Technology Report

Thermal characteristic evaluation system to evaluate 
heat transfer characteristics of mounted materials

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The increasing amount of heat generated by electronic devices is making 
devices thermal design and ways to combat heat more and more important 
issues to deal with. Therefore, we have developed a system able to evaluate 
thermally conductive materials such as conductive adhesives. The measurement 
technology is based on the steady-state method, and can evaluate heat transfer 
characteristics of mounted materials. In other words, it enables measurements of values 
not supported by conventional bulk thermal conductivity measurements - effective 
thermal conductivity and thermal resistance values that include the thermal resistance 
of the interface between the conductive adhesive and adhered material. This report 
provides an overview of the equipment we developed, and describes an example of its 
application.

Introduction

Recent advances in computers and the increasing power capacities of inverter devices 
are resulting in greater amounts of heat generated by semiconductor devices, creating 
the risk of heat adversely affecting the reliability of electronic devices. The heat transfer 
characteristics of thermally conductive materials used in junctions between 
semiconductor devices and heat sinks have therefore become a critical area of study. To 
explore this area, we investigated a method of evaluating the heat transfer 
characteristics of mounted materials, and developed a thermal characteristic evaluation 
system supporting thermally conductive materials such as conductive adhesives 
(die-attach materials for power devices and LED chips). 1, 2, 3 Conventional methods to 
measure the thermal conductivity of materials include the hot wire method and laser 
flash method. While these methods support bulk thermal conductivity and thermal 
resistance measurement, they provide no way to calculate the thermal resistance of the 
interface between the surfaces in contact, which is difficult for mounted materials. The
thermal characteristic evaluation system we developed applies the steady-state method set forth by standards such as ASTM and JIS. It uses test specimen cartridges that simulate mounted materials, to enable measurement of effective thermal conductivity and thermal resistance in a state that incorporates the thermal resistance of the interface between the surfaces in contact. This paper gives an overview of the developed equipment, provides verification of its accuracy, and presents an example of its use by measuring the thermal characteristics of a silver/epoxy-based conductive adhesive.

2. System overview

Fig.1 Thermal characteristic evaluation system (TCS-100)

Fig.2 Structure of the measurement unit

Figures 1 and 2 show an overview on our thermal characteristic evaluation system and its configuration. The system is based on the steady-state unidirectional heat flow steady-state comparison method (the steady-state method), specified by the ASTM D5470-01 and JIS H 7903 standards. It is composed of a measurement unit, control...
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unit (that sets measurement conditions and controls heating and cooling), and instrumentation unit (that calculates, displays and records heat transfer characteristics in real time). The test specimen is placed between the top and bottom thermal flux measurement rods in the measurement unit, which applies a constant load measured by a load cell. Table 1 lists the main specifications of our thermal characteristic evaluation system. Our analysis indicates that measurement uncertainty is no more than 10% for test material with effective thermal conductivity measured between 0.5 to 50 w/(m-K), and thickness comprised between 0.2 and 1mm. \(^1\,^2\,^6\)

<table>
<thead>
<tr>
<th>Method</th>
<th>Conventional comparison method of thermal flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen size</td>
<td>10, 20, 40 mm</td>
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<tr>
<td>Thermal conductivity ratio measurement</td>
<td>0.5 to 50W/ (m-K)</td>
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<td>Specimen temperature set range</td>
<td>(RT +10) to +125°C</td>
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<tr>
<td>Load setting range</td>
<td>10 to 200N</td>
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**Table 1. Main specifications of the thermal characteristic evaluation system (TCS-100)**

The system uses the test specimen cartridges shown in figure 2. The specimen have a three-layer structure created by joining two test sample blocks together with conductive adhesive. The thermal resistance of the interface is included for each adhering surface, enabling the system to calculate values for effective thermal conductivity and composite thermal resistance that include the resistance of this interface. Using a method described later on, the system can also isolate the thermal resistance of this interface. The blocks used in the test specimen have holes for temperature measurement, enabling direct measurement of the specimen temperature. This approach eliminates the need to consider thermal resistance due to contact between the specimen and top or bottom rod –a difficulty when using the conventional steady-state method. By replacing the top and bottom rods, test specimens between 10 and 40 mm of size can be measured. Figure 3 shows an example of temperature distribution for the top/ bottom rods and test specimen. The system uses the steady-state temperature distribution of the top/bottom rods and the temperature of the specimen cartridge to measure the effective thermal conductivity given by formulas (1) and (2), \( k_{\text{eff}} [W/(m\cdot K)] \), and the total thermal resistance, \( R_t [(m^2\cdot K)/W] \).
\[
(1) \quad k_{edt} = \frac{q \cdot t_s}{\Delta T_s}
\]
\[
(2) \quad R_t = \frac{\Delta T_s}{q}
\]

Fig. 3 Temperature uniformity of the specimen and top/bottom rods

Here, \( q \) (W/m\(^2\)) is the average penetrating thermal flux of the top/bottom rods calculated from the thermal conductivity of the top/bottom rods and the temperature gradient, \( t_s \) (m) is the thickness of the conductive adhesive, and \( \Delta T_s \) (K) is the temperature difference of the conductive adhesive. \( \Delta T_s \) is calculated by subtracting the temperature difference of the test blocks from the test specimen’s measured temperature difference.

