Review: Thermal Contact Resistance of Metallic Composite Pair

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ABSTRACT

Heat transfer is involved in many practical applications. To understand the transfer of heat between two surfaces having interface material as it affects the mode of heat transfer, is very essential in design of different heat transfer equipment. Here an objective is comprehensive review of thermal contact resistance across different composite material pair using different interface material. Also, summarized are the parameter influences on thermal contact resistance.

Keywords: Thermal contact resistance, Thermal interface material, composite material

1.INTRODUCTION

Heat transfer across a contact interface formed by any two solid bodies is usually accompanied by a measurable temperature difference because there exists a thermal resistance to heat flow in the region of the interface. The temperature difference at the contact interface is obtained by extrapolating the steady state unidirectional temperature distribution from regions far from the contact plane.

When two surfaces come into contact as shown in Figure1.1, they remain separated by their roughness elements. A gas or a liquid may also fill the spaces between the surfaces, and if the interface fluid has a lower thermal conductivity than the surface materials a contact resistance may exist that can become a design consideration.Figure1.1 also illustrates the type of temperature distribution that is encountered in such situations where a sharp temperature gradient across the small interfacial separation distance is caused by the contact resistance.

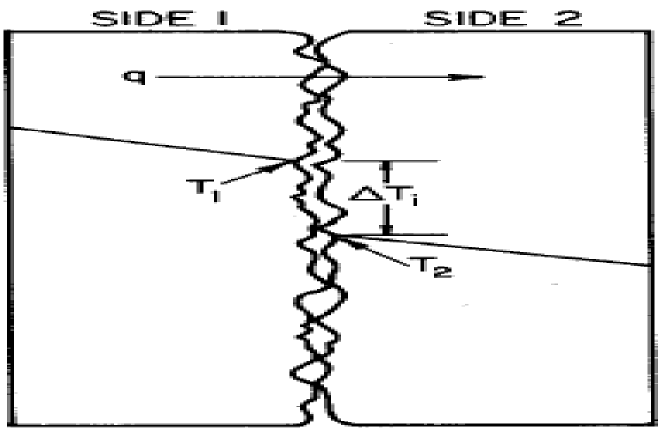

Figure 1.1 Interfacial Contact [32]

Thermal resistance is thermal property of a material and it indicates how it resists heat at a specific thickness. As shown below, thermal resistance is proportional to the thickness of the material, but it can be affected by gaps that occur between contact surfaces. These gap create contact resistance, contributing to additional thermal resistance not represented in above formula. Therefore, total thermal resistance in an application is represented by:[28-31]

$$Q_{cond,material} = \frac{T_1 - T_2}{R_m} \; (W)$$

Where,

$$R_m = \frac{L_m}{k_m A_m} \left({}^oC / W \right)$$

Here, R_m = Material Resistance

L_m = Thickness of Material (m)

k_m = Thermal conductivity of material (W/m K)

A_m = Area of material (m^2)

But, cnsidering the total thermal resistance due to the contact resistance and the material resistance, rate of heat flow can be expressed as

$$Q_{cond,material} = \frac{T_1 - T_2}{R_m + R_c} (W)$$

Where,

$$R_c = \frac{L_c}{k_c A_c} \left({}^oC / W \right)$$

Here, Rc = Interface contact Resistance (${}^oC/W$)

L_c = Thickness of contact resistance (m)

K_c = Thermal conductivity of contact material (W/m K)

A_c = Area of contact suraface (m^2)

Note that the thermal resistance of medium is depend on the *geometry and thermal properties* of medium.

