Thermal Conductivity of Thin Films

Xiaochuan Qiu*, Karina Schimdt, Nancy Mathis
Mathis Instruments Ltd.
21 Alison Blvd.
Fredericton, NB E3C 2N5
rqiu@mathisinstruments.com, Karina@mathisinstruments.com, Nancy@mathisinstruments.com

ABSTRACT

The present study describes the use of the modified hot wire technique to measure the thermal conductivity of regular printing paper and conductive transfer film. Testing methods have been developed to identify the effect of stacking on the thin films and to measure a specific layer of multi-layered materials using this interfacial technique. In comparison with the guarded hot plate, this transient technique measures thermal conductivity in seconds with the same level of accuracy, and results show that there is 1.5% difference in the measurement of conductive transfer film between the guarded hot plate and this technique.

INTRODUCTION

Thermal performance of thin films is crucial in many industries, ranging from battery and aerospace to the electronics industries. As a result, thermal characterization of thin films is important in developing new materials and optimizing device performance and reliability. As a key parameter of thermal characterization, thermal conductivity therefore is a consideration at all levels when thermal engineers design for optimum heat dissipation, bonding and homogeneity. Consequently, it is highly desired to use efficient, effective testing methods to measure the thermal conductivity of thin films.

Guarded hot plate, heat flow meter and laser flash diffusivity are frequently used to measure thermal conductivity [1][2][3]. One of the common drawbacks of these methods is that samples with a fixed dimension are required. In addition, the test time for guarded hot plate and heat flow meter is several hours or longer. When the new material development is required quickly to respond to the developments in industry, time cannot be wasted preparing samples or waiting for results. Compared with guarded hot plate, laser flash diffusivity provides rapid measurements but measures thermal diffusivity rather than thermal conductivity, and heat capacity and density are required to determine thermal conductivity. The hot wire technique is a rapid technique and has no sample size restrictions. This transient technique, nevertheless, is an intrusive method and involves inserting an electrically heated wire into material [4].

Compared with the methods described above, the modified hot wire technique is a non-destructive method that can measure thermal conductivity directly in seconds. The modified hot wire technique has been proved to be an efficient, effective method to measure thermal conductivity and thermal effusivity [5][6]. Also, due to the nature of the interfacial measurement, this technique has almost no requirement for sample preparation, significantly speeding up the testing process. Moreover, modified hot wire technique is able to measure a specific layer of multi-layered materials, simplifying sample preparation.

This study utilized the Mathis TC modified hot wire sensor to measure the thermal conductivity of thin films and described a testing method to evaluate the effect of stacking on thin films measurement. The measurement of a specific layer of multi-layered materials has been investigated in this study, and the results were compared with those generated from ASTM C177 method to further evaluate the Mathis TC performance.

MODIFIED HOT WIRE TECHNIQUE

When using the modified hot wire technique, one side of the heating element is in contact with the sample, while the other side is in contact with the backing material. During tests, a constant current or voltage electrical source supplies power to the heating element to generate a one-dimensional heat flow, which is perpendicular to the testing surface of the sample. As a result, the heat conduction of the heating element can be expressed as Equation (1) [7]:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{\partial x}\left(K \frac{\partial T}{\partial x} \right) \tag{1}$$

Where, ρ density (Kg/m^3)
C_P specific heat
T temperature of heating element (K)

According to Carslaw and Jaegar solution [8], thermal conductivity is inversely proportional to the rate of temperature rise of the heating element. Through testing three known materials, i.e., calibration standards, the relationship between thermal conductivity and the rate of temperature rise of the heating element can be established. The thermal conductivity of the sample, hence, can be measured by monitoring the rate of temperature rise at the interface.

EXPERIMENTAL

Sample Preparation

In this study, the thermal conductivities of regular printing paper and conductive adhesive transfer tape are measured. The samples used are shown in Table 1.

