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Effects of pressure, temperature, and surface roughness on thermal contact conductance across copper-aluminum interfaceSubtitle as needed

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***Abstract*—An experiment was conducted to investigate the effects of contact pressure, surface roughness, and interface temperature, on thermal contact conductance. The specimens were aluminum (384.0-F) and copper (Cu Ni 90/10) alloys, the contact pressure was in the range 0.1 to 0.3 MPa, the interface temperature ranged from 99 and 124 ℃, and the surface roughness were 0.85, 1.27, and 1.84 μm. All experiments were performed in ambient atmosphere condition. Results indicated that there is a power law relation between interface temperature and contact pressure with thermal contact conductance (TCC). After the results compared at maximum and minimum contact pressure TCC improve by 63%, 62%, and 60% for surface roughness which are 0.85, 1.27, and 1.84 μm respectively. Under the use of the same contact pressure effect, the TCC significantly enhances by 30% when the roughness is decreased from 1.84 to 0.85 μm. When increasing interface temperatures by 25℃, TCC improve by 21%, 36%, and 27% for the three surfaces roughness used respectively.**

Keywords— *thermal contact conductance; contact pressure; interface temperature; surface roughness*

I. Introduction

The resistance to the heat flow at the interface contact between two bodies called Thermal contact resistance (TCR). Thermal contact conductance (TCC), is the reciprocal of (TCR) The prime fields of engineering applications that investigated in TCR to date include electronic packaging, building heat transfer, medicine, thermal energy storage, nuclear energy, heat transfer in thermal power applications metal processing, tribology and aerospace. TCC changes with many factors like contact pressure, interface temperature, surface roughness, surface oxidation, heat flow direction, load cycling, and contact pressure overloading [1]. Zhe Zhao et al. [2], studied experimentally the effects of interfacial pressure and interface temperature on TCR between phenolic resin and carbon-carbon composites, aluminum, and copper. The results show that the sensitive of TCR value is a little when the range of temperatures between 50 to 250℃, in any case of the contact pressure applied. The TCR between aluminum and copper is more sensitive to contact pressure and interface temperature than that carbon-carbon composites and phenolic resin. L.S. Fletcher [3], Concluded that the effective (TCR) can be reduced by reducing the bond line thickness and using a TIM of high thermal conductivity. Ruifeng Dou et al. [4], studied experimentally the effects of interface temperature, interfacial pressure, and surface roughness, on TCC the specimens were stainless steel 304 the temperature at the interface was 360–640°C. The contact pressure was in the region 2.39 and 15.17 MPa, and the roughness between 0.25 to 2μm. All experiments were carrying out in ambient atmosphere conditions. They found that TCC increases with increasing interface temperature. They attributed it to the thermal conductivity of air confined in the contact area increases with increasing temperature. The Increase in surface roughness decreases TCC at the same temperature and contact pressure. Jevanashancara et al. [5], studied experimentally TCC of metallic contacts at low loads. They found that the behavior is extremely different from that in high pressure contact (with p/H > 0.0007), because to the increase important of gap fluid conductance at low pressure. The effect of thermal interface materials, thermal rectification mean and interface temperature are also found to be more clearly than those for high contact pressure condition. Ju Liu et al. [6], presented an experimental setup to test TCC between two contacted materials this setup was designed at room temperature and pressure ambient atmosphere. The specimen was brass and the parameters were the voltage of heater, contact pressure, thermal grease and temperature. When using thermal grease, the TCR is reduced by 12.5%. The maximum error between theoretical and experimental results was 72.6% at 1.2 MPa contact pressure. When the contact pressure rises from 0.166 to 2.636 MPa, the TCR decreased from 5.162*10-4(m2•℃/W) to 1.177*10-4 (m2•℃/W).

II. Theory

A. Experimental Setup

An experimental work was carried out to investigate the effect of parameters on the TCC between aluminum (384.0-F) and copper (Cu Ni 90/10). The photograph of the test rig is shown in Fig. (1).

