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IPC-TM-650
TEST METHODS MANUAL

Number **2.4.54**	
Subject **Test Method for Thermal Transmission Properties of Metal Based Printed Boards (MBPB)**	
Date **09/2022**	Revision **N/A**
Originating Task Group **D-33AA IPC-6012 Automotive Addendum Task Group**	

1 Scope

1.1 The scope of the test method is to describe a procedure for measurement of thermal resistance and calculation of an apparent thermal conductivity for single layer Metal Based Printed Boards (MBPB). This test method has been created to address the issue of measurement uncertainty for materials with low thermal resistance (high thermal conductivity and/or thin thicknesses).

1.2 Precise measured values of thermal resistance are very important, for multiple applications, especially within automotive sector, but also in other areas. For materials with a low thermal resistance, the measurement uncertainty increases significantly when using the steady state measuring method. The target for this test method is to provide good repeatability and reproducibility in the test result. A certified reference material must be used to guarantee the measurement quality.

The test method **shall** show a validity of different thermal resistance values represented by different thicknesses and materials used for the MBPB. The test method **shall** also describe a reliable thickness measurement.

1.3 Terms and Definitions Other than those terms listed below, the definitions of terms used in this test method are in accordance with IPC-T-50.

1.3.1 Thermal Conductivity Thermal conductivity applies in this case to the bulk value of the metal layers (λ_{base} or λ_{top} see Table 1 Equations 12 and 13) or the aluminum bars for hot or cold side (λ_h or λ_c see Table 1 Equations 1 and 2) and the dielectric material filled with oxide particles of different kind of filler degree (λ_{die}) (Figure 5).

1.3.2 Apparent Thermal Conductivity Apparent thermal conductivity includes the bulk thermal conductivity of the dielectric material filled with oxide particles, the treatment or adhesive layer and the thermal contact resistances (see 1.3.5) to the upper and lower metal layers ($\lambda_{app.,die}$ see Table 1 Equation 16).

1.3.3 Total Thermal Resistance Total thermal resistance $R_{th,total}$ applies to the measured thermal resistance of the MBPB and the contact liquid ($R_{th,total}$ see Table 1 Equation 10).

1.3.4 Apparent Thermal Resistance Specimen Apparent thermal resistance specimen $R_{th,\ app,specimen}$ applies to the measured thermal resistance of the MBPB. This has an upper and lower metal layer. In-between it has a dielectric layer with the two contact resistances to the metal layers ($R_{th,\ app,specimen}$ see Table 1 Equation 11).

1.3.5 Thermal Contact Resistance Thermal contact resistance applies to a contact phenomenon between two bodies. A contact resistance can arise due to suboptimal surface wetting, high surface roughness or influenced heat flow density at the boundary layer due to the following parameters: the filler concentration, particle percolation path, particle distribution and particle size. This contact resistance leads to a variance in measurement results.

1.3.6 Surface Area Surface area is calculated from the diameter of the meter bars in the dimension mm^2.

1.4 Technical safety requirements are not defined in this test method. The user must take measures to fulfil all statutory health, safety and environmental protection requirements.

2 Applicable Documents

2.1 IPC Documents[1]

IPC-4101C Specification for Base Materials for Rigid and Multilayer Printed Boards

IPC-TM-650 Test Methods Manual

2.1.1 Microsectioning, Manual and Semi or Automatic

2.1.1.2 Microsectioning—Semi or Automatic Technique Microsection Equipment

2.2 International Organization of Legal Metrology[2]

OIML G 14 Density measurement

2.3 ASTM[3]

ASTM E1461 Standard Test Method for Thermal Diffusivity by the Flash Method

ASTM E1269 Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry

3 Test Specimens

3.1 The sample thickness can be measured within the machine or before and after measurement. In both cases the accuracy should be smaller than 10 µm.

3.2 Prepare specimens from its original, treated or aged condition. Clean the surfaces from any kind of dirt. The solvents have to be chosen carefully as possible adverse reactions with the surface of the sample could occur (see IPC-TM-650 Test Method 2.1.1).

