

Performance and testing of thermal interface materials

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ABSTRACT: The increasing power and reduced die size of CPUs used in computers increases a need for significantly improved thermal interface materials (TIM). The TIM is used to reduce contact resistance at the CPU-heat sink interface. This work provides a state-of-the-art assessment on “thermal interface materials,” including fundamentals, materials used, their performance, and how interface resistance is measured. The performance of new commercial interface materials is given, as well as discussion of the advantages and disadvantages of different materials. The report notes that the recommended interface test method does not necessarily duplicate the installation and operating conditions in an actual computer installation. Recommendations are presented on the design and operation of an apparatus intended to simulate actual computer installation conditions. The innovative Penn State “low melting point alloy” thermal interface material is described and compared to other commercial materials.

1 NOMENCLATURE

A :	Surface area of the electronic component through which heat is emitted
k_{TIM} :	Bulk thermal conductivity of the thermal interface material
Q'' :	Power per unit area of the heat-emitting component
R_{int} :	Thermal interface resistance (commonly presented with units of [K-in ² /W])
$R_{contact}$:	Thermal contact resistance
$R_{contact1}$:	Thermal contact resistance between the TIM and the CPU surfaces
$R_{contact2}$:	Contact resistance between the TIM and the heat sink baseplate
R_{cond} :	Conduction resistance across the thickness of the TIM
t :	Thickness of the thermal interface material
T_{cpu} :	CPU or other electronic package surface temperature
T_{hs} :	Heat sink baseplate temperature
TIM	Thermal interface material

2 INTRODUCTION

Thermal interface material (TIM) is used to minimize the contact thermal resistance between the central processor unit (CPU) and the heat sink. The plan area of central processor units CPUs has been steadily decreasing. Further, the power dissipation has been increasing. For example, die size of the Pentium 2 was 25.4 mm square and the power dissipation was about 33 W. However, the Pentium 4 has 12 x 12.5 mm die size and will dissipate up to 80 W. Intel has attached a 1.5 mm thick, 31 mm square copper heat spreader to the CPU die in attempt to increase the die physical strength and reduce the heat flux. However, our CFD calculations show that the heat flux is very

non-uniform and the heat spreader has the same thermal resistance as for uniform heat flux on a 16 mm square area. Comparing the Pentium 4 (16 mm square effective die size) to the Pentium 2, we see that the heat flux has increased a factor of 6.1. For the Pentium 2, the TIM accounted for approximately 15% of the total allowable thermal resistance. If this same TIM were used on the Pentium 4, the TIM would use 80% of the allowed total thermal resistance. Further, increased CPU power is expected. By 2003, the CPU power should be approaching 120 W, which will further increase the interface heat flux. Because of this, significant work has been done to develop new higher performance thermal interface materials. In addition, the desire for increased yield and reliability requires lower operating temperatures (Viswanath et al., 2000).

The path of heat removal from an electronic package such as a CPU, involves conduction across the interface of the CPU case surface, through a thermal interface material (TIM), into a heat sink and then convection to the environment. There are many TIM products on the market today and it is difficult to perceive which are better than others. Data reported by a TIM manufacturer may not be reproduced by others, or validated in an actual computer installation. The first section of this paper presents a fundamental understanding of contact resistance, and the second section discusses options to reduce the interface resistance. The third section presents a classification of high performance thermal interface materials, with their advantages and disadvantages, and an assessment of recent advancements in interface material technology. Section four follows with a discussion of the measurement of thermal interface resistance and possible errors associated with the resistance measurement

3 BACKGROUND

Thermal interface resistance is a measure of how well heat is transferred across the interface of two mating rigid surfaces, such as a CPU and a heat sink baseplate (Figure 1a).

