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CHARACTERIZATION OF THERMAL INTERFACE MATERIALS USING A STEADY STATE EXPERIMENTAL METHOD

Benjamin Sponagle
Mechanical Engineering, Dalhousie University
Halifax, Nova Scotia, Canada

Dr. Dominic Groulx
Mechanical Engineering, Dalhousie University
Halifax, Nova Scotia, Canada

ABSTRACT

One method for characterizing the contact conductance of Thermal Interface Materials (TIMs) is the steady state one dimensional heat flow method typified by ASTM D5470. A test apparatus and procedure were developed which use the basic theory of steady state testing TIMs and improves upon the accuracy and repeatability of the standard test. This procedure and apparatus were used to test the contact conductance of the interface four commercial available TIMs. These materials include: Laird Tflex 720, Laird Tmate 2905c, Chomerics Cho-Therm T500, and Chomerics Cho-Therm 1671. It was found that the Laird products underperformed the available manufacturer published values and the Chomerics products only met performance expectations at relatively high clamping pressures (400 psi).

INTRODUCTION

When two surfaces contact one another, only a small percentage of their total area is in direct contact. This is due to the roughness and flatness of each of the surfaces. As a result, air gaps are formed between the two surfaces. If heat is being transferred across the interface, these air gaps will produce a thermal interface resistance [1].

A common example of a system with one or more interfaces is the cooling system for a microchip. Heat is being dissipated in the chip and must be removed through conduction to the heat sink. There will be interfaces between the microchip, the heat sink and possibly a heat spreader. [1]

Thermal Interface Materials (TIMs) are designed to be placed between two surfaces in order to reduce the thermal interface resistance. The performance of a particular TIM is determined by how well it can fill the imperfections in the surfaces forming the interface, how thick of a TIM layer is formed between the surfaces, and the effective conductivity of the TIM [1, 2].

There are several types of TIMs. A commonly used type is thermal grease. These consist of a polymer base which is filled with thermally conductive particle. These particles are often metallic or ceramic. Greases form a thin layer and easily fill the air gaps. However, greases are messy to apply and remove and their performance can degrade over time [3, 4]. Alternative materials include thermal pads which consist of particle filled elastomers. These are not free flowing like the greases so do not as easily fill the gaps. Also, they will not squeeze out of the interface like a grease so they generally form thicker interface layers. However, they are easy to apply and remove. They can also have additional roles such as electrically insulating the interface. Phase change materials are also used as they can be applied like a thermal pad but have better flow properties when the system is operating at high temperature [3].

The performance of a thermal interface material is difficult to quantify independently of a specific application. The interface resistance or conductance is a function of the properties of each of the surfaces (roughness, flatness), the properties of the TIM, the pressure applied to the interface, and the temperature of the TIM. Measuring the bulk thermal conductivity of a TIM will not allow the prediction of the thermal conductance of an interface with that TIM applied [2]. This necessitates an experimental method for characterizing the conductance of a thermal interface with an applied TIM.

There are two basic methods for characterizing the conductance of thermal interfaces: transient and steady state [1]. Both of these methods place a TIM in an interface between two conductive plates forming a test assembly which resembles a sandwich. The transient methods apply a heat flux to one end of the sandwich and then monitors the transient temperature response at the opposite side of the assembly. One example of a transient test method which has been presented in the literature is the laser flash method. In this case, TIM is places between two thin plates. One side of the test assembly is subjected to a laser pulse. The temperature response of the opposite side of the test assembly is then measured and translated into a contact conductance [5-8].

Steady state tests are typified by ASTM D5470. In these tests the TIM is placed between meter bars which are much thicker than the plates used in the laser flash test. A steady state heat flow is then set up through the assembly. The temperature in the meter bars are then monitored at two or more locations along their length. From those temperature readings, the temperature drop across the interface can be calculated and used to determine the resistance or conductance of the interface. [9]

The work presented in this paper focuses on the steady state method of characterizing TIM performance. A steady state characterization experiment was constructed and used to measure the performance of several commercially available TIMs. These values were then compared to manufacturer published values.

