

Component Level Testing of Application Specific Conditions for Pressure Sensitive Adhesive Thermal Interface Materials

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Abstract

A common issue with thermal interface materials (TIM) raised by engineers is that vendor data do not match the results obtained from actual applications. Typical reasons for these issues may be vendor variations in testing, such as variances in test procedure and set up, the test conditions of the test fixture, such as completely flat contact surfaces, and manufacturing variations in the TIM. This study compares vendor data with results obtained from both realistic and ideal test conditions under consistent test method and uniform test conditions.

This study examines the performance of thermal pressure sensitive adhesive (PSA) TIMs, and compares the thermal impedance of various materials from multiple vendors. Both flat and non-flat surfaces are used to examine the differences under ideal condition to that of more realistic in actual applications. Effects of material thickness, surface flatness, and adhesive curing are discussed along with comparisons of performance for the different materials and the resulting discrepancies to the vendor specified data are examined.

Key Words: Pressure sensitive adhesive, thermal interface material, PSA, TIM.

Introduction

PSA TIM is an effective self-mounting TIM for low to moderate power density applications and are being used extensively across the electronics packaging industry for its benefits of low cost and ease of use. However, choosing the right TIM for the application is necessary, and in most cases the actual field data do not match the data provided by the vendors. Materials are usually selected based upon the vendor specifications and engineers invariably go for materials with best thermal performance data that are derived under ideal conditions. However, what is not considered in this approach is that the variations in the thermal performance are not that much for the typical applications with PSA TIMs, and more importantly there may be other factors such as adhesion strength, reworkability, and gap filling ability. For low power to moderate power density applications, the temperature difference is not very large between the different materials if the contact surfaces are very flat. However, the material thickness and compliancy may be more important in determining the thermal performance for non-flat and larger contact surfaces, thus yielding different than expected thermal results. Various tests have been

conducted to study the performance of TIMs; this effort has been designed to provide a uniform test condition for comparing the results for PSA TIMs.

Governing Equations

The heat transfer mode through a TIM is purely by conduction. There is a misperception that the TIM performance is influenced by the cooling side, such as by the size of the heat sink used. The performance of the cooling side influences the accuracy of the measured heat applied across the TIM. This in turn introduces error in actual power used in thermal performance calculation, thus, the misperception. Care needs to be taken in designing the test fixture in order to reduce the uncertainty in power measurement. The current work leverages the calorimetry approach outlined in ASTM D5470-95 [1].

For the current test method, it is governed by the steady-state 1-D Fourier's Law of Heat Conduction given in Equation 1.

$$\dot{q} = -\frac{kA}{t}(T_2 - T_1) \quad 1$$

For a TIM application, in addition to the conduction through the bulk material, there are two interstitial layers contacting the two surfaces as shown in Figure 1 and it is useful to examine the overall heat transfer coefficient as expressed in Equation 2. Besides the bulk thermal conductivity of the bulk interface material layer, good wetting ability is more important in filling in all the microscopic voids between the contact surfaces.

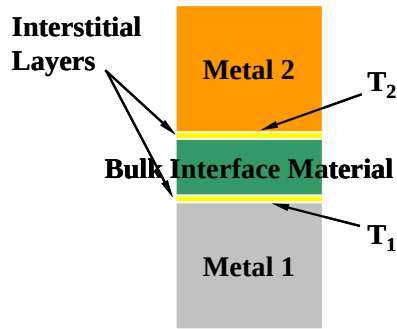


Figure 1: Thermal interfaces between two surfaces.

$$UA_{overall} = \left(\frac{kA}{t} \right)_{effective} \quad 2$$

In addition to the thermal conductivity and thickness of the TIM, $UA_{overall}$ is also a function of contact area, effective thickness, clamping force, surface flatness, and surface finish for TIM applications in filling in all the voids on the contact surfaces. Most of these parameters are difficult to empirically determine due to the microscopic length scale of the thin layers. Therefore, it is customary to report the performance in terms of effective thermal resistance to combine all these effects. It is the reciprocal of Equation 2 and usually normalized to unit area and expressed as the thermal impedance in vendor supplied data and is expressed in Equation 3. The *effective* subscript is used because it is beyond the capability of most testing to accurately determine the actual contact area A and the bond line thickness t , and typically the reference area, $A_{effective}$, is taken to be the total area of the mating surface.

$$\theta_{TIM} = \frac{1}{UA_{overall} / A_{effective}} \quad 3$$

θ_{TIM} is determined by measuring the temperatures of the surfaces on the hot side and cold side of the TIM and the measured power.