3.3 The specimen has to be manufactured e.g., by milling or other kind of processing. Remove burrs and flashes on the edge of the specimen.

3.4 Create three specimens from one raw laminate panel. Ensure a distance from the border of about 50 mm to avoid tolerance deviations of the dielectric material.

3.5 Ensure that the surface of the specimen is free of scratches, waviness or any kind of damage. Photos should be included into the test report.

4 Apparatus or Material

4.1 Figures 1 and 3 shows parts for an apparatus, which fulfills the requirements for this test method.

4.2 Ensure that the surfaces of the aluminum bars are free from scratches or other damages. The surface has to be smooth ($Ra \leq 1$ µm).

4.3 Use a method to measure the total thickness of the specimen like contactless with laser, LED detector or before and after measurement with a micrometer screw according to IPC-4101C.

4.4 Use insulated heat flow meter bars on both sides, hot and cold in order to prevent heat losses to the environment and thus improve the measurement accuracy.

4.5 Due to the forced heat flow, the apparatus needs both a heat as well as a cooling source. There are several options for heating and cooling. The recommended method of heating is the usage of an electrical heater which is embedded in a copper block. Other options can be liquid heaters. Regardless of the method. It is important to use constant temperatures at heat and cooling side.

4.6 The heat flow meter bars of the apparatus need to be constructed out of well-known and thermally characterized (see ASTM E1461 for thermal diffusivity, ASTM E1269 for specific heat capacity, and OIML G 14 for density) material in the

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[1] www.ipc.org

[2] www.oiml.org

[3] www.astm.org

observed temperature range. It is recommended to use high conductive metals for the heat flow meter bars when measuring high conductive specimens e.g., aluminum alloy with a thermal conductivity of 100 W/(mK) or higher.

4.7 Use more than two thermocouples for the heat flow measurement on each meter bar. It is recommended to use four thermocouples on every bar. This reduces the error in the slope (Figure 2). The thermocouples should be located in extreme proximity to the surfaces (about 1.5 mm) (Table 1 Equations 1 to 3). Use thin calibrated thermocouples with a diameter of < 0.6 mm and a measurement accuracy smaller than +/- 0.1 K. This increases the measurement accuracy significantly.

4.8 The heat flow meter bars are used to determine the temperature of the test surfaces by extrapolating the linear array of meter bar temperatures to the test surfaces (Table 1 Equations 4, 5 and 6). This should be done for both, the hot side and cold side meter bars (see Figure 1 Notes 2 and 3).

4.9 The recommended way to create a cooling source in the apparatus is with a metal block cooled by a temperature controlled circulating liquid (e.g., silicone oil or even water, depending on the temperatures, which should be measured).

4.10 The temperature stability of both, the heating and cooling source, should be very high due to stationary conditions during the test. Typical stabilities are +/- 0.1 K/(300 seconds).

4.11 The thermal contact resistances between the specimen and the heat flow meter bars is highly dependent on the contact pressure, which is the reason why this parameter is important. A high contact pressure reduces the thermal contact resistances and maintains the parallelism and alignment of the surfaces.

4.12 For MBPB a high pressure ≥ 2.0 N/mm² should be applied due to a significant reduction of the thermal contact resistant. This guarantees more accurate testing results.

