Review and Prospect of Thermal Contact Resistance Models

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Abstract. Multilayer structures are generally used in spacecraft engineering in order to improve high temperature resistance and ablation resistance. Thermal contact resistance (TCR) is an important parameter for determining temperature distribution of multilayer structures. It widely exists in scientific researches and engineering applications. The challenges for research on TCR are analyzed. Then the modeling of surface topography and TCR are reviewed. The future works are prospected in the end.

Introduction

Multilayer structures are generally used in spacecraft engineering in order to improve high temperature resistance and ablation resistance, especially in thermal protection system and rocket motor system [1,2]. Solid propellants and composite nozzles are typical multilayer structures. Under the effect of thermo-mechanical interaction, interfacial debonding phenomena probably occur. Then the mating relationships between components may be changed which convert from adhesive bonding to frictional contact. Because engineering surfaces are often rough and irregular, the imperfect contact creates a resistance, generally called thermal contact resistance (TCR). It is one of the important parameters for determining the temperature distribution of multilayer structures.

Because of complexity, TCR is totally ignored or assumed to a constant value during thermal structural design [2]. Up to now, it is unclear about the influence to thermal structural design. Therefore, the research on TCR is more significant. In this paper, the challenges for research on TCR are analyzed. Then the modeling of surface topography and TCR are reviewed. The future works are prospected in the end.

Challenges for Research on TCR

There are a number of challenges and difficulties for research on TCR. Firstly, surface topography is very difficult to simulate accurately. Surface imperfections such as voids or cracks may be present. Surface damage such as pitting and scratching can further increase the complexity of surface topography. Adhesive change the material properties of contact region. Interstitial material such as air, lubricants, dirt and polymer gas generated by adhesive under high temperature may be present which can affect the mechanical, thermal behavior of the interface. Sporadic contact between two surfaces can result in localized loading which require the inclusion of more advanced modeling including plasticity, fracture and creep [3]. Therefore, surface topography often requires multiphysics modeling to describe mechanical, thermal behavior.

Secondly, it is the multidisciplinary multiscale coupled problem which is difficult to solve. At macroscale, TCR problem includes many disciplines, such as geometry, material science, mechanics and heat transfer. Thermal contact of rough surfaces is essentially a thermo-mechanical interaction problem. It is influenced by material properties, mechanical properties, heat flow direction, surface hardness, contact surface pressure and interfacial material and so on. At microscale, contact between
rough surfaces occurs only at a few individual spots. It is influenced by surface roughness, surface topography and deformations of micro-asperity and so on.

In addition, material properties may be dependent on temperature. For example, elastic modulus and thermal conductivity are temperature dependent. Density is also a function of temperature. The mechanisms of heat transfer also depend on the length scale and temperature. As we know, thermal energy can be transferred between two surfaces by three different modes: a) conduction at the microcontact spot, b) conduction through the interstitial fluid in the gap between the contacting solids, c) thermal radiation across the gap. TCR at macro scale depends on the ratio of solid to interstitial conduction at micro scale. TCR across the contacting asperities at micro scale depends on the ratio of solid to interstitial conduction at nano scale. The nano asperities must support the load from the micro scales, and the micro scale asperities must support the load from the macro scale [3]. Thus, it is difficult to build and solve models with surface topography more than three orders of magnitude in length scale.

TCR problem was simplified in spacecraft engineering. Surface imperfections, damage and effect on interfacial adhesive of material properties were not considered. Interstitial material was assumed to be absent. The radiation heat transfer remains small and can be neglected for surface temperatures up to 700K [4]. The only remaining heat transfer mode is conduction at the microcontacts. The mechanical behavior of contact deformation of micro-asperity includes the elastic deformation [5], the plastic deformation [6] and the elastic-plastic deformation [7]. For more complex mechanical behaviors, such as fracture and creep are rarely considered. Because TCR problem depends on temperature and length scale, it is possible to solve by iterative method, solving the macro, micro, nano scale or even atomic scale. But in spacecraft structures, the feature sizes are far greater than mean free path of thermal carriers, the TCR problem can be solved only by macro and micro two scales [8,9].

TCR Models

Modeling of Surface Topography

Modeling of surface topography plays an important role in TCR problem. Up to now, there are four methods about modeling of surface topography.

The first method is direct simulation method. Based on the optical profilometry, the surface topography is obtained and simulated by using the finite element method [3]. It can give the detailed features of the surface topography, but it is expensive and not easy to calculate the contact problem due to irregular surface topography. Therefore, it is difficult to be applied to spacecraft structures.

