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Experimental Thermal Contact Conductance of Continuous Fiber Metal Matrix Composites

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EXPERIMENTAL THERMAL CONTACT CONDUCTANCE OF CONTINUOUS FIBER METAL MATRIX COMPOSITES

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ABSTRACT

Continuous graphite fiber reinforced aluminum matrix composites are being considered for replacement of the currently used aluminum alloy 6101-T6 in standard electronic module (SEM) frames (thermal planes). Graphite/aluminum composites offer greater stiffness, strength, and in-plane thermal conductivity, and lower density than aluminum alloys. However, the thermal contact conductance of the junction between the frame guide rib and aluminum A356-T61 chassis card rail has a substantial effect on the overall thermal performance of the frame. Hence, this investigation involved experimentally determining the thermal contact conductance of bare and electroplated silver coated K1100 graphite fiber reinforced aluminum 6063. Testing was performed over a range of contact pressures from 172 to 2758 kPa (25 to 400 psi) and mean interface temperatures of 20 to 100°C (68 to 212°F). Bare junction thermal contact conductance varied from 751 to 23340 W/m^2 (132 to 4104 Btu/h-ft^2°F), while the conductance of the silver plated graphite/aluminum ranged from 998 to 4418 W/m^2 (176 to 778 Btu/h-ft^2°F). Although the contact conductance of the bare graphite/aluminum is generally greater than that of the silver plated composite, silver plating is recommended to prevent galvanic corrosion of the composite in a marine or other corrosive environment. The through-plane thermal conductivity of the graphite/aluminum was measured to be approximately 80 W/mK (46 Btu/h-ft°F).

NOMENCLATURE

A	Contact area
D	Asperity slope
H	Vicker's microhardness
h	Thermal conductance
k	Thermal conductivity
R	Roughness
TIR	Flatness deviation (Total Included Reading)
t	Coating thickness
ΔT	Temperature difference
W	Waviness

Subscripts

a	Average
c	Contact or Coating
q	Root mean square (RMS)
s	Substrate
u	Uncoated

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INTRODUCTION

Power densities of electronics are continually increasing while size and weight constraints are becoming more stringent. Consequently, alternative materials with higher thermal conductivity and stiffness, as well as lower density are being considered for replacement of the presently used aluminum and copper in Standard Electronic Module (SEM) frames[1]. These frames are also referred to as thermal planes or heat sinks. Continuous graphite fiber reinforced metal matrix composites exhibit these advantages over metals, making them attractive alternative materials for applications in avionics, spacecraft, and satellites[1-4]. However, the thermal contact conductance of metal matrix composite frames to chassis card rails (Fig. 1) must be evaluated in order to predict the performance of metal matrix composites as SEM frames, and to allow comparisons to the current metallic frames. This information is essential

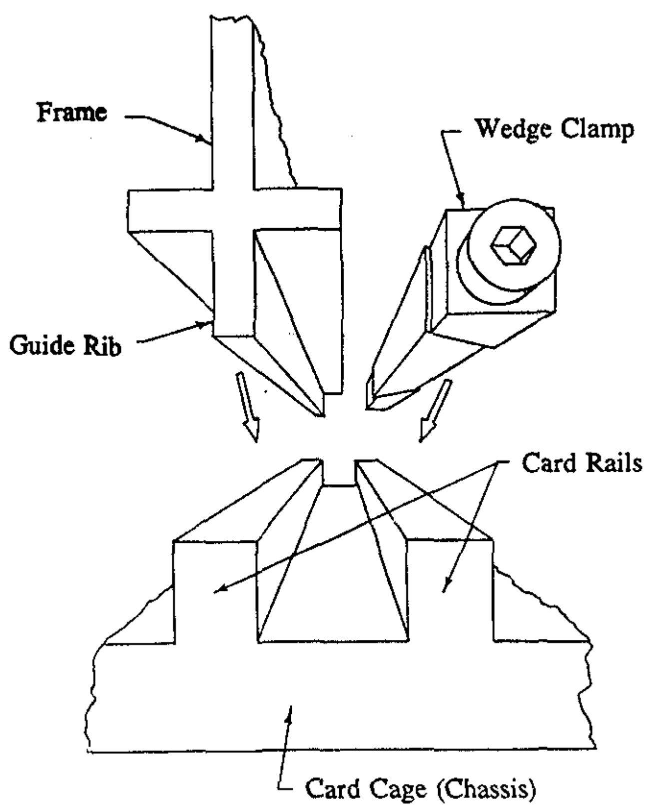

Fig. 1 Exploded view of Standard Electronic Module (SEM) junction.

for predicting the temperature discontinuity between the frame guide rib and the chassis card rail to which the module frame is clamped. Excessively large junction temperature discontinuities translate into higher circuit device (IC) temperatures and an increased failure rate.[5]

The only previous study of the contact conductance of metal matrix composites found in the open literature dealt with silicon carbide particulate reinforced aluminum alloys[6]. However, these composites are vastly different in structure from graphite fiber reinforced metal matrix composites, and are significantly harder than aluminum alloys[6]. This precludes using results for predicting the contact conductance of graphite fiber reinforced metal matrix composites.

