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A test-validated prediction model of thermal contact resistance for Ti-6Al-4V alloy

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HIGHLIGHTS

- Proposed a thermal contact resistance prediction model.
- Radiation effect whether to be considered is analyzed.
- The prediction model is experimentally validated.

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ABSTRACT

The precise prediction or test of thermal contact resistance is a key issue on increasing or decreasing thermal energy transmission efficiency between two solids. This paper raises a thermal contact resistance prediction model based on measuring actual surface topography under different loading pressures and different heating temperatures. The actual topography of contact surfaces is measured by a 3-D optical microscope named Bruker Contour GT-K. The contact surfaces are reconstructed with language Python according to the data of surface topography from the microscope and the numerical contact model is generated. Then the thermal contact resistance simulation is implemented with software ABAQUS. Based on the elastic-plastic constitutive equations and steady state heat conduction theory, finite element analysis of mechanical and heat transfer performance of the contact model is performed with ABAQUS in the light of sequential coupling method. The studied material pairs are Ti-6Al-4V—Ti-6Al-4V with three kinds of different interstitial material e.g., vacuum, air and conductive silicone grease. The effect of radiation on thermal contact resistance under air and vacuum atmosphere is further studied and analyzed. Besides, the solid thermal conductivity on thermal contact resistance is investigated. To verify the accuracy of the method, the simulated results from ABAQUS are compared with the experimental results of air gap with the same boundary conditions. The maximum deviation between simulation results and experimental results is 9.57% while 75% of the deviations are within 5%. A correlation of thermal contact conductance with the average contact surface temperature and loading pressure is proposed. The results show that this method has high precision to predict thermal contact resistance in the engineering application.

1. Introduction

Thermal contact conductance (TCC), which is the reciprocal of thermal contact resistance (TCR), has been utilized extensively in academics and industry, especially in the superconduction, cryogenics, nuclear industry, aircraft industry, spacecraft and satellites, microelectronics, nano-technologies, etc. [1]. Some applications, where a low value of the TCR is necessary. For example, cooling in electronic systems [2] and the fuel/can interface of a nuclear reactor [3]. Since the conduction through the contact interface is the first way to transfer the heat dissipated by the high power density chips, reducing the TCR becomes essential for the cooling technology development. The interfacial insert of appropriate material is adopted to minimise the thermal resistance of the metallic contacts [4]. The temperature difference between uranium dioxide fuel and the zircaloy sheath can reach several scores of degrees if the contact between them is poor. This can lead to overheating and potential melt down. On the other hand, there are several instances where a high value of TCR is desirable. In aerospace fields, the higher TCR is expected between the outer layer material and structure of aerodynamically heated supersonic flight vehicles. The

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higher TCR between the individual particles of a stationary packed bed can increase the effectiveness of the insulation. Therefore, during the past decades, numerous studies have been conducted to determine the TCR between various materials. A brief review will be conducted first for the experimental studies after the year of 2000 and followed by the theoretical considerations, prediction methods and models since 1974. In the experimental aspect, one dimensional steady state method is the most widely used method to measure TCR based on the ASTM standard D5470-06 [5], and the following order is listed according to the different measuring temperature. For room temperature, Madhusudana experimentally studied the effect of heat losses to the surroundings and analyzed the accuracy in TCC experiments [6]. Ding and Wang experimentally investigated the TCC of stainless steel-GFRP interface under vacuum environment [7]. Zhang et al. established a high-precision instrumentation to measure TCR using reversible heat flux mainly for electronic devices [8]. For high temperature, Liu et al. conducted experimental investigation on the TCR between high thermal conductivity C/C material and Inconel 600 up to 800 K [9]. For cryogenic temperature, Choi and Kim carried out experiment on TCR between metals below 100 K [10]. As indicated in the comprehensive review paper by Yovanovich that experiments can provide very limited and insufficient data of the TCR [11]. Meanwhile, with the fast development of computer industry and numerical methods, numerical modeling and simulating TCR becomes a more and more feasible and important approach. Numerical results of TCR simulation can provide the details of surface contacted locations which are beneficial to understand the mechanisms. Generally speaking, numerical simulation of TCR involves several aspects, including the descriptions of surface topography, the analysis of micro mechanical deformation, and the heat transfer models [1]. The contact surface topography should be described and reconstructed firstly. In this regard, the frequently-used methods can be classified into two categories: statistics of the roughness profile [12] and methods based on fractal theory [13]. The above two methods have the common characteristic that the roughness height is supposed to conform to a certain distribution function. Then the integral of the function can be adopted to figure up the number of contact spots or actual contact area. However, a number of assumptions are usually applied in these methods, leading to a great uncertainty of the results. Pennec et al. carried out the actual surface scanning work which decreased substantial uncertainty together with finite element modeling [14]. The deformation of the contact spots should be analyzed secondly. There are three deformation models: elastic, elastic-plastic and plastic. Different deformation models are mainly related to the loading pressure. Mikic [15] proposed an elastic contact model and investigated the effects of the three modes of deformation on the value of contact conductance and presented the criteria by which the deformation mode can be determined. Cooper et al. [16] proposed a plastic contact model and Yovanovich [17] proposed a further improvement of this model. Bush and Gibson adopted elastic and plastic modes of surface deformation to study the variation of thermal conductance with applied load [18].

