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EXPERIMENTAL INVESTIGATIONS ON THERMAL CONTACT RESISTANCE FOR DIFFERENT MATERIALS

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Abstract
Experimental investigations are conducted to investigate thermal contact resistance (TCR) between similar and dissimilar combinations of aluminium and copper under different operating conditions, such as pressure and heat input. The steady-state method is used as the major assumption to evaluate the thermal contact resistance. For Al-Al, results indicate that under pressure ranging from 1.5 bar to 6 bar and heat input ranging from 5W to 30W, thermal contact resistance decreases up to 43% for pressure and heat input ranging from 1.5 to 2 bar and 10W to 30W respectively, however pressure rises from 2 bar to 6 bar, the percentage of thermal contact resistance further decreases by 21%. According to the results for Al-Cu, the thermal contact resistance is decreased up to 43% for pressure and heat input ranges of 1.5 bar to 2 bar and 10W to 30W respectively, whereas, when pressure rises from 2 bar to 6 bar, the percentage of thermal contact resistance further decreases by 21%.
Keywords: Thermal contact resistance, Steady-state method, Pressure, Heat input

Introduction

In many crucial engineering fields, including electronic packaging, aerospace technology, optical electronic devices, metal processing, refrigeration, automotive manufacturing, etc., thermal contact resistance (TCR) is a crucial parameter used to characterise thermal transfer via contact interfaces for thermal management. Due to the non-flat and abrasive nature of the surfaces that touch, only a very small fraction of the entire surface is really in contact when two metal materials are brought together to create a junction, which is similar to the metal materials that touch. The conductivity at the contact point is sometimes the sole location where a consistent transfer of heat may take place if the heat flow happens via the joint.

The real contact area is substantially less than the visual contact area due to the few and small contact points. Small regions of contact result in thermal resistance, also known as contact resistance or thermal contact resistance. A phenomenon known as thermal contact resistance (TCR) obstructs the transfer of heat at the contact interface between two materials. Thermal contact resistance (TCR) is crucial to thermal management and may significantly affect how heat is distributed across interfaces, especially as device sizes go smaller.

Xian et al. [1] described the various steady state and transient methods to determine contact resistance between contact bodies, including Raman based-techniques, infrared thermography measurement, laser flash measurement, photo-acoustic technology, 3ω method, transitional thermal reflection technique under transient method, while conventional stability measurement is still recognized as a TCR measurement technology for bulk materials, and recent changes and improvements have increased their accuracy and reliability.

The effects of surface roughness, temperature, contact pressure, and heat flow direction on TCC have been experimentally studied by Tang et al. [2]. At contact pressures ranging from 0 to 150 MPa and temperatures ranging from 200°C to 350°C, the samples were obtained using TC4 and 30CrMnSi. The scientists came to the conclusion that contact pressure significantly affected TCC whereas temperature had little bearing on it. Additionally, contrary to the majority of literature findings, the data demonstrate that rough surfaces exhibit larger TCCs than smooth surfaces under the same circumstances. The TCC displayed a power law relationship with contact pressure and interface temperature, according to Dou et al. [3]. Surface roughness indexes range from 0.45 to 2.36, whereas contact pressure indexes range from 0.20 to 0.46. Compared to samples with lesser surface roughness, TCC rises with temperature more quickly. A 20% relative inaccuracy is shown by the correlation equation between thermal contact conductivity, contact pressure, and interface temperature.

Swamy and Satyanarayan [4] experimented on brass using with and without thermal interface materials (TIMs), suggesting that contact resistance of tin-coated brass was lower than that of bare brass under loading conditions. In addition, the contact resistance of TIM was reduced in terms of loading and surface finishing parameters (uncoating and coating surface). It was confirmed that the tin-coated brass showed better thermal transfer than the bare brass. Harmonic mean value method of TCR was proposed by Zhang et al. [5] to minimize the additive errors for heat flux exerting in both the directions. This resulted in having higher precision for harmonic mean value method. Narayan and Narayana [7] observed that TIMs with loads reduce thermal contact resistance to a greater extent than without loads. This clearly proves that the results obtained in the current study can be compared to other results, although the materials used are different. Zhang et al.,[5] in his previous work determined that the directional effect in contact of similar materials gives the evidence of its dependence on surface and mechanical properties. Whereas Zhao et al., [8] suggest that when pressure increases, the thermal pads as thermal interface material will undergo elastic deformation to plastic deformation, eventually pressure will exert a negligible effect on interface thermal resistance of thermal pads. P. Zhang et al., [6] suggest that the test results decrease with increase in pressure and maximum deviation is found to be 16% at forward and reverse heat flux cases.

