Thermal Performance Comparison Between Liquid and Pad Thermal Interface Material

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ABSTRACT
Power density of electronic devices has increased beyond what we thought possible merely a decade back. In addition, the dimension of the CPU/GPU has exceeded 70mmx70mm in size. Today, you find these large, high power processor packages in telecom, datacom, automotive, aviation, consumer electronics and more. The package size, power density and frequency of high-power cycling have created both challenges and opportunities for Thermal Interface Material (TIM) suppliers to address the thermal management needs of these new generation of devices. There are two primary types of TIM used in between the heat generating component and heat spreader. These are known as pad (a solid mat) and liquid (1 or 2 component paste). Standard heat spreader and heat generating component surfaces have very few contact points due to machined surfaces that are rough and wavy. These surface imperfection traps air in between the two surfaces creating a barrier for heat transfer. The objective of the "right" TIM is to replace the air and completely wet out both interfaces to reduce thermal resistance without damaging the delicate large packages.

Pad and liquid TIM use distinctly different assembly processes in applications. Gap pads need a certain amount of compression under pressure to fully wet out the surface and expel any air entrapped on the surfaces. Liquid TIM on the other hand needs little to no external compression force during assembly as it flows easily under stress. Current work is based on the hypothesis that a liquid TIM with the same effective thermal conductivity as a thermal pad will have lower thermal resistance/impedance due to its ability to wet out the interface better than a solid pad. Other factors, such as bondline thickness will also be explored to test the hypothesis that thinner bondline provides lower resistance regardless of TIM type.

Key words: Thermal Interface Material (TIM), thermal conductivity, thermal resistance, thermal impedance, bondline thickness, rheology, thermal testing.

INTRODUCTION
In electronics assembly thermal pathway from one end of the system to the other, contains multiple interfaces and even gaps that can be a barrier for heat flow. Figure 1 shows a schematic of a typical system with microelectronics packaging and various interfaces within the system.

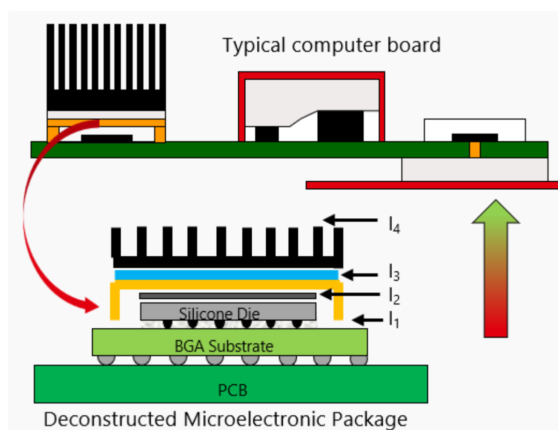

Figure 1. Typical electronic board. I_1-die to substrate interface, I_2-die to lid interface, I_3-lid to heatsink interface, I_4-heatsink to environment interface.

System engineers design metal base (Copper or Aluminum) heatsinks that go over ICs such as CPUs, GPUs, memory chips etc. to transfer the heat away from these heat generating components. With metal being a high conductor of heat, this concept would work well if there was intimate contact between the two surfaces. Unfortunately, there are relatively few contact points between the two surfaces that leaves a large area with air in between the two surfaces, Figure 2 graphically depicts this phenomenon in a qualitative manner. Air being an insulator, must be removed from the interface in order for the system to perform at its expected performance and reliability level. Figure 3. shows a graphical representation of the interfaces with air trapped in between.

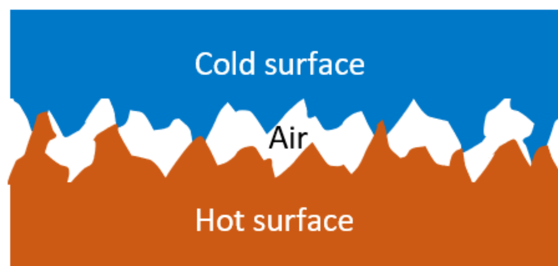

Figure 2. Graphical representation of air entrapment between hot and cold surfaces