The second method is fractal model. The creation of fractal geometry provides a new method for modeling of surface topography. Ji Cuicui et al.[10] used the fractal function of W-M to describe the rough surface topography. Majumdar[11] and Yan et al. [12]used the modified W-M fractal function to describe engineering surface. Warren [13], XU lie et al.[14] used contor fractal theory to describe the surface topography. Jackson [15], Patrikar et al. [16] compared the fractal method with statistical method. Z.Z Guan et al.[17] combined the fractal theory and the microscopic images to construct the rough surface. Fractal theory is independent on the observation scale, and it is of great significance for tribology. However, fractal model is reasonable to engineering surfaces with fractal characteristics. Not all of the engineering surfaces have fractal characteristics. Therefore, fractal model also suffers from limited applicability.

The third method is statistical model. Compared with the direct simulation method and fractal model, the statistical model is a more effective method. The pioneering work of statistical model started with Greenwood and Williamson [5], who modeled the contact between two rough surfaces as the contact between a rigid plane and a sum surface, the equivalent method now adopted by numerous researchers [18-22]. In the GW model, all the asperities were assumed to have the same radius at the summit but randomly varied surface heights with Gauss distribution. There were no interactions
between the asperities. Based on the GW model, the shape of the asperities and distribution of the statistical parameters were further developed. GW model used hemispherical asperities, followed by cuboid [18,23], cylinder[19], cone[24] and other regular shape. Nayak[25] developed a joint probability distribution function of random variables peak height and peak curvature. McCool [26] introduced Weibull distribution of two parameters to describe peak height. Most of the rough contact models were assumed that the deformations of asperities are independent of each other, and this assumption is only suitable to the case of a small load. Ciavarella [27] found that there were great errors between the results of interaction effect and GW model. Jeng and Peng [28] found that the interaction of the peaks had a significant effect on the contact behavior of non-Gauss rough surface.

The fourth method is multiscale model. The earlier multiscale model was proposed by Song and Yovanovich [29]. Although the model does not directly consider the effect of multiscale surface features, in the strict sense, was not a multiscale model, but the use of the empirical microhardness theory appears to have been effective at including these scale effects. With the development of computing, numerical simulation has become popular. Thompson [3] established surface topography by direct simulation method and studied iterative thermal/structural finite element model from macro to micro scale. Tengfei Cui [30] studied TCR of microelectronic packaging by lattice Boltzmann method and finite difference method, and simulated surface topography by direct simulation method.

Modeling of TCR

Based on the modeling of surface topography, the researchers have carried out the studies on TCR. The representative TCR model, CMY model, GW model, BGT model, MA model, MT model and so on was summarized in the literature[29]. The earlier TCR models were analytical, which combined the surface topography and the classical contact mechanics.

With the development of contact mechanics, the contact problem of rough surface can be solved by numerical method. The TCR models are developed to combine the surface topography and the numerical solution. Based on digital simulation to generate rough surface, Yang Guoqing [31] used the finite element method to achieve the real contact area, contact pressure distribution and other contact parameters. Liu Donghuan[19] used the regular shape to simulate rough surface, and built TCR model under high temperature by the finite element method(FEM). FEM can overcome the shortcomings of the analytical model, but it is of great challenges in the calculation of the scale and efficiency, especially for spacecraft structures.

Thompson [3] proposed a multiscale finite element iterative method from macro to micro scale. This method is more in coincidence with characteristics of thermo-mechanical interaction. But with increasing of computing scale, its calculation efficiency is hard to be guaranteed. The constitutive relation of TCR and the separation distance between the two contact surfaces is obtained by Belghith based on the homogenization technique, and the equivalent macro model was constructed, which provided a new method for the analysis of engineering structures [32]. But TCR was based on the finite element analysis of the surface micro asperities model. Therefore, the computation scale is still a very perplexing problem. Based on the elastic-plastic deformation theory proposed by Lin, Hong jun [33] studied the 3D shoulder-shoulder micro asperity contact model of thermal contact conductance combined the statistical homogenization technology, provided an effective method for analysis of engineering structures.

Prospect for Future Works

Based on the research status of TCR of multilayer structure and the features of spacecraft structures, the future works are put forward.

The first is TCR models under high temperature. The existing TCR models are considered to be a vacuum between intervals. It also assumed that surface temperature is not more than 700K and only has heat conduction at the microcontact spot. While the working environment of spacecraft structures is often under high temperature, it is necessary to construct an effective TCR model under high
temperature. The second is the coupled method for multilayer structures considering TCR under high
temperature. The multi-scale finite element iteration method from macro scale to micro scale has
great computation, which is not suitable for spacecraft structures. It is necessary to seek for a more
effective computation method.

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