NOMENCLATURE

Dimensional Variables

A	Interface area (cm^2)
d	Position (m)
k	Thermal conductivity (W/m·K)
Q	Heat conduction (W)
T	Temperature (K)
y	y-coordinate (m)

Greek Symbols

θ	Contact conductance (cm^2 K/W)

Subscripts

C	Cold side of the interface
H	Hot side of the interface

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. It consists of two meter bars which form the interface to which the TIM is applied. Each meter bar is a 3" × 1" square block of Al 6061 T6. Therefore, there is a one inch square test area which holds a sample during testing. A heater and cooler are used to setup a steady state heat flow through the assembly, both are machined from Al 6061 T6. The temperature of the meter bars are measured using platinum Resistance Temperature Detector (RTD) sensors at three different locations along their length. They are placed in 5/8" deep holes drilled into the side of the meter bars. The holes are filled with Laird T-Grease thermal paste before the sensors are inserted. This experimental assembly is then placed in a custom press which is used to apply pressure to the assembly as seen in Fig. 2.

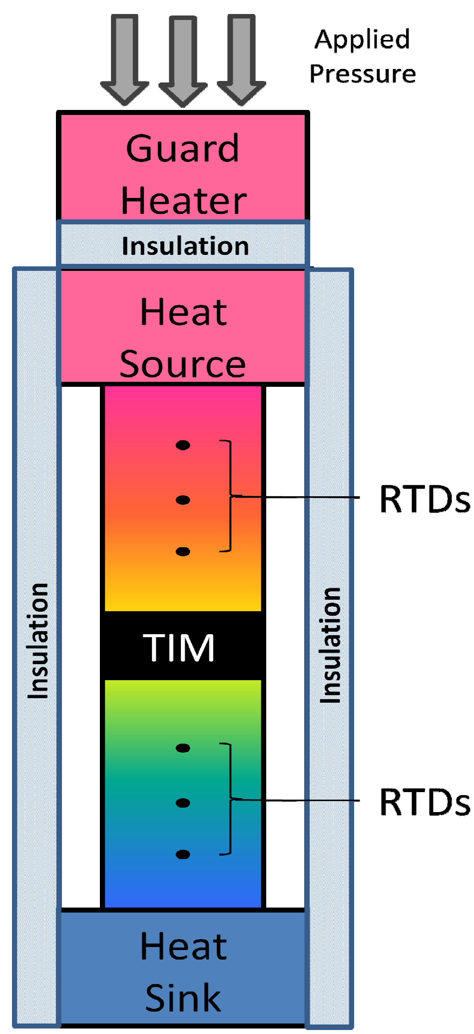

Figure 1. Schematic of the test assembly geometry.

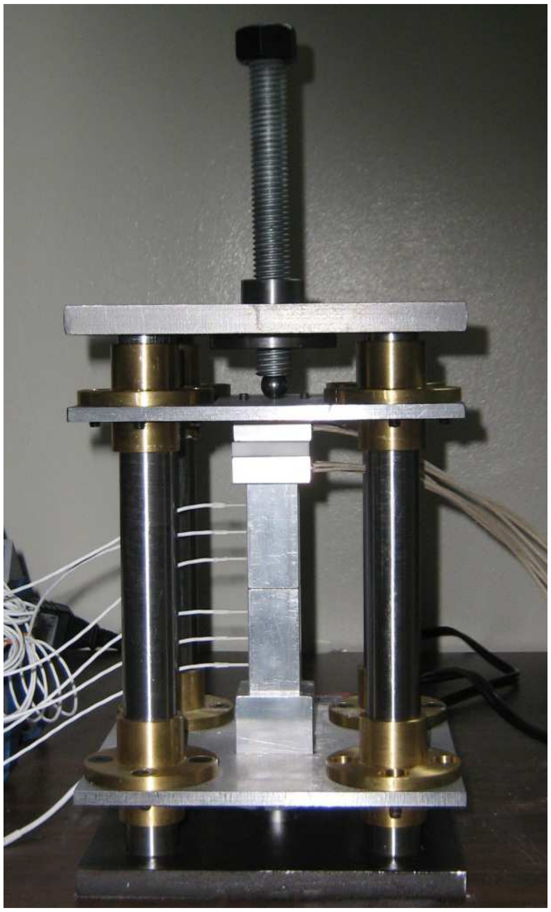

Figure 2. Photograph of the test assembly including the pressure application press but no insulation.

The heater block consists of two 50 W cartridge heaters which are inserted into an aluminum block. The cooler is a custom aluminum heat sink through which air is blown using a computer fan during testing. The pressure is monitored by a load cell located below the bottom free sliding plate.

