EXPERIMENTAL STUDIES ON SELECTED THERMAL INTERFACE MATERIALS

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The current work is an experimental study, with the primary goal of investigating and exploring ways to improve thermal contact conductance through a detailed examination and analysis of metallic contacts and discovering opportunities for enhancement, increased efficiency, and thus heat dissipation using thermal interface materials. The steady-state experiments have been carried out on a simple and calibrated experimental set-up. A comprehensive investigation was conducted to assess the thermal performance of Copper-Aluminum contacts for the selected range of contact pressures and temperatures to suit the electronic industry's distinctive characteristics and technical requirements. As a thermal interface material, Graphene paste has been tested under various combinations of interface pressure and heating circumstances against the bare metallic contacts. Error analysis has also been performed for the current experimental investigation. It has been demonstrated that using Graphene paste as a thermal interface material thermal contact conductance is improve, significantly enhancing heat dissipation. The results of Thermal contact conductance for graphene paste have been compared with the same for silicon grease from literature. The present results thus demonstrate the application and suitability of the selected thermal interface material in the specified range of heating and contact pressure conditions in the context of particularly thermal management applications.

Key words*: Thermal contact conductance; Thermal Interface materials; Graphene paste; Thermal management; Electronic industry*

1. Introduction

Thermal Interface materials (TIM) are widely used in LED lighting, solar energy, microelectronics, electrical engineering, aerospace, defense and many other fields to improve the rate of heat dissipation through interfaces [1]. There are many interfaces in the electronic packaging through which the heat produced by the electronic device is dispersed to the surrounding, particularly chip- substrate, mold compound-PCB, and PCB-heat sink. In the computer Industry, over-heating has been singled out to be the crucial issue. It is reported in a study by US Air Force Avionics Integrity Program that over-heating was the main issue for 55 % of the failures in electronic devices [2]. In 2004, the maximum power dissipation and heat flux from high-performance microprocessor chips were anticipated to reach approximately 360 W and 190 W/cm^2, respectively, by 2020, as per the International Electronics Manufacturing Initiative (iNEMI) technology roadmap [3]. Further, in 2007, it was reported that several electronic industries had trouble to remove heat-flux that was too high (about 300 W/cm^2) to keep the temperature below 85 °C [4]. Presently, numerous high-performance electronic gadgets generate far more heat than was anticipated under the iNEMI roadmap. More than half of all IC failures, according to reports, are caused by heat issues [5]. Thus, effective heat dissipation may be considered to be the key factor in the path of efficiency, miniaturization, and the reliability of electronic components due to the increase in power-density of the electronic devices. Hence, it is a crucial factor in the development of electronics and information systems.

The thermal contact conductance is an essential parameter that relates the heat transfer across the interface of a heat source and a heat sink as illustrated in Fig. 1. Thermal Interface materials tend to improve the thermal contact conductance with a material of better thermal conductivity replacing the interstitial gas present. Consequently, it reduces the contraction of the heat flow lines passing through the microscopic asperities, as shown in Fig. 2. TCC is considered to be a very crucial performance parameter for the analysis and selection of a better Thermal Interface Material.

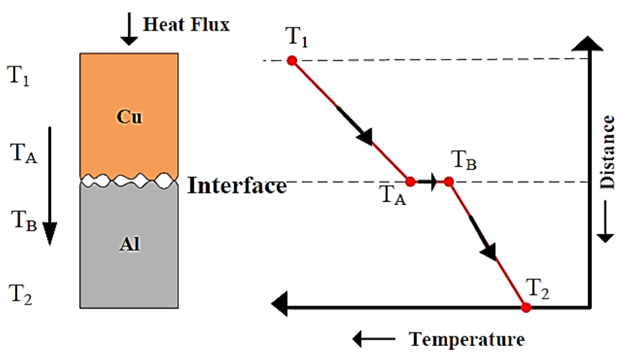

Figure 1. Concept of Interfacial heat transfer

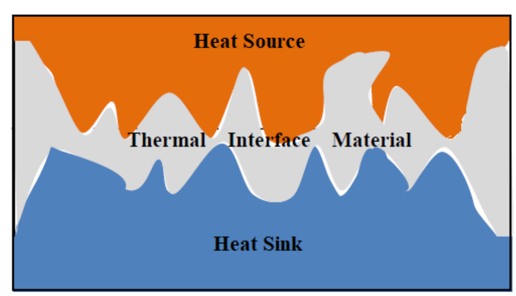

Figure 2. Heat source-sink interface with Thermal Interface Material

Therefore, a lot of work is currently in progress on various TIMs. For instance, Yu et al. [6] carried out experimental work on silver paste and silver nanoparticles before and after thermal cycling. It has been found that silver paste and silver Nano particles are good TIM with low thermal resistance. Devananda and Prabhu [7] evaluated the performance of TIM and load on heat transfer at the junction of cylindrical copper specimens. The TIMs used were pure silicon grease, and multi-walled carbon nanotubes permeated with silicon grease with L/D ratios of 1 and