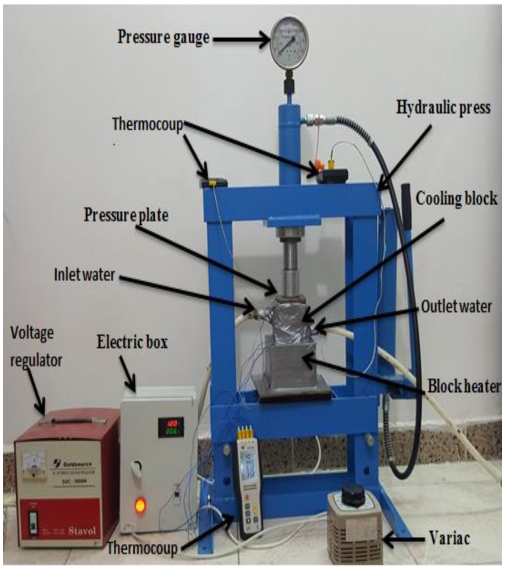

Fig. (1) Photography view of the test rig with instruments and measurements devices

The chemical composition of the specimens obtained using portable device for metal analysis. The chemical composition is provided in Table (1).

Table 1 Chemical composition of the specimens (wt. %).

Aluminum	Si	P	S	Al	Mn	Fe	Cu	Zn
	10.02	0.42	0.2	81.39	0.39	1.31	4.42	0.29
Copper	P	S	Cu	Mn	Fe	Ni	Zn	Cr
	0.094	0.096	86.6	0.99	1.25	9.1	0.5	0.08

The load was applied by means of a hydraulic press. The block heater consists of an aluminum block and pencil-type heater. The aluminum block dimension is 8cm length, 8cm width and 5cm high has two holes at the center of block with a diameter of 1.2 cm designed by a lathe. Inside each hole there are a pencil-type electric heaters 5cm length, 12cm diameter and 150 watt. An open system water tank made of galvanized plate with 4mm thickness which used to develop the axial heat flow and to maintained constant temperature. The two specimens are placed between the block heater and the cooling block. The heating and cooling block was well insulated using insulation consists of three layers. The first is ceramic fiber blanket 25 mm thickness. The second is a mica sheet - electrical and thermal insulation material 5mm thicknesses. The third layer is aluminum foil tape is used to prevent possible damages to package contents caused by moisture as shown in the Fig. (2).

Constant heat flow can be maintained and the output voltage adjustment can be manually by using continuous variable autotransformer. A composite pair of a two plates which it designed above each other. The upper specimen was equipped with a heat-sink while the lower specimen is fitted with a heater. Each specimen has two thermocouples on top and bottom surface the thermocouples used were type-K to measure temperature distribution of the two specimens. Thermal grease can be applied to the interface between the cold, hot, and sample plates to reduce TCR between the heating block, cooling block, and the specimens. An electric box contains of a Voltmeter and Ampere meter are used to measure the power consumed by electric heater.