A) Methods to Reduce Contact Resistance [13]

For solid of high thermal conductivity, the contact resistance may be reduced by the following two methods:

1) Increasing the area of contact spots, accomplished by
   - -Increasing contact pressure which will “flatten” the peaks of the micro roughness, and deflecting the mating surfaces to reduce any non-flatness, or
   - -Reducing the roughness of the surfaces before the interface is formed by grinding the surface to remove non-flatness and buffing the surface to reduce micro roughness
2) Using the Thermal interface material (TIM) of high thermal conductivity that can conform to the imperfect surface features of mating surfaces. Any interstitial substance that fill the gap between contacting surfaces, and whose thermal conductivity exceeds that of air, will decrease the contact resistance

B) Various Types of Interface Material [15]

1) Fluidic material:

- Thermal grease (silicon), Phase change material (Paraffin)

2) No fluidic Material:

- Metallic Foils (copper, indium, brass, gold, tin, lead)
- Coatings (Metallic/nonmetallic)
- Polymers (thermoplastic, thermosets, elastomers)
- Adhesives, cements
- Gases

C) Ideal Thermal Interface Material (TIM) Characteristics [13]

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

2.LITERATURE REVIEW

This Literature review consists of historical work done by different scientist in past. Heat flow across a mechanical joint results in a temperature drop, which depends on thermal resistance of the contacting interface. Thermal joint resistance is a function of pressure, surface morphology, interface material, hardness etc.

M. Michael Yovanovich (1971) [1] presented an analytical work performed to determine the thermal resistance to heat transfer at the interface formed by the contact of a hard smooth flat surfaces with a softer turned surface. The results are valid for surfaces in a vacuum environment when there is negligible radiation heat transfer across the gaps

C.V. Madhusudana (1974) [2] found out the effect of interface fluid on thermal contact resistance. Concluded that Contact conductance improves in the presence of a conducting medium. For all fluids such improvement is significant at low contact pressure; the solid spot conductance predominates at high pressure. Also, when interface medium is a good conductor, improvement is significant over the entire contact pressure.

P.W. O'Callaghan and S. D. Probert (1988) [3] developed computer based mathematical model for interfacial material which will minimize the thermal resistance of contact assembly. The model has also been used to predict the behavior of a joint formed between the flat surfaces of two, originally isothermal, cylindrical components, one of duralumin and the other of a titanium alloys. The use of a single layer of aluminum cooking foil (25μm thickness) at the interface between them proved to be a better choice than a selection of thicker special purpose thermal gaskets.

S. Lee, S. Song, K.P. Moran and M.M. Yovanovich (1993) [4] developed an analytical approximate solution for predicting the thermal contact resistance of bolted joint between two square plates of same material and different thickness. Plates are assumed to have perfectly flat and smooth surfaces, and they are joined by a bolted connection at the center of square, forming a concentric annular contact region at the interface. The results are presented over wide range of parameters including equal and unequal plate thickness, the plate thermal conductivity and contact radius. It was concluded that the existing simple correlation equation is adequate in predicting the joint resistance over the range of parameters.

Koichi Nishino, Shigemasa Yamashita and Kahoru Torii (1995) [5] studied the thermal contact conductance in vacuum environment under a low applied load with square test plate made of aluminum alloy. The experimental data for the thermal contact conductance are presented for two kinds of contact geometries; flat and rough. Also, developed a new technique for predicting thermal contact conductance in practical engineering applications which utilized a pressure measuring film that provided information about the contact pressure distribution.

Marcia B. H. Mantelli, M.R. Sridhar and M.M. Yovanovich (1995) [6] Studied the influence of the use of plastic and elastic models in the determination of the overall thermal resistance of bolted joints in vacuum conditions. The bolted joint studied is composed of two plates, which are fastened by a bolt. For this configuration, the use of plastic or elastic contact model had a small influence in the overall thermal resistance of bolted joints. This occurred because the magnitude of the contact resistances found in the junction were small when compared with the other resistance (constriction and material). Therefore, it is recommended that the choice of the deformation model should be based on the availability of the physical properties and the geometric parameters.

Seri Lee, Seaho Song, Van Au, Kevin P. Moarn (1995) [7] predicted an analytical model of constriction/ spreading resistances associated with heat transfer from various electronic components. Dimensionless expressions in the form of infinite series are provided for computing the average and maximum constriction resistance as a function of relative contact size, plate thickness and the Biot number.

A.M.Khounsary, D.Chojnowski, and L. Assoufid (1997) [8] measured the thermal contact resistance across a silicon-copper interface. They showed the variation of thermal contact conductance as function of applied interface pressure for Cu-Si interface. Various interstitial materials investigated include indium foil, silver foil and liquid eutectic (Ga-In-Sn).