5. Swamy and Satyanarayan [8] did a comprehensive investigation into the thermal performance of conventional and improved TIMs. They also looked at various methods for measuring TIM performance. Further, Naghibi et al. [9] investigated a non-curing thermal paste based on mineral oil and filled with a blend of graphene and few-layer graphene flake. The thermal paste's performance was compared to that of commercialized thermal pastes. Non-curing graphene TIMs were found to be superior to the finest available commercial pastes. Sudhindra et al. [10] investigated the experimental thermal contact resistance of non-curing graphene thermal interface materials with varied degrees of roughness on their surfaces. The thermal contact resistance was found to be non-monotonically dependent on graphene loading, with a minimum loading percentage of 15 wt% for the tested combination of graphene fillers. However, graphene based TIMs were reviewed extensively by Lewis et al. [11] in order to manage heat in the newest technological devices. Graphene has been found out to be a viable filler material capable of meeting the needs of high-speed and high-power devices. Therefore in 2021, Lewis [12] worked on few layers graphene (FLG) as thermal interface materials with varying concentration and varying heat dissipation rates. They observed that using FLG concentration as 7.3 vol.% resulted in a reduction in operating temperature up to 85 °C.

As a result, the literature has identified a number of advantages and disadvantages for distinct TIMs. Thermal pastes, for instance, are discovered to migrate away from an interface over time. They are sticky and challenging to apply and remove due to their high viscosity. In addition, they have trouble with phase separation, pump-out, and dry-out, which restricts their use as a useful TIM [8]. Leakage is a significant drawback for PCM in terms of practical application. Foils and pads must also be installed with extreme caution to prevent misalignment. However, thermal pastes are frequently utilized in electronic cooling applications to improve the TCC at the junctions of semiconductor component-heat spreader and heat spreader-heat sink. It has been recommended in the literatures that research should be focused on developing a low-cost, scalable, and simple process for producing high-performing TIM [13]. Carbon-based materials provide great potential to be used as thermal interface material for efficient heat dissipation between the source and sink in various applications. Specifically, graphene displays the highest thermal conductivity under standard conditions [13]. Hence, it is one of the best materials for forming a thermal interface material. It is utilized in several electronic systems in high-temperature level of working conditions. Due to the exceptional thermal properties of Graphene, composites are formed by polymer matrices and graphene fillers to be applied as Thermal interface materials [14]. From the literature, it has been identified that carbon base materials are best suited for the cooling of electronic devices due to their excellent thermodynamic properties. However, few studies have been found on graphene paste as thermal interface material in the present contact pressure and temperature range.

Therefore, in this work, Graphene paste with constant thickness has been tested as thermal interface material between the copper and aluminum specimens as source-sink pair with various conditions of heat flux and contact pressures. The input heat flux and the contact pressure are varied in order to meet the actual operating conditions of the electronic devices. Further, the results have been compared with the commercially available silicon paste, presently the most commonly used TIM for electronic devices. Thus, the present work may be significant for electronic cooling applications.

2. Experimentation

2.1. Experimental Set-up

The present experimental setup is essentially a heat flow apparatus to test the thermal interstitial materials of constant thickness across copper-aluminum pair under varying loading and heat flux conditions. The experimental setup consists of the Cooling arrangement, heating arrangement, Loading mechanism, Heating control, Insulations and Specimens. The heating arrangement comprises a heating block with heater rods, voltmeter, ammeter and dimmer stat for providing constant and controlled heat flux to the heating block. Heating block is essentially a cylindrical copper block of 50 mm length and 25 mm diameter having two vertical blind holes of diameter 6.5 mm along the length to insert heating rods of 150 W each. The heating block is insulated from the top surface by an insulating pad of glass wool. For cooling arrangement, chilled water from the chiller is circulated through the internal path of the copper cooling block. The loading system is a manual scissor car jack connected to a load cell, to quantify the applied load. The temperature measurement system includes a digital temperature indicator and thermocouples. Alumel-Chromel (K-type) thermocouples of very fine diameter (~0.5mm) are used to record the axial temperature data. Glass wool Insulations are provided to reduce axial and radial heat losses. Essentially, 1-D heat flow has been tried to be achieved through the heat flow column with negligible radial heat losses. The specimens are carefully selected with L/D ratio greater than one to support axial heat flow. A pictorial view of the experimental setup is demonstrated in Fig. 3.