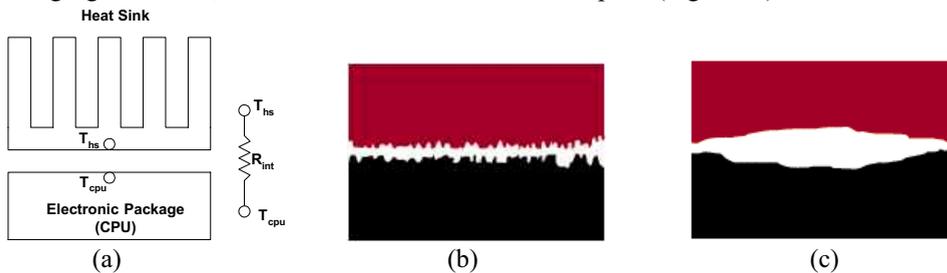


Figure 1: (a) Definition of thermal interface resistance, R_{int} . (b) heat sink and CPU surface roughness, and (c) poor heat sink and CPU surface flatness (deSorgo, 1996)

In the case of the CPU-heat sink interface (the focus of the present work), the interface resistance (per unit area) is defined as follows:

$$R_{int} = \frac{T_{cpu} - T_{hs}}{Q''} \quad (1)$$

where, T_{cpu} is the CPU (or other electronic package) surface temperature, T_{hs} is the heat sink baseplate temperature, Q'' is the power per unit area of the heat-emitting component. The R_{int} is commonly presented with units of $(K \cdot in^2 / W)$. As can be seen in the equation for R_{int} , the lowest possible interface resistance is reached when the heat sink temperature approaches that of the CPU.

The CPU and heatsink surfaces being joined contain a combination of surface roughness and surface non-flatness as shown in Figure 1b and 1c. The micro roughness is superimposed on a macroscopic non-planar in the form of a concave, convex or wavy surface, resulting in as much as 99% of the interface surface area being separated by air filled gaps (Figure 2a) unless a thermal interface

material is used. Theoretically, the contacting surfaces will only contact one another at no more than three points. Because air is a very poor thermal conductor ($k_{\text{air}} = 0.026 \text{ W/m-K}$ at room temperature), it acts as a thermal barrier preventing efficient heat transfer across the interface. If no TIM is used to enhance heat transfer across the interface, the total interface resistance, R_{int} is due to contact resistance, R_{contact} as shown in Figure 2a. Contact resistance, R_{contact} , is composed of two parallel resistances: (1) conductive resistance at the points where the mating surfaces contact and (2) conductive and/or radiative resistance across the gaps of non-contacting area. The existence of TIM material adds a thermal conduction resistance across the material of thickness “t.”

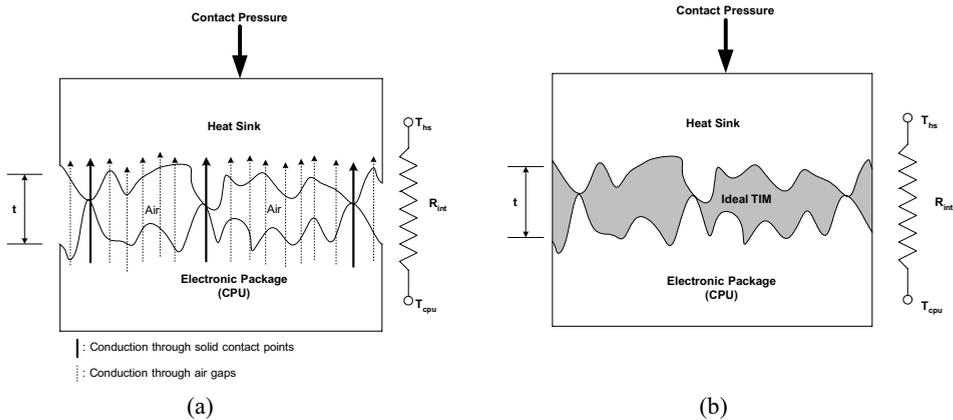


Figure 2: Exploded view of thermal interface when (a) no TIM is used. Note R_{int} is composed only of contact resistance, R_{contact} and (b) when an ideal TIM is used.

4 METHODS TO REDUCE CONTACT RESISTANCE

For solids of high thermal conductivity, the contact resistance may be reduced by the following two methods: (1) increasing the area of contact spots, accomplished by (a) increasing contact pressure which will “flatten” the peaks of the micro roughness, and deflecting the mating surfaces to remove any non-flatness, or (b) reducing the roughness of the surfaces before the interface is formed by grinding the surfaces to remove non-flatness and buffing the surface to remove micro-roughness; and (2) using a TIM of high thermal conductivity that can conform to the imperfect surface features of the mating surfaces (Incropera & DeWitt, 1996).