During testing the sides of the experimental assembly are insulated using a rigid fiber board insulation. A one inch thick layer of insulation surrounds the outside of the assembly. Additionally, a guard heater is used to insulate the top of the assembly. A piece of MACOR ceramic insulation is placed on top of the experimental heater and a guard heater is placed on top of the insulation. The guard heater is identical to the experimental heater and consists of two cartridge heaters inserted into an aluminum block. Table 1 gives details on the various components of the experimental setup.

Table 1. Specifications of the components which comprise the test assembly

Platinum RTDs	
Manufacturer	Omega
Part #	PR-11-2-100-1/16-2-E
Length	3"
Diameter	1/16"
Accuracy	Class A
Load Cell	
Manufacturer	Omega
Part #	LC304-500
Output	2mV/V
Accuracy	±0.5% Full Scale Output linearity, hysteresis, repeatability
Cartridge Heaters	
Manufacturer	Omega
Part #	CIR-1016/120V
Wattage	50 W
Fiber Board Insulation	
Manufacturer	Thermal Ceramics
Product Name	Superwool 607
Thermal Conductivity	0.06 W/mK
Thickness	1"
Ceramic Insulation	
Manufacturer	Corning
Product Name	MACOR
Thermal Conductivity	1.46 W/mK
Thickness	1/4"
Meter Bars	
Dimensions	3"×1"×1"
Material	Al 6061 T6
Thermal Conductivity	167 W/mK

TEMPERATURE SENSOR CALIBRATION

Platinum RTD sensors have a temperature varying accuracy. Class "A" RTDs have a tolerance of ±0.15˚C and ±0.35˚C at 0 and 100˚C respectively. In order to ensure that the probes were as accurate as possible, the probes used in these experiments were recalibrated using a FLUKE 7102 Micro calibration bath (see Table 2 for relevant specifications).

Table 2. Specification of the calibration bath used

Calibration Bath	
Manufacturer	FLUKE
Absolute Tolerance	±0.25 ˚C
Uniformity	±0.02 ˚C
Stability	0.015 ˚C @ -5˚C 0.03 ˚C @ 121˚C
Fluid	5010 silicone oil

The important temperature measurements that must be made during the characterization of TIMs are all differential measurements. Interchangeability of the sensors is the most important parameter, not absolute accuracy. As a result, a relative calibration was carried out. One of the RTDs in question was chosen as the standard and correction curves were produced for each of the other sensors to ensure that they were all interchangeable. All of the sensors were placed in the bath and temperature readings were made using the same DAQ system and specific channels that would be used in the experiment. Thirteen measurements were made in total going from 50 ˚C to 115 ˚C in 5 degree intervals. The sensors can then be corrected to be interchangeable within the uniformity tolerance of the bath. This was done by calculating the required adjustment for each sensor at each data point and then fitting a curve which related the required correction factor to the output of each sensor. The validity of this procedure can be verified by repeating the same calibration procedure with the sensors in different locations in the bath. After the correction curves are applied to the outputs of the sensors, they are interchangeable to within the stability tolerance of the bath. Tests have shown that they are interchangeable to within ±0.05 ˚C.

EXPERIMENTAL PROCEDURE

A sample TIM is applied to the interface between the two meter bars. The heaters and fan are turned on and the system is allowed to reach steady state without any pressure being applied via the press. The system is assumed to be at steady state when consecutive temperature readings taken at two minute intervals show a temperature change of less than 0.1ºC. When steady state is reached, pressure is applied to the system. The system is then allowed to restabilize and a data point is recorded using a National Instruments Compact DAQ system. The initial data point is ten minutes of data recorded at 4 Hz. Figure 3 shows an example of the data recorded.

Pressure measurements are made in parallel with the temperature measurements utilizing the same DAQ system. Additionally, the voltage and current being supplied to the heater is measured using multimeters at the beginning and end of each data point. The temperature difference between the guard heater is measured using type T thermocouples and kept below ± 0.2 ˚C during each data point measurement. This procedure is then repeated increasing the applied pressure.

