Comparative Evaluation of Thermal Interface Materials for Improving the Thermal Contact between an Operating Computer Microprocessor and Its Heat Sink

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Testing of the relative effectiveness of various thermal interface materials for improving the thermal contact between the well-aligned mating surfaces of an operating computer microprocessor (with an integrated heat spreader) and its heat sink shows that carbon black paste, whether by itself or as a coating on aluminum or flexible graphite, is more effective than silver paste (Arctic Silver), but is comparable in effectiveness to aluminum paste (Shin-Etsu). The carbon black paste by itself is as effective as the Shin-Etsu paste coated aluminum. The Shin-Etsu paste is more effective than Arctic Silver, whether by itself or as a coating. The relative performance is mostly consistent with that assessed by measuring the thermal contact conductance. The correlation is particularly strong for conductance below 3×10^4 W/m^2·°C. The discrepancy is attributed to the difference in surface roughness between computer and guarded hot plate surfaces. In the case in which the mating surfaces of microprocessor and heat sink are not well aligned, Shin-Etsu and Arctic Silver are more effective than carbon black.

Key words: Thermal interface material, thermal contact, heat sink, microprocessor, computer, thermal resistance

INTRODUCTION

During computer operation, the microprocessor gets hot and the heat needs to be dissipated. Overheating is the most critical problem in the computer industry, as it limits further miniaturization, power, performance, and reliability. An important way of alleviating this problem is to improve the thermal contact between the microprocessor and the heat sink.[1–5] For this purpose, a material is placed at the interface between the heat sink and the microprocessor. This material is known as a thermal interface material.[6] In the case of a microprocessor with an integrated heat spreader, a thermal interface material is also needed for the interface between the die and the heat spreader.

Thermal interface materials can be in the form of a paste (commonly based on silicone),[7–13] flexible graphite,[14–17] phase change materials,[18–20] low melting alloys[21,22] and nanostructured carbon materials.[10–13,23–26] A thermal interface material is most commonly in the form of a paste, which is known as a thermal paste. It is necessary for the paste to conform to the surface topography of the adjoining surfaces, because no surface is perfectly smooth and the valleys in the surface topography trap air, which is a thermal insulator. Thus, it is important for the thermal paste to displace the air out of the interface. For this purpose, a high level of conformability is necessary for the thermal paste.

The performance of a thermal interface material depends on its conformability, thermal conductivity, and thickness. A high thermal conductivity and a small thickness are preferred. For two mating surfaces that are flat and well aligned (i.e., very parallel), the thickness of the thermal interface material is ideally such that the interface material is just enough to fill the valleys in the surface topography of the mating surfaces. However, the two surfaces may not be flat, i.e., there may be some curvature in one or both surfaces. Moreover, the two surfaces may not be well aligned, due to the way that the two surfaces are brought together. The more different are the areas of the two surfaces, the greater is the chance of misalignment during fastening. In the case where the surfaces are not flat or not well aligned, the gap between the surfaces can be substantial, at least locally. As a result, the thermal

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interface material needs to be relatively thick and is referred to as a gap-filling material.

Due to the relatively large thickness, a gap-filling material may be in the form of a solid sheet, such as "flexible graphite,"[14–17] which is a graphite sheet that is flexible and is resilient in the direction perpendicular to the sheet. The resiliency is made possible by the microstructure, which involves the mechanical interlocking of exfoliated graphite in the absence of a binder.[27] In general, a gap-filling material in the form of a solid sheet may be made more effective by coating both sides of the sheet with a thermal paste. On the other hand, a thermal paste by itself can be used as a gap-filling material, if its rheology allows it to maintain a large thickness. For this purpose, thixotropic behavior is preferred in the paste.

A comparative study of various thermal interface materials should be performed by using surfaces that are controlled in roughness, flatness, and alignment and by using a controlled pressure for holding the surfaces together. Such studies have been previously made by using copper surfaces and a heat flux tester that used either the guarded hot plate method (a steady-state method) or the laser flash method (a transient method).[9–14] In contrast, this paper provides a comparative study of various thermal interface materials, while these materials are used at the interface between a microprocessor and a heat sink of a computer under operation.

The roughness, flatness, and degree of alignment of various combinations of microprocessor and heat sink differ. Moreover, the method and force of fastening the heat sink to the microprocessor differ from computer to computer. Therefore, the results of a comparative study of various thermal interface materials using a computer only apply to that particular computer. Therefore, from a scientific point of view, the results of testing using a computer are less meaningful than those obtained using a heat flux tester. Nevertheless, from an application point of view, testing using a computer is meaningful. Therefore, this paper provides the results of a comparative study of various thermal interface materials by using two computers. In other words, two sets of data are provided in this paper—one for each computer. The two computers differ mainly in the degree of parallelism of the two surfaces involved.