The total thermal resistance \( R_t \) [(m\(^2\)-K)/W] is the composite thermal resistance that combines the thermal resistance of the conductive adhesive, \( R_s \) [(m\(^2\)-K)/W], and the thermal resistance of the interface between the two adhering surfaces, \( R_i \) [(m\(^2\)-K)/W].

When total thermal resistance \( R_t \) is plotted on the Y-axis, and test material thickness \( t_s \) is plotted on the X-axis, the thermal resistance of the interface can therefore be calculated from the slope of the linear approximation, and the bulk thermal conductivity can be calculated from the y-intercept.\(^3\) The same graph can be used to isolate the thermal resistance of the interface by measuring various material thicknesses.

### Inspection of the accuracy on a standard specimen

Uncertainty analysis showed our system to have an effective thermal conductivity measurement uncertainty of no more than 10%\(^2,6\), so we used a standard test specimen to verify the measurement precision experimentally. Since there are no standard substances with known thermal conductivity values for testing materials such as conductive adhesives, we created our standard test specimen from a metal with a known thermal conductivity.

Photo 1 shows one of the standard test specimens we created. We selected stainless steel (SUS 304) with a thermal conductivity within the required measurement range, and created the test specimen blocks from copper (C1100). We used three SUS 304 thicknesses (0.25 mm, 1.45 mm and 10 mm), in 10 mm lengths. Since the surface of the SUS 304 was coated with electro less nickel plating of about 0.02 mm thick, the SUS 304 was joined to the test specimen block via this plating layer.

We measured the three thicknesses of standard test specimens at a temperature of...
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30°C and pressure of 0.3 MPa. Figure 5 shows the relationship between the total thermal resistance and thickness of the standard test specimen. As shown, the relationship is linear. The thermal conductivity of SUS 304 calculated from the slope of the linear approximation is 16.5 W/(m·K), or 3.1% greater than the official value of 16 W/(m·K). This result therefore verifies that our system satisfies an uncertainty of no more than 10% for thermal conductivity measurement.

![Photo 1. Test specimen](image1)

**Fig. 5 Relationship between total thermal resistance and specimen thickness**

4 **Thermal characteristic example: Evaluation (Conductive adhesive)**

We measured the thermal characteristics of conductive adhesive, one of the materials our system is designed to measure. Photo 2 shows one of the conductive adhesive test specimens we created. The conductive adhesive used was the commonly used silver/epoxy-based type. It was about 78% silver filler and 12% epoxy resin (by weight). We applied a coat of the conductive adhesive paste between two copper test sample blocks, adjusting its thickness using glass beads. The result was then thermally hardened in a kiln for 30 minutes at 150°C to create the finished conductive adhesive test specimens. The test specimens were 20 mm long, and three types of glass beads were used (0.2, 0.3 and 0.5 mm in diameter).

![Photo 2. Conductive adhesive specimen](image2)

We measured the conductive adhesive test specimens under the same conditions used for the standard test specimen. As with the standard test specimen, we calculated
thermal conductivity from the relationship between total thermal resistance and thickness. Using the linear approximation shown in figure 6, we calculated that the experimental silver/epoxy-based conductive adhesive had a thermal conductivity of 4.5 W/(m·K). We used the y-intercept to calculate the thermal resistance of the interface at 1.2 x 10⁻⁵ (m²·K)/W. Figure 7 shows the results measured for the effective thermal conductivity of the conductive adhesive. We found that the effective thermal conductivity including the thermal resistance of the interface was a lower value than the bulk thermal conductivity, verifying that effective thermal conductivity decreases as conductive adhesive thickness decreases.

This finding enabled the assessment that the thermal resistance of the interface affects the heat transfer characteristics of mounted materials. Our system therefore enables evaluation of heat transfer characteristics of mounted materials such as conductive adhesives.

**Fig. 6** Relationship between thickness of the conductive adhesive and thermal resistance

**Fig. 7** Relationship between thickness of the conductive adhesive and effective thermal conductivity
We sought to enable evaluations of heat transfer characteristics of mounted materials by developing a thermal characteristic measurement method and evaluation system that would support materials such as conductive adhesives. This paper has presented the technology we developed to enable good-precision measurement of heat transfer characteristics in mounted materials. This technology development work was done for a project commissioned by NEDO (New Energy and Industrial Technology Development Organization), and work is now being done on ISO standardization of test methods for conductive adhesives. Since electrical device heat should be an area of increasing concern in future, the outlook for our evaluation method should be promising in areas such as the development of high-performance bonding materials, and thermal design of devices generating high levels of heat.

This technology development work was part of a project commissioned by NEDO (New Energy and Industrial Technology Development Organization) to investigate the standardization of conductive adhesive mounting technology, and received some assistance from that project. The authors would like to express their heartfelt appreciation to all involved.

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