The Characterization of Thermal Interface Materials using Thermal Conductivity for Within Sample and Batch to Batch Variation Analysis

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ABSTRACT

The modified hot wire technique has been applied to evaluate consistency and homogeneity of thermal interface materials using measurements of thermal conductivity. A series of tests were conducted on various thermal interface materials manufactured by eight different companies. The results show that the accuracy and precision of the modified hot wire technique are better than 4% and 2%, respectively. It was found that the heterogeneity and inconsistency of thermal interface materials vary significantly and that the inconsistency of batches and heterogeneity can be as high as 11.3% and 9.8%, respectively. Neither inconsistency nor heterogeneity may be used to estimate the other.

INTRODUCTION

The increased power levels and minimization of electrical devices have substantially increased volumetric heat dissipated, which impacts considerably on the performance of electric equipment. Thermal management, therefore, is becoming a critical factor in achieving the design performance. To this end, many new thermal interface materials have been developed to improve the thermal management. As a key parameter of thermal management, thermal conductivity is a consideration at all levels of the design and manufacture of electronic components. Given the fact that consistency and homogeneity can significantly affect the performance of thermal interface materials, it is desirable to efficiently and effectively measure and utilize thermal conductivity to evaluate consistency and homogeneity of thermal interface materials.

Guarded hot plate, heat flow meter, laser flash diffusivity, and hot wire are frequently employed to measure thermal conductivity [1][2][3][4]. A common drawback of the first three methods is that samples must have fixed dimensions. This presents challenges in the sample preparation and measurement of some materials such as thermal greases. Long testing time and the inconvenience of evaluating product homogeneity are the additional shortcomings of guarded hot plate and heat flow meter methods. Laser flash diffusivity is a rapid method but measures thermal diffusivity rather than thermal conductivity. Thus, heat capacity and density have to be known in order to determine thermal conductivity. The hot wire technique is an intrusive method and may not be appropriate for some solid thermal interface materials.

As an alternative to these methods, the non-destructive modified hot wire technique can accurately and rapidly measure thermal conductivity or thermal effusivity of a wide variety of materials such as pastes, powders, and solids [5][6][7]. The thermal conductivity can be determined as long as samples have a flat area with 25mm x 5mm or 17 mm diameter. The interfacial nature of the measurements and small testing area make the modified hot wire technique highly effective in the evaluation of the homogeneity of products and batch-to-batch product consistency.

In the present study, the modified hot wire technique was used to measure the thermal conductivity and evaluate the consistency and homogeneity of various thermal interface materials using

measurements of thermal conductivity. The results indicate a large variation in the consistency and homogeneity in the thermal interface materials investigated.

EXPERIMENTAL

Apparatus

The Mathis TC-01^{TM} system utilized in the study to perform the thermal conductivity measurements is shown in Figure 1.

Figure 1. Mathis TC-01^{TM} thermal conductivity measurement system

This thermal conductivity measurement device is based on the modified hot wire (MHW) heat reflectance technique [7]. The difference between this method and traditional hot wire techniques is that the heating elements are supported on a backing, which provides mechanical support, electrical insulation, and thermal insulation. This modification eliminates the intrusive nature of the hot wire technique, thereby allowing solids to be tested without melting or otherwise modifying the sample to conform to the geometry of the test cell. The sample is tested by first placing the heating elements of the sensor against the surface of the sample. A known quantity of electrical current is then passed through the heating elements of the sensor for a given time, resulting in a temperature rise of the heating element. The sensor is designed so that the bulk of the heat generated is transferred one dimensionally into the sample, and only a minor amount of the heat is transferred to the backing, as shown in Figure 2.

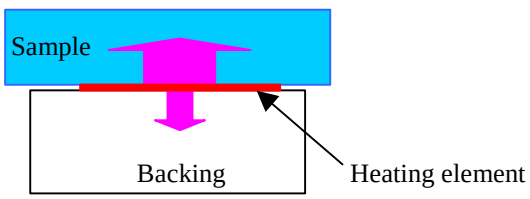

Figure 2. Schematic of the Modified Hot Wire technique

Since the rate of temperature rise at the heating element is inversely proportional to the thermal conductivity of the material, this material property can be determined by measuring the rate of voltage rise when a constant current is applied [7]. Voltage increase can be correlated with thermal conductivity through a calibration with reference materials having known thermal conductivity. From this calibration, the conductivity of unknown materials can be determined.

MATERIALS

Eight interface materials were tested including three thermal interface films and five thermal greases. These materials are listed in Table 1. A different company manufactured each interface material studied. Three samples of each material were tested and each sample was from a different batch.

Table 1. Thermal Interface Materials Investigated in this study

Material	Type	Thickness/Properties
F1	Thermal interface Film	1.5mm
F2		2.0mm
F3		3.5 – 4.5 mm*
G1	Thermal grease	Non-silicon
G2		Unknown
G3		Non-silicon
G4		Silicone based
G5		Non-silicon

* Measured by micrometer

METHODS

All the thermal conductivity measurements were conducted using a TC external sensor at 25^{o}C. The thermal conductivity of specimens from each of the three batches gave lot-to-lot product consistency while measurements made at three different locations on each specimen were used to evaluate the homogeneity of the products. Three measurements were performed at each location to assess the test method reproducibility.