Metal matrix composite frames are stiffer than metallic frames, and thus, may reduce flexural fatigue of solder bonds between devices and the printed wire board[1]. However, the decreased compliance of metal matrix composite frames may reduce the contact area of the guide rib/card rail junction, thereby increasing the thermal contact resistance. Also, metal matrix composite frames often exhibit greater variations in flatness than metallic frames[1], which may also increase contact resistance.

Inasmuch as thermal contact resistance at the guide rib/card rail junction is one of the most significant sources of thermal resistance of SEM's, a complete evaluation of metal matrix composite frames must include determination of contact conductance.

EXPERIMENTAL PROGRAM

The present investigation involves the experimental determination of the thermal contact conductance of a candidate graphite fiber/aluminum matrix composite frame material in contact with the presently utilized aluminum A356-T61 chassis material over a range of contact pressures and mean junction temperatures experienced by electronic modules.

Experimental Facility

The thermal contact conductance experiments are performed in the facility illustrated in Fig. 2. The apparatus consists of a frame for supporting the cylindrical specimens in a vertical column. Interface pressure between the specimen contact surfaces is controlled by varying the pneumatic pressure in the load bellows, while the interface load is measured with a load cell. Each source-sink-holder assembly is equipped with an electric heater and contains a coolant passage through which refrigerated ethylene glycol from a constant temperature bath may be circulated. Thus, by supplying power to one heater and coolant to the opposite fixture, an axial heat flux may be generated. Load is transferred from the frame to the fixtures through hardened steel ball bearings which serve to maintain uniform interface pressure as the ball bearings cannot exert significant bending loads on the specimen column.

The entire apparatus is encased in a vacuum jar which is held at 4.0^{-2} torr by an Alcatel two-stage rotary pump. The vacuum pressure is measured by thermocouple gauges connected to a Perkin Elmer Monitorr 300 digital indicator. Thermocouple voltages are measured to high accuracy by a

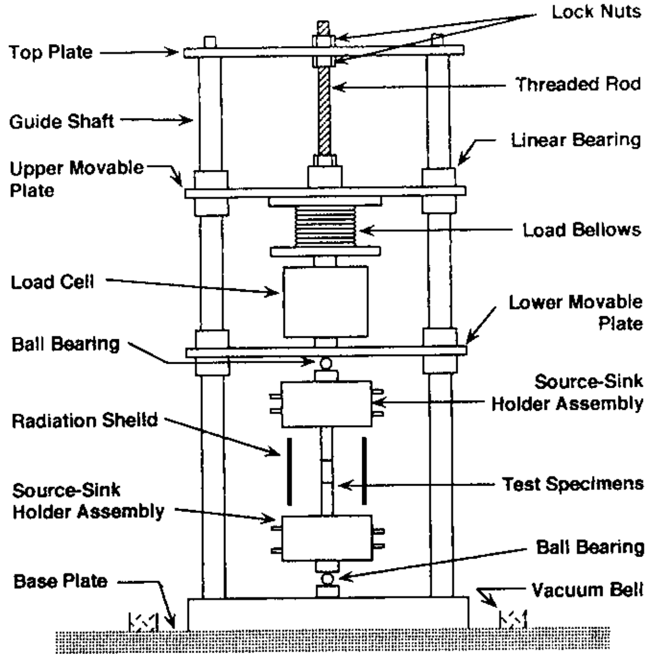

Fig. 2 Experimental apparatus.

Hewlett Packard (HP) 3497A datalogger. The facility is controlled by an IBM-compatible 486-66MHz personal computer.

Materials

The candidate metal matrix composite SEM frame material was fabricated by Americom, Inc. of Chatsworth, California. It is composed of 42% by volume K1100 (Amoco Corp.) graphite fibers with a balanced cross-ply (0-90) orientation in a matrix of aluminum alloy 6063. K1100 fibers are employed for their high axial thermal conductivity; the fiber name is derived from its approximate thermal conductivity, 1100 W/mK (636 Btu/h-ft°F). Aluminum alloy 6063 is also used for its relatively high thermal conductivity (201 W/mK (116 Btu/h-ft°F) for the -T6 quenched and aged condition and 218 W/mK (126 Btu/h-ft°F) when annealed) compared to the commonly used aluminum alloy 6061-T6 (167 W/mK (96 Btu/h-ft°F)). Aluminum alloy 6101-T6 (218 W/mK (126 Btu/h-ft°F)) is the material specified in the production of most presently employed monolithic metal SEM frames. Thermal conductivity values for these various aluminum alloys are taken from the Metals Handbook[7].