Sridhar and Yovanovich presented an elastoplastic contact conductance model for isotropic conforming rough surfaces and compared the results with experiments [19]. The purposes of all the deformation models are to get the distribution of contact spots and the real contact area under tested contact conditions. To finally acquire the TCR values for a test condition, some specified methods and heat transfer models should be employed. Cui et al. carried out a multiscale simulation with coupling the lattice Boltzmann (LB) method and the traditional finite difference (FD) method to calculate the heat transfer between two rough surfaces in electronic packaging. The LB method and the FD method are, respectively, applied to two different regions with different meshes (fine meshes and coarse meshes) [20]. Verma and Mazumder extracted the TCC from temperature and heat flux distributions obtained from direct numerical simulations of heat conduction across the interface. No assumptions are made pertaining to the shape, size, and height of the asperities and ensuing contacts, the topography of the interface is stochastically reconstructed from commonly measured surface roughness descriptors [21]. Zou et al. developed a random number model based on fractal geometry to calculate TCC [13]. Murashov and Panin numerically simulated the contact heat transfer problem of hardened rough surfaces [22]. A basic work with surface scanning and the use of FEM for the thermal contact conduction calculation from Thompson should be acknowledged [23]. Similar conclusions are drawn about the effect of the medium in the gap in that thesis. Gou et al. proposed an approach to predict TCR based on the practical topography of the two rough surfaces using ANSYS [24]. In their study two material pairs Ti-6Al-4V—Ti-6Al-4V and C/C-SiC—high temperature ceramic (HTC) were investigated and relatively good results were obtained. From the brief review of the existing references the present authors consider that several aspects of the model and method still can be modified to improve the accuracy and efficiency. Firstly, in the previous work the radiative heat transfer influence on the TCR is neglected [22,24]. This influence is especially important for high temperature cases because TCR is positively correlated with the average temperature of the contact surfaces. Secondly, the thermal conductivity of the material used in the heat transfer model are usually based on the arithmetic mean temperature not the material regionally local temperature which could decrease the accuracy of the heat transfer model. Finally, the gap conductance is simplified by an empirical parameter TCC and an average gap distance. In fact, there are numerous contact pairs filled with gap to conduct the heat from the high temperature surface to the low temperature surface with individual gap conductance instead of an empirical parameter TCC. In order to overcome the above three inefficiencies, a more comprehensive predict model for TCR highly needs to be developed. This new model can deal with the above stated three main drawbacks.

In this paper, a new predict model is proposed to obtain the TCR of a pair of contact surfaces of Ti-6Al-4V—Ti-6Al-4V which are processed by the sand blasting and the roughness is obvious larger than the previous pair presented in reference [24]. The surface topography is acquired from the 3-D optical microscope which has a resolution in height measurement of 0.1 nm; and the measured coordinates of the roughness distribution are used to generate the numerical grid points. Then the commercial software ABAQUS is employed to implement the TCR calculation. Besides, the TCR for 12 cases under air gap with different temperatures and loading pressures are experimentally measured by a specially design test apparatus based on 1-D steady state heat flux method. The numerical results of all cases agree very well with the experimental data. In the following, the numerical model will first be presented (Section 2), focusing on how to transfer the measured surface roughness to the software ABAQUS as input data to reconstruct the rough surface. The numerical methods are fully implemented in ABAQUS generating results with temperature distribution and heat flux. And the numerical TCR can be obtained with data reduction. Then a home-made test platform will be described in Section 3. Both the numerical and test results will be presented and compared in Section 4 and several influence factors affecting on TCR are analyzed. Finally some conclusions are drawn in Section 5.

2. Numerical model

2.1. Test specimen and computational domain

Fig. 1 shows two test specimens Ti-6Al-4V and contact surfaces topography. Fig. 2 shows the schematic diagram of the two specimens and the computational domain studied. The specimen are cylinders with diameter of 48 mm and height of 52 mm. T_1 to T_6 are temperatures obtained from the thermocouples located at the drilled holes in different heights. The distance between the contact surface and the holes at the three levels are 8 mm, 16 mm, 16 mm, respectively. In each level four holes are uniformly located in the circumferential directions and each temperature is acquired from the average temperature of the four