2.2. Specimens

In this particular experiment, a combination of Copper and Aluminum was utilized to simulate the heat spreader and heat sink contact, as it is in electronic devices. The test samples were developed by cutting cylindrical metal rods to dimensions of 30 mm in length and 25 mm in diameter. To facilitate temperature measurement, four holes were bored into each sample. These holes had a depth of 12.5 mm and a diameter of 2 mm, and were spaced at intervals of 9 mm, positioned 1.5 mm away from the ends of the samples, allowing for the insertion of thermocouples, as shown in Fig. 3.

2.3. Experimental Methodology

The experiments have been carried out using the setup described in the previous section. Firstly, all the blocks are thoroughly cleaned with acetone before use. The specimens are placed in contact between the heating and cooling blocks. Thereafter, the required loading is applied, heat input is supplied and cooling water is made to flow in the cooling block. After starting the heater and coolers, the setup is allowed to achieve steady-state heat transfer, which takes around 2-3 hour. The temperature was recorded by the thermocouples in both the specimens every 20 minutes till the change in temperature readings was around 0.2 °C and the steady-state achieved. Firstly, the experiments are performed on Cu-Al specimens in direct contact with no interface material. The input heat flux is supplied as 24 kW/m^2 contact pressure is kept at 0.1 MPa. Similarly, all the sets are conducted for four loading conditions (0.1, 0.2, 0.3 and 0.4 MPa) at 24 kW/m^2 input heat flux. Consequently, the heat flux is changed to the next levels i.e., 41 kW/m^2 and 67 kW/m^2 for bare Cu-Al metal contacts. Further, Graphene paste has been pasted uniformly on the lower specimen and the upper specimen is placed over it. Now, the experiments are repeated with graphene paste as TIM in the same way as explained above for all the test conditions of four heat flux and four contact pressures.