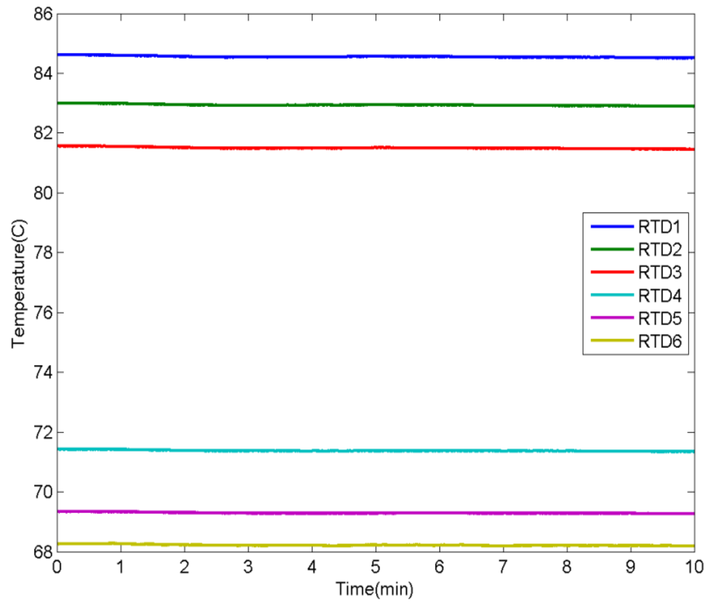

Figure 3. Example of temperature measurements made at steady state. Measurements were made with no TIM in the interface at 149 psi with 14.9 W of heat transfer.

DATA PROCESSING AND ANALYSIS

The thermal properties of an interface can be characterized by the contact conductance θ (W/cm^{2}K). If we assume that the system is well insulated and approximates a one dimensional heat flow, we can calculate the contact conductance of the interface as follows.

$$\theta = \frac{Q}{A(T_H - T_C)} = \frac{k\,dT/dy}{(T_H - T_C)} \tag{1}$$

Where T_H and T_C represent the temperature of the hot and cold side of the interface. However, directly measuring the temperature at the interface is problematic. These temperatures are instead extrapolated from the measurements made in the meter bars. Assuming the system in linear we calculate the temperature gradient in each of the meter bars (see Fig. 4 for an illustration). This method requires the location where each of the temperature measurements was made. A coordinate measuring device was used to measure the locations of the holes in which the RTD probes were placed. Table 3 summarizes the measurements that were made.

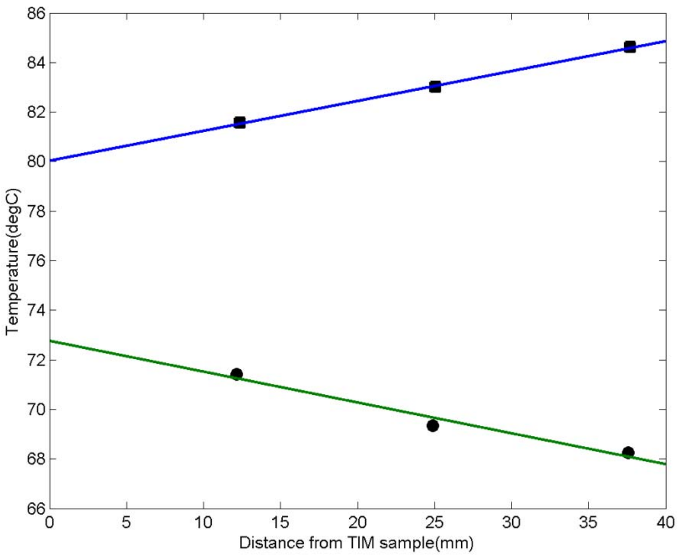

Figure 4. Example of the line fitting calculation used to determine the temperature drop across the Interface. Measurements were made with no TIM in the interface at 149 psi with 14.9 W of heat transfer.

In order to use Eq. (1) to calculate the contact conductance, the heat transfer through the test assembly must be known. This can be calculated by using the temperature gradient and Eq. (2) or measured via the wattage of the input heater.

$$Q = k\,A\left(\frac{dT}{dy}\right) \qquad (2)$$

The thermal conductivity *k* is the conductivity of the meter bar material (Al 6061 T6) and was taken as 167W/m·K.

The temperature data collected at each pressure is used to calculate the temperature differences between each sensor and an average value for each is calculated. These average values are then used to determine a single contact conductance values for each applied pressure.