Production of the graphite/aluminum panels proceeds as follows. First, the graphite fibers are given a sub-micron thick, chemically vapor deposited (CVD), proprietary coating which protects the fibers from the molten aluminum during casting and increases wettability. The coated fibers (or fiber bundles, called tows) are layered to make a preform by a process called paddle winding, which is similar to filament winding. The preform is positioned in the mold which consists of metal plates ground to the required dimensions and subsequently treated with a boron nitride release agent to facilitate removal of the composite panel after casting. The preform/mold assembly is instrumented with thermocouples and placed in a pressure casting unit with the required quantity of matrix material (aluminum 6063).

Table 1 Thermal Conductivity*, Vickers Microhardness**, and Surface Profile Data*** for Test Specimens

Base Material -Sample****	Coating Material	ks / k-Ni / k-Ag (W/mK)	Hu / Hc (kg/mm ^ 2)	t-Ni / t-Ag (um)	Ra (um)	Rq (um)	Wa (um)	Wq (um)	TIR (um)	Dq (rad)
A356-F4	Bare	152 / ---- / ----	115 / ----	0 / 0	0.62 / 0.57	0.81 / 0.73	0.45 / 0.53	0.55 / 0.65	7.85 / 8.40	0.155 / 0.142
Gr/Al-L1	Bare	79.2 / ---- / ----	42 / ----	0 / 0	0.91 / 0.91	1.16 / 1.05	0.92 / 0.82	1.14 / 1.00	12.20 / 10.35	0.146 / 0.141
Gr/Al-L2				0 / 0	0.86 / 1.00	1.12 / 1.28	1.25 / 1.23	1.47 / 1.53	14.95 / 18.65	0.128 / 0.162
Gr/Al-L3				0 / 0	0.80 / 0.69	1.06 / 0.88	1.61 / 0.64	1.97 / 0.81	14.20 / 9.60	0.148 / 0.115
Gr/Al-L4				0 / 0	0.78 / 0.96	0.97 / 1.22	0.94 / 0.57	1.07 / 0.71	12.30 / 12.05	0.092 / 0.171
Gr/Al-L5				0 / 0	0.88 / 0.89	1.13 / 1.16	1.18 / 1.19	1.62 / 1.44	15.35 / 13.45	0.163 / 0.151
Gr/Al-M1	Electro-	79.2 / 5.02 / 427	42 / 86	24.6 / 12.7	1.83 / 2.08	2.34 / 2.68	1.31 / 1.95	1.57 / 2.46	30.70 / 35.80	0.142 / 0.125
Gr/Al-M2	plated Ag			24.6 / 26.2	0.86 / 0.97	1.09 / 1.27	2.08 / 2.51	2.62 / 2.86	18.80 / 31.90	0.117 / 0.127
Gr/Al-M3	over Electro-			24.6 / 39.1	1.00 / 1.26	1.27 / 1.66	1.62 / 2.27	2.05 / 2.68	24.05 / 28.20	0.095 / 0.106
Gr/Al-M5	less Ni			22.6 / 52.2	0.94 / 0.90	1.17 / 1.12	3.03 / 3.36	3.95 / 4.19	24.90 / 22.65	0.086 / 0.086

* k for nickel plating from Gawrilov[17], and k for silver from Touloukian and Ho[18].

** H_u is VHN of uncoated substrate material, and H_c is VHN of coating/substrate combination. As a point of reference, Tabor[19] lists the hardness of annealed silver as 25 kg/mm^2.

*** The pair of values for each surface profile parameter are for mutually perpendicular traces across the surface.

**** All graphite/aluminum specimens were tested in contact with the aluminum A356 heat flux meter.

The pressure casting unit is evacuated and back-filled until the required vacuum level is attained, then the unit's heaters are activated. The assembly temperature is increased to approximately 20°C (36°F) above the melting point of the matrix material. The unit is pressurized with nitrogen gas to ensure full densification of the composite, the heaters are turned off, and an active cold plate is brought in contact with the casting assembly to reduce the time-at-temperature exposure. Nitrogen pressure is maintained until the assembly reaches room temperature. Once cooled, the assembly is removed from the casting unit and excess matrix material is mechanically removed. The assembly is opened and the composite panel is extracted. A fine abrasive pad is used to remove any residual release agent from the panel surfaces. Three panels measuring nominally 7.62 × 7.62 cm (3.0 × 3.0 in.) were produced, each with a different thickness: 1.236 cm (0.4863 in.), 0.742 cm (0.2920 in.) or 0.248 cm (0.0975 in.).