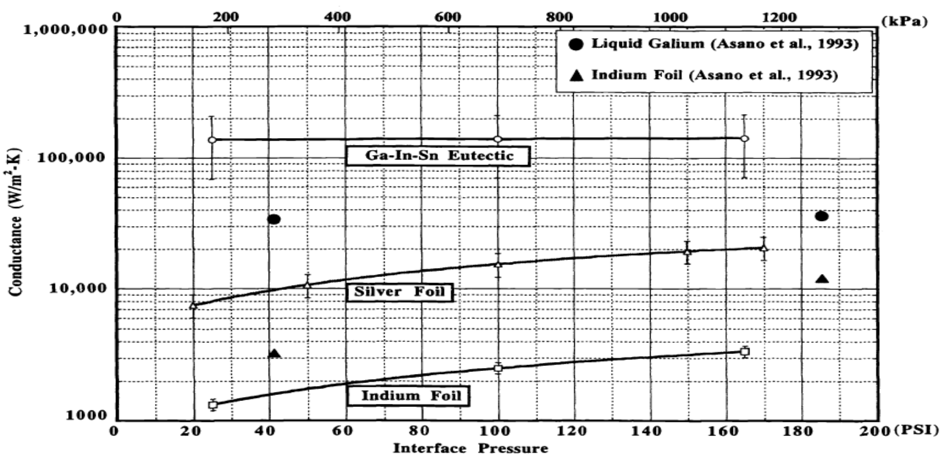

Figure 2.1 Variation of thermal contact conductance with pressure across a silicon-copper interface with indium foil, silver foil, or an In-Ga-Sn eutectic [8]

As expected, thermal contact resistance decreased as interface pressures increased, expect in the case of the eutectic, in which it was nearly constant. The softer the interstitial material, the lower the thermal contact resistance. Liquid metal provides the lowest thermal contact resistance across the Cu-Si interface, followed by indium foil, and then the silver foil. Thermal contact conductance increases as interface pressure is increased because of increased deformation of interstitial material leading to larger contact area. Errors arise from inaccuracies in temperature measurement, thermocouple location, thermal conductivity data used, heat flux measurements and estimation of the temperature drop across the interface a linear temperature profile. The results of that analysis indicate about 47%, 29%, 11 % uncertainty in the thermal contact conductance values for Ga-In-Sn, indium, and silver interstitial materials, respectively.

E.G. Wolff and D.A. Schneider (1998) [9] Studied that effect of pressure, surface roughness, material hardness and thermal properties of the interface material on thermal contact resistance between two smooth surfaces, also, predicted temperature discontinuities when solids, fluids or gases are present in the interface. The guarded hot plate method for thermal conductivity measurements was chosen to determine temperature drops across interfaces like air gap, annealed copper plate foil, indium foil, Teflon foil, heat sink compound and silver paint. Silicone based heat sink compound and silver paint improved the conductance more than metallic foil such as indium & annealed copper. Also, Teflon tape showed increasing conductance with increasing load up to 45.4 kg, but little improvement when the load was increased to 113.4 kg. Both the indium & annealed copper foil showed an increase in conductance as the load was increased.

Syed M.S. Wahid, C.V. Madhusudana (2000) [10] Studied that experimental measurement of thermal contact conductance across the gap filled with either single or a mixture of gases. The interface fluids used were helium, argon, Carbon dioxide, nitrogen and mixture of argon and helium. It also proposes a correlation for the estimation of the gap conductance.

D.D.L. Chung (2001) [11] reviewed materials for thermal conduction include materials exhibiting high thermal conductivity, as well as thermal interface materials. It included metals, diamond, carbon, graphite, ceramics, metal-matrix composites and ceramic-matrix composites. Also, included were polymer based pastes, silicate based pastes and solder. Materials of high thermal conductivity are needed for the conduction of heat for the purpose of Heating or cooling. Also, reviewed copper is best material for thermal conduction because of high thermal conductivity, high coefficient of thermal expansion and does not suffer from the corrosion & Aluminum is best due to low density, light weight, low cost and low melting point (660^{o}C).