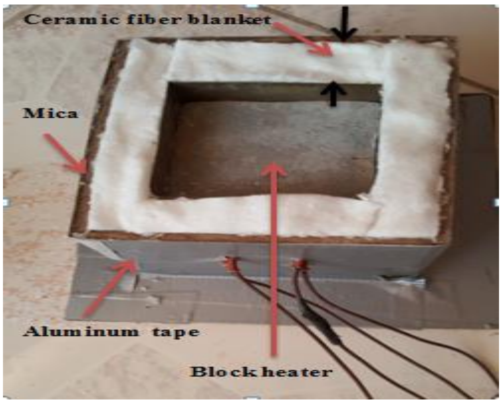

Fig. (2) Insulation layers of block heater

The experimental procedures are as following: The samples were machined and treated with a lathe machine with thickness 1cm. The samples were machined and finished using grinding and polishing set with difference sand paper according to the degree of surface roughness required. Wattage provided to the heater is calculated by measured the voltage and ampere using voltmeter and ammeter. Water cooling arrangement is done in the tank with the water inlet and outlet arrangement. The water control valve is adjusted to maintain a uniform heat flux. To study effect of pressure on TCC, the mechanical load was applied by a hydraulic press from highest to lowest step by step. The temperature was read in each load step when the temperature variation is less than 0.1 ℃ in 30 to 45 minutes. Stability ($T1$) is maintained using the autotransformer. To study the effect of interface temperature, which can be obtained by calculate the average temperature at the interface of two contact materials, the source temperature is increased by increasing the voltage using the autotransformer, It is allowed to increase the temperature of the interface, to study its effect on the TCC. The temperature is recorded after reaching steady state. To study effect of surface roughness, Three different degrees of surface roughness were used, and their effect on TCC was studied twice, the first when increasing contact pressure and the second when increasing interface temperatures.

B. Experimental calculation and error analysis

TCR can be quantitatively calculated by calculated heat flow in each specimen using [7]:

$$q^\circ = k\,\frac{\Delta T}{\Delta x} \qquad (1)$$

Fig. (3) Illustrate the experimental definition of thermal contact resistance.

$$q^\circ_{avg} = \frac{q^\circ{}_1 + q^\circ{}_2}{2} \qquad (2)$$

$$R_c = \frac{(T_2 - T_3)}{q^\circ_{avg}} \qquad (3)$$

$$R_c = \frac{1}{h_c} \qquad (4)$$

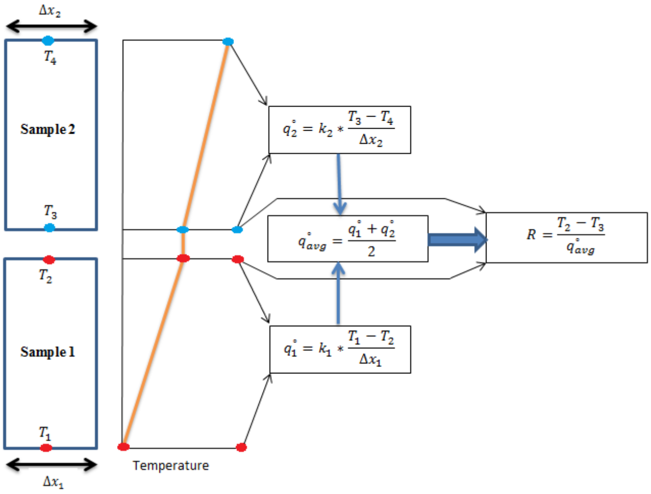

Fig. (3) Graphical representation of calculation procedure

The uncertainty of heat load input was found to be 6.5% using [8]:

$$U_Q = \sqrt{(UI)^2 + (UV)^2} \quad (5)$$

The voltage and the ampere used were 120V and 0.6A respectively. The uncertainty in the current and voltage were measured at 3% amp and 5 volt respectively.

The uncertainty of the total area of specimens was found to be 3.2% using:

$$U_A = \sqrt{(UL)^2 + (UW)^2} \quad (6)$$

The width and length of specimens used was 8cm. The uncertainty in the width and length was 2mm.

The uncertainty of temperature sensor was found to be 2.2% using:

$$U_T = \sqrt{(UT_1)^2 + (UT_2)^2 + (UT_3)^2 + (UT_4)^2} \quad (7)$$

The temperatures degree used in experiment as follow: $T_1 = 92.4℃, T_2 = 91.2℃, T_3 = 88.4℃, T_4 = 87.2℃$. The error was estimated for all measured temperatures are$\pm 1℃$.