Table 1. Samples utilized

<table>
<tr><th>Sample</th><th>Material</th><th>Thickness (mm)</th><th>Number of layers stacked</th><th>Format</th></tr>
<tr><td>A</td><td rowspan="2">Printing paper</td><td rowspan="2">0.109*</td><td rowspan="2">7</td><td rowspan="2">econosource Multi-purpose paper, 8.5" × 11"
White, 84 brightness, 20 lb, Grain long</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td><td rowspan="2">Conductive adhesive transfer tape</td><td rowspan="2">0.38**</td><td rowspan="2">2</td><td rowspan="2">3M™ high adhesion thermally conductive adhesive transfer tape 8815, white, Filled Acrylic Polymer, Dual liner using silicone-treated polyester</td></tr>
<tr><td>D</td></tr>
</table>

* Measured using micrometer
**Provided by the manufacturer

To prepare Sample A, seven pieces of paper were cut from the same paper sheet. All of them were cut into 1”×3” and then were stacked together. To prepare Sample C, two pieces of the conductive adhesive tape were cut into 1”×3”, and the transparent plastic covers of these two pieces were peeled off. The open surfaces of these two pieces of adhesive tape were then attached together, leaving their blue plastic covers untouched. This is due to the fact the blue plastic cover is strongly attached on the tape, and the peeling can generate air pockets, resulting in measurement errors. Samples B and D were prepared in the exact same manner as Samples A and C, respectively, and Sample B was prepared using the same paper sheet as Sample A, and Sample D was prepared using the same package as Sample C.

Apparatus and Conditions

The Mathis TC-01™ was utilized in this study, as shown in Figure 1. The Mathis TC-01™ encompasses the modified hot wire technique and can measure directly thermal conductivity and effusivity in seconds. Also, it is able to measure thermal conductivity/effusivity of samples through covers, thus simplifying sample preparation and avoiding dissembling samples.

Figure 1. Mathis TC-01™

All the tests were carried out at room temperature (25^{o}C). During the tests, a 652g weight was placed on the sample to improve the quality of stack and to ensure good contact between samples and sensor.

Testing Method

Three parameters, i.e., test time, start time, and cooling time, need to be defined to perform a test using the Mathis TC-01™. Start time defines the elapsed time from the beginning of the test to the time point counted as the first valid data for the calculation of thermal conductivity/effusivity. Contact resistance, therefore, can be mitigated using the appropriate start time. Cooling time is the time period between two successive tests to ensure the same temperature condition of the tests. Test time defines the time period from start to finish of passing current through the heating elements to perform a single test. Consequently, the longer test time, the further heat penetrates in samples, as shown in Figure 2.

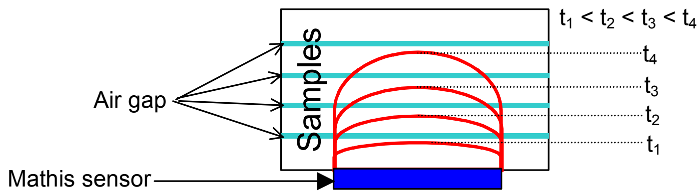

Figure 2. Heat penetration thickness vs. testing time

When the materials are stacked together (see Figure 2), the measured thermal conductivity will depend on the number of layers tested due to the effect of air on the overall thermal conductivity which varies with the number of layers tested. On the other hand, the measurements generated from different penetration times will be the same when the effect of air gap is negligible for the thickness penetrated. Therefore, the influence of the air gap between layers can be examined by comparing measurements that have the same start time but have different test time.

To ensure that the sample is not entirely penetrated by heat during testing, each sample was first tested twice to identify penetration time. In one test, one open surface of the sample was in contact with the sensor and the other open surface was in contact with the foam of the weight. In another test setting, one open surface of the sample was in contact with the sensor while the other open surface was in contact with high density polyethylene (HDPE) of the weight, which has much higher thermal conductivity than foam. If the test time is longer than the penetration time, the heat wave will pass through the film and enter into the foam or HDPE of the weight. The penetration time therefore can be obtained by finding the deviation points of two measurements, as shown in Figure 3.