V. Sartre, M. Lallemand (2001) [12] Carried out experimental study, the performance of various interstitial materials, used to enhance the thermal contact of electronic assembly.

Test specimens	Cu-Al (127mm × 127mm × 4mm)
Surface roughness	Cu: 16µm and Al: 0.4-0.5 µm
Interface material	7 commercial grease and 12 foils (thickness: 0.2-2.2mm)
Torque	variable
Pattern Configurations	6 screw

Results/Conclusions: Results show that the most influential parameter is the applied torque. The contact resistance decrease as the heat flux or the film thickness decreases. The highest dimensionless contact conductance factors (E) are achieved with greases ($3 < E < 6$). Phase change material-coated foils exhibit E-values ranging from 2.5 to 3.5. Graphite or metallic foils have E-values lower than 2 and for silicon foils E is significantly reduced ($E < 1$). Thus, phase change material-coated foils seem to be very promising materials, since they are efficient, easy to implement and do not migrate and vaporize out of the contact area.

J.P. Gwinn, R.L. Webb (2003) [13] found that current test methods do not reliably define the thermal resistance of a TIM in an actual CPU/heat sink application, because the thermal resistance is sensitive to flatness, roughness and contact pressure. Surface roughness, flatness, and contact pressure are critical factors in affecting the performance of TIM. There is need to develop an acceptable cleaning method to remove TIM material from the surface pores of interfacing test surfaces. The highest performance interface materials available today are greases and PCM (metal and non-metal). The Penn state LMTA has performance competitive with the best thermal greases, but does not have their disadvantages.

C.L.Yeh, Y.F. Chen, C.T. Wen, K. T. Li (2003) [14] Experimentally investigated thermal contact resistance of aluminum honeycomb (made of Al3104-H19 and Al3003-H16) sandwiched by two aluminum blocks was conducted specimens aligned in either axial or lateral orientations. Honeycombs adopted include two different cell diameters (dc), 6.3 and 12.7 mm, as well as two different axial heights (Hz), 7.8 and 14.8mm.For Axial tests, Honeycombs sandwich specimens were joined by four or eight pieces of bolts with an applied torque ranged from 1 to 6 Nm. The interfacial contact pressure was measured by pressure measuring film. For lateral tests, the honeycomb was simply inserted between two aluminum blocks without using bolts to fasten. Results showed that the thermal contact conductance of axial honeycomb is greater than that of honeycomb in the lateral orientation under the condition with the same specimen height. An increase of either the cell diameter or specimen height of honeycomb lead to a decrease of axial total conductance. Moreover, the axial total conductance was substantially enhanced by a doubling the number of bolts used in the assembly of honeycomb specimens. It was found that the contact pressure of bolt-joined honeycombs in the interface increase evidently with an increase of either the bolt torque or the number of bolts. The empirical correlations between contact pressure and applied torque were also obtained for different joint conditions.

I. Savija, J. R. Culham, and M.M. Yovanovich (2003) [15] reviewed analytical and empirical models for calculating the thermal conductance across mechanically formed joints conductance models that dealt with interstitial substances, films and coatings for the enhancement of thermal joint conductance of conforming, rough surfaces and provided an effective procedure for determining the significance of properties in the predication of contact, gap and overall joint conductance. Finally, founded numerous micro and macro surface characteristics and surface micro hardness are required to characterize properly the mechanical and thermal response of joints to load and heat transfer.

M. Rosochowska, K. Chodnikiewicz, R. Balendra (2004) [16] proposed a new method of measuring thermal contact conductance. Experiments were conducted on thin cylindrical specimens retained under axial pressure between two tool surfaces. A clear advantage of this method was the ability to measure the conductance under continuously sustained thermal conditions and under pressure of the yield strength of the work material. Experimental results were provided and experimental errors were defined.

S. Sunil Kumar, K. Ramamurthy (2004) [17] determined the influence of interface temperature in the range of 50-300K on thermal contact conductance between aluminum-stainless steel joints. Experimental investigations showed that the variation of thermal contact conductance due to changes of interface pressure are less at the lower values of interface temperatures. Also, the variation of thermal contact conductance with changes in surface roughness is likewise found to be small at low temperatures.