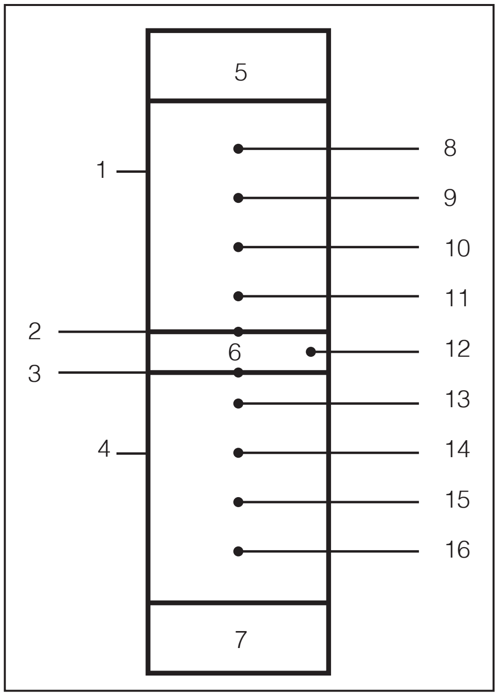

Figure 1 Hot and Cold Meter Bards with More Than Two Thermocouples

Note 1 – Hot Meter Bar, see 1.3.1
Note 2 – T_H
Note 3 – T_C
Note 4 – Cold Meter Bar
Note 5 – Heat Source
Note 6 – Specimen
Note 7 – Heat Sink
Note 8 – $T_{HB,1}$
Note 9 – $T_{HB,2}$
Note 10 – $T_{HB,3}$
Note 11 – $T_{HB,4}$
Note 12 – T_S, see 6.4.2 and Table 1 Equation 18
Note 13 – $T_{CB,1}$
Note 14 – $T_{CB,2}$
Note 15 – $T_{CB,3}$
Note 16 – $T_{CB,4}$

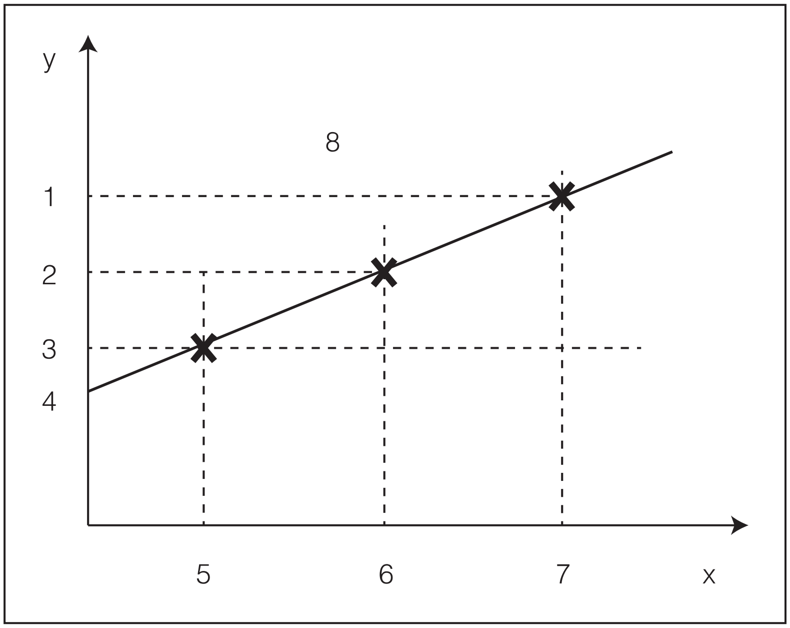

Figure 2 Linear Regression to Determine the Heat Flow in the Hot Meter Bar Out of Three or More Thermocouples

Note 1 – $T_{HB,1}$
Note 2 – $T_{HB,2}$
Note 3 – $T_{HB,3}$
Note 4 – T_H
Note 5 – $S_{HB,3}$
Note 6 – $S_{HB,2}$
Note 7 – $S_{HB,1}$
Note 8 – Slope: $\left(\frac{dT}{ds}\right)_{HB}$
Note 9 – x – Path s in m
Note 10 – y – Temperature in K