Load constraints on electronic components and circuit boards make it unfeasible to use high contact pressure. Manufacturing highly finished surfaces is not practical due to cost constraints. Therefore, the practical alternative is to use a thermal interface material applied at a moderate contact pressure. Intel specifies 25 lbf. maximum heat sink clip force can be applied for the P4 processor in the 423-pin package, which results in 16.78 psi. on the 31 mm^2 integrated heat spreader (Intel Corp., 2001), and their reference design heat sink clip applies 7 to 23 lbf or 5 to 16 psi. (Intel Corp., 2000). Any interstitial substance that fills the gap between contacting surfaces, and whose thermal conductivity exceeds that of air, will decrease the contact resistance (Incropera & DeWitt, 1996). The ideal thermal interface material (Figure 2b) would have the following characteristics:

1. High thermal conductivity
2. Easily deformed by small contact pressure to contact all uneven areas of both mating surfaces, including surface pores, eliminating R_{contact} .
3. Minimal thickness.
4. Would not leak out of the interface.
5. Would maintain performance indefinitely.
6. Non-toxic.
7. Manufacturing friendly (easy to apply and remove).

Ideal thermal interface material has not yet been discovered, but several options are available to provide reduced interface resistance. However, an actual thermal interface material will not be able to completely fill the cavities, and small air pockets will likely remain on both sides of the interface material (See Figure 3a).

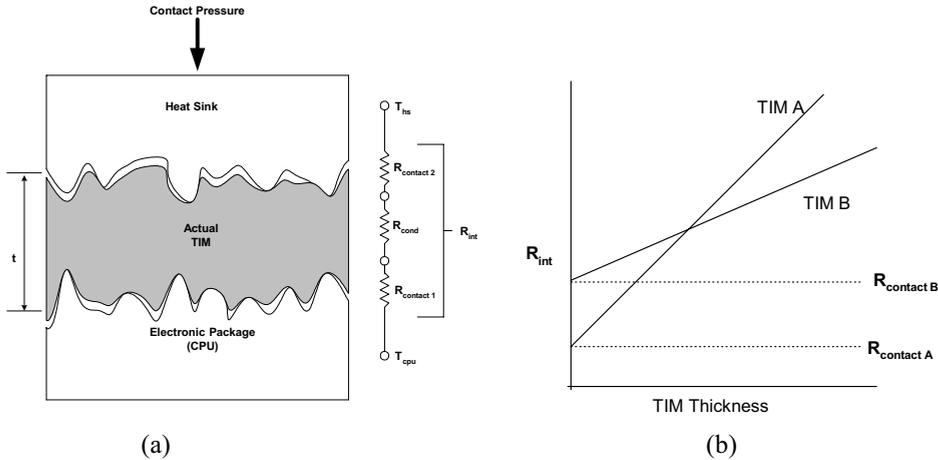


Figure 3: (a) exploded view of thermal interface with actual TIM and (b) example plot of R_{int} vs. t for two TIMs (Chu et al., 1997)

As shown in Figure 3a, the interface resistance is actually composed of three resistances in series. The total interface resistance is expressed as follows:

$$R_{int} = R_{contact1} + R_{cond} + R_{contact2} \quad (2)$$

$$R_{cond} = \frac{t}{k_{TIM} A} \quad (3)$$

$R_{contact1}$ is the contact resistance between the TIM and the CPU surfaces, R_{cond} is the conduction resistance across the thickness of the TIM, $R_{contact2}$ is the contact resistance between the TIM and the heat sink baseplate, A is the surface area of the electronic component across which heat transfer occurs, k_{TIM} is the TIM bulk thermal conductivity and t is the thickness of the thermal interface material (Chu et al. 1997).