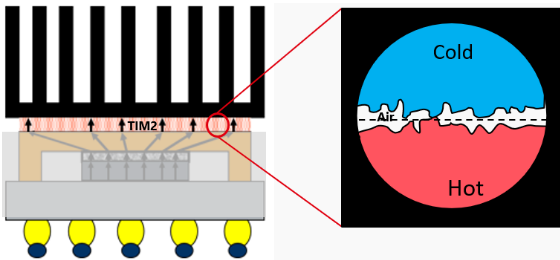

Figure 3. Illustration of rough interfaces

Design engineers mitigate this issue by carefully selecting Thermal Interface Materials (TIMs) to bridge the gap created by imperfect surfaces. Efficiency of heat transfer from the hot component to the cold heatsink depends on effective thermal conductivity of the bulk TIM (impacting bulk resistance) and contact resistance at both interfaces. There are many choices when it comes to selecting a TIM that works for these high-power components. Examples are thermal pads (known as gap pads), 2 component liquid gap fillers, 1 component gap fillers (known as gel or putty), thermal grease, phase change material, to name a few. However, the two most commonly used solutions are gap pad and gap filler. In this discussion, we will focus on gap pad and thermal gel only to test out the hypothesis presented earlier.

GAP PAD DESCRIPTION

Gap pad is a soft, conformable solid mat/pad that goes in between component and heatsink. Gap pad thickness could be from 0.5mm to over 6mm. Hardness and modulus can vary widely making it rigid to almost putty like consistency. Gap pad application methods are very simple and usually done manually. One of the biggest disadvantages of gap pad is its requirement of compression to help wet out the surfaces. Even with 40-50% compression, you may not get all the trapped air out of the interface resulting higher interfacial resistance.

THERMAL GEL DESCRIPTION

Thermal gel is a thixotropic liquid which is also shear thinning in nature. These material properties are known as "rheology" of the material. A typical description of the rheology is given by Oxford Languages (1) as "the branch of physics that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids." A thermal gel's key rheological properties are high viscosity, high thixotropic index and shear thinning behavior. Shear thinning behavior helps to dispense under high shear and thixotropic behavior help to retain its shape when stress is removed. Figure 4 shows an example of gap pad and gel in typical applications.

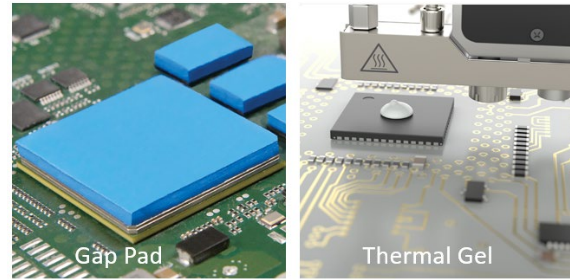

Figure 4. Example of gap pad (on left) and thermal gel (on right) in typical applications.

THERMAL PERFORMANCE

Before we continue to the experimental study, it is important to address the key thermal performance characteristics of TIM that is used in assessing the effectiveness of a TIM solution. Thermal performance includes thermal conductivity, thermal resistance and thermal impedance.

Thermal Conductivity

Thermal Conductivity (TC), designated as *k*, is the bulk property of a material that indicates its ability to conduct heat. It does not depend on the geometry or interfacial conditions of the test set up. Fourier's law of thermal conduction provides us a way to calculate *k* using the equation (1). Visual representation of Fourier's equation is shown in Figure 5.

$$Q = -kA\frac{\Delta T}{d} \quad (1)$$

Q - Heat flux (W)
K - Thermal conductivity (W/m-K)
A - Area (m^2)
D - Thickness (m)

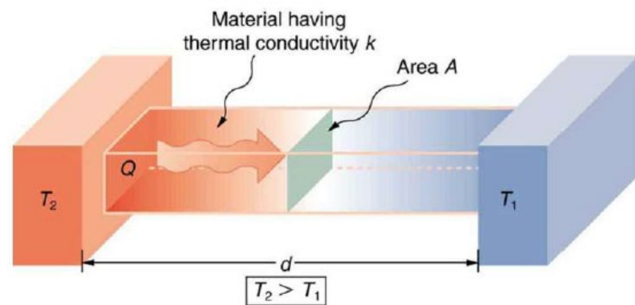

Figure 5. Fourier's law representation

The term "Thermal Conductivity" applies to homogeneous materials only. Thermal interface materials are heterogeneous, better known as composite materials. Hence the proper terminology to describe the conductivity of TIM is "Effective or Apparent Thermal Conductivity". Effective thermal conductivity is calculated by the equation (2).