Table 3. Locations of the holes as measure by CMD

Hot Meter Bar	
	Distance From Interface (mm)
$d_{RTD\ 1}$	38.03
$d_{RTD\ 2}$	25.35
$d_{RTD\ 3}$	12.62
Cold Meter Bar	
	Distance From Interface
$d_{RTD\ 4}$	12.58
$d_{RTD\ 5}$	25.29
$d_{RTD\ 6}$	38.00

The uncertainty in the conductance values was calculated using standard error propagation techniques. Contributions to this include the uncertainty in the RTD and CMD measurements, as well as random error in the temperature measurement data. Of these the most significant is the bias on the temperature measurements. Our calibration allowed us to reduce the bias on the temperature difference measurements to ±0.05 ˚C. However, this still represents the largest contribution to the uncertainty.

Additionally, the uncertainty of a conductance measurement is tied to the magnitude of the conductance value. This is because as the performance of the tested TIM increases and the conductance value increases, the temperature drop across the interface becomes small. As the temperature drop across the interface becomes small the bias error in the temperature measurements becomes more significant. This means that the better the performance of a TIM the more difficult it is to characterize with precision.

RESULTS AND ANALYSIS

To establish a base line to which the performance of the TIMs can be compared, the contact conductance of the interface with no TIM applied was measured. Figure 7 shows the contact conductance of the interface as a function of applied pressure. They are compared to results from Xu et al. [10] for an interface without an applied TIM.

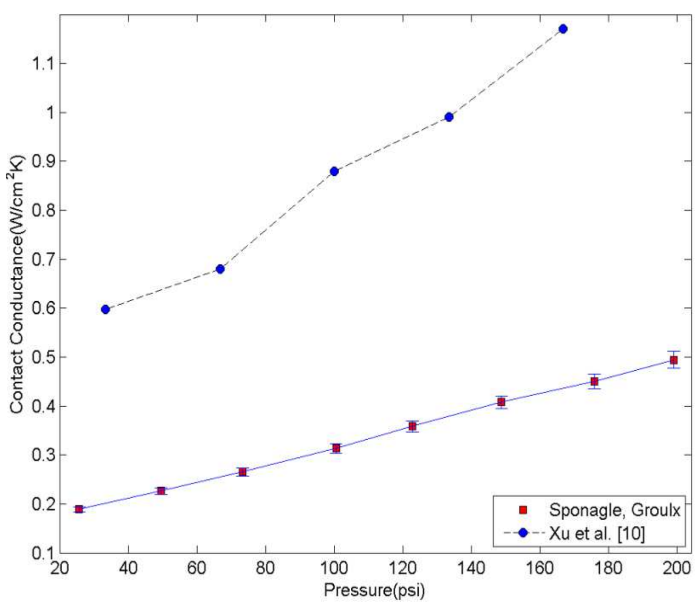

Figure 5. Contact conductance plotted vs. applied pressure for an interface with no TIM applied.

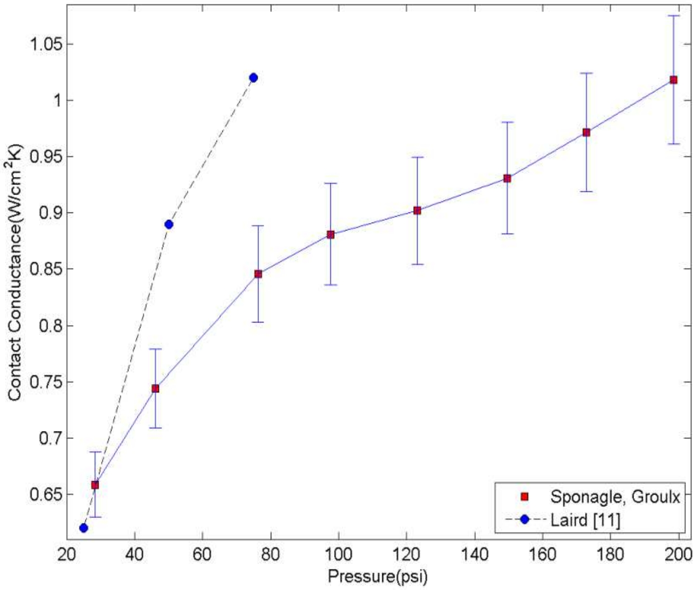

Figure 6. Contact conductance plotted vs. applied pressure for Laird Technologies Tflex 720.