Prior work on testing using computers has been limited to a very small number of types of thermal interface materials in any given study. Moreover, it is unpublished, other than some reports on the internet.

The objectives of this study are (1) to provide a comparative study of thermal interface materials (including thermal pastes and solid sheets that have been coated with a thermal paste on both sides of the sheet) while the materials are used in computers under operation, (2) to study how the relative performance of various thermal interface materials depends on the computer, (3) to compare the results of the comparative study obtained by computer testing with results obtained by heat flux testing, and (4) to provide recommendations concerning the choice of thermal interface materials for various application conditions.

EXPERIMENTAL METHODS

Two personal computers, labeled A and B, were used for testing various thermal interface materials. Computer A had an Intel (Santa Clara, CA) Pentium III flip-chip pin-grid array (FC-PGA) microprocessor (processor core frequency 866 MHz, system bus frequency 133 MHz, L2 cache size 256 Kbytes, core voltage 1.7 V; silicon in a ceramic package of size 1.1×0.9 cm) and its associated heat sink (5.5×5.5 cm, aluminum with fan), as illustrated in Fig. 1. The pins of the pin-grid array (PGA370) were made of Au/Ni plated Kovar. The microprocessor and heat sink were mechanically fastened together by using clips. Due to the large difference in area between the microprocessor and the heat sink, the degree of alignment between the microprocessor and heat sink surfaces could not be well controlled, in spite of the clips, which exerted pressure directly over the center of the die.

Computer B had an Intel Pentium IV flip-chip pin-grid array 2 (FC-PGA2) microprocessor (processor core frequency 1.7 GHz, system bus frequency 400 MHz, L2 cache size 256 Kbytes, core voltage 1.75 V) in a 478-pin package, which was integrated with a heat spreader (area = 960 mm^2) made of nickel-coated copper. The pins, which were made of Au/Ni plated Kovar, were inserted in a socket that was made of a fiber-reinforced polymer (resin). The thermal interface material under evaluation was placed at the interface between the heat spreader (30×30 mm) and an aluminum heat sink (area of 88×64 mm), as illustrated in Fig. 2. The areas of the mating surfaces were comparable in Figs. 2 and 1. This similarity in area, together with a sturdier fastening mechanism, caused the mating surfaces to be better aligned in Fig. 2 than in Fig. 1.

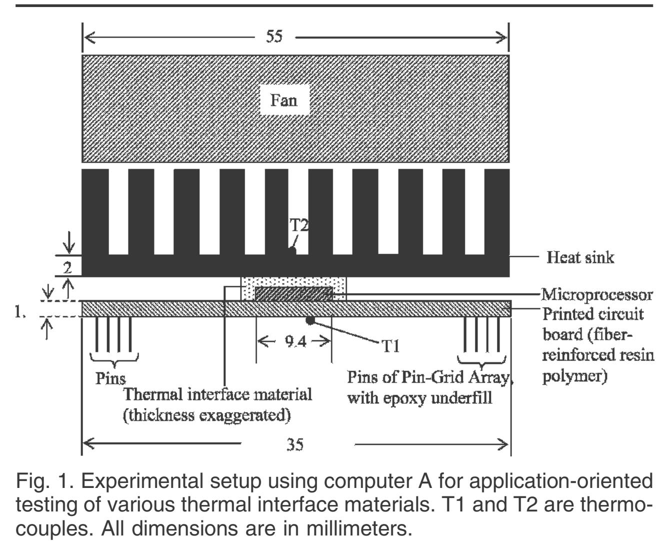

Fig. 1. Experimental setup using computer A for application-oriented testing of various thermal interface materials. T1 and T2 are thermocouples. All dimensions are in millimeters.

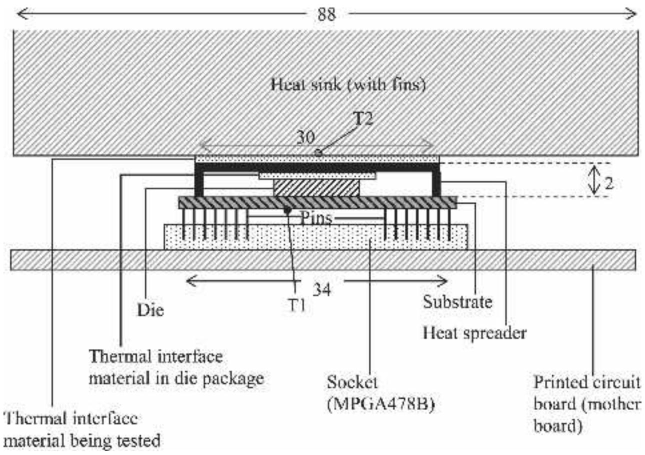

Fig. 2. Experimental setup using computer B for application-oriented testing of various thermal interface materials. T1 and T2 are thermocouples. All dimensions are in millimeters.