V.V. Rao, M.V. Krishna Murthy, J. Nagaraju (2004) [18] carried out thermal contact resistance across AL_2O_3/AL-ALN type metal matrix composite (MMC) contact in vacuum at different pressures. Also, experimental results were compared with the theoretical models available in the literature for metallic contacts. The Experimental investigations conducted on AL_2O_3/AL-ALN MMCs showed that thermal contact conductance increases, as a function of contact pressure and it is weak function of mean interface temperature.

Vishal Singhal, Paul J. Litke et al. (2005) [19] developed the numerical model for prediction of thermal contact conductance at metal to metal contact interfaces. Using the model, it was shown that contact conduction can be predicted from a knowledge merely of the surface topography and material properties of the two contacting surfaces for a given contact pressure and apparent area of contact. Studied was the effect on thermal contact conductance of variations in interface pressure, surface finish, and types of materials.

Ruiping Xu, Lie Xu (2005) [20] Carried out the study of effect of surface topography and interfacial temperature on the thermal contact conductance of the pressed stainless steel 304 contacts in the range 125-210 K and 1-7 MPa in the vacuum environment (0.02 Pa). The surface roughness of the test specimen was between 1.5μm and 17.6 μm.

At low temperatures, the hardness of the stainless steel increased as the temperature decreased. The increment of the hardness gave rise to small real contact area and small conductance. The small conductance at low temperature ascribed partly to the small thermal conductivity. Since the low temperature gave rise to the small thermal conductivity and the hardness for the stainless steel, the low temperature resulted in the bad contact heat transfer.

It was showed that the thermal contact conductance decreased with the increased roughness and the ratio of rms roughness to mean absolute slope (σ/m).

Majid Bahrami, M. Michael Yovanovich, J. Richard Culham (2005) [21] Carried out parametric study revealed that the elastic deformation effect was an important phenomenon at low contact pressures. The effect of elastic deformations was investigated beneath the plastically deformed micro contacts on TCR. Also, model was compared with experimental data and good agreement was observed at low contact pressures.

G.P. Voller, M. Tirovic (2007) [22] analyzed thermal contact resistance across bolted joint in commercial vehicle disc brake. Work dealt with the surface morphology of measuring TCR and defining its relationship with the change of interface pressure, temperature and interface conditioning. Approach ensured results of a generic nature applicable to a variety of bolted joints.

C. Fieberg, R. Kneer (2008) [23] determined thermal contact resistance between steel-aluminum and steel - steel at transient temperature in the range of 60^oC to 280^oC where pressure varied from 7.5 Mpa to 85 Mpa. The results showed thermal contact resistance was almost linear dependent on contact pressure, whereas the temperature influence for the investigated temperature range seem to be negligible.

Prashant Mishra, J. Nagaraju (2010) [24] measured thermal contact conductance between oxygen free high thermal conductivity Cu and brass in vacuum, nitrogen and argon environments. It was observed that the thermal contact conductance in gaseous environment was significantly higher than that in vacuum due to the enhanced thermal gap conductance. In gold plated contacts, thermal gap conductance showed an increase with increasing gold plating thickness.

Wang Zongren, Yang Jun, Wang Shuang, Zhang Weifang (2013) [25] measured the thermal contact conductance (TCC) between interfaces of two contact solid materials GH4169 & K417 and new compensating heater was proposed to better achieve the one dimensional axial heat transfer. The measured values of TCC with and without compensation heater were studied and compared. The result showed that the measured TCC with compensation heater was larger than that without compensation heater under the same condition and the compensation heater worked better at high temperature

Donghuan Liu, Yan Luo, Xinchun Shang (2015) [26] experimentally investigated thermal contact resistance between high thermal conductivity C/C material and Inconel 600 at very high temperature (more than 300^{o}C). Results showed that thermal contact resistance between two materials was about 5×10^{-5} m^2K/w under the pressure of 2.82 Mpa. Also, Show that Thermal contact resistance was strongly pressure and temperature dependent.