To test conductive adhesive transfer tape, one layer of blue plastic cover was placed between the calibration standards and sensor to eliminate the effect of the plastic cover. For all the samples, three tests have been performed automatically at the same location in Autotest mode.

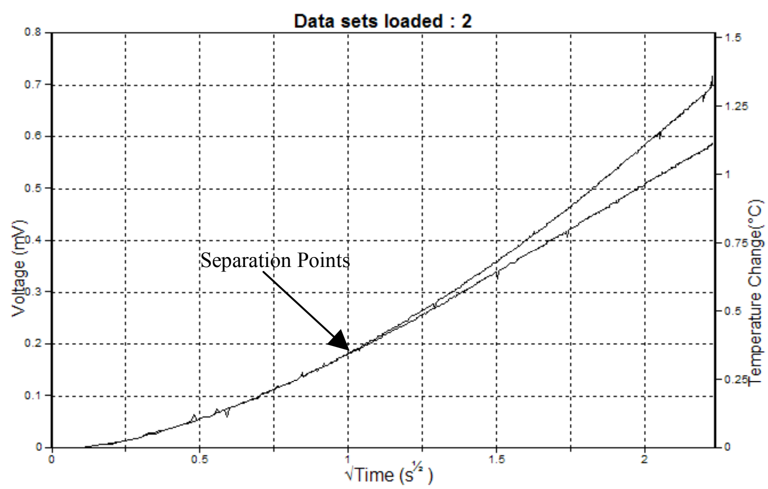

Figure 3. Identify penetration time

RESULTS AND DISCUSSION

The penetration time of Samples A and B is 1.1 seconds while the penetration time for Samples C and D is 1 second. The final test results are shown in Table 2. The accuracy of all the measurements was evaluated by testing one of the standards employed, Lexan, and it was found that the accuracy of all tests is better than 5%.

Table 2. Test results

Sample	Mean K* (W/m·K)	RSD** (%)	Test time (s)	Start time (s)	Cooling time (Minute)	Calibration standards
A	0.119	0.41	0.8	0.4	2	LAF20 Lexan HDPE
A	0.121	1.31	0.9	0.4	2	
A	0.120	0.53	1	0.4	2	
B	0.118	1.4	0.8	0.4	2	
C	0.609	1.27	0.9	0.5	2	Lexan HDPE Pyrex
D	0.594	1.26	0.9	0.5	2	

*Mean thermal conductivity K was calculated from three automatic tests.
**Relative Standard Deviation, RSD, was calculated from the three automatic tests.

As shown in Table 2, all RSD values are lower than 2%, illustrating the high precision of the measurements. Also, as indicated in Table 2, the thermal conductivities of Sample A measured with the same start time but with different test times are very close to each other, indicating that the effect of the air gap between layers is negligible for the number of layers measured in these tests. Hence, the measured thermal conductivity is representative. Also, 0.8% difference between the thermal conductivities of Samples A and B suggests that the paper tested is highly homogeneous.

For the 3M™ high adhesion thermally conductive adhesive transfer tape 8815, the thermal conductivity is 0.6 W/m·K [9], which was measured using ASTM C177 method. As indicated in Table 2, there is only 1.5% difference in the measurements between modified hot wire technique and guarded hot plate technique for the transfer tape tested, indicating the same level of accuracy of these two different methods. On the other hand, the test time of modified hot wire technique is less than 1 second and therefore is much shorter than guarded hot plate, which is counted in hours. Further, as shown in Table 2, the thermal conductivities of Samples C and D are very similar, revealing that the adhesive tape 8815 is also homogeneous.

CONCLUSION

The Mathis TC-01 was used to measure thermal conductivity of regular printing paper and conductive cohesive transfer tape, and an efficient testing method was developed to examine the effect of stacking on the thin film measurements. The results reveal that the thermal measurement of the TC-01 is within seconds and has 2% or better precision and the same level of accuracy as that of the guarded hot plate. This study has confirmed that abilities of the TC-01 to measure thermal conductivity of a specific layer of multilayered materials and to evaluate the homogeneity of materials tested.

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