Dou et al., [9] experimented on C/C and Inconel 600. Results show that TCR between the C/C material with the highest thermal conductivity and the Inconel 600 superalloy at contact pressure of 2.82 MPa is approximately $5x10^5$ m^2-K/W and is strongly dependent on pressure and temperature. It is necessary to take into account the effects of thermal contact resistance in the construction of structures relating to high thermal conductivity C/C materials. At the same time, high-temperature C/C materials are very fragile and require special consideration in engineering practice for high-temperature C/C materials. This happens due to the directional dependence upon the value of thermal contact resistance between two dissimilar metals as to the direction of heat flow.

Hu et al., [13] experimented thermal contact resistance using copper and indium taking surface roughness of the materials into account, as it plays an important part in microelectronic devices. Electronic packaging is taken in consideration as an application where copper and indium are used as an interface and thermal contact resistance is investigated using numerical methods. Finite element method is used to determine the temperature field of the copper – indium contact model. The results suggested that under the influence of air and grease in finding the thermal contact resistance of copper-indium was that the thermal resistance will rapidly when there is increase in pressure but there will be decrease in the cost-effectiveness ratio.

Sidappa, Tariq [14] investigated the thermal contact conductance (TCC) using copper-copper at different cryogenic temperatures. Experiments were carried out on a novel experimental setup where temperature and pressure are used as parameters ranging between 50 to 300K and 0.5 to 8MPa respectively. Surface roughness was also varied between 0.8 and 10 µm. The main motive of this experiment is to find the non-linear dependency of TCC with temperature and pressure. An empirical correlation was proposed that involves reduced dimensionless TCC with dimensionless pressure and temperature.

2. Experimental

The method for measuring solid TCRs that is most frequently employed is the steady state approach. The steady state technique is superior to the transient method in terms of accuracy since it is a widely accepted method for calculating TCR. The key benefit of employing the steady state approach is that it is more precise than the transient method. The drawbacks of the steady-state method are:

a) Around 7 to 8 hours of long waiting period is required to obtain steady state measurement condition of the contact bodies,
b) For obtaining steady-state, the change of behaviour of the contact bodies due to invasive temperature measuring method by inserting the sensors, [10] due to this contact bodies cannot be very thin.

As shown in Figure 2, the experimental setup consists of four vertical bars of 200 x 200 mm stainless steel mounted in between two plates of mild steel. Base plate is used to support the weight and maintain balance of the test setup. Pneumatic Actuator is mounted at the top plate for the application of pressure. Pan heater is placed on insulating material such as ceramic plate to ensure there is no heat loss due to high temperature as temperature can go above 250°C. 6 k-Type thermocouples are inserted into the specimen. Polystyrene sheet is wrapped around the test setup (not shown in the photo) to prevent heat loss during experimentation. The Electric Control Panel consists of voltmeter, ammeter to measure the voltage and current. Dimmer-stat is used to adjust the voltage and current. Temperature sensors to indicate temperature sensed by the thermocouple and pressure sensor that indicates the pressure applied to the specimen. Table 1 represents the range of the instruments used in this experimentation.