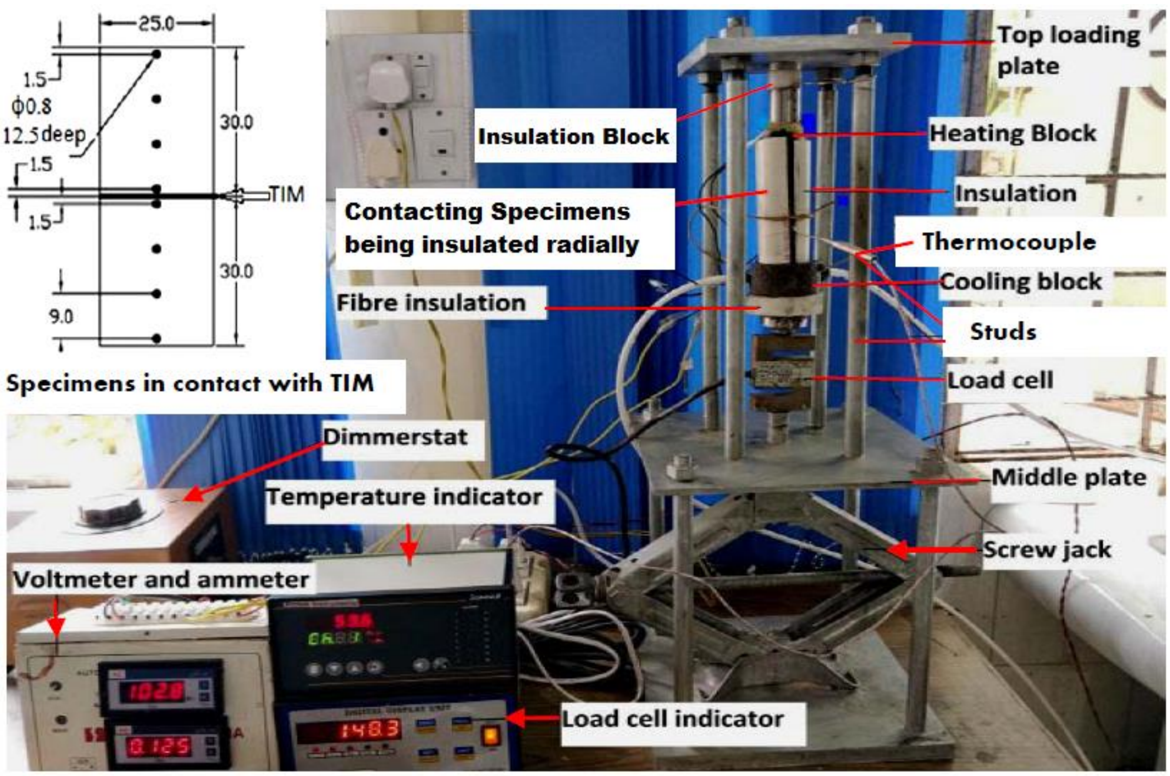

Figure 3. A pictorial view of experimental setup and schematic of specimens contact with Thermal Interface Material

3. Estimation of TCC

The evaluation of Thermal Contact Conductance (TCC) was carried out using a well-established and validated steady-state method. This method involves achieving one-dimensional axial heat transfer through the contact sample and recording temperature readings at different axial positions of the two samples once they reach the steady state. Consequently, the TCC is calculated using the expression:

$$\text{TCC} = \frac{q_{avg}}{\Delta T} \tag{1}$$

where, q_{avg} is calculated as:

$$q_{avg} = \frac{q_{Cu} + q_{Al}}{2} \tag{2}$$

where, q_{Cu} and q_{Al} (the heat flux in the Copper and Aluminum samples respectively) are calculated at the steady state using Fourier's law of heat conduction knowing thermal conductivity and temperature gradient within the sample.

Further, the temperature jump at the interface, ΔT, is calculated by the linear extrapolation using the temperature variations in both the samples. Further, the Percentage heat dissipation from the source to sink is estimated as: $\frac{q_{Al}}{q_{\text{Cu}}} \times 100$

4. Error analysis

The reliability of the obtained results is influenced by various sources of uncertainty, including errors in thermal conductivity with respect to temperature, inaccuracies in temperature measurements, and uncertainties in thermocouple placement. Despite the insulation provided by high-quality glass wool, some convective heat transfer still occurs, leading to heat losses. The maximum displacement observed in the axial position of the thermocouples is 0.2 mm, resulting in a positional uncertainty of 2.2 %. Similarly, the maximum radial displacement of the thermocouples is found to be 0.2 mm, resulting in a positional uncertainty of 1.6 %. Considering these positional errors collectively, the total positional uncertainty is determined to be 3.8 %. All the thermocouples used for temperature measurement have undergone laboratory calibration and are deemed accurate within a range of 20.5 °C. Therefore, the maximum uncertainty in temperature measurement is determined to be 1.25 %. The thermal contact conductance at the interface is calculated using Equation (1). By applying the law of error propagation, the overall maximum uncertainty in estimating the TCC is obtained and calculated as 23.96 % for bare Copper-Aluminum contacts and 20.8 % with graphene paste as TIM. A similar order of uncertainties has been reported in the literature [15,16] for materials like brass, aluminum and copper.

5. Results and Discussion

The study focused on investigating how the utilization of thermal interface materials affects the rate at which heat is dissipated and the variations of thermal contact conductance for various heat flux inputs and contact pressure conditions.

5.1. Direct contact

The copper-aluminum contacts had the effective average roughness (R_a) of 3.13 μm. The experiments are done with varying the nominal contact pressure from 0.1 to 0.4 MPa and heat flux from 24 to 67 kW/m². The results obtained for the thermal contact conductance (TCC) of the bare copper-aluminum contacts, are presented in subsequent sections.

5.1.1 Variation with contact pressure

Figs. 4-5, the effects of contact pressure on the temperature drop and thermal contact conductance (TCC) at the interface are depicted. Specifically, Fig .4 demonstrates that the temperature-drop is found to reduce with the increase of contact pressure. It is noted within the range of 4.1 to 14.5 ºC, for the presented pressures and heat flux ranges.