P.E. Larry, Rick Schlobohm and Bill Brownell [27] compared mechanical and electrical properties of Copper (cu) and Aluminum (Al). It was concluded that for applications, where weight was concern, Al may be the better choice depending on the equipment type and its application. If space and size were a consideration, Cu may be the better choice. Also, Al was selected for its particular specification like less weight, cost. Whereas Cu was elected for its particular specification like High thermal conductivity, low thermal expansion coefficient, high tensile strength.

4.CONCLUSION

From the literature study, it is concluded that significance work has been done on thermal contact resistance (TCR). It has been observed that

1) Thermal contact resistance (TCR) depends on applying pressure, temperature at interface, surface morphology, interface material and hardness
2) As pressure increase a greater asperity deformation happens and the thermal contact resistance reduces.
3) In case of bolted joints, For example, as the pressure is non-uniformly distributed, the heat flux lines are distorted. The thermal contact resistance is minimal under the bolt head and steeply increases with the distance from the bolt centerline.
4) Thermo physical properties of contacting materials like's high values of thermal conductivity and thermal expansion coefficient have favorable effect on the resistance. As thermal conductivity and thermal coefficient vary with the temperature, the thermal contact resistance depends on the temperature at the interface
5) The surface characteristics such as flatness, waviness and roughness have major impact on the thermal contact resistance. It decreases surface flatness and decreases in waviness & roughness
6) Interface material likes grease, oil, gases and foils between two surfaces are the most popular to reduce the thermal contact resistance. Thermal contact resistance is least for foils compared to grease and grease filled with powder. The best thermal performance was observed for indium, lead and tin foils, which are softer than aluminum or copper foils.
7) Another parameter that controls the thermal contact resistance is the hardness which affects the deformation amplitude of the surface under a load. Softer the material, lesser the thermal contact resistance. Under a given load, the asperity deformation is grater for a soft material than for a hard one. Hence, the effective contact surface area is larger and the thermal contact resistance reduces.

REFERENCES

PAPERS

[1] M.M.Yovanovich, "Thermal Contact Conductance of turned surfaces," Aerospace science pp. 71-80, 1971.
[2] C.V.Madhusudana, "The Effect of interface fluid on thermal contact conductance," International Journal Heat and mass Transfer, vol. 18, pp. 989-991, 1974.
[3] P.W.O'Callaghan, S.D.Probert, "Reducing the Thermal Resistance of a Pressed Contact," Applied Energy, vol. 30, pp. 53-60, 1988.
[4] S.Lee, S.Song & K.P.Moran, M.M.Yovanovich, " Analytical modeling of thermal resistance in bolted joint", Enhanced cooling Techniques for Electronics Applications ASME, pp. 115-122, 1993
[5] Koichi Nishino, Shigemasa Yamashita and Kahoru Torii, " Thermal contact conductnace under low applied load in a vacuum environment" Experimental Thermal and Fluid Science, pp. 258-271, 1995.
[6] Marcia B.H. Mantelli, M.R. Sridhar and M.M.Yovanovich, " Influence of elastic and plastic contact models on the overall thermal resistance of bolted joints", Eleventh IEEE SEMI, pp.39-47.
[7] Seri Lee, Kevin P. Moran, Seaho song, Van Au "Constriction/Spreading Resistance Model For Electronics Packaging," ASME/JSME Thermal Engineering Conference, vol. 4, pp. 199-206, 1995.
[8] A.M.Khounsary,D. Chojnowski, L. Assoufid, "Thermal Contact Resistance across acopper -silicon interface," SPIE, vol. 3151, pp. 45-51, 1997.
[9] E.G.Wolff, D.A. Schneider "Prediction of thermal contact resistance between polished surfaecs," International Journal Heat and mass Transfer, vol. 41, pp. 3469-3482, 1998