Table 1: Range of Instruments used in experimentation

Sr. No.	Instruments	Range
1	Pneumatic Actuator	1.5 to 8 bar
2	Voltmeter	0 to 300 Volts
3	Ammeter	0 to 5 Amp

4	Pressure Sensor	0 to 10 bar
5	Temperature Sensor	0 to 200°C
6	Pressure Transmitter	1 to 10 bar

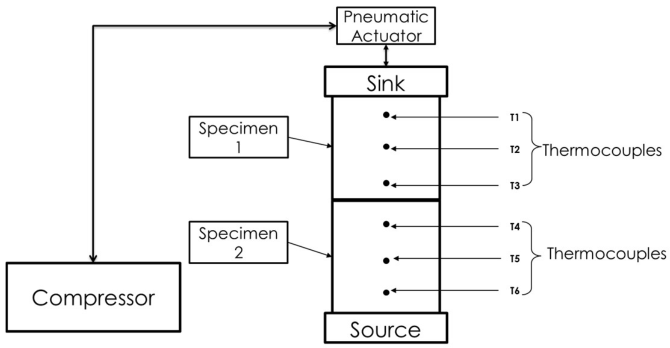

Figure 1: Schematic arrangement of test setup

3 holes of 2mm diameter each are drilled for each specimen to measure the temperature. Thermocouples are inserted in these holes to identify the temperature. T_1, T_2, T_3, T_4, T_5 & T_6 are the temperature points at a distance of 5, 25 & 55 mm for each specimen. To measure the contact resistance at the interface, T_3 & T_4 points are used.

$$\Delta T = T_3 - T_4$$

Heat Flux is calculated where heat input is divided by the cross-sectional area at the interface,

$$\dot{Q} = \frac{q}{A}$$

The thermal contact resistance is calculated by combining the above equations,

$$R_{th} = \frac{\Delta T}{\dot{Q}}$$

In this study aluminium and copper are used as the specimens. Aluminium and Copper bars were cut from commercially available Al & Cu rods of diameter 30 mm and length 60 mm respectively. An electrical pan heater heats the specimen's bottom end during experiment runs, and a dimmer-stat (shown in Figure 2) allows the user to manage the amount of heat input. For both specimens, the surface roughness is maintained at 1.5 µm. The specimens were thoroughly cleaned before to conducting the experiments to prevent any interference from extraneous particles during the experiment.

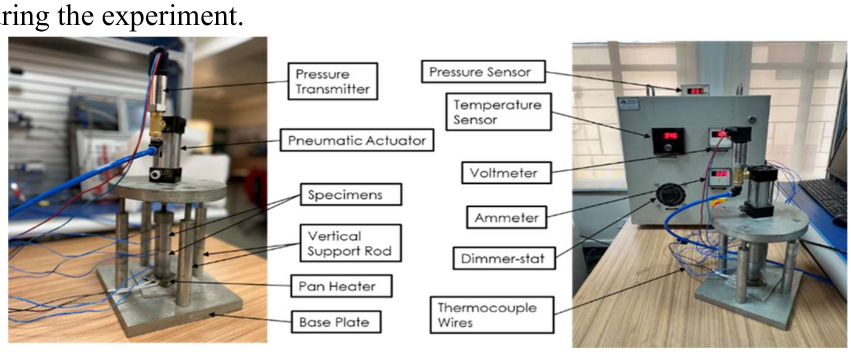

Figure 2: Experimental Setup

The pressure loadings are all pre-determined from 1.5 to 6 bar. The data is recorded by measuring after keeping the test rig running for 8 hours to obtain a steady state. The lower specimen is heated by pan heater. Temperatures are measured by inserting K-type thermocouples into the holes drilled (2 mm diameter) in the specimen 5, 25 and 55 mm apart in both the specimens. Since all tests are performed in an atmospheric environment, air is present at the contact interface. The conductivity of air rises with temperature, increasing the conduction of contact gases.

The electrical heater's power is adjustable and can reach up to 230V. In experiments, the voltage is set to 50V (5 Watts) as the initial voltage, then adjusting it to 75V (10.08 Watts), 100V (20 Watts) & 125V (30.5 Watts) respectively. The pneumatic load is gradually modified from 1.5 bar to 6 bar by adjusting the pressure valve applied to the specimens and is measured by the digital indicator. The temperature along the specimens is measured on the axis by a 6 K-type thermocouple located at a distance equal to the axis, as shown in the Fig. 1. Experiments were conducted by varying pneumatic pressure from 1.5 to 6 bar by changing heat input from 5W to 30W for every pressure. As the method of experimentation is steady-state method, the test rig is kept on for 8 hours to obtain accurate results. Measured temperature values are used to calculate the thermal contact resistance at the interface.

