

The heat flux through the upper and lower fluxmeters was assumed to be the same as that through the electrolytic iron sample. Using Fourier's law, the temperature-dependent thermal conductivity for each fluxmeter was calculated. The calibration results compared favorably with published data.[22]

Experimental Test Procedure

The aluminum sheet samples were stacked with their roll grinds oriented in the same direction. The specimens were installed in the test facility and a radiation shield was placed around them and the fluxmeters. A slight pressure was applied to the column to ensure that the surfaces remained in contact during evacuation of the chamber. After reaching a vacuum level of 10^{-5} Torr, temperature and apparent contact pressure were set by adjusting the heater to the required power and pressurizing the load bellows. Data were taken when the fluxmeter temperatures did not vary by more than 0.2°C in a 45-min period. Thermal equilibrium was usually established in 6–8 h.

The thermal gradients in the upper and lower fluxmeters were obtained by applying a least-squares fit to the measured centerline temperatures. Applying Fourier's law, these gradients and the calibrated thermal conductivity were used to determine the heat fluxes in the upper and lower fluxmeters. An average of these fluxes was used as an estimate of the heat flux through the layers of aluminum samples. The temperature drop across the layers was determined by extrapolating the thermal gradients in the upper and lower fluxmeters to the junction surfaces as shown in Fig. 2. The overall thermal conductance was calculated by dividing the heat flux through the samples by the temperature drop across the samples.

Results and Discussion

The overall thermal conductances of multilayered aluminum alloy 3004 sheet material are shown in Fig. 3, as a function of apparent contact pressure and mean junction temperature. Overall conductance data for multilayered aluminum alloy 5042 and 5182 also have been determined and are similar to aluminum alloy 3004.[2] The data include both the thermal contact conductances between the samples and the overall bulk conductance of the layers. In general, the data indicate that there is an increase in overall conductance with both pressure and temperature. There is a reduction in the overall conductance with an increase in the number of stack layers. All of these trends are as expected.

For all of the alloys the thicker samples provided more consistent data than the thinner samples. There is an orderly increase in the overall conductance with both temperature and pressure for the thicker sample data. The more scattered data from the thinner samples may be due to large gauge variations between the thinner specimens, variations in the surface characteristics between samples, and the difficulty in

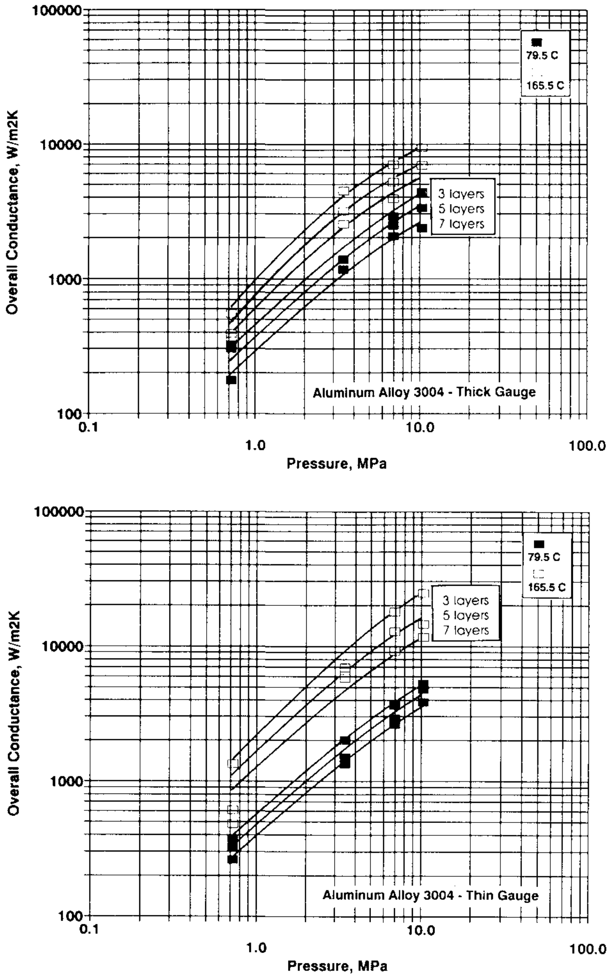

Fig. 3 Overall thermal conductance as a function of apparent contact pressure and mean junction temperature for layered aluminum alloy 3004.

ensuring the alignment of the extremely thin layers in the test facility.

In order to demonstrate the repeatability of measuring the overall thermal contact conductance, a second series of data was taken for five layers of the thinner aluminum alloy 5182 at 165.6°C (330°F). The two test runs were compared as a function of apparent contact pressure. While there is a slight difference at 0.689 MPa (100 psi), the data at higher apparent contact pressures compare quite well.

The thermal contact conductance between individual layers must be derived from the overall thermal conductance data and thermal conductivity of the layered material. The overall contact resistance is defined as the sum of the thermal contact resistances and the bulk resistances of the layers, such that

$$R_{c,\text{overall}} = \sum R_{c,\text{contacts}} + \sum R_{c,\text{bulk}}$$

For one layer

$$R_{c,01} = 2R_{c,c} + (t/k)$$

where $R_{c,c}$ is the thermal resistance per unit area between the flux meters and the layer material.