A microprocessor die consists of two areas, namely, the processor core and the cache. While the entire die generates heat, the active area of heat dissipation is essentially the processor core area. Figures 3 and 4 illustrate the relative areas of core and cache on a die for computers A and B, respectively, as estimated by examining a photograph of each of the dies.[28,29] The processor core area occupies approximately 63% and 80% of the die area for computers A and B, respectively. Table I shows that computer B has 50% more transistors, 180% more power, and 35% more power density than computer A. This means that the demand for an effective thermal interface material is greater for computer B than computer A.

For both computers A and B, the maximum temperature difference across the interface between the microprocessor and heat sink surfaces, as obtained by two thermocouples (type T), was measured as a function of time from the start of operation of the microprocessor. The microprocessor temperature increased with time, causing the temperature difference between the two thermocouples to change with time. The temperature difference at time = 5 min. was used for the comparative study of the performance of gap-filling materials. For the same computer, the smaller is the temperature difference, the less is the thermal resistance and the better is the performance. Due to the fact that the Pentium IV die (computer B) got much warmer than the Pentium III die (computer A), comparison of the temperature difference between the two computers is not meaningful.

The thermal contact conductance between two 1 in. × 1 in. (25 mm × 25 mm) copper blocks with thermal interface materials between them was measured using the guarded hot plate method, which is a steady-state method of heat flux measurement (ASTM method D5470). Copper surfaces of area 1 in. × 1 in. (25 mm × 25 mm) were used to sandwich a thermal interface material. The pressure in the direction perpendicular to the plane of

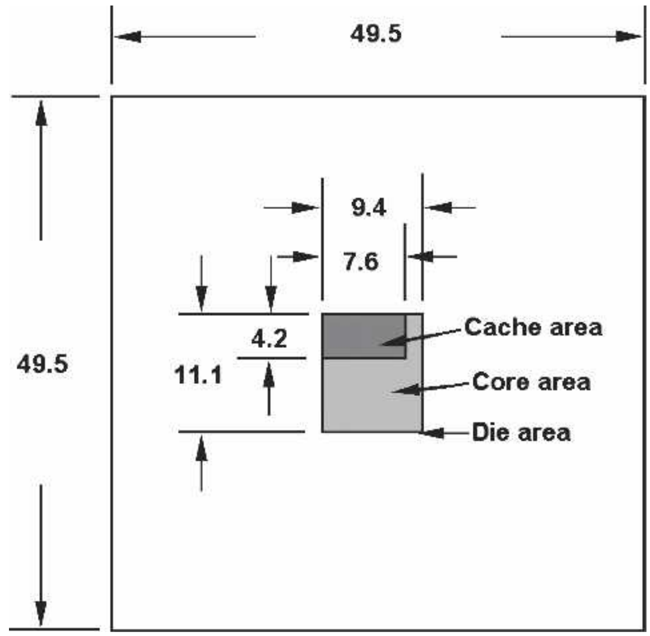

Fig. 3. Functional die layout for computer A. All dimensions are in millimeters and were taken from a photograph of the die.

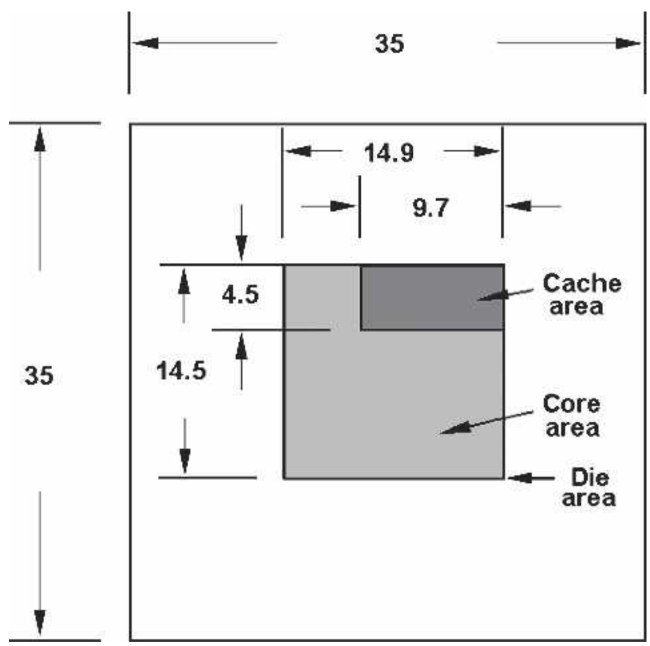

Fig. 4. Functional die layout for computer B. All dimensions are in millimeters and were taken from a photograph of the die.

the thermal interface was controlled by using a hydraulic press at pressures of 0.46 MPa, 0.69 MPa, and 0.92 MPa (i.e., 67 psi, 100 psi, and 133 psi, respectively). The pressure of 0.46 MPa is comparable to or above typical pressures provided by clips for affixing heat spreaders or heat sinks in computers. For details of the method, refer to Ref. 13.