$$k_{eff} = d/Z \quad (2)$$

k_{eff} - Effective Thermal Conductivity, W/m-K
Z - Thermal Impedance, ^{0}C-m^2/W

Thermal Resistance

Thermal Resistance (TR) can be thought of as the opposite of thermal conductance. For a steady state conduction as shown in Figure 5, the Fourier's equation for thermal resistance can be written as (3).

$$R = \frac{d}{kA} \quad (3)$$

R - Thermal resistance, ^{0}C/W

Thermal Impedance

Thermal Impedance (TI) is similar to thermal resistance and often used interchangeably. However, there is a distinct difference between thermal resistance and impedance. TI is defined as the temperature gradient per unit of heat flux, passing through the interface. As shown in (4), TI is obtained by simply multiplying the resistance, R, by the area over which the heat is dissipated.

$$Z = RA \quad (4)$$

TI includes bulk thermal resistance of the TIM and contact resistance between TIM and the two surfaces in contact with the TIM. As the thermal resistance is directly proportional (3) to the thickness of the TIM, the thinner the TIM, the lower the thermal resistance. Contact resistance on the other hand depends on the two contacting surface conditions and the ability of the TIM to fill in the surface roughness (Figure 3). Surface roughness and unevenness can trap air reducing the effectiveness of TIM to transfer heat. Figure 6 is a graphical representation of the resistance in series across the component and heatsink assembly. Total impedance is proportional to the sum of all three resistances.

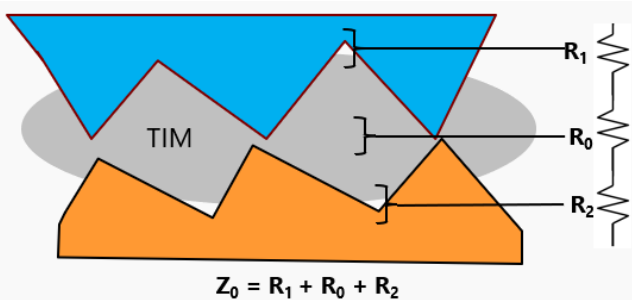

Figure 6. Thermal Impedance explanation

CHARATRIZATION TECHNIQUE

There are two common types of testing done at the material level to characterize thermal conductivity. They are steady state and transient testing. The most common steady state testing equipment are based on ASTM D5470 standard and transient testing is based on ASTM E1461 Laser Flash method. These methods are discussed at length in the previous body of work [2] and have been used to characterize TIM performance in many studies across the industry.

EXPERIMENTAL STUDY

As explained earlier, thermal performance of a TIM depends on the thermal conductivity, bondline thickness, area over which the heat is dissipated, and contact resistance at both interfaces. Contact resistance on the other hand depends on the TIM's ability to wet out (fill in the microscopic surface imperfection that could trap air) the mating surfaces. Better wet out can be achieved by various means. Examples are, smoother surfaces, TIMs wetting ability and increased pressure for better contact. A cross-section example of TIM wet out showing pad vs. liquid is shown in Figure 7.

This experimental study is based on the hypothesis that "a liquid TIM with the same bondline thickness and mating surface conditions will provide a lower thermal performance as compared to a solid pad". In addition, "thinner bondline will exhibit lower bulk resistance leading to improved overall thermal performance of TIM". The above hypothesis was tested by using a thermal gel (liquid TIM) and thermal pad (solid TIM) with the same effective thermal conductivity. Table 1 shows typical characteristics of these two materials used for this study. To get a better understanding of the effect of TIM type and bondline thickness, two types of tests were conducted. Test 1 consisted of using a TIM tester that follows ASTM D5470 test method to test both type of TIM at a fixed bondline thickness. Test 2 consisted of using a thermal test vehicle (TTV) that represents a real word application scenario.