One can determine the total contact resistance ($R_{contact} = R_{contact1} + R_{contact2}$) by measuring thermal resistance data for a range of TIM thickness and plotting R_{int} vs. t . The R_{int} vs. t data exhibits the following linear relationship:

$$R_{int}(t) = R_{contact} + \frac{t}{k_{TIM} A} \quad (4)$$

The slope is equal to the inverse of the product of the TIM conductivity, k_{TIM} and the area A . The intercept of the R_{int} axis is equal to $R_{contact}$ (Chu et al. 1997). An example of the plot that will be obtained for two different interface materials is presented in Figure 3b. The $R_{contact1}$ and $R_{contact2}$ resistances may differ, because each of the two contact surfaces (the silicon die and the heat sink base) may differ in roughness or flatness.

Increasing the contact pressure will reduce R_{int} . Pressure increases the actual contact area and reduces the amount of air remaining at the interface, thus reducing contact resistances, $R_{contact1}$ and $R_{contact2}$, on either side of the interface material. Increasing contact pressure can also decrease the conduction resistance, R_{cond} , of the interface material itself, by reducing its thickness, t . The pres-

sure required to reduce the thermal interface resistance of a given TIM is a function of its compressibility and surface properties as well as the surface properties of the mating surfaces (Latham, 1996).

Interface resistance is application specific, because of its dependence on mating surface properties. R_{int} data measured in a given test facility will not necessarily be applicable to different installations of a TIM, because the surface roughness and flatness of the mating surfaces will likely differ in each application. Thus, the TIM resistance values reported by TIM manufacturers may not be applicable to an actual computer installation. Further, it is not clear that the use of a heat sink clip will provide uniform pressure on the interface material, and estimation of interface resistance based only on the conductivity of the TIM will likely result in an under prediction of R_{int} .

5 POSSIBLE THERMAL INTERFACE MATERIALS

Incropera & DeWitt (1996) lists two classes of materials that are well suited for the reduction of R_{int} - thermal greases and soft metals. In addition to these, commercially available TIMs have been developed that make use of phase change materials (PCM), thermally conductive elastomers, and thermally conductive adhesive tapes. Most thermal interface materials, except pure metals, are composed of a polymer matrix filled with thermally conductive particles (i.e. metals, ceramics) (Viswanath et al. 2000). Whatever the TIM used, CPU manufacturers recommend that it be sized and positioned on the heat sink baseplate to insure the entire processor die area is covered to compensate for heat sink package attach mis-alignment (Intel Corp, 2000).

Many TIMs available are not suitable for use for CPU cooling. Soft metals require unacceptably high contact pressures to conform to the mating surfaces. Tests at Penn State showed that 350 psi contact pressure is required to produce a readable impression of a U.S. 25¢ coin in an ingot of pure indium. Thermally conductive elastomer pads also require unacceptably high contact pressures (300-500 psi) to fill interstitial voids (deSorgo, 1996). Thermally conductive compounds (elastomer paste filled with thermally conductive particles) are an improvement on elastomer pads that can be applied in paste form and cured in-situ to conform to mating surface, allowing metal to metal contact and minimal thickness. This, however, only yields moderate thermal performance (Chromerics, 2001). Thermally conductive adhesive tapes have poor thermal performance (test data show only slightly better performance than a dry joint) (deSorgo, 1996).

Feasible TIM candidates for CPU cooling are categorized below with advantages and disadvantages. Commercially available candidates are listed in Table 1 with manufacturer published interface resistance data and the test contact pressure. The reader should note that performance data are published at various contact pressures. The highest performance (most expensive) TIM listed in Table 1 is Arctic Silver thermal grease with suspended silver conductive particles ($R_{int}= 0.0028$ K-in²/W at 12 psi). The next highest performance thermal grease (and more cost effective) is ShinEtsu G751 ($R_{int}= 0.0157$ K-in²/W at unspecified contact pressure). The highest performance phase change material listed is Thermax HF-60110-BT; a low-melting-temperature-alloy PCM concept ($R_{int} = 0.007$ K-in²/W @ 3-100 psi). However, Penn State tests have shown that the performance of the Thermax TIM significantly degraded under thermal cycling conditions. The performance of phase change materials varies by a factor of 4.5 (not including Thermax HF-60110-BT). The highest performance, phase change material reported is PowerStrate 60(AG) and 51 (AF) ($R_{int}= 0.022$ K-in²/W at 10 psi.).