There are obvious discrepancies between the two data sets. However, the results from Xu et al. were achieved using the transient laser flash method. More importantly, the surface of the plates used by Xu et al. were mechanically polished. In contrast, the meter bars used by the authors were machined to a standard #6 finish to better represent a real world application. With this discrepancy in mind, one would expect that the conductance of an interface with higher surface roughness to be less, which is what the results from Fig. 7 show.

Figure 8 shows the results for Laird Technologies Tflex 720. This TIM is a soft silicone elastomer filled with ceramic particles. The TIM is very deformable and has the consistency of a soft clay or putty.

The published data sheet for the Tflex 700 series of products does not include any data for the Tflex 720 TIM. The closest data that is published is for Tflex 740. The difference between these two products is the preinstalled thickness. The Tflex 720 sample is 0.02" thick while the Tflex 740 is 0.04" thick. The data for Tflex 740 is shown in Fig. 8.

While a direct comparison is not possible because of the lack of published data, some relevant observations can be made. A thicker sample of TIM will have a lower conductance than a thinner sample. The tested data was half as thick as the closest published values. Therefore, it would be expected that the tested sample would perform better than the published data for Tflex 740. This is not the case, the tested sample was measured to have a similar or lower conductance than the published values depending on the clamping pressure.

A similar trend can be seen with Laird Tmate 2905. This product consisted of a thin layer of phase change material that is adhered to a metal foil. With this product one side of the interface is in contact with the phase change material while the other contacts the metal foil. The conductance measurements are shown in Fig. 9. The published data sheet for this material quotes a single conductance value at 20 psi of 2.22 W/cm^{2}K. The measured conductance curve does not correspond to the published data. Again the measured performance is significantly lower than the manufacturer published data. It should be noted that data sheet for this TIM places the phase change softening temperature between 50˚C and 70˚C. The average temperature of the sample was between 67.8˚C and 71.9˚C.

The measured results for the two Chromerics products that were tested are shown in Fig. 10 & 11. Both the Cho-Therm T500 and 1671 consist of silicone elastomers filled with boron nitride particles and reinforced with glass fiber. They can be differentiated from the other TIMs tested by the fact that they are not designed to soften or flow while in use. This makes them more rugged. Samples of the two Laird products deformed and adhered to the interface during use. When they were removed the samples were destroyed. The Chromerics samples did not visibly deform and were removed intact.

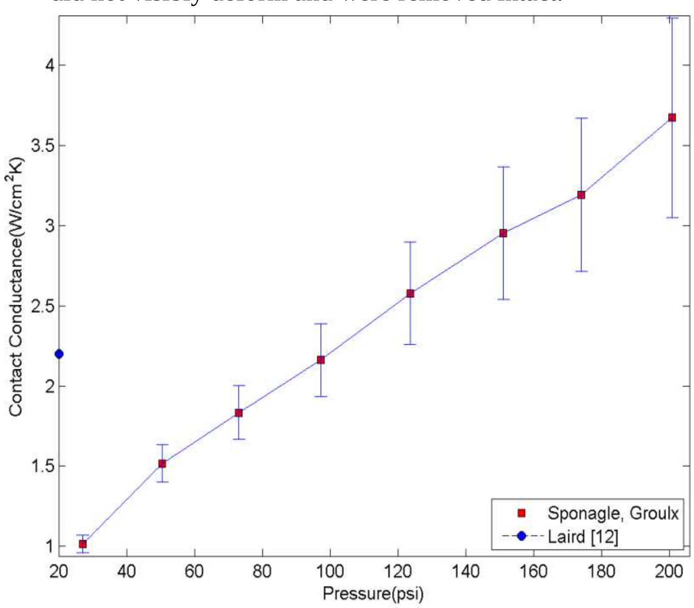

Figure 7. Contact conductance plotted vs. applied pressure for Laird Technologies Tmate 2905.