These derived layer thermal resistance equations may also be written in terms of the thermal contact conductance, such that for one layer

$$(1/h_{c,01}) = (t/k) + (2/h_{c,c})$$

and for three, five, and seven layers

$$(1/h_{c,03}) = (2/h_{c,c}) + (3t/k) + (2/h_{c,l})$$

$$(1/h_{c,05}) = (2/h_{c,c}) + (5t/k) + (4/h_{c,l})$$

$$(1/h_{c,07}) = (2/h_{c,c}) + (7t/k) + (6/h_{c,l})$$

Based on the thermal conductivity determined for aluminum alloys 3004, 5042, and 5182, and the overall thermal contact conductance data shown in Fig. 4, it is possible to obtain derived values for the thermal resistance between layers.

The derived values for the thermal contact conductance between layers of rolled aluminum alloy 3004 are shown in Fig. 4 as a function of temperature and apparent contact pressure. Derived values for the thermal contact conductance of rolled aluminum alloy 5042 and 5182 are similar to aluminum alloy 3004.[2] As expected, the layer contact conductance increases (the contact resistance decreases) with an increase in apparent contact pressure. Furthermore, the layer contact conductance increases (the contact resistance decreases) with an increase in mean junction temperature. Note that several independent values of layer contact conductance can be derived using the foregoing equations and the overall contact conductance data. The most suitable layer conductance values were selected from the available data and are shown in Fig. 4.

In order to develop a means for predicting the thermal contact conductance between layers, published correlation equations have been compared with the present data. Al-

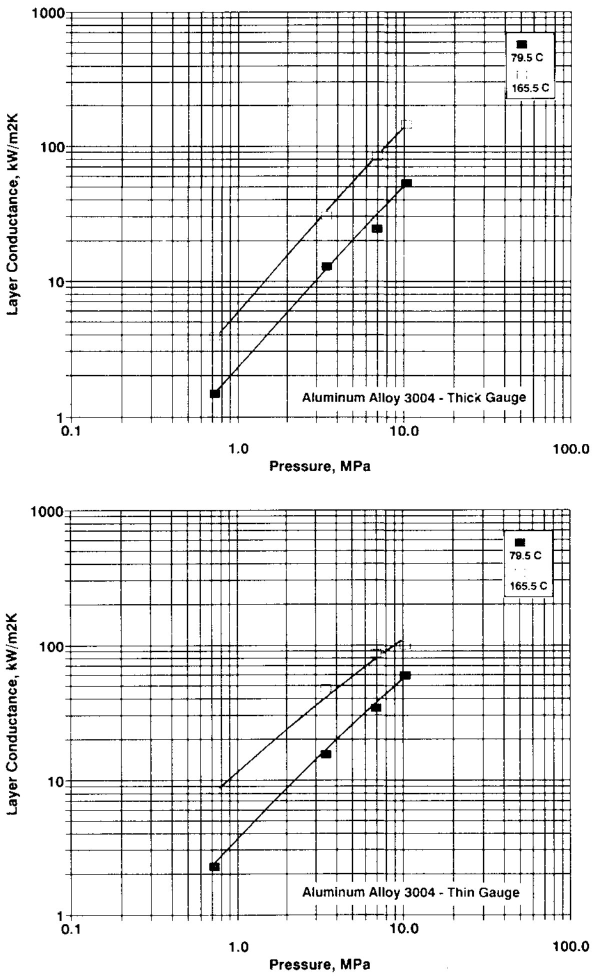

Fig. 4 Derived thermal contact conductance between layers as a function of apparent contact conductance and mean junction temperature for rolled aluminum alloy 3004.

Astrabadi et al.[9] developed an expression for the dimensionless conductance as a function of dimensionless pressure for multilayer stacks of stainless steel, razorblade steel, brass, tool steel, electrical steel laminations, and tin-coated steel. Layers of aluminum were not included in the analysis. The correlation was developed for a wide range of data, resulting in the following relationship.

$$(h_{c,l}t_l/k_l) = 3.025(P/H_M)^{0.58}$$

where H_M is the hardness of the surface of a layer. This relationship is shown in Fig. 5 for comparison with the present data. While the magnitude of the correlation compares favorably with the present data, it does not include the effect of temperatures investigated.

Miller and Fletcher[23] developed a dimensionless correlation for the thermal contact conductance of sintered porous metals. Materials composed of metal fibers and metal powders were included. The correlation was formulated in terms of the physical properties of the porous metals, in the form

$$(h_c t/k) = 2.335[(P/H_M)(1 - \varepsilon)]^{0.72}$$

where ε is the porosity. When the porosity is set equal to zero for a solid material, the equation takes the form of the correlation reported by Al-Astrabadi et al.[9] The Miller and Fletcher correlation also is shown in Fig. 5 for comparison. This expression also compares favorably in terms of magnitude but does not include the effect of temperature. No data were included for aluminum. Furthermore, this analysis was established for single layers of materials rather than multiple layers.