Materials Tested

The list of materials tested is provided in Table 1 along with the vendor specified thermal performance data. Materials from three vendors (Vendors A, B and C) are tested. 2 different materials from Vendors A and B are tested, while the same material of different thicknesses are tested for Vendor C. Data are compared for the same material thickness of 0.254mm for all three vendors; to study the effects of material thickness Vendor C material is tested for four different thicknesses. As seen from the performance data provided by the vendors, there can be quite a large range in thermal performance, but the testing shows otherwise and will be discussed in later sections. Also, the pressure that each vendor uses in its testing is not consistent amongst the industry as seen from the pressure tested provided by vendors listed in the last column. However, PSA TIMs are used exclusively without external pressure applied.

Vendor Designation/ Material	t (mm)	θ_{TIM} (°C-cm ² /W)	P (kPa)
A1	0.254	11.1	69
A2	0.254	15.9	69
B1	0.254	6.5	<6.9
B2	0.254	11.9	69
C1	0.127	3.1	--
C2	0.254	5.7	--
C3	0.381	7.5	--
C4	0.508	9.7	--

Table 1: Thermal interface materials tested.

Test Method

Test-Stand

The complete experimental test-stand is shown in Figure 2. Figure 3 shows the lower portion of the test-stand, which consists of the heater and test head assembly and the fan heat sink is removed. What is not shown in these figures is the foam insulation used to insulate the heater/test head assembly to minimize heat loss to the surrounding. The test fixture has been designed to suit the testing needs of PSA TIMs. In almost all applications with PSA TIMs, the secondary usage of the TIM is to attach the heat sink to the heated component directly. Therefore, there

are no external mounting devices to provide pressure in the 69kPa range which is often specified by vendor's testing. The only load is from the heat sink weight. A fan heat sink is used to mimic a realistic pressure on the TIM during testing. The flatness of the surface on the test head is tightly controlled since it is machined. The heat sink side flatness can vary as much as the standard extrusion flatness tolerance.

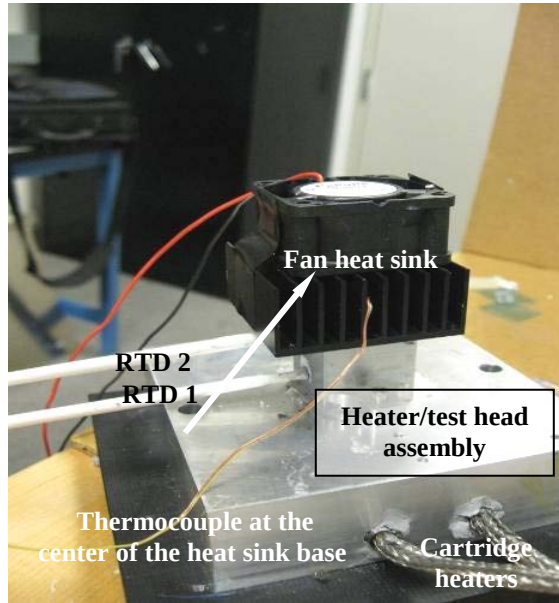


Figure 2: Test Setup.

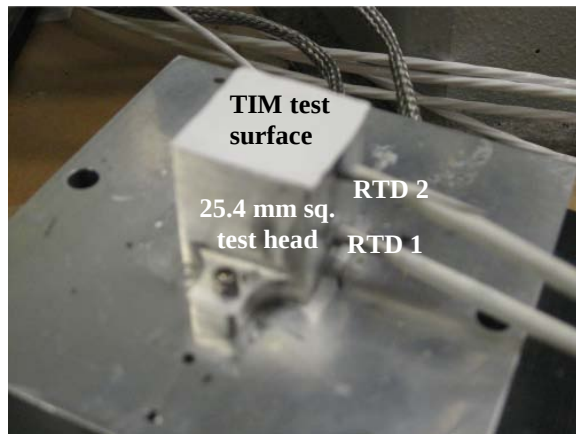


Figure 3: Heater/test head assembly.

Heater/Test Head Assembly

The heater/test head assembly consists of two cartridge heaters embedded in the platform base and a test head pedestal where the TIM under test is in contact. The heater platform base and the test head pedestal are constructed from Al-7075 which has a thermal conductivity of 153.5W/m-K.

The test head pedestal is machined and the contact area is 25.4mm square. Two test heads are used in the testing to evaluate performance differences between flat and non-flat surfaces: one is machined flat, and the second one is machined with a concave curvature of 0.05mm deep at the center.

Two RTDs, RTD 1 and RTD 2, are inserted in the pedestal at 1.524cm apart in order to calculate from Equation 1 the actual heat applied to the TIM under test. The temperature at the test surface is extrapolated based upon the temperature of RTD 2 and the known distance, which is 0.508cm, between RTD 2 and the test surface. This surface temperature is used as the hot side temperature in calculating the thermal impedance of the TIM under test.