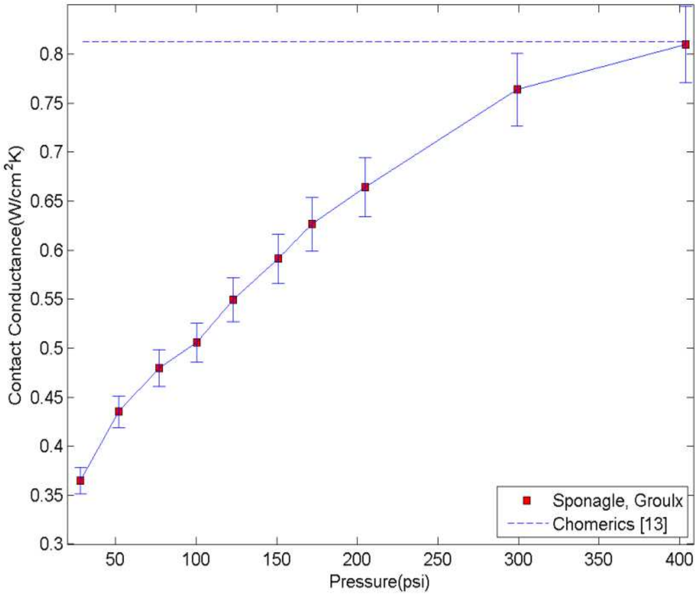

Figure 8. Contact conductance plotted vs. applied pressure for Laird Technologies Cho-Therm T500.

The conductance data quoted by the Chomerics data sheets did not specify a clamping pressure. However, they do state the optimum clamping pressure for the use of the Cho-Therm products is 300-500 psi. At 400 psi the published value does fall within the uncertainty bounds of the measured conductance values for Cho-Therm T500 and the Cho-Therm 1671 is approaching the published value. However, the performance is strongly dependant on clamping pressure and the measured value is less than half of the published value at 25psi.

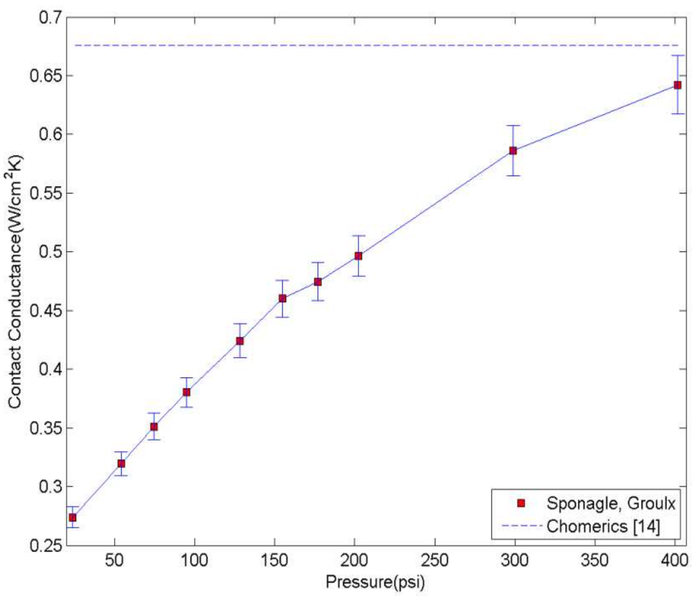

Figure 9. Contact conductance plotted vs. applied pressure for Laird Technologies Cho-Therm 1671.

The measured values for all of the TIMs tested were lower than the published values with the exception of the elastomer pads at high clamping pressures. This deviation is not surprising given that the surface conditions are not quoted on manufacturer data sheets. The fact that those experimental values for the Laird materials were consistently lower could indicate that the published results were conducted with a more finely polished testing surface. Without a specific clamping pressure associated with the Chomerics published values, it is difficult to make solid conclusions. However, it should be expected that interface conductance tests would be more consistent at higher pressures as the resistance contribution of the interface interaction is reduced and the thickness of TIM layer begins to dominate the resistance. This helps to lessen the importance of surface finish.

CONCLUSIONS

The interface conductance of: Laird Tflex 720, Laird Tmate 2905c, Chomerics Cho-Therm T500, and Chomerics Cho-Therm 1671 were measured using a steady state characterization method. The results were compared to manufacturer published values and were found to be consistently lower. The only exception being that the measured values for the Chomerics products did converge on the published values at higher clamping pressures (400 psi).

It would be beneficial if manufacturers data was quoted at a larger range of clamping pressures and at several surface roughness values. This would not account for variations in surface flatness but would nonetheless improve the usefulness of their information.

One potential source of bias error in the steady state method of characterization is the assumption that the system approximates a one dimensional system. Any heat losses or none uniformity in the heaters will produce a bias error in the results. One potential way of accounting for this error is to use FEA simulation to model the experiment in three dimensions. This would allow the experimenter to account for heat losses to the environment as well none uniformity in the heaters.

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