For the measurements made on thermal interface films, samples were cut into 75 mm × 25mm specimens. For each measurement, the specimen was placed on the sensor surface directly and a 652 g weight was placed on the top to ensure good contact between the specimen and sensor. Thermal grease materials were measured using a liquid specimen bag. Each liquid specimen bags held 20 ml grease. A 766 g weight was then placed on the top of the grease specimen for each test to ensure good contact between the specimen and sensor.

For thin specimens with high thermal conductivity, the heat generated from the sensor may pass through the specimen during the test, resulting in significant errors. To ensure that the heat does not penetrate specimens during the measurement, each specimen was tested using sample backing materials with significantly different thermal conductivities. The materials selected for backing materials were foam and high density polyethylene (HDPE). The heat wave penetration time can be determined by identifying the deviation point of measurements when these two tests are overlayed on the same plot, as

shown in Figure 3. At the separation point, the heat wave has passed through the specimen and has entered the specimen backing material. The test time was selected to be shorter than this penetration time.

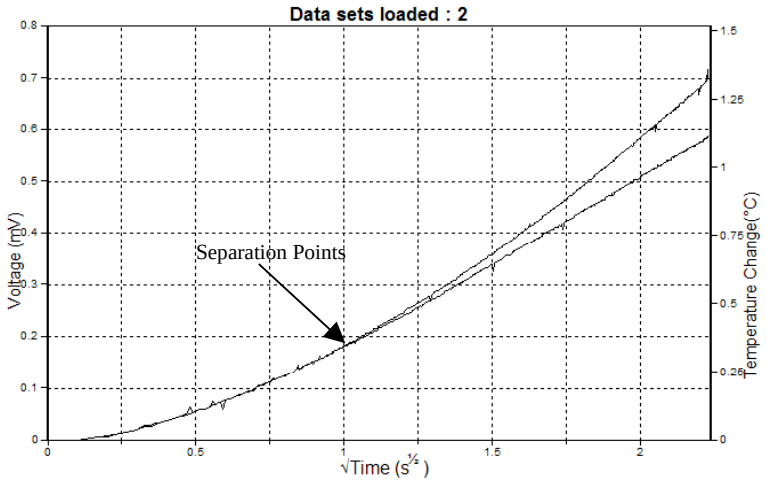

Figure 3. Determination of the heat wave penetration time

Following the above optimization of test time, the accuracy of each set of measurements was examined by performing measurements using a reference material with similar thermal conductivity to the specimen. The test time and reference materials employed for the accuracy evaluation are listed in Table 2. For all the tests of reference materials, a 4% or better accuracy and 2% or better precision are observed.

Table 2. Test Times and Reference Materials

Material	Test time (s)	Reference materials evaluated	k of reference material at 25 °C (W/m·K)	Measured k of reference material at 25 °C (W/m·K)	Accuracy (%)
F1	1	Macor	1. 591	1.543	3.02
F2	4	Titanium	6.691	6.681	0.15
F3	5	Macor	1. 591	1.607	1.01
G1	5	HDPE	0.5817	0.5724	1.6
G2	5	Pyrex	1.142	1.145	0.26
G3	5				
G4	5	Pyroceram	3.851	3.7553	2.48
G5	5				

RESULTS AND DISCUSSION

Figure 4 shows the average of measured thermal conductivity of each material at 25^{o}C, which is based on the measurements of three batches. For all the tests conducted, RSD value of each set of measurements is better than 2%, indicating the precision of the measurements conducted using the Mathis TC-01 is better than 2%. As illustrated in Figure 4, thermal conductivity of the interface materials studied ranges from 0.5 W/m·K (G1) to 6.9 W/m·K (F2).

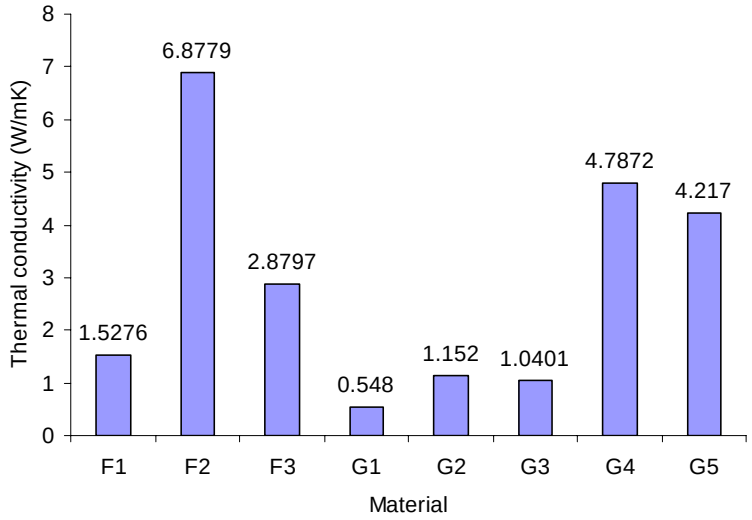

Figure 4. Average measured thermal conductivity of each material investigated.