Table 1: CPU Cooling Commercial TIM Candidates

	Manufact. Spec.			Notes
	R _{int} (K-in ² /W)	Pressure (psi)	Conductivity (W/m-K)	
Thermal Grease				
Arctic Silver	0.0028	12	>7.5	Silver particle filler
ShinEtsu G751	0.0157	NP	4.5	Silicon fluid w/ alumina powder filler
ShinEtsu G765	0.06	NP	2.89	Silicon fluid w/ alumina powder filler
ShinEtsu G750	0.0257	NP	3.5	Silicon fluid w/ alumina powder filler
Berquist TIC-7500	0.035	50	7.5	- -
Phase Change Material (PCM)				
Thermax HF-60110-BT	0.007	3-100	20	LMTA Concept (failed in thermal cycling tests)
PowerStrate 60 (AG)	0.022	10	3	Al foil substrate
PowerStrate 51 (AF)	0.022	10	3	Al foil substrate
Chomerics T725	0.03	50	0.7	No Substrate
Orcus inc. FSF 52	0.03	4.5	NP	No Substrate
Chomerics T454	0.04	50	0.6	No Substrate
Thermagon T-pcm 905c	0.049	10	0.7	No Substrate
Bergquist HiFlow	0.05	40*	1	No substrate (printable)
Bergquist 200U	0.04	10	1.6	No Substrate
Bergquist HiFlow 225-U	0.08	10	1	No Substrate
Bergquist HiFlow 225-UT	0.09	10	0.7	No Substrate (natural tack)
Chomerics T443	0.1	50	1	Fiberglass substrate
Thermally Conductive Elastomer				
Chomerics Therm-A-Form T642	NP	NP	1.2	Thermally conductive compound (elastomer matrix w/)

*: Assumed since based on ASTM E1530

NP: Not Published

5.1 High performance TIM categories.

THERMAL GREASE is composed of a thermally conductive filler dispersed in silicone or a hydrocarbon oil to form a paste (de Sorgo, 1996). Recent improvements have been made in the application of thermal greases by developing “printable” greases, which can be screen-printed onto a heat sink baseplate at a specified thickness. Thermal interface resistance values for several commercially available thermal grease products are presented in Table 1.

- Advantages: High thermal performance at small contact pressures. Silicon-based thermal greases are attractive on the basis of their ability to fill the interstices and eliminate the interstitial air with a material whose thermal conductivity is much higher than that of air (Incropera & DeWitt, 1996). For example, the thermal conductivity of ShinEtsu G751 Thermal Grease, $k = 4.5 \text{ W/m-K}$, which is 172 times greater than that of air at room temperature. As shown in Table 1, high performance thermal greases have higher effective thermal conductivity than other classes of TIMs (Viswanath et al., 2000). Interface pressure causes excess grease to flow from the interface and form a thin thermal joint and surfaces to contact. It is probable that all of the air pockets are not eliminated. They do not require curing (Viswanath et al., 2000). Intel recommends the use of thermal grease, and uses it in a thermal solution reference design. (Intel Corp, 2000).
- Disadvantages: Thermal greases are not manufacturing friendly in that they are messy and difficult to apply and remove. Excess grease that flows out of joint must be removed to prevent contamination and possible electrical shorts. Joint integrity must be maintained with mounting

hardware. Heat sink removal and re-installation requires cleaning the grease from the interface and a new application. Grease does not provide electrical insulation between contacting surfaces. Grease can be “pumped out” of the interface under thermal cycling because of the relative motion of the mating surfaces under thermal expansion and contractions. Grease joints can dry out with time, resulting in increased thermal resistance. Grease degradation rate is a strong function of operating temperature and number of thermal cycles (Viswanath et al., 2000).