Cooling Side

The cooling side of the test setup consists of an aluminum heat sink with a 40mm square 12V fan attached. The heat sink details are provided in Table 2. A thermocouple is embedded in a blind thermocouple well in the center of the heat sink base to monitor the temperature of the cold side of the TIM. The heat sink base is relatively thin and, based upon hand-calculation, the error is negligible in using the temperature reading directly on the cold side of the TIM. This temperature is used along with the surface temperature discussed in the previous paragraph in deriving the temperature rise across the TIM.

Overall dimensions, LxWxH (cm x cm x cm)	4.7 x 4.7 x 2
t_{base} (mm)	2
t_{fin} (mm)	1
Fin count (unit)	10

Table 2: Heat sink specifications.

Procedure

Since the surface flatness is controlled on the test head that is on the heater/test head assembly, the TIM is first applied to this side. The fan heat sink is then placed on top of it.

The TIM test samples are cut to the test head surface dimensions of 2.54cm square. Care is taken when the samples are applied onto the test head to

insure that there are minimal air bubbles trapped between the TIM and the test head.

A 4.6-kg weight is placed on top of the test setup for a duration of 20 seconds. This is performed to maintain consistency in assembling the test setup for each sample tested. The test setup is either tested immediately after this step to check the performance without curing or left to cure overnight, then tested.

To obtain proper measurement resolution on power and temperature difference, about 20-25W power is applied through the test head. Using the temperature readings and power measurement obtained, the thermal impedance of the material is calculated from Equation 3.

This same test method is applied to testing of both flat and non-flat test heads for the different materials.

Results and Discussions

Repeatability and Sensitivity to Curing

To verify the repeatability of the test procedure, multiple samples are tested for each material. The results for testing with the flat test head are summarized in Table 3 for materials A1 and B1.

Vendor Designation/ Material	Notes	Sample	θ_{TIM} (°C-cm²/W)		Vendor data
			Flat Test Head		
			θ_{TIM}	$\theta_{TIM,Ave}$	
A1	Cured Overnight	1	11.5	11.5	11.1
		2	11.5		
	Tested Immediately	1	13.0	13.1	
		2	13.0		
		3	13.0		
		4	13.4		
B1	Cured Overnight	1	12.6	12.7	6.5
		2	12.8		
	Tested Immediately	1	14.1	14.2	
		2	14.1		
		3	14.3		
		4	14.5		

Table 3: Repeatability and the effect of curing.

The results for multiple samples confirm that the test process is sound and repeatable. Although the difference between curing overnight and uncured is only 12-14%, if care is not taken in testing the materials and not allowed to cure properly, it will yield worse results with uncertain errors. To eliminate this uncertainty, it is recommended to cure the samples before testing or use. For Material A1, the results between the current testing and vendor data are very close for the cured samples.

Effect of Surface Flatness

Table 4 summarizes the results of all the materials. At least two samples of each material are tested, and each material is tested with the flat and non-flat test heads to examine the performance behavior of each material under different flatness conditions.

Vendor Designation/ Material	Sample	t (mm)	θ_{TIM} (°C-cm²/W)				Vendor data
			Flat Test Head		Non-Flat Test Head		
			θ_{TIM}	$\theta_{TIM,Ave}$	θ_{TIM}	$\theta_{TIM,Ave}$	
A1	a	0.254	11.5	11.5	11.8	11.9	11.1
	b		11.5		12.1		
A2	a	0.254	8.9	9.0	9.2	9.2	15.9
	b		9.0		9.2		
B1	a	0.254	12.6	12.7	14.5	14.5	6.5
	b		12.8		14.5		
B2	a	0.254	9.0	9.0	9.4	9.6	11.9
	b		9.0		9.9		
C1	a	0.127	8.7	8.9	18.1	18.1	3.1
	b		9.0		18.1		
C2	a	0.254	7.0	7.0	7.9	7.9	5.7
	b		7.0		7.8		
C3	a	0.381	10.8	10.7	13.0	13.0	7.5
	b		10.6		13.0		
C4	a	0.508	11.0	10.9	14.5	14.7	9.7
	b		10.8		14.9		

Table 4: Thermal performance comparison between flat and non-flat surfaces.

Both materials from Vendor A are least sensitive to the current flatness condition with only 3% difference between flat and non-flat surfaces. For Vendor B, material B2 is less sensitive with 8% difference, while material B1 differs by 14%. For Vendor C, the C2 material, that has the same thickness as the other three vendors, has a difference of 12%. However, the difference is over 100% for the thinnest material, C1, at 0.127mm thick. This will be further analyzed and discussed in a later part of this section.

Comparing between materials with the same thickness, the thermal performance varies between 7.0 and 12.7°C-cm²/W for the flat test head, and 7.9 and 14.5°C-cm²/W for the non-flat test head. C2 performs the best and B1 is the worst. But, comparing the best material from each vendor, the performance is between 7 to 9°C-cm²/W and 7.9 to 9.6°C-cm²/W, for flat and non-flat test heads, respectively. This illustrates that these vendors are all very competitive in respect to thermal performance of their materials.