Figure 5 shows the average location-to-location variation of the thermal conductivity of each material investigated.

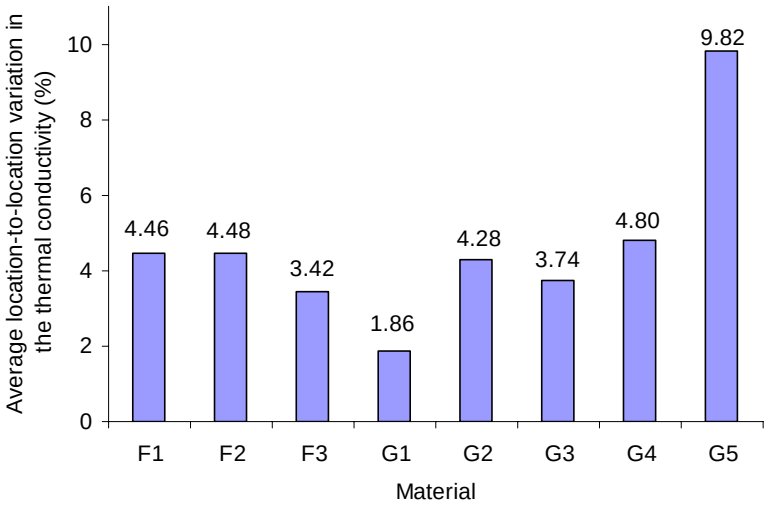

Figure 5. Average location-to-location variation in the thermal conductivity of each material investigated.

Figure 6 shows the average batch-to-batch variation in the thermal conductivity of each material investigated.

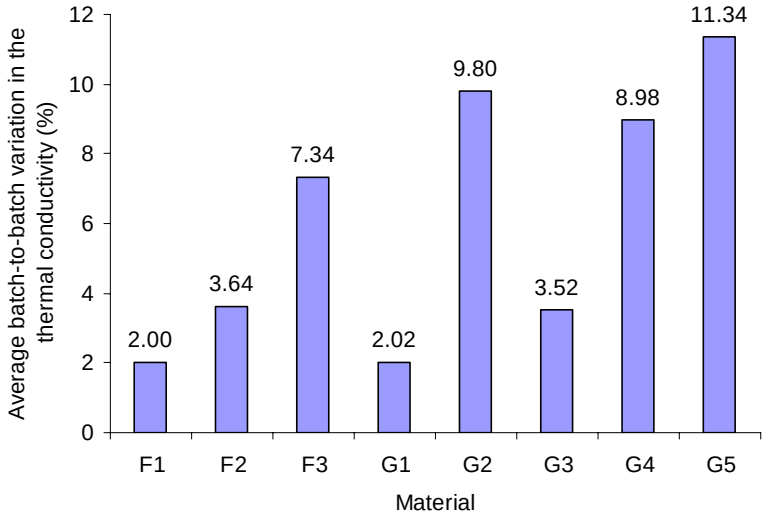

Figure 6. Average batch-to-batch variation in the thermal conductivity of each material investigated.

From the results shown in Figure 5, thermal interface materials can vary significantly in thermal conductivity from location to location. While seven of the eight materials studied have less than 5% variation in thermal conductivity at different locations, one material has variation as high as 9.8%. Four of the materials have variations in thermal conductivity of between 4% and 5% at different locations and one material investigated has less than 3% variation. This suggests that most thermal interface materials are moderately homogeneous, and a small portion of interface materials is heterogeneous.

The batchwise variations presented in figure 6 show that four of the eight materials show higher than 7% difference in thermal conductivity between batches, the highest being more than 11%. This suggests a high level of product inconsistency. In comparison, the other four materials have lower than 4% variation in thermal conductivity between batches. In particular, two of them have 2% variation in thermal conductivity. Therefore, thermal interface materials can have very different product consistency in terms of thermal conductivity. Also, due to the fact that half of materials investigated have more than 7% variation between batches, it is highly recommended to include consistency as a measure in the evaluation of the performance of thermal interface materials.

Furthermore, as shown in Figures 5 and 6, low homogeneity will result in low consistency. This is especially true of sample G5. Nonetheless, homogeneity evaluation cannot be used to estimate the consistency level and vice versa. Sample F3, for example, has moderate homogeneity (3.42% location-to-location variation) but fairly high inconsistency (7.34% batch-to-batch variation). Consequently, it is insightful to conduct both homogeneity and consistency tests for the evaluation of the performance of thermal interface materials.

CONCLUSIONS

The results show most thermal interface materials investigated are moderately homogeneous with lower than 5% location-to-location variation in thermal conductivity. Existence of higher than 9.8% location-to-location variation in one of the samples provides a strong incentive to evaluate of homogeneity to ensure the efficiency of the thermal interface materials.

It was also found that product consistency varies significantly from one thermal interface material to another. A higher than 7% lot-to-lot variation was observed in half of materials investigated and neither the homogeneity nor inconsistency of the thermal conductivity measurements could provide a good estimation for the other. It is therefore valuable to use product consistency as one of the standard measures of the performance of thermal interface materials.

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