PHASE CHANGE MATERIALS (PCMs) are made of a mixture of suspended particles of high thermal conductivity, such as fine particles of a metal oxide and a base material. Although phase change of the base material is implied, this is not the case. These materials do not actually change phase, but their viscosity diminishes so that they flow (Ollila, 1999). The base material can be a natural material such as fully refined paraffin, a polymer, a co-polymer, or a combination of all of these (Rauch, 2000). The base material is solid at low temperatures (i.e. room temperature), but behaves much like grease after reaching the “phase change” temperature (50-90°C for typical products available). Phase change materials can be supplied in the form of compound only, or in composite form in a specified thickness applied to a substrate. Thermal interface resistance values for several commercially available PCM products are given in Table 1.

- Advantages: High published thermal performance at moderate contact pressures. Material flows throughout the thermal joint to fill air gaps and provide minimum thickness by allowing the mating surfaces to come into contact. When the joint becomes thin, the viscosity prevents “pump out” from mechanical flexure of the interface surfaces (Viswanath et al., 2000). It handles easily (like a thermal pad) for installation.
- Disadvantages: Requires compressive force to bring materials together and cause the TIM to flow. The desired “phase change” property limits the choice of polymer and filler combinations; limiting the thermal performance of these materials (Viswanath et al., 2000). Published thermal performance is difficult to reproduce in independent test facilities, as found in work done at Penn State (Gwinn et al., 2002) and Showa Denko K.K. (Showa, 2000). Intel Corp. discourages the use of PCMs, because of low thermal performance (in contrast to Table 1) as determined by their thermal characterization tests. Intel also states that the strong adhesive bond formed by PCMs between the CPU package and heat sink may cause damage to the motherboard and CPU, because of high loads measured during their mechanical shock or drop tests (Intel Corp, 2000).

5.2 *New interface material technology*

This section assesses new concepts that have recently been advanced including the following technologies: corrugated copper substrate with thermal grease, gel TIM and low-melting-temperature-alloy (LMTA).

Corrugated copper substrate with thermal grease is described by Raiszadeh, 2001. This TIM construction has high lateral conductivity and distributes the heat in the lateral direction more evenly. This would be of value if the heat flux were non-uniform in the interface region. It is constructed of high performance thermal grease and a proprietary corrugated pure copper substrate. A thermal interface resistance of 0.021 K-in²/W was found for this new TIM construction at 50 psi contact pressure. Work is being done to find a corrugation geometry that will reduce the required contact pressure. This construction achieved a 40% lower interface resistance than measured for the best thermal grease alone. This does not seem to be a desirable TIM because its reliance on thermal grease.

A gel-like TIM has been developed by Thermoset of Lord Chemical Products (Wells et al., 1998) that has thermal performance similar to high thermal conductivity greases, but does not leak out of the interface. Test data was obtained on a “custom built apparatus” and no error analysis is presented. This TIM can be dispensed or printed onto the surface of a heat sink baseplate. While this product may eliminate the problem of the TIM leaking out of the interface, the problem of messy assembly and disassembly remains.

Low-Melting-Point-Alloy (LMTA) TIM is a solder alloy that has a low melting temperature. It can reduce thermal interface resistance of a metal-to-metal joint by a factor of 10 (Cook & Token,

1984). The LMTA is selected to melt before reaching the maximum CPU operating temperature at which point, it flows to fill the air gaps and significantly reduces contact resistance. The composition of the LMTA is chosen for a desired melting point. LMTA interface materials make use of the high conductivity of metals while eliminating the problems mentioned above associated with implementing soft metals. Since the alloy is liquid at the critical operating condition, low contact pressure is required to force the liquid LMTA into the interstitial voids. Another advantage is the ease in disassembly of the joint after cool down since many LMTAs do not adhere to surfaces unless they are clean and free of oxidation (Cook & Token, 1984). This is a very promising thermal interface solution. Lehmann & Davidson (2001) have shown that the use of LMTA decreases the thermal resistance of a bare interface of two oxidized aluminum surfaces having 22 μm flatness deviation by 50% in the solid phase and 95% in the liquid phase. Their results show that the liquid phase performance is competitive with phase change materials of Table 1 ($R_{\text{int}} = 0.03 \text{ in}^2\text{-K/W}$ with 3.4 psi contact pressure) (Penn State has developed a TIM consisting LMTA tinned on a 50 μm thick copper substrate. Tests show that the performance is comparable to that of high performance grease. Further detail is provided in (Gwinn & Webb, 2002).