These results illustrate the importance of testing under realistic conditions. The difference between vendor data and test results are any where from 4 to 76% for the flat test surface and 7 to 82% for the non-flat surface, and the trends are not consistent

from material to material from the same vendor nor from vendor to vendor. To illustrate these points, let's review first the data for Vendor A. Comparing the test results with the spec performance for the first material (A1), one might jump to the conclusion that Vendor A's test process yields results that are better than other vendors because the spec performance is in very good agreement with the current test results. However, when the same comparison is carried out for the second material (A2), it is no better than the trends for the other vendors.

Material Thickness

Theoretically, Equation 1 implies that the TIM performs better as it gets thinner. However, due to the imperfection of the real-world conditions as stated in Figure 1 and Equation 2, it is not always the case that thinner materials perform better for the applied situation. This is due to other parameters, such as adhesion strength, wettability, or material softness, on how well the gaps are filled. This is illustrated by testing the same material with different thicknesses. Vendor C materials, C1-C4, for thicknesses of 0.127, 0.254, 0.381, and 0.508mm are tested. The results are plotted in Figure 4 for the non-flat surface condition.

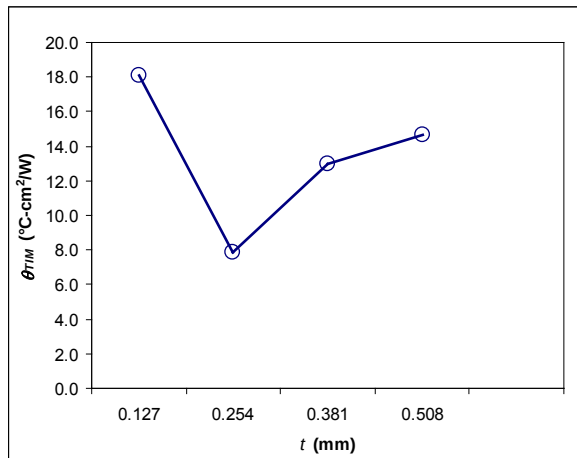


Figure 4: Thermal performance of Vendor C materials at different thicknesses with the non-flat test head.

For this material and the thicknesses tested, it performs the best at 0.254mm. The performance drops for thickness on either side of this, with the right side complies to the trend predicated by Equation 1. In this example, the thinnest material turns out to have the worst performance. For a 10W applied power, the temperature rise across the TIM is

18°C with the thinnest material, and only 8°C for 0.254mm thick material.

Power Density Consideration

To determine a suggested power density upper limit in using PSA TIMs, let's evaluate the temperature rise across the TIM for a typical heat source size of 2.54cm square. Table 5 shows the temperature rise across the TIMs tested at two power levels, 10W and 5W. In most practical designs, for a 10W component with a lid size of 2.54cm square, probably 3-5W is dissipated into the board, with the remaining 5-7W dissipated into the heat sink. From these calculations, it is suggested that PSA TIM is safe to be used for no more than 10W of total component power at 2.54cm square lid size, which translates to a power density of about 1.6W/cm². For applications with power density in this range, the resulting temperature rise across the TIM is not very different between all the materials tested and they are all within a reasonable range of around 10°C or less. For applications with power density higher than this should be handled on a case by case basis and it will be more important in testing and picking the right material because the temperature rise is significantly higher than 10°C and the differences between different materials can be quite large.

Vendor Designation/ Material	θ_{TIM} (°C-cm²/W)	ΔT_{TIM} (°C)	
		$q' = 10W$	$q' = 5W$
A1	11.9	18	9
A2	9.2	14	7
B1	14.5	22	11
B2	9.6	15	7
C2	7.9	12	6

Table 5: Temperature rise across the TIMs for a 2.5cm square heat source.

Conclusions

A simple and practical test-stand and test procedure have been presented for the empirical evaluation of pressure sensitive adhesive thermal interface materials. This test-stand can be used in evaluating vendor data under ideal flat surface condition, as well as application-specific surface conditions. The test-stand design is flexible in dialing in the surface requirement by machining to the application-specific condition.

This work has examined different factors that will influence the performance of this class of TIMs. If the appropriate power density is used, the performance differences between the different materials from different vendors are not that much. In this situation, other factors might play a more significant role in determining the selection. Some of these factors may include adhesion strength, cost, reworkability, and ease of handling. However, for power density levels that are much higher than the suggested level, thermal performance of the material is more critical. It is crucial that extensive testing is performed to identify the material that will minimize the temperature rise across the TIM for this situation.

References

- [1] ASTM D 5470-95, "Standard Test Methods for Thermal Transmission Properties of Thin Thermally Conductive Solid Electrical Insulation Materials", West Conshohocken, PA, USA, 1995.