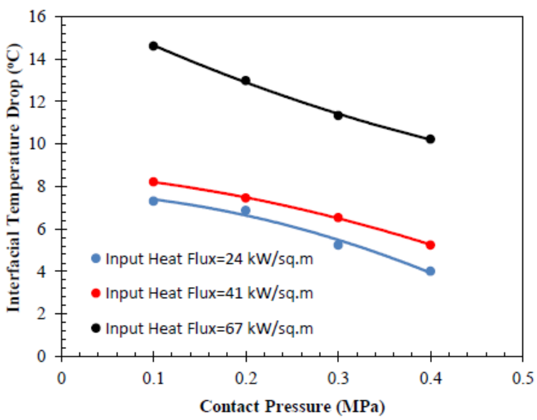

Figure 4. Variation of temperature drop with contact pressure for bare contacts

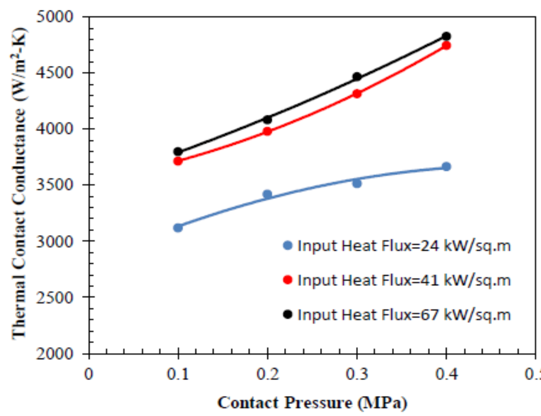

Figure 5. Thermal contact conductance with contact pressure for bare contacts

Fig. 5 illustrates the link between contact pressure and thermal contact conductance (TCC). It is evident that TCC exhibits an upward trend as contact increases. The rise in pressure can be attributed to the compression of contact points, leading to an expansion of the effective contact area. The increased contact area leads to a higher TCC, which subsequently leads to a decrease in the temperature drop at the interface. Further, a percentage increase in TCC was noted as 27.04 % from 0.1 to 0.4 MPa with input heat flux as 67 kW/m². From Fig. 5, it is clear that thermal contact conductance is also increasing with the rise in input heat flux condition. Similarly, the temperature drop at the interface is also growing with an increase in input heat flux condition.

5.1.2 Variation with mean interface temperature

The data presented in Fig. 6 shows the relationship between thermal contact conductance (TCC) and the average interface temperature for bare copper-aluminum contacts. The input heat flux is varied from 24 to 67 kW/m² while maintaining a constant contact pressure between 0.1 and 0.4 MPa. The results demonstrate that as the mean interface temperature increases, the TCC is also increased. It is noteworthy that the maximum variation in TCC is 31.6 % when the temperature rises from 48 to 59 ^{o}C at contact pressure of 0.4 MPa. Notably, it has been observed that as the interface temperature rises, the rate of increase in TCC is more significant at higher contact pressures. The TCC is affected by the interfacial temperature primarily due to changes in the gap conductance.

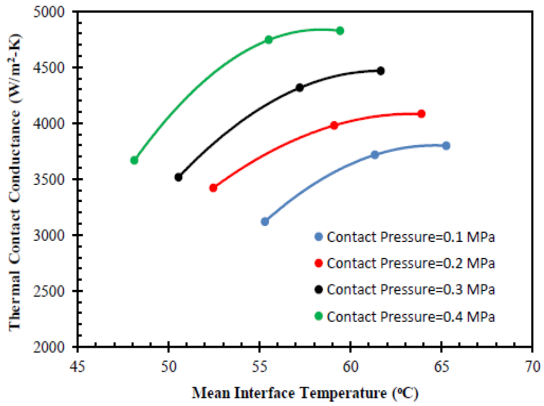

Figure 6. Thermal contact conductance with mean interface temperature for bare contacts