[10] Syed M.S.Wahid, C.V.Madhusudana "Gap Conductance in contact heat transfer," International Journal Heat and mass Transfer, vol. 43, pp. 4483-4487, 2000.
[11] D. D. L. Chung, "Materials for thermal conduction," Applied Thermal Engineering, vol. 21, pp. 1593-1605, 2001.
[12] V.Satre, M. Lallemand "Enhancement of thermal contact conductance for electronic systems," Applied Thermal Engineering, vol. 21, pp. 221-235, 2001.
[13] J.P.Gwinn, R.L.Webb "Performance and testing of thermal interface materials," Microelectronic Journal, vol. 34, pp. 215-222, 2002.
[14] C.L.Yeh, Y.F.Chen, C.Y. Wen, K.T. Li "Measurement of thermal contact resistance of aluminum honeycombs," experimental Thermal and Fluid Science, vol. 27, pp. 271-281, 2003.
[15] I.SAvija, J. R. Culham, M.M.Yovanovich, "Review of thermal contact conductance models for joints incorporating enhancement materials," Journal of thermophysics and heta transfer, vol. 17, pp. 43-52, 2003.
[16] M.Rosochowska, K.Chodnikiewicz, R. Balendra, "A new method of measuring thermal contact conductance," Journal of materials and processing technology, vol. 145, pp. 207-214, 2004.
[17] S.Sunil Kumar, K. Ramamurthi, "Thermal Contact Conductance of Pressed contacts at low temperature," Cryogenics, vol. 44, pp. 727-734, 2004.
[18] V.V.Rao, M. V. Krishna Mrthy, J. Nagaraju, "Thermal Conductivity and thermal contact conductance studies on Al2O3/Al-AlN metal matrix Composite," Composites Science and Technology, vol. 64, pp. 2459-2462, 2004.
[19] Vishal Singhal, Paul J.Litke, Anthony F. Black, Suresh V. Garimella, "An Experimentally validated thermo-mechanical model for the prediction of thermal contact conductance," Internatiional Journal Heat and mass Transfer, vol. 48, pp. 5446-5459, 2005.
[20] Ruiping Xu, Lie Xu "An Experimental Investigation of thermal contact conductance of stainless steel at low temperatures," Cryogenics, vol. 45, pp. 694-704, 2005.
[21] Majid Bahrami, M.Michael yovanovich, J.Richard Culham, "Thermal Contact resistance at low contact pressure: Effect of elastic deformation," International Journal Heat and mass Transfer, vol. 48, pp. 3284-3293, 2005.
[22] G.P.Voller, M. Tirovic "Interface pressure distributions and thermal contact resistance of a bolted joint," Mathematical Physical & Engineering Sciences, vol. 461, pp. 2339-2354, 2005.
[23] C.Fieberg, R.Kneer, "Determination of thermal contact resistance from transient temperature measurement," International Journal Heat and mass Transfer, vol. 51, pp. 1017-1023, 2007.
[24] Prashant Misra, J.Nagaraju, "Thermal gap conductance at low contact pressure(<1MPa): Effect of gold plating and plating thickness," International Journal Heat and mass Transfer, vol. 53, pp. 5373-5379, 2010.
[25] Wang Zongren, Yang Jun, Wang Shung, Zhang weifang, "Compensation Heating Technique for experimental investigation of thermal contact conductance across GH4169/K417 interface," Sciencedirect vol. 42, pp. 1572-1575, 2013.
[26] Donghuan Liu, Yan Luo, Xinchun Shang, "Experimental Investigation of high temperature thermal contact resistance between high thermal conductivity C/C material and Inconel 600," International Journal Heat and mass Transfer, vol. 80, pp. 407-410, 2014.
[27] Larry Pryor P.E, Rick Schlobohm P.E, and Bill Brownell P.E, " A Comparison of Aluminum Vs. Copper as used in Electrical Equipment"

BOOKS

[28] F.P.Incopera,D.P. Dewitt, Fundamental, Fundamentals of Heat and mass Transfer, Sixth edition, willey, New york, pp 57-101,2005
[29] Y. A. Cengel, Heat Transfer: A Practical Approach, Second Edition., McGraw-Hill publication, pp 2-40 & 128-143, 2003
[30] Holman J.P. Heat Transfer, Tenth Edition, McGraw Hill Publication,pp 1-57, 2010
[31] Lienhard IV & V John H. A Heat transfer textbook, Third Edition, Phlogiston press, Cambridge, U.S.A, pp 3-96, 2008
[32] T.F.Irvine Jr. Themal contact resistance, Hemisphere publishing corporation, pp 2.4.6.1-2.4.6.4, 1983

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