6 MEASUREMENT OF THERMAL INTERFACE RESISTANCE

ASTM D-5470 describes a method to measure R_{int} . The apparatus consists of two copper blocks, across which heat is transferred. The TIM is inserted at the interface between the two blocks. Electric heat is applied at the bottom of one block. Two or more temperature sensors (i.e. thermocouples) are installed in each copper block. The surface temperature of each block is measured from the temperature gradient in each block.

The analysis should be performed at steady state because transient methods are not suitable for analyzing materials with temperature-sensitive thermal and mechanical properties such as phase change materials (PCMs) (Tzeng et al., 2000). Also, transient systems such as the Laser flash method and the “Fitch” calorimetry method require additional material properties including density and heat capacity that introduce additional sources of error.

The heat flux must accurately be measured to resolve interface resistance. Typical constructions use electric cartridge heaters installed in blocks of high thermal conductivity material. A finite distance below the heaters is required for the heat flux to become uniform. It is extremely important that the temperature sensors are installed in a *uniform* heat flux location and that guard heaters or thermal insulation be used to limit heat losses (Tzeng et al., 2000). It is suggested that non-uniform heat flux may be a problem with some testers. Further, the heat flux measurement must be calibrated to ensure accuracy and allow estimation of the error range.

Mating surface temperatures must be accurately measured to determine R_{int} . Factors effecting surface temperature measurement accuracy are (1) temperature sensor location uncertainty, (2) resolution of temperature sensor, (3) distortion of temperature gradient by temperature sensors, (4) uniformity of heat flux at the temperature sensor (Gwinn et al., 2002). Contact pressure must be applied and measured to represent the end use of a TIM in a thermal solution. A consistent and high-quality compression mechanism is needed to insure the repeatability and sensitivity of test (Tzeng et al. 2000).

Surface flatness and roughness affects the performance of a TIM. The results obtained in an “interface test apparatus” will be specific to the surface roughness and flatness of the block faces used in the apparatus (Chu et al., 1997). Surface cleanliness may also affect the repeatability of results. Further commentary on these factors is given below.

The cleaning method and test sequence is important because thermal interface materials such as thermal grease will contaminate the test surfaces. An unavoidable residue of different performance TIM left in minute surface roughness pores contaminates the test results of another TIM by combining the performance of the second TIM with that of the first. Data are presented showing a calibrated CPU internal diode temperature is reduced by more than 10% after applying and “removing” thermal grease because of thermal compound remaining in the microscopic valleys of the

interfacing surfaces (House, 2001). A cleaning method is recommended that includes a boiling bath to open the pores of the interface surfaces so that TIM residue can be removed (Arctic Silver LLC, 2001). One must take care that the temperature of the bath does not change the flatness of the heater block surfaces before the next test.

We emphasize that the results obtained in a “thermal interface tester” may not duplicate the installation and operating conditions of an actual CPU-heat sink installation (Eaton, 2001). For example, the surface roughness and flatness of the CPU baseplate and the heat sink may be different from that existing in the thermal tester. Further, the heat sink clip used in a computer application may not place uniform pressure on the interface. If the results are to be meaningfully interpreted for actual CPU-heat sink applications, tests should seek to duplicate the contact pressure, roughness and flatness of the CPU and heat sink interfaces. For this reason, the ability to swap out test blocks with different materials and surface finishes is desirable. However, this would require relatively expensive and time-consuming tests (Chu et al. 1997). There is currently no test method existing that can accurately define the thermal interface resistance of TIM in an application. Rank order comparisons are the most relevant tests that can be performed.

7 CONCLUSIONS

Current test methods do not reliably define the thermal resistance of a TIM in an actual CPU/heat sink application, because the thermal resistance is sensitive to flatness, roughness and contact pressure. Surface roughness, flatness, and contact pressure are critical factors in affecting the performance of a thermal interface material. There is a need to develop an acceptable cleaning method to remove TIM material from the surface pores of interfacing test surfaces. The highest performance interface materials available today are greases and phase change materials (metal and non-metal). The Penn State LMTA has performance competitive with the best thermal greases, but does not have their disadvantages.

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