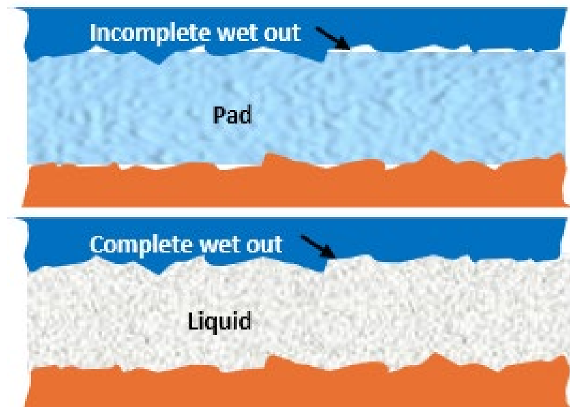

Figure 7. Example cross section of TIM and different wet out scenarios in application

Table 1. Material properties

Material	TIM type	Thermal Conductivity
Bergquist TGP 6000ULM	pad	6 W/m-K
Bergquist TLF 6000HG	gel	6 W/m-K

Test 1 Methodology

First part of the study was conducted using ASTM D5470 test method at a bondline thicknesses of 0.6mm. Bondline thickness for gap pad was achieved by applying 40% strain to a pad with original thickness of 1.0mm. Gap pad samples were cut to a diameter of 33mm to cover the test platen used in this study. Thermal gel was applied to the test platen with a measured volume to achieve desired thickness with a diameter of 33mm as shown in Figure 8. Multiple replicates of both pad and gel samples were tested to obtain a statistically valid result. Figure 9 shows a graphical

representation of the test set up. Detail of the test method can be found elsewhere [2].

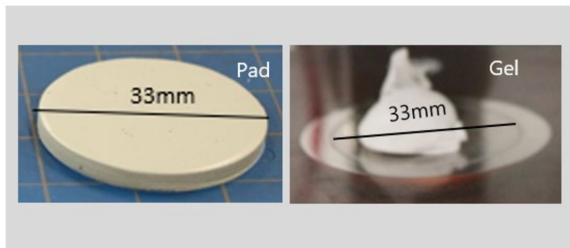

Figure 8. Gap pad and gel test samples

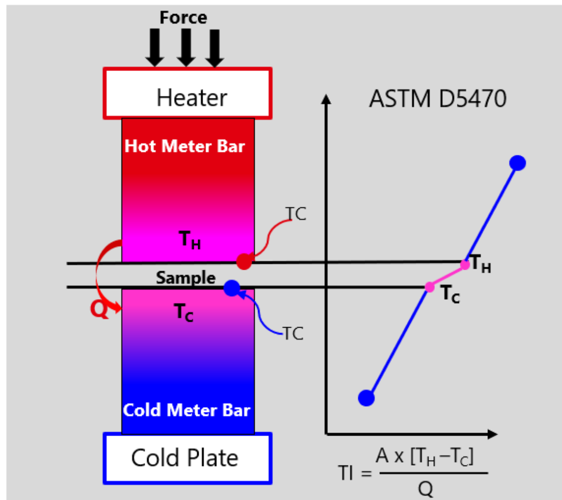

Figure 9. Schematic of Steady State Thermal Test Method

Test 2 Methodology

The second part of this study follows the same "pad vs liquid" concepts with the addition of multiple bondline thickness as a variable. A specially designed thermal test vehicle (TTV) that represent a real-world application was used for this part of the study. The TTV is comprised of a N-type TO-220 MOSFET transistor mounted to a heat sink with TIM positioned in-between the two components. The focus of this study was to understand thermal performance vs. bondline thickness for both pad and liquid TIM at a constant power input. A spring clip with ~35 psi is used in this test to provide minimum bondline thickness. Different bondline thicknesses are achieved by using heatsinks with mechanical standoffs of 0.5 to 2.5mm to give the target bondline thickness.

Thermal resistance in °C/W was calculated using equation (4).

$$Thermal\ Performance\ \left({}^{\circ}C/_{W}\right) = \frac{(T_r - T_s)}{Power} \quad (4)$$

Where:

T_r = Temperature of the transistor
T_s = Temperature of the heatsink
Power = Constant

Temperature of the transistor (Tr) and heatsink (Ts) were measured by in-situ thermocouples that are inserted into holes drilled equidistant into the transistor and heatsink respectively. This is shown in Figure 10. Constant power of 28.1W was used for both gap pad and liquid gel test set up.