Table 1 Equations

Equation	Unit	Reference
$\dot{Q}_H = \lambda_H \cdot A \cdot \left(\frac{dT}{ds}\right)_{HB}$	W	1
$\dot{Q}_C = \lambda_C \cdot A \cdot \left(\frac{dT}{ds}\right)_{CB}$	W	2
$\dot{Q}_{mean} = \left(\dot{Q}_H + \dot{Q}_C\right)/2$	W	3
$T_H = T_{HB,3} - s_{HB,3} \cdot \left(\frac{dT}{ds}\right)_{HB}$	°C	4
$T_C = T_{CB,1} + s_{CB,1} \cdot \left(\frac{dT}{ds}\right)_{CB}$	°C	5
$\Delta \mathrm{T}_{\mathrm{HC}} = \mathrm{T}_{\mathrm{H}} - \mathrm{T}_{\mathrm{C}}$	K	6
$\mathrm{R}_{\mathrm{th,liquid}} = \frac{\Delta \mathrm{T}_{\mathrm{HC}}}{\dot{Q}_{mean}}$	K/W	7
$\mathrm{R}_{\mathrm{th}} \cdot \mathrm{A}$	mm²K/W	8
$\lambda_{app.\ total} = \frac{\mathrm{d}_{total}}{\mathrm{R}_{\mathrm{th}} \cdot \mathrm{A}}$	W/(mK)	9
$\mathrm{R}_{\mathrm{th,total}} = \mathrm{R}_{\mathrm{th,app.,specimen}} + 2 \cdot \mathrm{R}_{\mathrm{th,liquid}}$	K/W	10
$\mathrm{R}_{\mathrm{th,app.,\ specimen}} = \mathrm{R}_{\mathrm{th,total}} - 2 \cdot \mathrm{R}_{\mathrm{th,liquid}}$	K/W	11
$\mathrm{R}_{\mathrm{th,base}} = \frac{\mathrm{d}_{\mathrm{base}}}{\lambda_{\mathrm{base}} \cdot \mathrm{A}}$	K/W	12
$\mathrm{R}_{\mathrm{th,top}} = \frac{\mathrm{d}_{\mathrm{top}}}{\lambda_{\mathrm{top}} \cdot \mathrm{A}}$	K/W	13
$\mathrm{R}_{\mathrm{th,app.,\ specimen}} = \mathrm{R}_{\mathrm{th,base}} + \mathrm{R}_{\mathrm{th,top}} + \mathrm{R}_{\mathrm{th,die}}$	K/W	14
$\mathrm{R}_{\mathrm{th,die}} \cdot \mathrm{A}$	mm²K/W	15
$\lambda_{\mathrm{app.,die}} = \frac{\mathrm{d}_{\mathrm{die}}}{\mathrm{R}_{\mathrm{th,die}} \cdot \mathrm{A}}$	W/(mK)	16
$\mathrm{d}_{\mathrm{total}} = \mathrm{d}_{\mathrm{base}} + \mathrm{d}_{\mathrm{top}} + \mathrm{d}_{\mathrm{die}}$	µm	17
$\mathrm{T}_{\mathrm{S}} = \frac{(\mathrm{T}_{\mathrm{H}} + \mathrm{T}_{\mathrm{C}})}{2}$	°C	18

4.13 Use an element that maintains plane parallelism of the specimen and/or the meter bars themselves (see Figure 3).

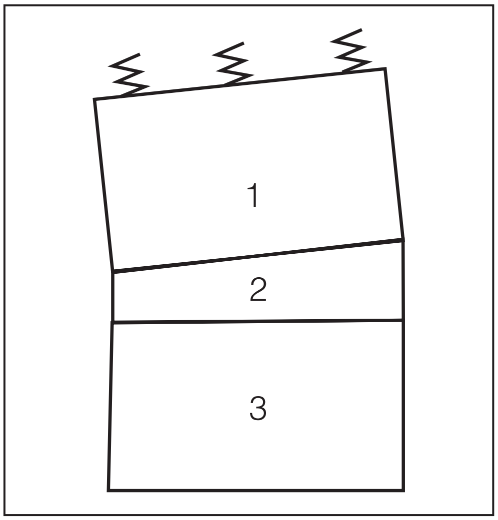

Figure 3 Element to Maintain the Plane Parallelism of the Specimen

Note 1 – Hot Meter Bar
Note 2 – Specimen
Note 3 – Cold Meter Bar

4.14 An appropriate device is required to produce the micro section. In order to generate clean and reproducible results in the form of micro section, the device must be able to grind and polish the sample (see IPC-TM-650 Test Methods 2.1.1 or 2.1.1.2).