Test Specimens

The upper and lower heat flux meters are fabricated from the aluminum A356-T61 card chassis material and are both 10.16 cm (4 in.) long. The middle specimen is graphite/aluminum composite and is one of three thicknesses, 1.236 cm (0.4863 in.), 0.742 cm (0.2920 in.) or 0.248 cm (0.0975 in.). The flux meters and composite specimen all measure 2.54 cm (1.00 in.) in diameter.

The upper and lower heat flux meters each contain five holes drilled radially to their centerlines at 0.635 cm (0.25 in.) intervals. Type K (chromel-alumel) special limit of error (1/2 normal, 1.1°K) thermocouples are inserted into the holes, and are held in place by aluminum powder which is packed into the holes. The metallic powder ensures good thermal contact of the thermocouple bead to the entire periphery of the hole. The metal matrix composite specimen is not instrumented for through-plane thermal conductivity tests. It is instrumented with four Type K thermocouples bonded at equally spaced intervals around the specimen's periphery midway between the upper and lower surfaces.

Coating Procedures

Some graphite fibers are left exposed during fabrication of the graphite/aluminum panels. The large electrochemical potential difference between aluminum and graphite[8] would cause galvanic corrosion of the aluminum in the presence of a marine or other corrosive atmosphere, if the composite is not protected by a suitable coating.

The presently utilized monolithic aluminum 6101-T6 SEM frames are given a hard anodic coating, synthesized in a low-temperature sulfuric acid electrolyte (designated Type III in Military Specification A-8625E[9]), for corrosion protection. However, apart from the fact that anodic coatings reduce thermal contact conductance in comparison to metal contacts[10], graphite/aluminum cannot be anodized. Exposed fibers draw current away from the aluminum, preventing synthesis of the anodic coating (aluminum oxide, Al_2O_3).

As part of a previous investigation, Lambert and Fletcher[11] determined that electroplated silver coatings provide ample corrosion protection in addition to significantly enhancing thermal contact conductance. The plating is achieved by a three step process. First, the graphite/aluminum specimens are electroless nickel plated in a solution developed by Maclean and Karten[12] using methods described by Krieg[13]. An underplating of nickel is recommended to improve adhesion of the silver overplating[14]. The electroless nickel plating is 22.6 to 24.6 μm (0.890 to 0.969 in.) thick.

Second, a very thin "strike" silver coating is applied, using a solution described by Blair[15], which improves adhesion of the third and final coating, the thicker outermost main silver plating. This final layer is deposited in an electrolyte formulated by Sova and Bollhalder[16], which yields relatively soft silver platings. Four electroless nickel plated graphite/aluminum specimens were silver electroplated to four thickness: 12.7, 26.2, 39.1, and 52.2 μm (0.00050, 0.00103, 0.00154, and 0.00205 in., respectively), to evaluate the effect of silver plating thickness on contact conductance.

Microhardness Measurements

The Vickers microhardness (VHN) of the aluminum A356-T61 and the bare and silver electroplated graphite/aluminum was measured using a Beuhler microhardness tester for a range of indentor loads from 10 to 500 grams force. Average VHN values are listed in Table 1.

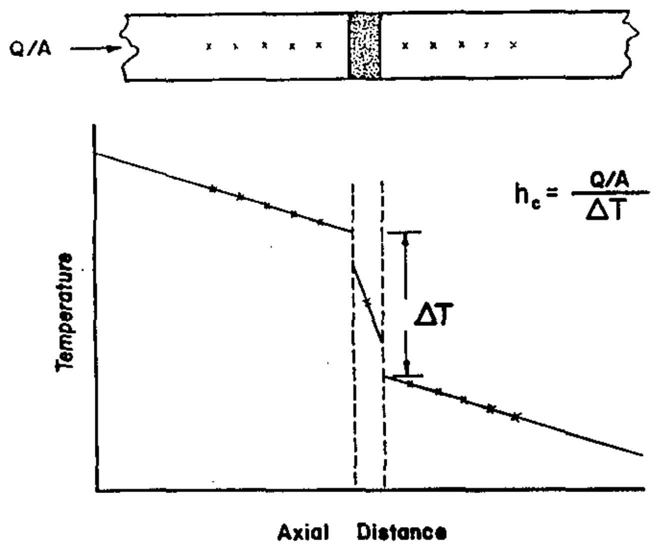

Fig. 3 Schematic of temperature profile through specimens and method for calculating thermal contact conductance.