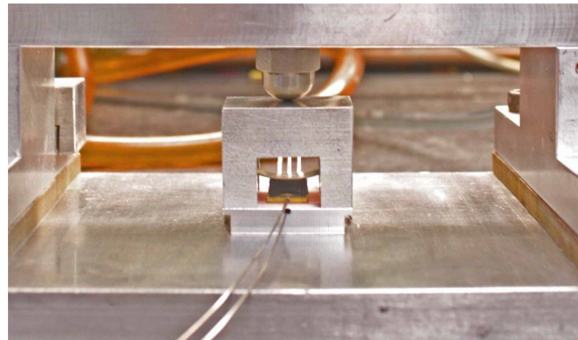

Figure 10. Test assembly sowing TO-220 component and heatsink with thermocouples attached

Figure 11 shows a typical set up for the TO-220 TTV. Detail of the test description is published elsewhere [3].

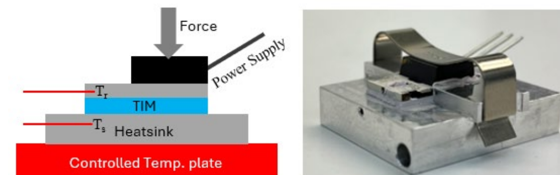

Figure 11. TO-220 test sample assembly for liquid Gel

Table 2 shows initial pad thickness along with final bondline thickness for TO-220 test vehicle using gap pad. Bond line thickness for gel was achieved as described before.

Table 2. Initial and final bondline thickness for TO-220 TTV

Target BLT (mm)	Nominal thickness (mm)	% Strain
<0.50	1,00	>50
0.50	1.00	50
1.50	2.00	25
2.00	2.50	20
2.50	3.18	17

RESULTS AND ANALYSIS

Test 1 Results

Figure 12 shows the box plot comparison of thermal impedance for pad and gel at a bondline thickness of 0.6mm. ANOVA analysis and Tukey test for pairwise mean comparisons for the same data set is shown in Figure13.

As hypothesized, the results below confirm the prediction that a liquid TIM, gel in this case, wets out the surface better providing a lower thermal resistance for the heat to flow from hot surface to cold plate. ANOVA analysis, with a P-Value of 0.007 indicates that the difference we observe in this experiment is statistically significant. This is further confirmed by the Tukey pairwise comparisons. As we observe from Figure 13 pad and gel belong to two distinctly different group. Above analysis leads to the conclusion that

there is 32% improvement in thermal resistance is achieved by simply going from a solid pad to a liquid base TIM at a bondline thickness of 0.6mm.

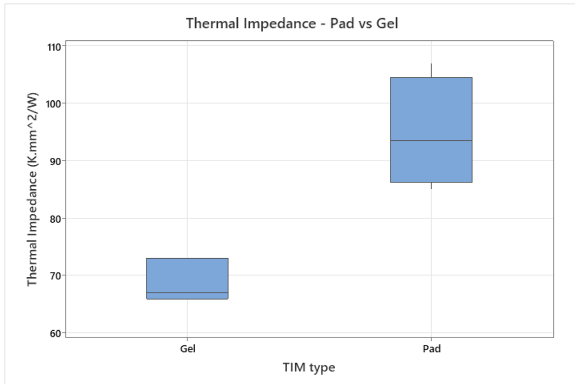

Figure 12. Comparison of TI for Gap Pad vs. Thermal Gel

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
ID	1	1166.3	1166.30	19.35	0.007
Error	5	301.4	60.28		
Total	6	1467.7			

Tukey Pairwise Comparisons

ID	N	Mean	Grouping	
Pad	4	94.75	A	
Gel	3	68.67		B

Means that do not share a letter are significantly different.

Figure 13. One way ANOVA result Tukey pairwise comparisons of Gel vs. Pad

Test 2 Results

Box plot for TO-220 TTV test with multiple bondline thickness is shown in Figure 14. ANOVA analysis and Tukey pairwise comparisons for different bondline thickness are shown in Figure 15 a. and 15b.

P-Value of 0.0 for both TIM type is a clear indication that bondline thickness is statistically significant when it comes to interfacial resistance. Thinner bondline providing lower resistance as expected. This observation agrees with the working hypothesis.