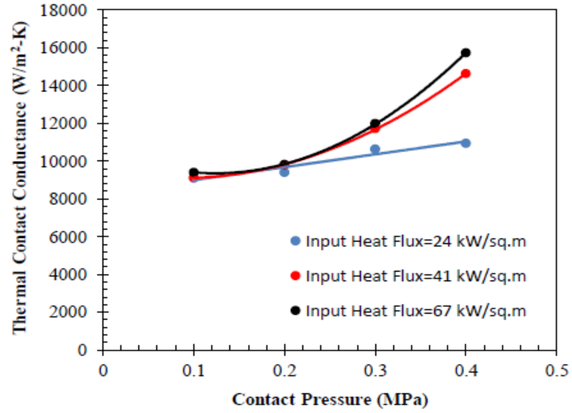

Figure 7. Thermal contact conductance with contact pressure using graphene paste

5.2. Graphene paste

This section presents the results using graphene paste as a thermal interface material between copper and aluminum materials. Three different sources of heat were provided as input (24, 41, and 67 kW/m²) to examine their influence on TCC. The thickness of the graphene paste, is kept below 25 μm. The subsequent sections present detailed insights into the effects of various parameters on the TCC with TIM.

5.2.1 Variation with contact pressure

The variation of Thermal contact conductance with interface pressure using graphene paste as TIM has been shown in Fig. 7. Notably, a similar trend of TCC is observed with contact pressure as in Fig. 5 for bare contacts. However, the effect of contact pressure is more dominant at higher heat flux input for Graphene paste. It has been noted that the percentage of TCC improvement is 43 % with input heat flux from 24 kW/m^2 to 67 kW/m^2 at the highest contact pressure. Further, Fig. 8 compares Thermal contact conductance using Graphene paste with the same for bare contacts. Fig. 8 clearly depicts the improvement in TCC using Graphene paste as TIM. It is due to better thermal properties of Graphene paste (k = 10 W/m-K) to fill the voids and cavities at the contact interface as compared to air (k = 0.026 W/m-K) in case of bare contacts. From the Fig. 8, it is noted that maximum improvement is 147-226 % for 0.1-0.4 MPa contact pressures with an input heat flux of 67 kW/m^2. Moreover, the improvement in TCC is found to be more significant for higher contact pressure. Similar range of TCC is stated in [17] for flexible graphite-coated thermal paste between two copper disks for a contact pressure of 0.46 MPa.

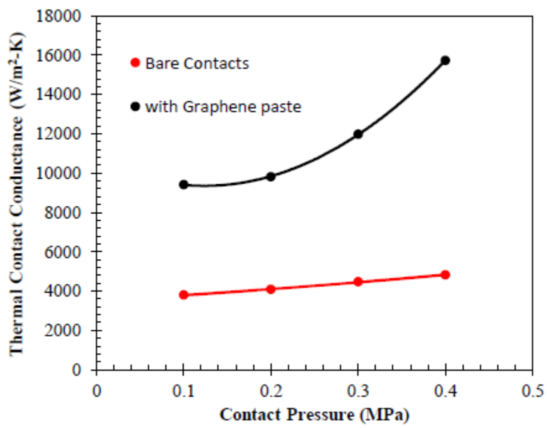

Figure 8. Comparison of Thermal contact conductance with and without TIM at 67 kW/m^2 heat flux

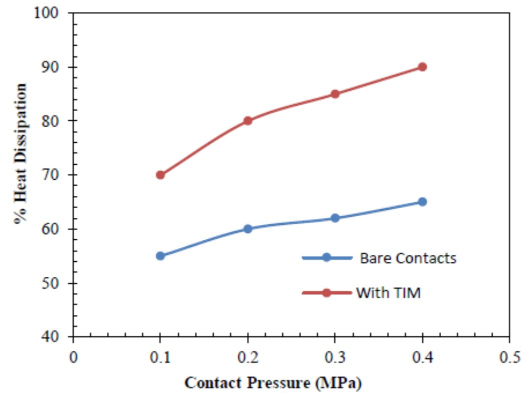

Figure 9. Comparison of heat dissipation with and without TIM at 67 kW/m^2 heat flux

5.2.2 Variation of Heat Dissipation

In order to maintain the temperature of the heat source within a specified limit, it is necessary to effectively dissipate the heat generated. One approach to improve heat dissipation at the contact point is by using a thermal interface material. Fig. 9 presents the results of heat dissipation for direct contacts as compared to those applied with graphene paste. The graph shows that the rate of heat dissipation rises with contact pressure for all the cases. The percentage heat dissipation for bare contacts ranges from 55% to 65%. However, the percentage heat dissipation significantly increases to 70% to 90% for graphene paste under the same range of contact pressure. These findings clearly indicate the suitability of graphene paste as a TIM for the specified parameters, as it effectively enhances heat dissipation.