Uncertainty Analysis

To ascertain if the overall uncertainty of the testing apparatus's interface thermal resistance is significant, a thorough study of uncertainty is carried out. Table 1 displays all measured quantities as well as their level of uncertainty. The uncertainty in each quantity which is calculated [5] can be calculated as:

$$U_z = \sqrt{\left(\sum_{i=1}^{n}\left[\frac{\partial Z}{\partial x_i}U^2\right]\right)}$$

Kempers [11] took into account the probes' uncertainty in measuring temperature, their uncertainty in their positions, their uncertainty in measuring heat flow, and their ambiguity in measuring contact area resistance at the junction. The influence of thermal properties, geometry, the number of probes, and the surrounding filler materials on measurement uncertainty were examined by Warzoha [14].

According to papers [11,12], the uncertainty of the interface thermal resistance is ± 5 mm^2-K/W for the standard set of test parameters (k = 118.3 W/m-K, Δx = 20 mm, ΔT = 2 °C, q = 6.67 x 10^3 W/m^2). The greatest error of the interface thermal resistance is 6 mm^2-K/W when additional uncertainties such as applied pressure, heat loss, and surface roughness are taken into consideration.

Table 2: Uncertainty in measured quantities

Measured quantity	Uncertainty
Temperature calibration accuracy	±0.01°C
Thermocouple sensor position	±50 µm

Pressure	±0.2% of rated load
Cross-sectional area of specimen	±0.1%
Heat Loss	±0.5%

Error Analysis

The experiments are conducted and measured considering the uncertainties of the various instruments mentioned in Table 2.

By conducting error analysis, it can be assumed that there is up to 5% change in the thermal contact resistance when pressure gradually increases that is applied to the specimen. Whereas, by changing the heat input, the thermal contact resistance deflects up to 6%. From the above analysis, it can be concluded that there is some fluctuation due to vibrations of thermocouple while measuring the temperature during the experimentations.

Results and Discussion

Experimentations are done on Aluminium and Copper specimens by varying pneumatic pressure and heat inputs. Based on the calculated data, thermal contact resistance at various operating conditions, graphs are plotted.

Figure 3 & 4 shows the variation of thermal contact resistance for similar combination (i.e., Aluminium – Aluminium) at different pressures and heat inputs respectively. By observing the plot of TCR vs Pressure, it shows that when pressure increases the thermal contact resistance decreases. From Figure 3, it is observed that the thermal contact resistance is found to be decreasing when the pressure increases from 1.5 to 6 bar. This reduces the gaps consisting of air which happens to be a hinderance at the interface. At 1.5 bar & 5 Watts, the thermal contact resistance for Aluminium-Aluminium is 0.000224 m^2-°C/W, whereas at 6 bar & 30.5 Watts, the thermal contact resistance is 0.0000252 m^2-°C/W.