The surface roughness of the computer B heat sink, computer B microprocessor package (integrated heat spreader), and each of the two copper surfaces sandwiching the thermal interface material during contact conductance measurement was

Table I. Die Layout and Power

	Number of Transistors (Million)	Power (W)	Power Density (W/cm^2)	Die Size (cm^2)	Core Size (cm^2)	Cache Size (cm^2)
Computer A[a]	28.1	22.9	21.9	1.046	0.726	0.32
Computer B[b]	42	64	29.6	2.16	1.724[c]	0.436[c]

[a]Ref. 28.
[b]Ref. 31.
[c]Based on measurement on the photograph of the die.[29]

measured by using a surface roughness tester (Surftest SJ-201P, Mitutoyo America Corp., Aurora, IL). The tester is a profilometer. The stylus tip material is diamond. The stylus tip radius is 5 μm. The measuring force is 4 mN. The measuring speed is 0.02 in/s (0.5 mm/s).

The thermal interface materials tested in this work are listed in Table II, where FG is the flexible graphite of thickness 0.13 mm and Al is aluminum foil (1145) of thickness 0.007 mm. The aluminum foil was obtained from All-foils, Inc. (Brooklyn Heights, OH). In addition, materials in the form of pastes were evaluated; they are carbon black (1.25 vol.%), polyethylene-glycol (with 3 vol.% dissolved ethyl cellulose) paste,[10,11] Arctic Silver 5 (polyol ester filled with micronized silver particles, together with smaller quantities of submicron particles of boron nitride, zinc oxide, and aluminum oxide, such that all the conductive fillers together make up 88 wt.% of the paste, from Arctic Silver Inc., Visalia, CA), and Shin-Etsu X-23–7762 (aluminum particle filled silicone from Shin-Etsu MicroSi, Inc., Phoenix, AZ). Flexible graphite and aluminum foil that had been coated with one of the pastes on both sides were also included in the comparative study.

The specific heat of each type of thermal interface material was measured using a differential scanning calorimeter (DSC 7, Perkin-Elmer Corp., Shelton, CT). A sapphire disc (Specific heat kit, 02190136, Perkin-Elmer Corp.) was used as a standard specimen and the specific heat of the paste specimen being tested was calculated using the equation

$$C_{ps} = (M_r/M_s)(H/h)C_{pr} \qquad (1)$$

where C_{ps} is the specific heat of the specimen being tested, C_{pr} is the specific heat of standard specimen, M_r is the mass of the standard specimen, M_s is the mass of the paste specimen being tested, H is the difference in heat flow between the paste specimen and the baseline, and h is the difference in heat flow between the standard specimen and the baseline. Three specimens of each type of thermal interface material were tested.

Table II. Surface Roughness (μm)

Computer B heat sink (against grains)	21.1 ± 0.7
Computer B heat sink (with grains)	12.0 ± 0.5
Computer B microprocessor package	8.3 ± 0.4
Copper block (top)	18.8 ± 0.8
Copper block (bottom)	14.3 ± 0.3

RESULTS AND DISCUSSION

Figure 5 shows the variation of the specific heat with temperature from 30°C to 74°C for the three thermal interface materials. The high volume fraction (96%) organic vehicle (polyethyleneglycol) in the carbon black paste explains why the specific heat is higher for this paste than the other two pastes, which contain a much lower volume fraction of the organic vehicle. A high value of the specific heat is attractive for absorbing the heat evolved by the heat sink. This absorption provides an additional mechanism of heat transfer.

Table II shows that the surface of the computer B heat sink is quite rough, such that the roughness is greater in the direction against the grains than in the direction with the grains. The surface of the computer B microprocessor package is relatively smooth. The two copper blocks used in the contact conductance measurement are rougher than the computer B heat sink in the direction with the grains and are smoother than the computer B heat sink in the direction against the grains. The roughness of the two copper blocks is close to 15 μm, which is the size of the abrasive particles used in the final stage of mechanical polishing of these surfaces.