The uncertainty of heat flux was found to be 7.1% using:

$$U_q = \sqrt{\left(U_Q\right)^2 + (U_A)^2} \quad (8)$$

Finally the uncertainty in thermal contact conductance was found by:

$$q = h_c * \Delta T \quad (9)$$

The root mean square uncertainty in calculating thermal contact conductance:

$$U_{hc} = \sqrt{\left(U_q\right)^2 + (U_T)^2} \quad (10)$$

The value ofU_{hc}, which represents TCC uncertainty, was found to be 8%.

III. Results and Discussions

A. Effect of contact Pressure on TCC for different surfaces roughness

The effect of contact pressure used varied between 0.1 MPa to 0.3 MPa, the experiments were carried out with three test surfaces having different Root Mean Square (RMS) of roughness which are 1.84, 1.27, and 0.85 μm. The effect of pressure on TCC for dissimilar pair (Al-Cu) for all (RMS) of roughness used in the experiment are shown in Fig. (4), as expected the TCC improves with increasing contact pressure. The highest TCC value of 25024 $W.m^{-2}.℃^{-1}$ was obtained at (RMS) of roughness value of 0.85 μm at the highest contact pressure of 0.3 MPa. At 0.1 MPa the effect of contact pressure on both 1.27 and 0.85 μm is fairly convergent but it starts to diverge when the pressure increases, this indicates that the effect of the pressure on both surfaces roughness are more sensitive than 1.84 μm. When the results compared at maximum and minimum contact pressure the rate of enhancement in TCC was 67% for (RMS) of roughness of 1.84 μm , 65% for (RMS) of roughness 1.27 μm, and 64% for (RMS) of roughness of 0.85 μm. The steady state condition was reached after thirty to forty five minutes had.

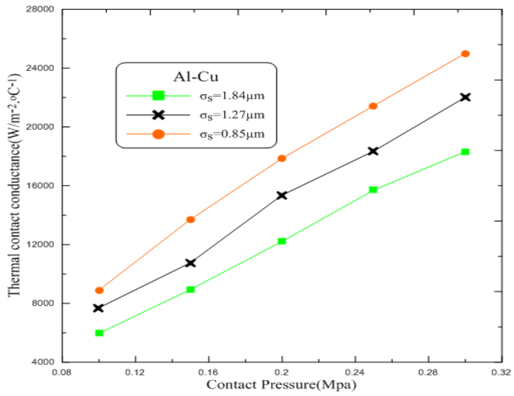

Fig. (4) Effect of contact pressure on TCC

It can be seen from the figures above, there is a power law relation between contact pressure and TCC. It could be explained by the increases in contact pressure increase heat flux at the interface because the amount of the actual contact area grows. This is due to the deformation in the contact asperities which lead to a new asperities coming into contact. On the other hand, the contribution of solid spot in the thermal contact conductance will be increase to enhance contact heat transfer. The high value of the TCC value is attributed to that every metal of this pair has specifications that lead to this result. The copper has relatively little yield strength, it will deform before aluminum, which growing the actual contact area of copper and thus increase the total contact area between the two metals, since aluminum has high thermal conductivity.It will take advantage of this feature to increase the rate of heat transfer, then improving TCC.

The TCC has been evaluated against the same contact pressure used for different levels of surface finish namely 1.84, 1.27, and 0.85 μm. The effect of roughness on the TCC is a reverse effect, and this can be explained easily. The contact points at the interface increase when the roughness decreases, which leads to more heat flux at the interface contact. Thus decreasing the thermal contact resistance and increasing TCC. The roughness was measured after each experiment when the metal was subjected to a certain pressure, a slight decrease in roughness was found. This indicates that the asperities become close to flatten after the experiment, which indicates the exposure of the metals to plastic deformation at conducting the experiment. Therefore, the amount of improvement in the TCC value was found by comparing the TCC before and after reducing the roughness. The improvement in TCC after reducing the roughness from 1.84 to 1.27 and 0.85 μm was 16% and 34% respectively.