5 Procedure

5.1 First of all the heating and cooling source should be tempered. Tempering of the apparatus / the system could have an influence of the measured force and gap.

5.2 After the apparatus is tempered, tare the force measuring device, when the heat flow meter bars do not touch.

5.3 After the force is tared, the thickness measuring device needs to be set to zero as well, if it is implemented in the machine. Otherwise, it has to be measured before and after measurement. Therefore, the specified surface pressure should be applied without any specimen between the meter bars. When the temperature field inside the meter bars is in steady state condition ($\Delta T/t \leq 0.2$ K/300s) the thickness measurement can be tared.

5.4 Use a liquid like oil or water-glycol to reduce the contact resistance between the meter bars or the meter bars and the specimen.

5.5 Use a surface pressure of ≥ 2.0 N/mm² to reduce the influence of the contact resistances and improve the repeatability of the measurements.

5.6 Measure first the pure liquid (which reduces the contact resistances between the sample to the meter bars) between the meter bars at the same surface pressure as the sample (Table 1 Equation 7). From the measured thermal resistance of the metal based substrate with the used liquid on the upper and lower side, subtract the measured thermal resistance two times from this value. See Equations 10 and 11 in Table 1.

5.7 We recommend having a temperature difference ΔT across the sample ≥ 1.5 K to reduce the uncertainty. Measure below the glass transition point (TG) to avoid nonlinear behavior. Show the middle temperature, the ΔT across the sample and the uncertainty in the results file.

5.8 The measured values are the apparent thermal resistance of the stack (e.g., Al-die-Cu) (Table 1 Equation 11). Show the results of the thermal resistance in the dimension (mm²K)/W (Table 1 Equation 8) and the total apparent thermal conductivity in W/(mK) (Table 1 Equation 9).

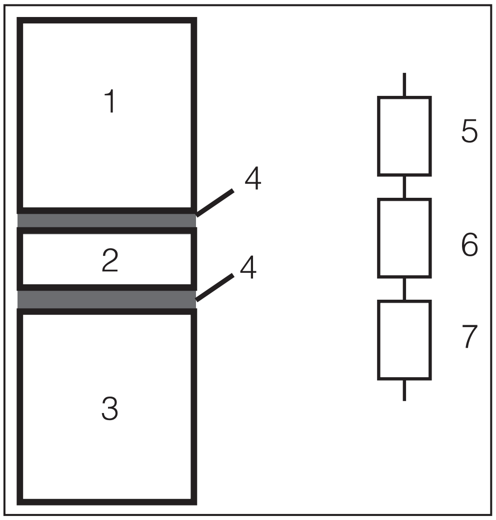

Figure 4 Order of Materials in the Measuring Section (incl. the liquid) and Substitute Image Regarding the Thermal Resistances

Note 1 – Hot Meter Bar
Note 2 – Specimen
Note 3 – Cold Meter Bar
Note 4 – Liquid to Reduce the Thermal Contact Resistances
Note 5 – $R_{th,liquid}$
Note 6 – $R_{th,specimen}$
Note 7 – $R_{th,liquid}$

5.9 In order to get the apparent thermal conductivity and the thermal resistance of the dielectric layer between top and base plate of the sample, it is necessary to know the layer thicknesses of every sample layer. To measure these thicknesses a microsection of the sample must be made (see IPC-TM-650 Test Methods 2.1.1 or 2.1.1.2 and Table 1 Equation 14). With known thermal conductivities of the base and top plate of the sample (show in the results the assumed thermal conductivity of the metals), the thermal resistances of these layers can be determined (Table 1 Equations 12 and 13). With a subtraction of the determined resistances from the apparent thermal resistance of the specimen, the thermal resistance of the dielectric layer (incl. thermal contact resistances) can be determined (Table 1

Equation 14). With the thickness from the microsection it is possible to calculate the apparent thermal conductivity of the dielectric layer (Table 1 Equation 16). This calculated value must be shown in the measurement report including the dimensions (mm²K/W) (Table 1 Equation 15) as well as the apparent thermal conductivity in W/(mK) (Table 1 Equation 16) and the thicknesses in µm.