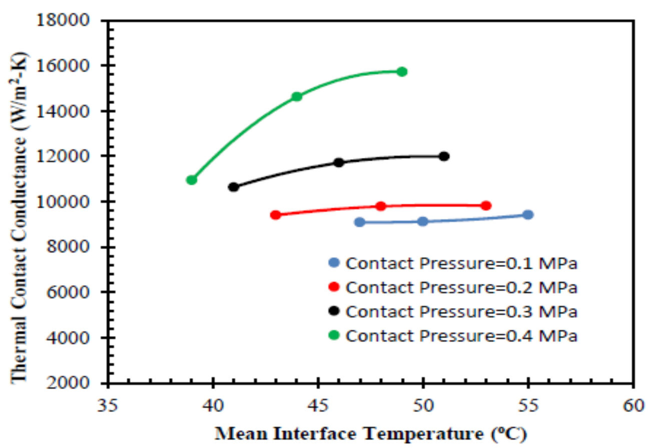

Figure 10. Thermal contact conductance with mean interface temperature using TIM

5.2.3 Variation with mean interface temperature

Fig. 10 displays the effect of mean interface temperature on TCC for the graphene paste. It is found that the increment of TCC with mean interface temperature is low except at highest pressures. It is noted that the highest variation in TCC with temperature (39 – 49 °C) is 43.7 % at 0.4 MPa. Further, it has been observed from Figs. 6 and 10 that there is a significant change of TCC with temperature using Graphene paste as TIM as compared to bare contacts, especially at higher pressures. Most possibly, it is due to more changes in the thermal properties of graphene paste with temperature and better filling of voids and gaps between the interface due to the fluidic nature with temperature. Similar results have been reported by Asif and Alok [18] for Stainless Steel contacts with graphene paste.

5.2.4 Comparison with Silicone Grease

Silicon Grease is one of the most popular TIM for electronic devices. It is reported in [19] that TCC of commercial silicone grease with copper-aluminum contacts lies in the range of 6800-8000 W/m^2-K. However, in the present study, TCC for Graphene paste has been obtained in the range of 9500 to 15000 W/m^2-K for copper-aluminum contacts. In fact, it is due to the higher thermal conductivity of graphene paste than silicone grease. Hence, it can be concluded that Graphene paste is more effective compared to Silicon grease for the present working range. Further, the average costs of silicon grease and Graphene paste have been estimated as Rs. 0.0172 and Rs. 0.129 respectively, for 4.9 cm^2 surface area and 23 μm thickness of TIM for the present study. Therefore, it is worthy to note that graphene paste is 7.5 times costlier than silicone grease but is more effective in heat dissipation.

6. Conclusions

Thermal interface materials have been examined with the help of thermal contact conductance for a range of contact pressures and temperature conditions for copper-aluminum contact best suited to electronics applications. TCC is found to rise with applied loading for all the contacts with and without TIM. However, for bare Copper-Aluminum contacts, the effect of temperature on TCC is insignificant as compared to that of Graphene paste. The relative increment in TCC with Graphene paste is found to be 147-226 % from the bare contacts for the selected pressure range. Further, the application of Graphene paste for Copper-Aluminum contacts results in a significant improvement in heat dissipation from 35 % to 90 % as compared to direct contact. The results have shown that the application of Graphene pastes with input heat flux levels of 24, 41, and 67 kW/m^2 allows the effective control of the mean interface temperature within the range of 32 to 65 °C. Further, it is found that graphene paste is more effective TIM than silicone grease, but costlier. The overall maximum uncertainty for TCC evaluation has been calculated as 23.7 % for bare Cu-Al contacts and 20.8 % for graphene paste. The outcomes of the present study may be suitable for improving the performance of thermal systems, especially in electronic cooling applications.

Conflict of interest

The authors declare that there is no conflict of interest.

Nomenclature

L	Length of the sample	**Subscripts**	
D	Diameter of the sample	avg	Average
A	Cross-sectional Area	Cu	Copper
T	Temperature	Al	Aluminum
k	Thermal Conductivity	**Abbreviations**	
q	Heat Flux	TCC	Thermal Contact Conductance
ΔT	Interfacial Temperature drop	TIM	Thermal Interface Material
R_a	Effective average roughness	IC	Integrated Chip
P	Contact Pressure	PCM	Phase Change Material
Greek Symbols			
$\emptyset$	Dia of thermocouple hole	CNT	Carbon-nanotube

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