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Steady state experimental investigation of thermal contact conductance between curvilinear contacts using liquid crystal thermography

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ABSTRACT

Heat transfer components comprise of several types of metallic contacts. Commencing from the conventional conforming rough surface contact combinations, the situation might culminate in terms of the complex non-conforming rough curvilinear contacts of the real heat transfer devices. Available theoretical models fail to correctly predict thermal contact conductance (TCC) over the broader range of influencing parameters, even for the simplest geometry, and thus experiments plays a pivotal role in the field. Researchers are indefatigably working for developing accurate experimental methodologies to get precise estimate of TCC, and create broader database of results for upcoming theoretical models.

In this regard, this paper presents steady state thermal contact conductance analysis on two solid bodies of brass, carrying flat and curvilinear contact combinations, under variable loading conditions ranging in between 0.27 and 4.0 kN. A customized and standardized experimental set up has been used to measure steady state TCC for three different types of geometrical configurations, which are flat-flat, cylinder-flat and cylinder-cylinder contacts. At the start, TCC has been evaluated on the basis of centrally placed high response, super accurate, ungrounded thermocouples, which are mounted axially across the contacting bodies. In the later part of the paper, an optical, non-invasive and inexpensive method, based upon liquid crystal thermography (LCT) has been implemented to get the precise estimate of TCC for different configurations under consideration. The region close to the interface, which has the profound effect on the axial temperature distributions, is identified. Eventually, the separation region, where dramatic variation in the thermal conductivity occurs and classical Fourier law tends to fail has been identified. The separation region is further segregated in sub-regions on the basis of distinct temperature zones, which allows estimating the effective thermal conductivity of the materials in gap. The precise temperature jump close to the interface is extrapolated, and consequentially used to predict the steady state TCC for all three geometrical configurations. The value of TCC is evaluated again on the basis of effective thermal conductivity concept, and the results have been compared together. The present investigation establish a unique methodology for TCC estimation on the basis of steady state liquid crystal (LC) measurements, and provide valuable insight of heat transfer across the curvilinear contacts, and can be treated as the base line measurements for any of the upcoming scale resolved numerical models.

1. Introduction

Accurate knowledge of heat transfer occurring through interfaces of metallic bodies in contact is of great concern in the designing of microelectronics cooling, nuclear reactor cooling, heat exchangers and thermal control systems for spacecraft applications. Furthermore, many of the times, the interface resistances might be small, however they becomes critical in structures where there are numerous interfaces, such as super-lattices and ultra large scale integrated circuits. Evidently, the heat transfer across the interface is influenced by a number of parameters, including the thermophysical and mechanical properties, surface roughness and contact loading. When two solid surfaces form a contact, presence of surface roughness limits their physical contacts to a limited

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number of discrete points at their interface. This imperfection causes a constriction in the heat transfer at the interface termed as thermal contact resistance and its reciprocal is called thermal contact conductance (TCC) and is defined as:

$$h = \frac{Q/A_c}{\Delta T} = \frac{q}{\Delta T} \tag{1}$$

where Q is the heat transfer through the interface of two contacting solid, A_c is the contact area, $\varDelta T$ is the temperature jump at the interface, and q is the average interfacial heat flux.

A large number of theoretical and experimental investigations on interfacial heat transfer have been carried out over the last five decades as compiled by Yovanovich [1] and Fletcher [2]. Cooper et al. [3] developed surface deformation model as well as thermal model to predict thermal contact resistance which became a benchmark for many models developed subsequently. Later, Mikic [4] proposed theoretical formulations of TCC on the basis of modes of deformation of contact surfaces for nominally flat surfaces. Jeng et al. [5] developed a TCC model by considering elastic, plastic and elastoplastic deformation of the asperities and compared the predicted results with the experimental data. Most of the theories tend to overpredict or underpredict the estimated TCC derived from the experimental measurements as models and correlations developed are suitable for only limited conditions. Recent work [6] highlighted the limitation of available models in which the fraction of proposed real contact area is relatively small and the contact spots are assumed to be circular and separated. It was also argued that these aforesaid two assumptions were not valid in the conditions characterized by large fractions of real contact area. These limitations of models make the experimental investigation, still an effective way to estimate the TCC for practical applications.