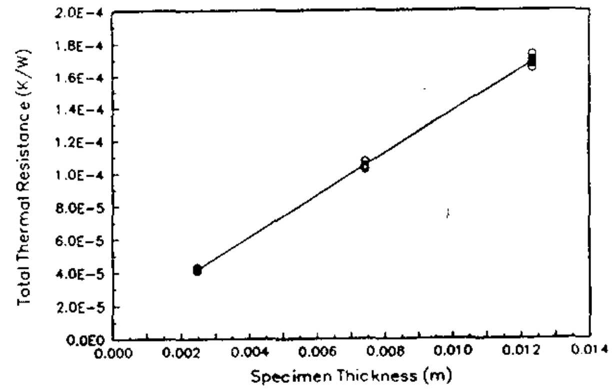

Fig. 4 Total through-plane thermal resistance vs. specimen thickness for all fifteen (five each of three thicknesses) graphite K1100/aluminum 6063 specimens at median specimen test temperature (80°C).

Surface Measurements

The surface profiles of contacting surfaces significantly affect their contact conductance. Thus, the surfaces of all test specimens were characterized using a Surfanalyzer 4000/5000 surface profilometer from Federal Products. Measurements include: root mean square (RMS) and centerline average (CLA) roughness, rms and average waviness, overall flatness deviation (TIR), and rms asperity slope. These surface characteristics, as well as specimen conductivity and microhardness measurements, are listed in Table 1. Note that the silver plated graphite/aluminum specimens exhibit approximately twice the roughness, waviness, and flatness deviation of the bare graphite/aluminum specimens.

Thermal Conductivity Calibration

Aluminum A356-T61 Heat Flux Meters

The thermal conductivity of the upper and lower aluminum A356 specimens was measured, so that the heat flux across the contact could be accurately measured. Toward this purpose, the upper and lower aluminum A356 flux meters were replaced by a pair of electrolytic iron heat flux meters of known conductivity[20], fabricated from material furnished by the National Institute of Standards and Technology (NIST). These iron flux meters are identical in configuration to the aluminum A356 flux meters. The middle composite specimen was replaced by a third aluminum A356-T61 flux meter, machined from the same stock used to fabricate the two flux meters used for contact conductance testing. This additional aluminum A356 flux meter is 3.81 cm (1.5 in.) long and is instrumented with five Type K thermocouples at 0.635 cm (0.25 in.) intervals. Use of the calibrated electrolytic iron flux meters allows the measured conductivity of the aluminum A356-T61 to be traceable to a universally accepted standard.

During calibration, Fourier's Law of heat conduction is used to compute the heat flux in each iron meter from its known conductivity and computed temperature gradient, obtained from a least-squares linear regression of its thermocouple readings. The heat flux through the aluminum A356 meter is estimated as the average flux through the two iron meters. Fourier's Law is again used to calculate the conductivity of the aluminum A356 from its estimated heat flux and computed temperature gradient.

Graphite/Aluminum Composite Specimens

The through-plane thermal conductivity of the graphite/aluminum composite must also be known in calculating the thermal contact conductance of the interface between graphite/aluminum and aluminum A356. None of the graphite/aluminum specimens is thick enough to allow the temperature gradient through its thickness to be explicitly measured with thermocouples placed at intervals along its axis. Thus, the through-plane thermal conductivity was determined as follows.

The total thermal resistance of five specimens of each of the three panel thicknesses (fifteen total specimens) was measured, using the electrolytic iron standard heat flux meters. The total thermal resistance is the sum of the bulk thermal resistance of the graphite/aluminum and the contact resistance of the two interfaces with the iron flux meters, and is defined as the heat flux divided by the total temperature change between the electrolytic iron flux meters, as illustrated in Fig. 3. The through plane thermal conductivity of the graphite/aluminum is the slope of the total thermal resistance versus specimen thickness. Total resistance is plotted as a function of specimen thickness in Fig. 4 for the example case of the median test temperature, 80°C (176°F).

All specimens were tested over a temperature range of 20° to 140°C (68 to 284°F). Dow Corning Type 340 heat sink compound was applied to the contacting surfaces and a constant contact pressure of 3447 kPa (500 psi) was maintained to obtain minimized, more uniform contact resistance for all fifteen specimens at a given average specimen temperature.

Thermal Contact Conductance Experimental Procedure

Each test is begun by cleaning all contact surfaces with acetone. The uncoated or silver over nickel plated graphite/aluminum specimen is inserted between the aluminum A356 flux meters and a light load is applied. The composite specimen is visually aligned, then initially loaded to 2758 kPa (400 psi). This pressure is applied to simulate the standard practice of exerting maximum rated torque to wedge clamps when installing SEM's. The thermocouples are connected to the datalogger. The vacuum jar is sealed over the apparatus and a vacuum is drawn. The specimens are allowed to outgas, and the coolant valve for the selected source-sink-holder assembly is opened. The interface of interest is the one at which heat passes from the composite specimen (SEM frame) to the aluminum A356 flux meter (card chassis). The data acquisition and control program is then executed; it computes contact conductance at three minute intervals while maintaining the desired pressure and temperature.