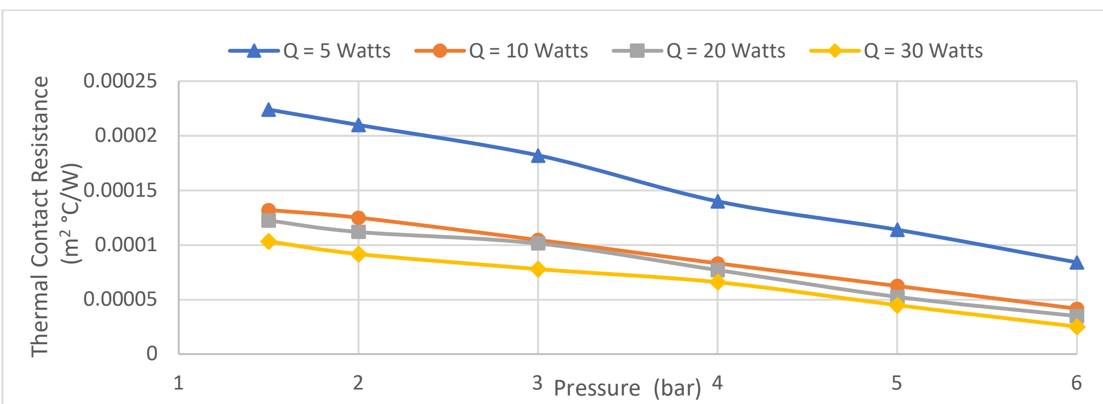

Figure 3: Variations of TCR vs Pressure for Aluminium-Aluminium

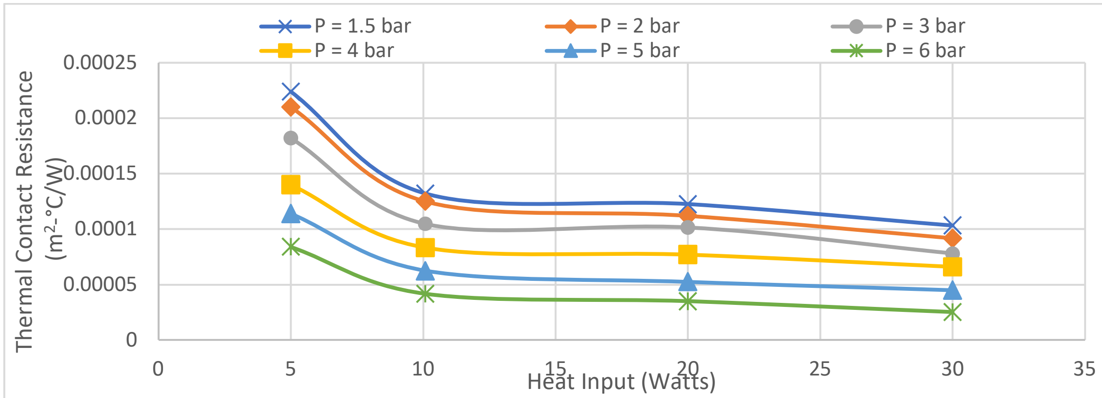

Figure 4: Behaviour of TCR under Different Heat Input for Aluminium-Aluminium

From Figure 4, results suggest that the thermal contact resistance suddenly decreases from 5W to 10W when pressure is 1.5 bar to 6 bar i.e., there is an average of 43% decrease in thermal contact resistance when heat input goes from 5 Watts to 10 Watts for all the pressure range.

After increasing the heat input from 10W to 30W, there is a minimal deflection in thermal contact resistance. This clearly indicates that the temperature distribution is uniform for the higher loads because when the load is applied between the interfaces, the air gaps are minimized and the mating is perfect and the surface helps to conduct more heat and the temperature increases at the interface.

Figure 5 & 6 represents the variation of thermal contact resistance for dissimilar combination (i.e., Aluminium – Copper) at different pressures and heat inputs respectively. By observing the plot of TCR vs Pressure, it shows that there is decrease in thermal contact resistance when there is increase in pressure.