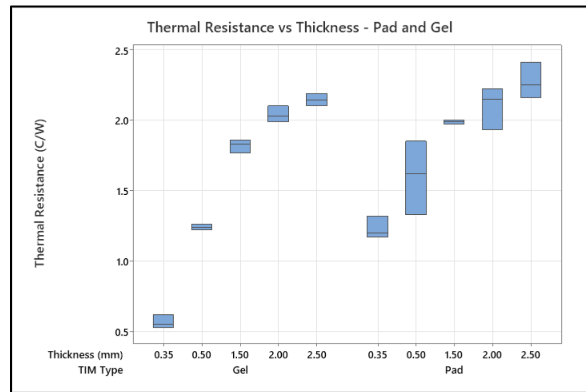

Figure 14. Thermal resistance comparison

One-way ANOVA: Pad versus Thickness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Thickness	4	2.1192	0.52981	23.36	0.000
Error	10	0.2268	0.02268		
Total	14	2.3460			

Tukey Pairwise Comparisons

Thickness	N	Mean	Grouping		
2.50	3	2.2733	A		
2.00	3	2.1000	A		
1.50	3	1.98667	A	B	
0.50	3	1.600		B	C
0.35	3	1.2300			C

Means that do not share a letter are significantly different.

Figure 15a. ANOVA analysis and Tukey pairwise comparisons for TO-220 TTV with BLT as the main variable

One-way ANOVA: Gel versus Thickness

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Thickness	4	5.07102	1.26775	578.20	0.000
Error	9	0.01973	0.00219		
Total	13	5.09075			

Tukey Pairwise Comparisons

Thickness	N	Mean	Grouping			
2.50	3	2.1433	A			
2.00	3	2.0400	A			
1.50	3	1.8200		B		
0.50	2	1.2400			C	
0.35	3	0.5667				D

Means that do not share a letter are significantly different.

Figure 15b. ANOVA analysis and Tukey pairwise comparisons for TO-220 TTV with BLT as the main variable

As shown in Figure 15a and b, Tukey pairwise comparison shows there is a statistical significance between the thin and thick bondline regardless of the TIM type. The difference is more evident for gel as it wets out the interface better than a pad. It is also observed from Figure 14 that gel has lower resistance as compared to pad at all bondline thickness tested

here. However, the resistance difference becomes less significant as the bondline thickness increases. That is expected as the bulk resistance becomes dominating factor as the bondline thickness increases. This phenomenon is shown graphically in Figure 16.

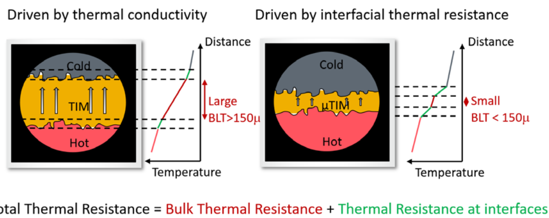

Figure 16. Impact of BLT on thermal resistance

SUMMARY & CONCLUSION

This study tested the hypothesis that a liquid TIM with the same effective thermal conductivity as a gap pad will have lower thermal resistance in application due to its ability to wet out the interface better than a solid pad. Also hypothesize here, bondline thickness has a significant effect over total thermal resistance. This comparative study used the ASTM D5470 test method and a custom TTV to characterize TIM thermal impedance and resistance at different thickness. Based on the results from Test 1, we can conclude that liquid TIM's physical nature and rheological properties do provide a measurable improvement to both thermal impedance and resistance at the same BLT. Based on the same theory, results from Test 2 leads us to the conclusion that regardless of the BLT, liquid TIM outperforms pad at all bondline thickness tested.

A solid pad that requires some pressure to compress causing elastic/plastic deformation has limited capability to fill the uneven surface at both interfaces. Most gap pads cannot be compressed more than 50% of their original thickness as it will have performance loss. This limiting their ability completely wet out the interface. Liquid TIM on the other hand flows with little to no stress or compression force providing excellent wet out of the interfaces.

The performance distinction highlighted here is impactful as next generation electronic device package size, power density and frequency of high-power cycling continue to increase across many markets. Understanding which TIM to select for these devices as well as those with complex design and high number of components is crucial to the thermal management and reliability of these applications.

RECOMMENDATIONS

The study described here shows that a liquid TIM has a higher ability to wet out the surfaces reducing thermal resistance and improving heat transfer. However, it is impractical to expect that liquid TIM is always a better choice over a solid pad. Gap pad has many process advantages that could overcome the shortfall of lower thermal efficiency, making it the choice of TIM for specific applications. Authors here recommend that end users of TIM to have a technical discussion with TIM suppliers to ensure they are selecting the right TIM type for their application. There is no one solution that fits every application. Careful considerations must be given in TIM selection process to ensure that the correct TIM format is selected for the application.

ACKNOWLEDGEMENT

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