Figure 6 shows the variation with time of the measured temperatures at the microprocessor and heat sink, as recorded by the two thermocouples in

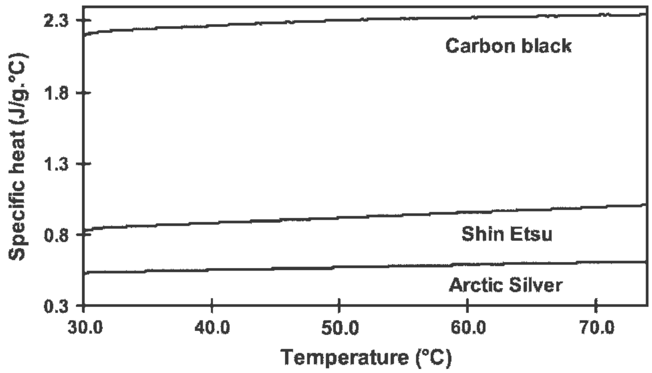

Fig. 5. Variation of the specific heat with temperature for each of three thermal pastes.

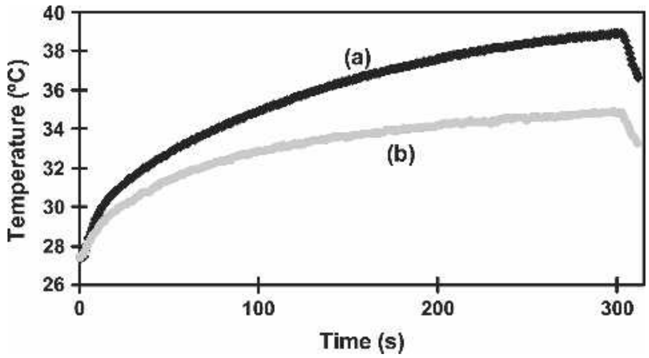

Fig. 6. Temperature versus time of computer operation (up to 5 min.) for computer A with carbon black paste as the thermal interface material: (a) microprocessor temperature and (b) heat sink temperature.

Fig. 1 for computer A with carbon black paste as the thermal interface material. The microprocessor was allowed to run for 5 min., after which it was turned off. Both temperatures increased monotonically with time, such that the microprocessor temperature was above the heat sink temperature, as expected. The maximum temperatures of the microprocessor and heat sink were 38.9°C and 34.8°C, respectively.

Figure 7 shows the corresponding results for computer B (Fig. 2), also with carbon black paste as the thermal interface material. The maximum temperatures of the microprocessor and heat sink were 52.8°C and 49.5°C respectively. At the same time of computer operation, computer B got hotter than computer A, as expected.

Since the generated power of computer B is almost three times as much as that of computer A, the demand on the thermal interface material is higher for computer B than computer A. An increase in performance is characterized by a decrease in the temperature difference between the microprocessor and the heat sink. The performance of the carbon black paste increases from computer A to computer B, whereas that for Arctic Silver decreases from computer A to computer B, as shown in Table III. Furthermore, the Arctic Silver paste outperforms the carbon black paste for computer A, but the carbon black paste outperforms the Arctic Silver paste for computer B, as also shown in Table III.

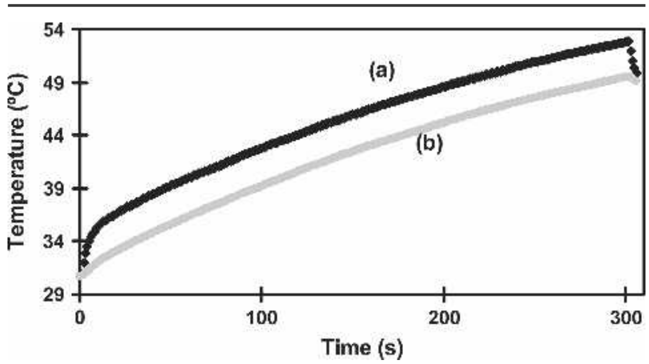

Fig. 7. Temperature versus time of computer operation (up to 5 min.) for computer B with carbon black paste as the thermal interface material: (a) microprocessor temperature and (b) heat sink temperature.

The bulk thermal conductivity within a thermal interface material is to be distinguished from the thermal contact conductance, which describes the effectiveness of the thermal interface material in improving a thermal contact. The thermal conductivity values of the carbon black, Arctic Silver, and Shin Etsu pastes are shown in Table IV. As expected, the carbon black paste is much lower in thermal conductivity than the other two pastes. In spite of its low thermal conductivity, the performance of the carbon black paste increases from computer A (a less thermally demanding situation) to computer B (a more thermally demanding situation) and the carbon black paste outperforms the Arctic Silver paste in computer B. Additionally, the carbon black paste performs similarly compared to the Shin Etsu paste. Moreover, in spite of its high thermal conductivity, the performance of the Arctic Silver paste decreases from computer A to computer B. These observations imply that, due to the influence by other factors (to be discussed) on the performance, the thermal conductivity within the thermal interface material and the power density of the computer are not the main factors that govern the performance of a thermal interface material.