5.10 Measure three identical samples across the board and list all results in the measurement report. In addition, the mean value and the standard deviation must be listed as well in the report.

5.11 To measure the DIE thickness a cross section according to IPC-TM-650 Test Method 2.1.1 should to be made.

5.12 To embed the sample, the specimen is first cut in half using a e.g., metal saw. Afterwards the specimen gets embedded, grinded and polished.

5.13 The thicknesses of the top and dielectric layer are measured in the microsection on five different points using a microscope. Calculate the middle value of the five measured values for each layer. From the total thickness of the sample, the thickness of the base layer can be determined by subtraction (see Table 1 Equation 17).

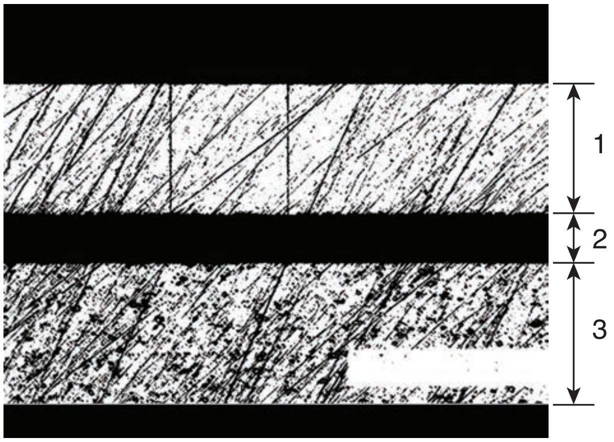

Figure 5 Layer Structure of a Metal-Based Board

Note 1: Top layer: $d_{top,}$ see 1.3.1
Note 2: Dielectric layer: d_{die}
Note 3: Base layer: d_{base}

6 Notes

6.1 The following information should be given in the measurement report associated with the measurement. Show all measured values and the mean value for all parameters:

6.2 General information:
6.2.1 Measurement institution
6.2.2 Testing apparatus (identification)
6.2.3 Date
6.2.4 Contact person

6.3 Specimen identification:
6.3.1 Name of the manufacturer
6.3.2 Batch or lot number
6.3.3 Grade designation
6.3.4 Nominal thickness
6.3.5 Any other information pertinent to the identification of the material

6.4 Results and thermal properties
6.4.1 Number of layers used in the test
6.4.2 Average temperature of the specimen (@ max pressure)
6.4.3 Temperature difference over the specimen (@ max pressure)
6.4.4 Pressure used during testing
6.4.5 Apparent thermal conductivity (@ max pressure)
6.4.6 Thermal resistance (@ max pressure)
6.4.7 Uncertainty of the thermal measurement (@ max pressure)
6.4.8 Layer thicknesses of top, base and dielectric layer
6.4.9 Microscopic images of the layer thicknesses
6.4.10 Used material to reduce contact resistances between meter bars and specimen
6.4.11 Assumptions of the thermal conductivity of the top and base plate to determine the thermal properties of the dielectric layer
6.4.12 Determined thermal conductivity of the dielectric layer (@ max pressure)

6.5 The following information show how to use the values from this method for CFD simulation.

Build up a three-layer system in your simulation tool according to Figure 5. Use for upper and lower metal layer the mean value of the thickness from microsection and the thermal conductivity of each metal layer. Use the mean value of apparent thermal conductivity (Table 1 Equation 16) and thickness of the dielectric material.