Conductance data for each specimen were obtained for mean interface temperatures of 20, 60, and 100°C (68, 140, and 212°F, respectively). For each mean interface temperature, pressure was increased over a range of five values, specifically, 172, 345, 689, 1379, and 2758 kPa (25, 50, 100, 200, and 400 psi). Steady-state was assumed to have been achieved when none of the ten most recent conductance measurements (taken over the preceding half hour) varied by greater than 0.5% from the average value for the ten readings.

Data Analysis

Thermal contact conductance is defined as the heat flux over the interface divided by the temperature discontinuity across the interface. The temperature gradients through the two aluminum A356 flux meters are obtained from least-squares linear regressions of their thermocouple readings. The heat flux through each aluminum A356 meter is then calculated from Fourier's Law and its known temperature gradient and conductivity. The heat flux through the composite specimen is estimated as the average flux through the aluminum meters, and Fourier's Law is employed again to calculate the temperature gradient through the composite from its calibrated conductivity and this estimated heat flux. The interface temperature of the flux meter is computed directly from its regression equation. The interface temperature of the graphite/aluminum specimen is extrapolated from its explicitly known average temperature (from the readings of its four thermocouples) and its computed temperature gradient. This method is illustrated in Fig. 3.

Uncertainty Analysis

Uncertainty in the experimentally determined thermal contact conductance values arises from a number of sources, predominantly uncertainties in the thermocouple readings. These are due to slight inhomogeneities in the thermocouple alloys and signal noise in the instrumentation. The method of Kline and McClintock[21] was used to estimate the overall uncertainty.

The uncertainty in the thermal conductivity of the aluminum A356 is 2.4%, while that for the through plane thermal conductivity of the graphite/aluminum is 6.4%. The uncertainties in the contact conductance experiments are 5.0% for the heat flux and 2.2% for the temperature discontinuity. The overall uncertainty in the conductance data is 8.7%.

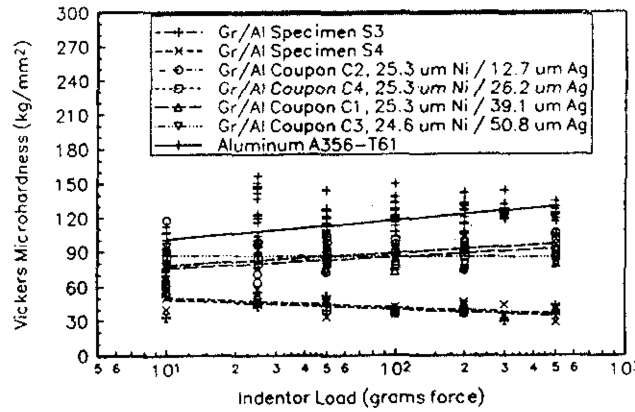

Fig. 5 Vickers microhardness vs. indentor load for aluminum A356-T61 and bare and electroplated silver over electroless nickel plated graphite K1100/aluminum 6063.

RESULTS AND DISCUSSION

The thermal contact conductance of bare and silver over nickel plated K1100 graphite fiber/aluminum 6063 composite in contact with aluminum A356-T61 was measured. Graphite/aluminum is a candidate material for replacement of the currently used aluminum alloy 6101-T6 in electronic module frames. Testing was performed over a pressure range of 172 to 2758 kPa (25 to 400 psi) and at three interface temperatures: 20, 60, and 100°C (68, 140, and 212°F, respectively). The through-plane thermal conductivity of graphite/aluminum was also measured, as it affects the thermal performance of the composite. Vickers microhardness and surface profile measurements were also performed.

Vickers Microhardness

As illustrated in Fig. 5, the Vickers microhardness (VHN) of the silver over nickel plated graphite/aluminum is essentially independent of both indentor load and silver plating thickness. This suggests that the very hard (VHN=600)[22] electroless nickel underplating does not affect the indicated hardness, even for the thinnest silver overplating at the highest indentor load. The average hardness of the silver/nickel plated graphite/aluminum is 86 kg/mm^2, which is relatively low for silver electroplatings.

The microhardness of the bare graphite/aluminum decreases moderately with increasing indentor load and has an average value of 42 kg/mm^2, very nearly half that of the silver/nickel plated graphite/aluminum. The aluminum 6063 matrix is probably annealed, because the composite was not quenched from the melt temperature, resulting in a very low hardness.

The aluminum A356-T61 chassis material is a quenched and age hardened alloy, being harder than both the bare and silver/nickel plated graphite/aluminum frame materials. The hardness of the aluminum A356 increases moderately with increasing load and has an average value of 115 kg/mm^2.

