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Thermal contact conductance of coated surfaces

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Abstract

The thermal contact resistance phenomena are increasingly important as the size of mechanical and electronic components decrease. Applying a coating material with high thermal conductivity is an effective way to enhance the thermal contact conductance. This work conducted an experimental and theoretical study to investigate the effects of diamond film coatings on the thermal contact conductance. A model based on statistical elastoplastic surface contact mechanics was developed to study the thermal contact conductance of coating material. Diamond films were sputtered on the substrate of ceramics by microwave plasma chemical vapor deposition. Test samples have different surface roughnesses, deposition times and deposition qualities. A range of test conditions was conducted to evaluate the thermal contact conductance of coated films and for comparisons with the theoretical model.

Keywords: Thermal contact conductance; Diamond film; Coated surface

1. Introduction

The heat generation within the high-density devices such as integrated circuit chips will cause thermal failure if appropriate techniques are not employed to dissipate the heat generated. Increasing the thermal contact conductance is the desirable way to decrease the operation temperature. When two surfaces are in contact, the presence of surface roughness produces imperfect contact at their interface. In many applications involving rough surface contact, it is important to know the thermal contact resistance through real contact areas. Therefore, there have been many efforts to study the thermal contact resistance.

Cooper et al. [1] developed the pioneering thermal contact resistance model (CMY model) with a surface contact of elastic deformation. This pioneering model laid the foundation for many later studies. Whitehouse and Archard [2] presented a thermal contact conductance model (WA model) with an elastic surface contact. Bush et al. [3] developed an asymptotic thermal contact conductance model (BGT model) to deal with a surface contact of elastic deformation. The paper of Sridhar and Yovanovich [4] summarized a detailed review of the thermal contact conductance models. Later, Sridhar and Yovanovich [5] established a thermal contact conductance model based on an elastoplastic model for sphere-flat contacts. The fundamental difference between these models is the contact deformation model used.

Yovanovich et al. [6] extended the CMY model to study the heat transfer of coated surfaces in contact and established the relationships between modified parameter of contact area heat transfer, contact area and heat transfer coefficient. Antonetti [7] established a theoretical model to study the contact heat transfer of coated surfaces with a plastic surface contact. Williamson and Majumdar [8] developed a thermal contact conductance model to deal with contact heat transfer of coated surfaces with elastic deformation and plastic deformation.

The model proposed in this study is based on the thermal contact model developed by Cooper et al. (CMY model) [1] and modified by Yovanovich et al. [6] to study the heat transfer of contacting coated surfaces. For micro-contact de-

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formation model, the model developed by Greenwood and Williamson [9] is employed to calculate the elastic deformation. The fully plastic deformation is based on a micro-geometry model proposed by Abbott and Firestone [10]. The elastoplastic deformation of asperities was taken into account by using the model developed by Zhao et al. [11]. The model proposed by Zhao et al. [11] considers the continuity and smoothness of variables across elastic, elastoplastic and fully plastic deformation. This work uses the three models to deal with elastic, elastoplastic and plastic deformation, investigating the thermal contact conductance of surfaces with coating material.

Experimental study was also conducted to measure thermal contact conductance of coated surface. This investigation uses microwave plasma chemical vapor deposition (MPCVD) to sputtered diamond film on the substrate of ceramics to make the specimen. Test samples have different surface roughness, deposition time and deposition quality. A range of test conditions was conducted to evaluate the thermal contact conductance of coated films and for comparisons with the theoretical model.

2. Theoretical model

2.1. Surface contact model

The surface contact models proposed by Greenwood and Williamson [9], Abbott and Firestone [10] and Zhao et al. [11] were adopted to characterize the elastic, fully plastic and elastoplastic deformation phenomena of surface asperity contact, respectively.

The interference ω is an important factor to determine the extent of the asperity deformation, which can be defined as follows:

$$\omega = z - d \tag{1}$$

where z is the asperity height measured from the mean of asperity heights and d is the separation based on asperity heights as shown in Fig. 1.

2.1.1. Elastic contact

When the interference ω is small enough, the asperity deforms elastically. The elastic asperity micro-contact model presented by Greenwood and Williamson (GW model) assumed that each asperity on the contact surface is hemispherical with the same radius of curvature R_m and the distribution of the surface asperities is Gaussian distribution [9]. In GW model, the real contact area between two contact surfaces can be described as follows:

$$A_e = A_n \eta \pi R_m \int_d^{\infty} (z - d)\phi(z)\,dz \tag{2}$$

According to Hertz theory and for the geometry of a single asperity with mean radius of curvature R_m and a smooth plate contact under elastic deformation conditions, the relationship between the maximum contact pressure P_m and the mean contact pressure P_a for the asperity can be expressed as [12]

$$P_a = \frac{2}{3} P_m = \frac{4E'}{3\pi} \left(\frac{\omega}{R_m} \right)^{1/2} \tag{3}$$

in which E' is the equivalent Young's modulus of two contact surfaces

$$E' = \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]^{-1} \tag{4}$$

where ν_1 and ν_2 are the Poisson ratios for the two contact materials, respectively. Moreover, E_1 and E_2 are Young's moduli for the two contact materials, respectively. Then Eq. (3) can be rewritten as

$$\omega = \left(\frac{3\pi P_a}{4E'} \right)^2 R_m \tag{5}$$

Tabor [13] showed that when the maximum contact pressure $P_m = 0.6H$, or mean contact pressure $P_a = 0.4H$, the material may reach the yielding point. Therefore, the relationship between the mean contact pressure P_a and hardness of the softer surface can be expressed as

$$P_a = kH \tag{6}$$

By substituting Eq. (6) into Eq. (5), the critical interference for elastic deformation ω_1 can be obtained as

$$\omega_1 = \left(\frac{3\pi k H}{4E} \right)^2 R_m \tag{7}$$

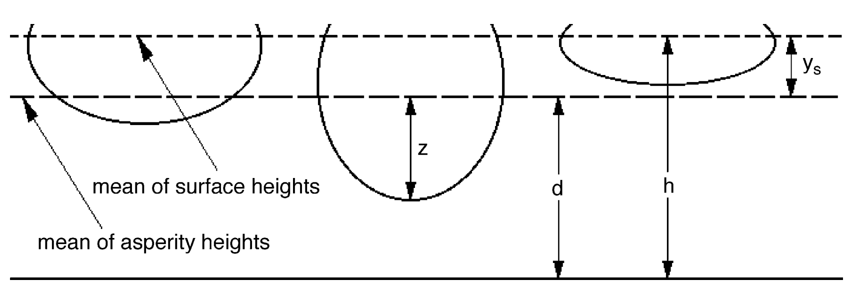

Fig. 1. Contacting rough surfaces.