Additional support of the low level of influence of the thermal conductivity within the thermal interface material on the performance is given by the observation that, for computer B, the use of carbon black alone and the use of Shin-Etsu in combination of aluminum foil give a similar performance, as shown by both computer testing and thermal contact conductance measurement (Table III), though the latter is obviously higher in thermal conductivity.

The alignment between the surfaces of the heat sink and the die is poor in computer A, due to the clipping method and a large difference in area between the mating surfaces. The poor alignment for computer A compared to computer B makes the thermal conductivity of the thermal interface material more important for computer A than computer B. Thus, the observations mentioned above regarding the heat transfer can be explained in terms of the poor alignment for computer A compared to computer B.

When the mating surfaces are misaligned, the ability of the interface material to fill a substantial gap will be important. The resulting high bondline thickness will increase the demand for a high thermal conductivity within the thermal interface material, as in the case of computer A. However, when the mating surfaces are well aligned, the thermal conductivity within the thermal interface material may play only a minor role in affecting the performance, as in the case of computer B.

As shown in Table III, the best thermal interface materials (i.e., the ones that give the smallest temperature difference) for computer A are Shin-Etsu, Arctic Silver, and A1 foil coated with Arctic Silver, the second best materials for computer A are A1 foil coated with carbon black or Shin-Etsu and flexible

Table III. Temperature Difference at 5 Min. of Computer Operation and Thermal Contact Conductance for Various Thermal Interface Materials; FG = Flexible Graphite

Thermal Interface Material	Temperature Difference (°C) Computer A	Temperature Difference (°C) Computer B	Thermal Contact Conductance (10^4 W/m^2·°C)*
Carbon black	4.54 ± 0.28	3.32 ± 0.16	4.85 ± 0.13
Arctic silver	3.13 ± 0.11	4.30 ± 0.39	6.31 ± 0.39
Shin-etsu	2.93 ± 0.11	3.07 ± 0.53	7.41 ± 0.47
FG	5.76 ± 0.14	6.55 ± 0.43	1.40 ± 0.09
FG + carbon black	3.77 ± 0.10	3.67 ± 0.27	2.93 ± 0.09
FG + arctic silver	3.62 ± 0.19	6.01 ± 0.55	1.74 ± 0.15
FG + Shin-Etsu	4.21 ± 0.10	4.04 ± 0.58	2.63 ± 0.18
Al	11.18 ± 0.51	6.63 ± 0.48	1.32 ± 0.06
Al + carbon black	3.91 ± 0.18	3.92 ± 0.24	3.67 ± 0.31
Al + arctic silver	2.90 ± 0.05	5.06 ± 0.44	2.46 ± 0.18
Al + shin-etsu	3.66 ± 0.53	3.27 ± 0.35	4.59 ± 0.48

*Measured using the guarded hot plate method, with the thermal interface material between copper surfaces squeezed together at a pressure of 0.46 MPa (50 psi).

Table IV. Thermal Properties of Interface Materials

	Density (g/cm^3)	Thermal Conductivity (W/m K)	Specific Heat (J/g·°C) 35 °C	Specific Heat (J/g·°C) 45 °C	Specific Heat (J/g·°C) 55 °C
Shin Etsu	2.6[a]	6.0[a]	0.86 ± 0.04	0.89 ± 0.03	0.93 ± 0.01
Arctic Silver	4.05–4.15[b]	8.4–9.0[c]	0.54 ± 0.03	0.56 ± 0.02	0.58 ± 0.01
Carbon black	1.109	0.19–0.20[d]	2.24 ± 0.03	2.29 ± 0.03	2.32 ± 0.04

[a]Ref. 32.
[b]Ref. 33.
[c]Estimated using previous generation products Arctic Silver II and 3.[34,35]
[d]Calculated using the geometric rule of mixtures[36] with the components being (1) carbon black (thermal conductivity 24 W/m·K, according to the website of Reade Advanced Materials (East Providence, RI[37])), (2) ethyl cellulose (thermal conductivity 0.159–0.29 W/m·K[38]) and (3) polyethylene glycol (molecular weight 400, thermal conductivity 0.183–0.185 W/m·K, as calculated based on the equation for the thermal conductivity of the homologous series of glycols[39]).

graphite coated with carbon black or Arctic Silver, and the third best materials for computer A are flexible graphite coated with Shin-Etsu and carbon black by itself. The worst material for computer A is the uncoated aluminum material, which is outstandingly bad. The poor performance is due to the small thickness (7 μm) of the aluminum foil and the poor alignment of the mating surfaces in computer A. The superiority of Arctic Silver and Shin-Etsu over carbon black (each by itself) for computer A reflects the poor alignment of the mating surfaces. The misalignment results in regions of thick gap at the interface and thus favors a thermal interface material that has a high thermal conductivity. Silver and aluminum are more conductive than carbon.