Through-Plane Thermal Conductivity

The through-plane thermal conductivity of the graphite/aluminum is plotted in Fig. 6. Note that the

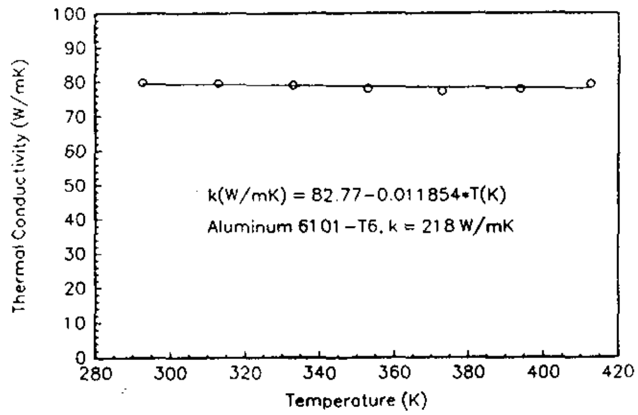

Fig. 6 Through-plane thermal conductivity vs. temperature for graphite K1100/aluminum 6063.

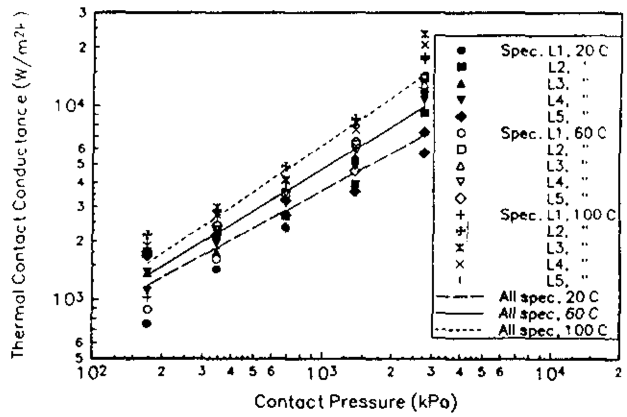

Fig. 8 Thermal contact conductance vs. apparent contact pressure for bare graphite/aluminum to aluminum A356-T61.

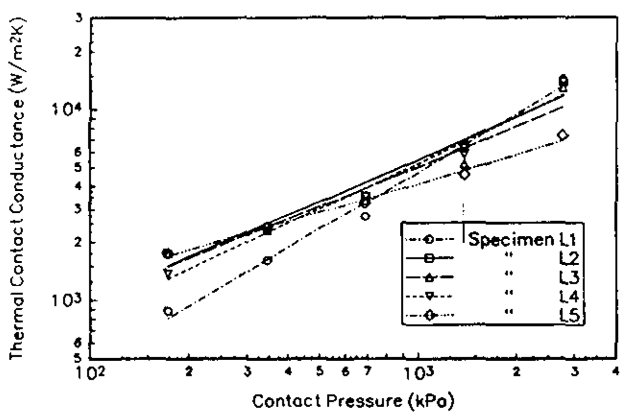

Fig. 7 Thermal contact conductance vs. apparent contact pressure for bare graphite/aluminum to aluminum A356-T61 at *median interface temperature* (60°C).

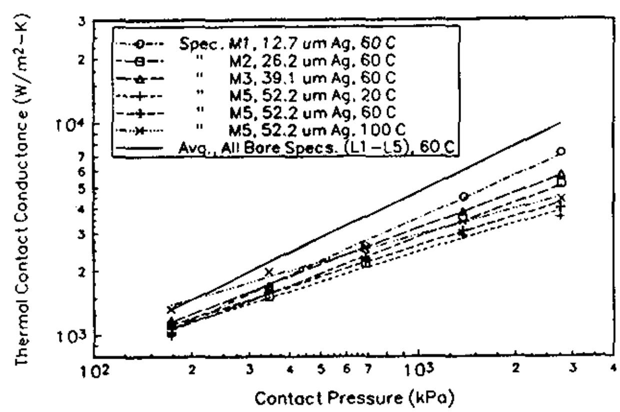

Fig. 9 Thermal contact conductance vs. apparent contact pressure for electroplated silver over electroless nickel plated graphite/aluminum to aluminum A356-T61.

conductivity bears almost no dependence on temperature. The room temperature, 25°C (77°F) value, 79.2 W/mK (46 Btu/h-ft°F), is approximately 36% of the thermal conductivity of the currently used aluminum 6101-T6 module frame temperature, 218 W/mK, (126 Btu/h-ft°F).