Based upon the detailed literature review, it has been observed that most of the experiments were performed to quantify TCC for typical flat-flat contacts. Sridhar and Yovanovich [7] performed experiments on tool steel specimens for flat-flat contacts and proposed elastoplastic model for estimating TCC. Yuncu [8] did extensive experiments on 26 pairs of steel, copper, brass and aluminum specimens and proposed that dimensionless TCC across the contacting solid spots depend on dimensionless contact pressure. Misra and Nagaraju [9] did an experimental study on flat-flat contacts to show the presence of thermal stress in contacts and its effect on TCC. Tariq and Asif [10] performed steady state experiment to calculate solid spot conductance for several experimental parameters and compared the results with the existing theoretical models. It was observed that most of the available theoretical models had limitation in correctly predicting TCC within the range of experimental parameters. Later, based upon the non-dimensional parameters, suitable generalized correlations of TCC for nominally flat metallic contacts were presented by Asif and Tariq [11] in order to fulfill the obligations for the design engineers/researchers.

Veering away from the flat-flat metallic contact, very limited amount of investigations were performed on contact conductance for cylindrical and cylinder-flat contacts due to their complex geometrical arrangements. Evidently, the value of TCC across cylindrical and cylinder-flat contacts is an important consideration for the design of a thermal system in an industry. Ayers [12] reported diverse applications of cylindrical contacts such as composite cylindrical tanks, space structures, power transmission lines, electronic devices, nuclear fuel elements, air conditioning systems, and pipelines. Madhusudana [13] presented an analysis for the prediction of the thermal conductance of cylindrical joints for radial heat flow. The value of TCC depends on the geometrical, thermos-physical and surface properties of the cylinders as well as heat flux and maximum operating temperatures. The developed theoretical model was compared with the experimental data of other researchers with minimal information on surface parameters and maximum temperature rise. Kumar et al. [14] developed a mathematical model to predict TCC between curvilinear surfaces and conducted experiments in vacuum for the measurement of TCC between stainless steel and aluminum cylindrical contacts over a range of contact pressure. It was found that the value of TCC was of lower magnitude in cylindrical contacts as compared to flat contacts. Mcgee et al. [15] presented a line contact model for the thermal resistance of a cylinder-flat contact, and compared the results with the experimental measurements. It was observed that the validity of line-contact model was dependent on limiting minimal contact loading, and below a certain value of load parameter large errors were reported along the contacting surfaces. Evidently, due to the lack of reliable theoretical models for cylinder-flat and cylindrical contacts, it is difficult to predict a definite value of TCC for any practical application. Complexity of the field calls for the dismal need towards reliable experimental investigations to predict the TCC for different curvilinear contacts, which can also act as the reliable database towards validating any of existing and upcoming theoretical modelling for estimating TCC [10].

As far as the methodologies for estimating the TCC are concerned, there exist two way to predict the TCC, namely steady state method and transient method. Zhang et al. [16] discussed about the relative merits and demerits of transient and steady state methodologies stating that, the transient experiments are of short duration compared to long duration steady state experiments. However, due to the greater precision and reliability, the steady state methodologies have been emphasized as standard procedure to determine the TCC as compared to the transient approach. Among all these experiments, thermocouples are the most conventional and widely used intrusive measurement of temperatures inside a heat conducting body. In TCC experiments, obtaining accurate interface temperature is quite essential for the correct assessment of interfacial temperature jump. In the conventional approach, temperature jump across the interface is estimated by extrapolating temperature gradient measured far from the interface. Significant work on extrapolation error was published by Thomas [17]. As much as 19% extrapolation error was reported in the calculation of interfacial temperature jump. This extrapolation error will substantially affect the correct realization of TCC. Several researchers have explained the demerits and limitation of intrusive way of temperature measurements. Woolley and Woodbury [18] reported that the use of thermocouples inside a heat conducting body distorts the temperature field in the body and which may lead to a significant bias in the temperature measurement. Fieberg and Kneer [19] noted that temperature measurements with thermocouples modifies the thermal behavior of the bodies and tend to give inaccurate TCC results. Evidently, TCC estimate is strongly influenced by the uncertainty in elemental temperature measurement, and the degree of correct estimate of temperature jump at the interface, and therefore dismal need exist to look forward with available non-invasive tools in the field of TCC estimation.

Furthermore, the accuracy of interfacial temperature gradient is one of the major parameter which directly influences the TCC estimation while using the steady state approach. The sharp temperature drop at the interface is the outcome of the remarkably low value of real contact area (<2%) between the mating surfaces due to restricted asperities contact spots [20], which are generally of the order of few microns in height even for the smoothest surfaces. Lot of effort has been made in past, and researchers are still struggling to develop the multi-asperity theories to correctly predict the real contact area, hence in general the existing theories are believed to give correct results only for very small loads and limited contact