For computer B, the best materials are carbon black by itself, Shin-Etsu by itself, and Al coated with Shin-Etsu, the second best materials are flexible graphite coated with carbon black or Shin-Etsu and Al coated with carbon black, the third best materials are Arctic Silver by itself and aluminum coated with Arctic Silver. The superiority of carbon black and Shin-Etsu over Arctic Silver (each by itself) for computer B reflects the good alignment and smoothness (Table II) of the mating surfaces and the consequent thin gap at the interface. The thin gap favors a thermal interface material that exhibits high conformability, in spite of a moderate thermal conductivity.

The difference in results between computers A and B means that the most effective thermal interface material depends strongly on the combination of roughness, flatness, and parallelism of the surfaces that sandwich the thermal interface material. It is significant that, for computer B, carbon black by itself is more effective than Arctic silver by itself, carbon black coated aluminum is more effective than Arctic Silver coated aluminum, and carbon black coated flexible graphite is more effective than Arctic Silver or Shin-Etsu coated flexible graphite. Furthermore, for computer B, Shin-Etsu is more effective than Arctic Silver, whether by itself or as a coating. This is attributed to the greater fluidity of Shin-Etsu compared to Arctic Silver and the resulting higher conformability for Shin-Etsu. However, for computer A, Arctic Silver is more effective than Shin-Etsu, whether by itself or as a coating, due to the poor alignment of the mating surfaces in computer A and the high thermal conductivity of silver.

In computer A, the use of flexible graphite in combination with a thermal paste gives improved performance relative to the use of the thermal paste alone when the thermal paste is the carbon black paste, but diminishes the performance when the paste is either the Shin Etsu paste or the Arctic Silver paste (Table III). This observation reflects the gap-filling ability of flexible graphite and the relatively poor gap-filling ability of the carbon black paste when it is used alone. Due to the lower viscosity of the carbon black paste compared by the Shin Etsu or Arctic Silver pastes, the gap-filling ability is superior for the Shin Etsu and Arctic Silver pastes compared to the carbon black paste.

Table III shows results on the thermal contact conductance obtained using copper mating surfaces of roughness shown in Table II. A higher contact conductance should correspond to a lower temperature difference. Due to the poor alignment of the mating surfaces in computer A, the results of computer A do not correlate well with the thermal contact conductance results obtained by using the guarded hot plate method, as also shown in Fig. 8a. However, the results of computer B do, as also shown in Fig. 8b. Comparison of the computer B results and the guarded hot plate results in Table III shows that a low value of the temperature difference correlates with a high value of the contact conductance in most cases. The main discrepancy pertains to the results for carbon black by itself and for Arctic Silver by itself. The temperature difference is lower for carbon black by itself than for Arctic Silver by itself, but the contact conductance is lower for carbon black by itself than for Arctic Silver by itself. This discrepancy is attributed to the greater smoothness of the computer B microprocessor package than the copper surfaces used in the contact conductance measurement (Table II). The carbon black paste is more fluidic than Arctic Silver, so it has greater conformability, thus performing particularly well for smoother surfaces.[10] The computer B heat sink surface is rough, so conformability to the surface topography of the heat sink can be attained for both carbon black paste and Arctic Silver. However, conformability to the computer B microprocessor surface is attained to a greater degree by the carbon black paste than Arctic Silver. The superiority of carbon black by itself to Arctic Silver by itself for computer B is consistent with prior work involving measurement of the heat flux across copper mating surfaces that are very smooth (roughness = 0.05 μm).[10]

Figure 8 shows the extent of correlation between the results of computer testing and those of thermal contact conductance measurement, as based on the data of Table III. The data point correspondingly to the uncoated aluminum foil in relation to computer A is not included in the correlation plot, because this data point is associated with exceptionally poor performance. The correlation is clear for computer B (Fig. 8b), but is almost absent for computer A (Fig. 8a). The near absence of correlation for computer A is consistent with the poor alignment of the mating surfaces in computer A. The correlation for computer B is actually limited to the regime with conductance below 3×10^4 W/m^2·°C (i.e., temperature difference above 4°C). In this regime, a higher conductance is associated with a lower value of the temperature difference, as expected. In the remaining regime, the temperature difference is essentially independent of the conductance. For example, thermal contact conductance measurement shows that Shin-Etsu by itself is more effective than carbon black by itself, but the values of the temperature difference obtained by computer testing are close for these two cases (Table III). This behavior is due to the fact that the thermocouples used in computer testing are separated by not only the thermal interface material, but also the microprocessor package, the substrate, and the socket (Fig. 2). The separation makes the measured temperature difference substantial even though the actual temperature difference across the mating surfaces may be small. Thus, the computer testing method is not suitable for evaluating high-performance thermal interface materials.