The through-plane thermal conductivity is important for more than merely determining thermal contact conductance. The conductivity indicates how well heat generated by the electronic devices mounted on the frame is spread to the high conductivity graphite fibers. Low through-plane thermal conductivity is a potential drawback of organic matrix (e.g., epoxy and polyamide) graphite reinforced composite frames[4].

Thermal Contact Conductance of Bare Graphite/Aluminum

Thermal contact conductance results for the five bare graphite/aluminum specimens tested are shown in Fig. 7 for the median interface temperature of 60°C. Both the magnitude and slope of the contact conductance vary moderately from one specimen to another. This is possibly due to the differing surface profiles of the specimens, which dictate the size and shape of the macroscopic contact area. Note the substantial flatness deviations (TIR) of the graphite/aluminum specimens in Table 1. Nonlinearity in the conductance data for some specimens may be caused by distortion under increased load, resulting in increased macroscopic contact area.

The influence of interface temperature on the thermal contact conductance of the bare specimens is portrayed in Fig. 8. The contact conductance (averaged for all five bare specimens) increases with increasing temperature, though not greatly. Softening of the annealed aluminum 6063 matrix is quite likely responsible for this behavior.

Contact Conductance of Silver Plated Graphite/Aluminum

Figure 9 illustrates the contact conductance of electroplated silver over electroless nickel plated graphite aluminum. The contact conductance decreases minimally with increasing silver plating thickness. The conductance increases very slightly with increasing temperature, since the aluminum A356 softens very little over the temperature range tested, while any softening of the silver is imperceptible.[23]

The conductance of the silver/nickel plated graphite/aluminum exhibits considerably more uniform, linear trends than do the conductance results for the bare

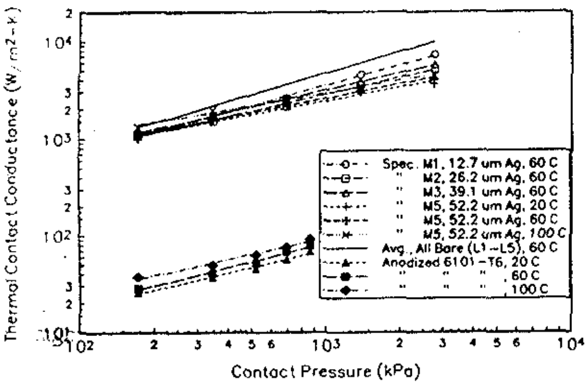

Fig. 10 Thermal contact conductance vs. apparent contact pressure for electroplated silver over electroless nickel plated graphite/aluminum to aluminum A356-T61 compared to thermal contact conductance of anodized aluminum 6101-T6 to aluminum A356-T61.

graphite/aluminum. In all cases, the contact conductance of the plated graphite/aluminum is less than the average conductance for the bare graphite/aluminum. This may attributable to the greater hardness and flatness deviations for the silver/nickel plated composite.

Comparison of Thermal Contact Conductance

The thermal contact conductance of the bare and silver/nickel plated graphite/aluminum is some thirty times greater than the conductance of the presently utilized anodized aluminum 6101-T6 as determined by Lambert and Fletcher[22]. This vast difference is caused by the very low thermal conductivity (0.0292 W/mK)[9] and high hardness (VHN=280 kg/mm^2)[22] of the anodic coating on the aluminum 6101-T6.

CONCLUSIONS AND RECOMMENDATIONS

The current investigation involved experimentally determining the thermal contact conductance of the metal matrix composite, graphite K1100 fiber reinforced aluminum 6063, being considered as a replacement material for standard electronic module frames. The results demonstrate that its thermal contact conductance in junction with the aluminum A356-T61 chassis card rail is far greater than that of currently used anodized aluminum 6101-T6 frames. The conductance of the bare graphite/aluminum is markedly greater than the conductance of the silver over nickel plated composite. However, since galvanic corrosion is a distinct possibility, and graphite/aluminum cannot be anodized due to exposed fibers, the silver/nickel plated composite should be employed.

Inherently thin chromate conversion coatings may provide sufficient corrosion protection at lower cost than the silver/nickel plating. The thermal contact conductance of conversion coatings should be evaluated.

The through-plane thermal conductivity of the graphite/aluminum was determined to be approximately 36% of the reported conductivity for aluminum 6101-T6. The in-plane thermal conductivity of the composite should also be ascertained, as it is of importance in evaluating performance of the module frame.

Graphite fiber copper matrix composites are being considered for replacing electroless nickel plated copper C11000 frames in high power modules. Characterization should include measurement of the through-plane and in-plane thermal conductivity and thermal contact conductance. In addition, contact conductance tests of electroless nickel plated graphite/copper and electroplated silver over electroless nickel plated graphite/copper should also be performed, since this composite is susceptible to galvanic corrosion.

ACKNOWLEDGEMENTS

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