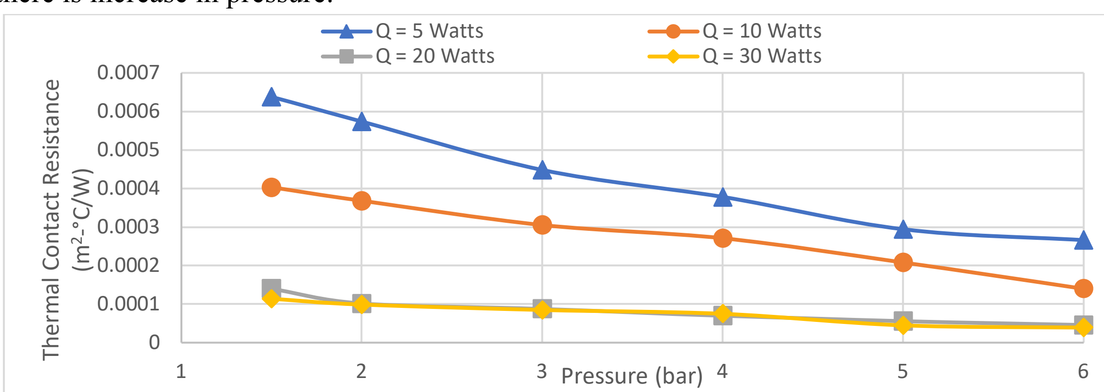

Figure 5: Variations of TCR vs Pressure for Aluminium-Copper

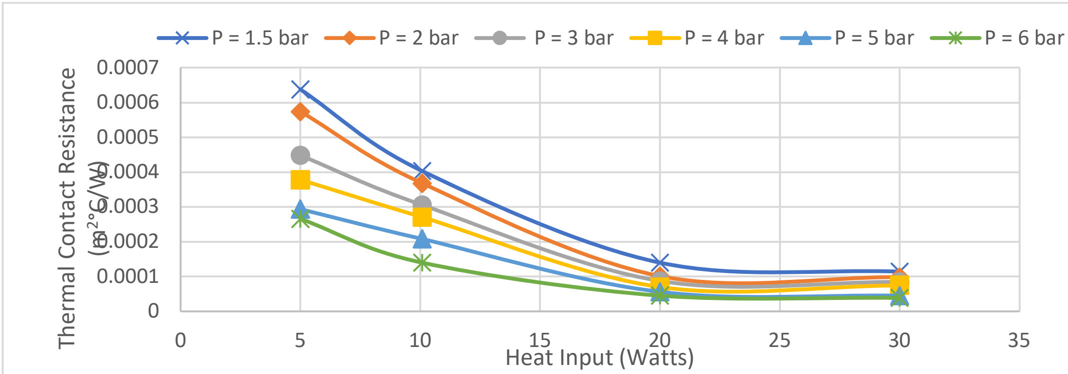

Figure 6: Behaviour of TCR under Different Heat Input for Aluminium-Copper

Figure 5 shows variations in thermal contact resistance under different pressures applied on the specimen. The thermal contact resistance for Al-Cu ranges from 0.000638 to 0.000039 m^2-°C/W. As pressure continues to increase, the thermal contact resistance decreases at a significantly slower rate. After the pressure exceeds 4 bar for heat input ranging from 20 Watts to 30 Watts, the thermal contact resistance is almost constant. Even if pressure increases continuously, it had a negligible effect on interface thermal resistance. In Figure 6, the thermal contact resistance has a nature of curve is steep till the point it reaches to 20 Watts. After 20 Watts, there is a minimal change in thermal contact resistance. This occurs as a result of the direction of heat flow being dependent on the value of thermal contact resistance between two different metals.

Conclusions

The objective of these tests is to investigate the effect of different pressure and heat input on thermal contact resistance of different materials.

Results suggest that:

a) The thermal contact resistance decreases as the contact pressure increases. This is due to the curtailing of gap which helps to conduct more heat which results in increase in temperature at the interface.

b) For Aluminium – Aluminium, there is a decrease in thermal contact resistance up to 43% when pressure increases from 1.5 to 2 bar at the interface with heat input from 5 Watts to 30 Watts. Whereas, percentage decrease in thermal contact resistance when pressure increases from 2 bar to 6 bar is up to 21% only. By comparing the above results, the thermal contact resistance is directly proportional to increase in pressure irrespective of its change in heat input. The nature of curve for thermal contact resistance is steep when pressure and heat input ranges from 1.5 to 2 bar and 5W to 10W at the interface, whereas, the nature of slope appears to be flat when heat input ranges from 10W to 30W.

c) For Aluminium – Copper, there is up to 54% drop in thermal contact resistance when pressure ranges from 1.5 to 2 bar at the interface with heat input ranging from 5W to 20W. The percentage change in thermal contact resistance is up to 19% when heat input ranges from 20W to 30W for pressure ranging from 1.5 bar to 6 bar. Upon considering the above results, the nature of curve for thermal contact resistance is steep when pressure and heat input ranges from 1.5 to 2 bar and 5W to 20W at the interface, whereas, the nature of slope gets flat when heat input ranges from 20W to 30W.

d) It has also been observed that there is only a slight shift in thermal contact resistance when the heat input is increased from 10W to 30W. The fact that the air gaps are minimised and the mating is ideal when the weight is applied between the interfaces, the surface helps to transfer more heat, and the temperature rises at the interface, clearly shows that the temperature distribution is uniform for the higher loads.

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