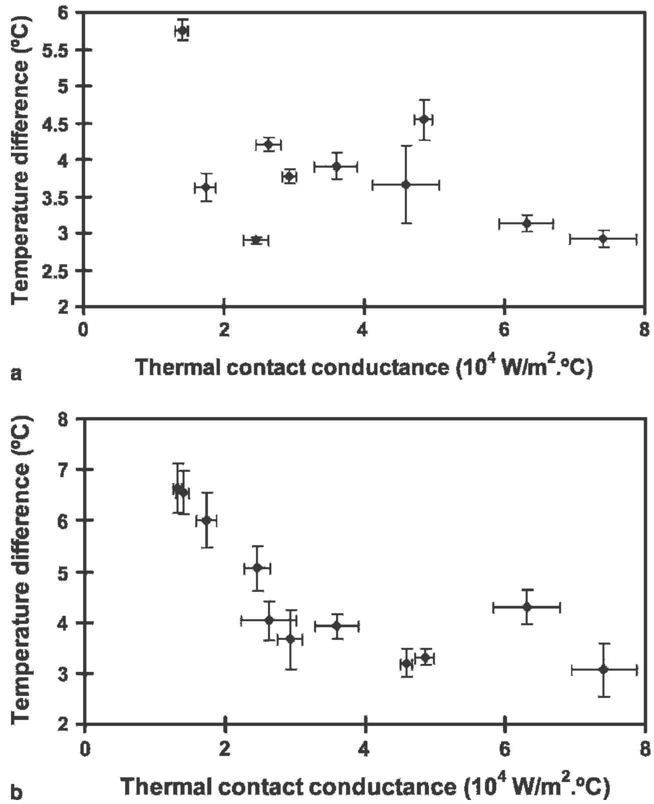

Fig. 8. Temperature difference in computer testing versus thermal contact conductance in guarded hot plate measurement: (a) computer A and (b) computer B.

Our observation that results of thermal interface material evaluation from computer testing and heat flux measurement (e.g., guarded hot plate method) are not necessarily consistent with one another reflects the nonideal nature of the heat sink (or heat spreader) setup. The nonideal nature relates to the flatness, roughness, and alignment being not as controlled as those in the heat flux measurement. The possible inconsistency has been previously noted.[30] In addition, our observation that results from testing using different computers are not necessarily consistent with one another reflects the variability of the heat sink (or heat spreader) setup among computers. The variability pertains to the flatness, roughness, alignment, and pressure.

A true assessment of the effectiveness of a thermal interface material is the measurement of the thermal contact conductance. The additional testing of the material in a specific application environment, such as a computer, will provide further insight into its capacity to perform in that specific environment.

CONCLUSIONS

The relative performance of various thermal interface materials depends on the degree of alignment of the mating surfaces. The degree varies from computer to computer. For a computer that has surfaces that are well aligned, the relative performance assessed by computer testing is in most cases consistent with that assessed by thermal contact conductance testing using the guarded hot plate method. Discrepancies are due to the difference in surface roughness between the computer surfaces and the guarded hot plate surfaces. Correlation of the results of computer testing and the guarded hot plate method is particularly strong for conductance below 3×10^4 W/m^2·°C.

For use as a thermal interface material between a microprocessor (with an integrated heat spreader) and a heat sink that are well aligned, the carbon black thermal paste by itself is more effective than Arctic Silver 5 by itself. Carbon black paste coated flexible graphite is also more effective than Arctic Silver 5 coated flexible graphite or Shin-Etsu coated flexible graphite. Carbon black paste coated aluminum is more effective than the Arctic Silver 5 coated aluminum, but is less effective than the Shin-Etsu coated aluminum. The carbon black paste by itself is as effective as the Shin-Etsu coated aluminum. Moreover, Shin-Etsu is more effective than Arctic Silver 5, whether by itself or as a coating.

For use as a thermal interface material between microprocessor and heat sink mating surfaces that are not well aligned, Shin-Etsu and Arctic Silver 5 are more effective than carbon black. In this case, the relative performance of the various thermal interface materials is not consistent with the thermal contact conductance results obtained by using the guarded hot plate method.

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