B. Effect of interface temperature on TCC for metals for different surfaces roughness

The effect of changing the interface temperature on the TCC was studied with keeping the contact pressure at 0.1 MPa, and then gradually rising the temperature. The effect of interface temperature on TCC for the three (RMS) of roughness are shown in Fig. (5). For σ_s=1.84 and σ_s=0.85 µm the improving in TCC was 21% and 27% respectively at increasing interface temperature by 25℃, the increase in TCC was at its peak and reached to 36% at σ_s=1.27 µm by increasing the same amount of interface temperature. It could be explained that the reason of improving the TCC when increasing the temperature by two reasons. The first reason is the decreases of the yield strength of the contact materials when the interface temperature rises, which causes an increase in the contact area at the same contact pressure. The second reason, since all the experiments were conducted in the atmospheric condition, which means the gaps are filled with air. The thermal conductivity of trapped air increases with rising interface temperature, leading to increasing the gas conduction (h_g). The second reason was not entered into the calculations of TCC because (h_c) gives the conductance at solid-solid interface.

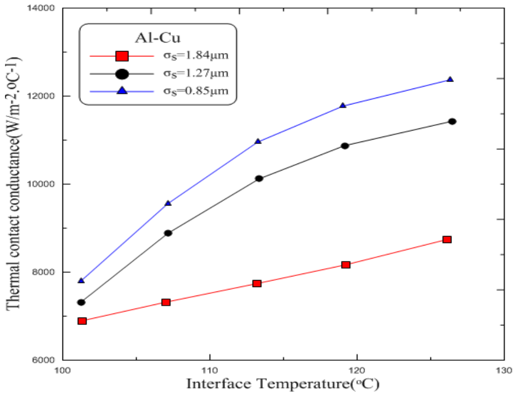

Fig. (5) Effect of interface temperature on TCC

When studying the effect of the interface temperature on TCC, it was observed that the thermal properties effected more than the mechanical properties due to the use of constant pressure. The most properties that affects TCC when rising interface temperatures is the thermal conductivity. This effect is more evident at the lowest degree of roughness used.

By studying the effect of temperature and pressure on the TCC, it was found that the TCC values differ due to the different thermal and mechanical properties of the tested metals. The thermal properties include the thermal conductivity, the specific heat capacity and the thermal diffusivity. The thermal conductivity greatly influences the amount of TCC. Thermal diffusivity depends on the thermal conductivity, density and specific heat capacity. A metal that has a higher thermal diffusivity will reach to the steady state more quickly. Steady state access required the same time period that was reached when testing the effect of contact pressure on the TCC. The mechanical properties, including yield strength, Poisson's ratio, and modulus of elasticity. Yield strength is one of the most important mechanical properties that effect on TCC value, it is related to the capability of the material to deform and that is moreover regarding with hardness for asperities plastic deformation and elasticity for asperities elastic deformation. The material which has lower yield strength will subject more deformation of surface asperities when pressed or when increasing interface temperature. This leads to an increase in the contact area results from it to a greater value of TCC. The modulus of elasticity and Poisson's ratio is affected their effect on the elastic deformation only.

The TCC for metals has been evaluated against the same interface temperature used by keeping the contact pressure at constant, for different levels of surface finish. The improving in TCC after reducing the roughness from1.84 μm to 1.27 μm, and 0.85 μm was 28% and 20% respectively.

12584. Present Work Validity

The results of the experiments were verified with several models which shown in table (2). The figures (6) show the validation for the experiments results with models. Obviously, the experimental results of TCC are in good agreement with empirical correlation of models. It is noted that the maximum deviation (of the flat rough surfaces for plastic deformation, which are the same surfaces that were used in the experiments) in TCC with the models was 15%, and the minimum deviation was approximately 3%. The average deviation (of spherical, rough surfaces) in TCC with the model was 27%. Deviations between the results of the experiment and theoretical models can be attributed to the variation in the values of the mechanical and thermal properties used in the calculation at different interface temperatures. As is known, there will be an increase or decrease in the properties when the temperature and pressure vary.