A dimensional analysis of the experimental data indicated that the overall conductance depends upon P, H_M, t, k, T, and β, the coefficient of linear expansion, such that where

$$h_{c,t} = f(P, H_M, t, k, T, \beta)$$

$$(h_{c,t}t/k) = f[(P/H_M), \beta T]$$

Based on these correlating parameters, the data are shown in Fig. 6 with correlations of the form

$$(h_{c,t}t/k)(1/\beta T) = C(P/H_M)^n$$

An analysis of these data suggests the following two correlations:

$$(h_{c,t}t/k) = 40{,}000(\beta T)(P/H_M)^{1.15} \quad \text{(thick gauge samples)}$$

$$(h_{c,t}t/k) = 2{,}500(\beta T)(P/H_M)^{0.97} \quad \text{(thin gauge samples)}$$

Unfortunately, one correlation could not be determined for all of the data. However, the fact that each correlation represents material with approximately the same processing history suggests the existence of a more involved dimensionless parameter to describe the thermal contact conductance. This parameter might take into consideration the material's surface roughness or microstructure. Until that connection is determined, the present correlations provide excellent estimates of the thermal contact conductance between layers of aluminum sheets subjected to the same processing history as the samples.

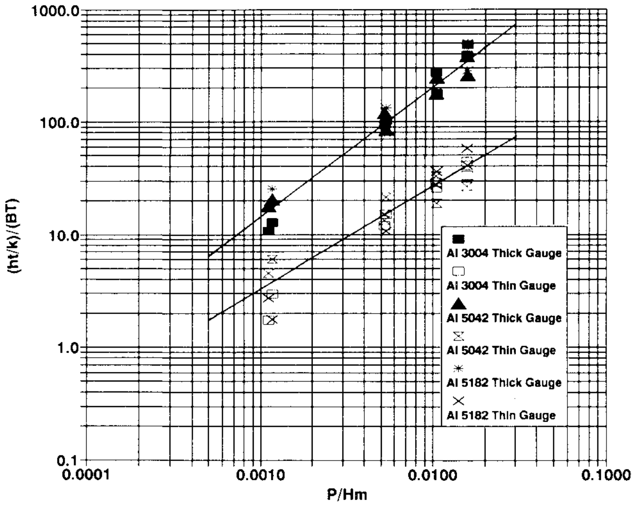

Fig. 6 Comparison of the nondimensional derived thermal contact conductance as a function of nondimensional pressure and temperature.

One issue that needs to be studied in greater detail is the effect of rolling on the thermal conductivity of each aluminum alloy. Deformation of the aluminum crystal lattice during processing affects its thermal conductivity. In determining the overall thermal conductances in this research, the thermal conductivity was assumed to be the same for each sample thickness. In addition, the thermal conductivity sample was taken from thicker plate which experienced a different processing history from the sheets used for the conductance samples. Due to the thinness of the samples, accurate and precise thermal conductivities of the rolled sheets could not be determined using the described test facility. One solution to this problem would be to measure the electric conductivity of the material and use the Wiedemann-Franz law to calculate the thermal conductivity.

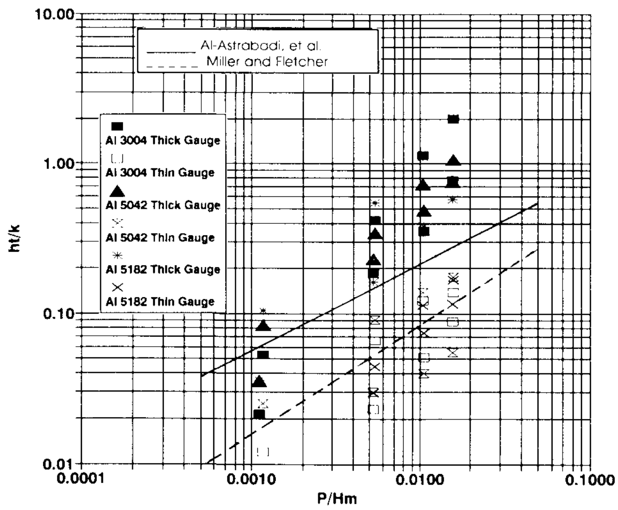

Fig. 5 Comparison of the derived thermal contact conductance with published correlations.

Conclusions

An experimental investigation was conducted to determine the thermal conductivity, the overall thermal conductance, and the thermal contact conductance between layers of stacked aluminum alloy 3004, 5042, and 5182 sheet. Tests were conducted for aluminum sample thicknesses of 0.0305–0.3074 cm (0.012–0.121 in.), mean junction temperatures of 79.5 and 165.5°C (175 and 330°F), and apparent contact pressures of 0.689 to 10.34 MPa (100 to 1500 psi). The overall thermal conductance increased with increasing contact pressure and increasing temperature. It decreased with an increased number of aluminum layers.

The experimental data were used to derive thermal contact conductance between layers of stacked aluminum sheet. From these derived values, a correlation for the thermal contact conductance was developed. The resulting expressions are presented as a function of dimensionless parameters for the layer material, apparent contact pressure, and mean junction temperature.

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