Table (2) the models of thermal contact conductance

Model name	Correlation	Remarks
B.B.Mikic(plastic) [9]	$h_c = 1.13 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P}{H}\right)^{0.94}$	Plastic, flat, rough surface
Cooper, Mikic, and yovanovich (CMY)[10]	$h_c = 1.45 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P}{H}\right)^{0.985}$	Plastic, flat, rough surface
Tien [11]	$h_c = 0.55 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P}{H}\right)^{0.85}$	Plastic, flat, rough surface
Yovanovich [12]	$h_c = 1.25 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P}{H}\right)^{0.95}$	Plastic, flat, rough surface
Mikic and Rohsenow [13]	$h_c = 0.9 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P}{H}\right)^{0.941}$	Elastic macroscopic deformation, plastic microscopic deformation. Spherical, rough surfaces
B.B.Mikic(elastic) [9]	$h_c = 1.55 * \left(\frac{K_s.m_s}{\sigma_s}\right) * \left(\frac{P\sqrt{2}}{E'm_s}\right)^{0.94}$	elastic, flat, rough surface

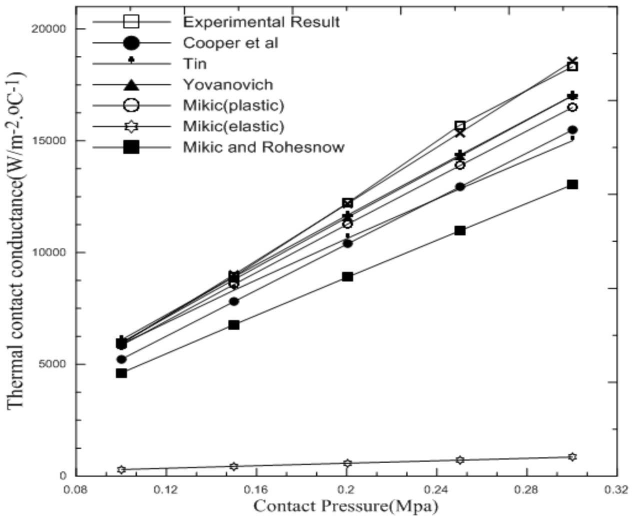

Figure (6) Comparison between experimental results with models

V. Conclusions

This experimental study the effects of interface temperature, surface roughness, and contact pressure on the TCC between copper-aluminum. Results reveal that: Increasing contact pressure from 0.1 to 0.3 MPa improved TCC by 63%, 62%, and 60% for surface roughness which are 0.85, 1.27, and 1.84 μm respectively. When rising interface temperatures by 25℃, TCC improve by 21%, 36%, and 27% for the three surfaces roughness used respectively. Using the same contact pressure effect, the TCC significantly enhances by 34% when the roughness is decreased from 1.84 to 0.85 μm.

SYMBOLS

k: Thermal conductivity, $(w/m.℃)$

y: Yield strength, (N/m^2)

TCR, R_c: Thermal contact resistance, $(m^2.℃/W)$

TCC, h_c: Thermal contact conductance, (W/m^2.℃)

$q°$: Heat flux, (w/m^2)

K_s: Effective thermal conductivity, $K_s = \frac{2*k_1*k_2}{k_1+k_2}$

σ_s : Root Mean Square (RMS) of roughness, $\sigma_s = \sqrt{(\sigma_1)^2 + (\sigma_2)^2}$

$(\sigma_{1,2})$ surface roughness of upper and lower specimens respectively, (μm)

m_s : Effective absolute mean asperity, $m_s = \sqrt{(m_1)^2 + (m_2)^2}$

$(m_{1,2})$: Asperity slopes of upper and lower specimens respectively, (-)

P: Contact pressure, (N/m^2)

H: Micro hardness, (N/m^2)

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