Several Problems in the Thermal Contact Resistance Research of Solid Interfaces at Low Temperature

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According to our experiences in the research of the thermal resistance between solid interfaces at low temperature, some modeling problems such as surface topography, the interface deformation and the improvement of thermal contact of the solid surfaces are introduced in this article. A new thermal contact fractal model is developed. The novel measure equipment is developed which is capable to measure the thermal conductivity and the thermal contact resistance between solid surfaces simultaneously and the test error is analyzed. The experimental results were compared with the prediction data.

INTRODUCTION

In many new technologies, problems of thermal contact resistance are often met. For example, cooling a detector in a satellite, cooling large scale integrated circuit chips and exchanging heat with great efficiency of heat flow in a satellite, are all done via contact heat exchangers. In these fields, the thermal contact resistance determines the work condition of some key equipment. Especially in many spacecraft electronic components, such as focal-plane detector arrays used in satellite imaging systems, operate efficiently only at low temperatures within narrow limits.

Prediction of operating temperatures needs correct modeling of the heat path from source to sink. A primary factor influences heat transfer is the thermal contact resistance across metal contacts. Therefore, proper model and accurately measurement of thermal contact resistance between metal interfaces at low temperatures is necessary.

In this article, the surface roughness of the metal samples was measured by using STAR-1 profile meter. A prediction model was developed by applying a discretization method to obtain the rough height and deformation mode based on the measurement of surface roughness. Then, the thermal contact resistance between a pair of stainless steel samples and a pair of Al samples were measured experimentally.

MECHANISM OF THERMAL CONTACT RESISTANCE

Engineering surfaces are never absolutely smooth and surface irregularities are apparent when observed under a microscope. As a result, when two solid faces are pressed together, contact is made only at a few discrete spots separated by relatively large gaps. Therefore, the heat flow shrinks at the interface and the temperature difference between the two contact faces appears, as shows in Figure 1. It indicates that the thermal contact resistance exists between two solid interfaces.

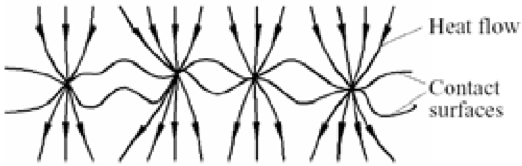

Figure 1 The constriction of heat flux at the interface

PREDICTION MODELS

The thermal contact conductance h_c (the reciprocal of the thermal contact resistance) between two metal interfaces can be predicted theoretically by used the following equation.

$$h_c = \frac{2\bar{a}N\lambda}{\psi} \tag{1}$$

Here, h_c is the thermal contact conductance; $\bar{a}$ is the average dimension of the contact points; N is the contact point's number; λ is the conductivity of the material; and ψ is contraction coefficient between the two contact surfaces. The profile model and the deformation model about the surfaces determine these parameters.

However, the routine contact deformation models about the surfaces are based on some ideal assumptions. For example, the assumptions in G-W elastic contact deformation model are: the heights of the surface micro-heaves distribute as normal type, the curvature of the surface micro-heaves is a fixed value and the most of the surface micro-heaves deform elastically [1]. The Y (Yovanovich [2]) elastic contact model is based on the assumptions that all the gradients of the micro-heaves distributing random and all the micro-heaves deforming elastically.

Due to the complexity of the surface profiles and the contact conditions, the assumptions are different from the practical ones. The results based on all the former models deviate from the experimental results. Based on the measurement of the practical surfaces profiles, the mathematic model on the thermal contact conductance is established by application profile discretization method to calculate practical deformations at different heights about micro-heaves [3].

The contact between two rough surfaces can be simplified by introducing the concept of a equivalent rough surface. This condition could regard as the contact between an equivalent rough surface and a rigid and smooth surface. The equivalent rough surface may be discretized into many small sections, and then the contact pressure on each section could be calculated. Then, the thermal contact conductance could be calculated.

MEASUREMENT OF THE SAMPLE SURFACE

The STAR-1 surface profile gauge with computer data processing system is used to measure the surface roughness of the samples. The end of detector the STAR-1 surface profile gauge is $4\mu m$ in diameter, and its sampling distance is $2.5\mu m$. In the experiments, the scanning distance is 17.5mm in length; therefore, there are 7000 data on each scanning. These data recorded in computer are enough to analyze the surface topography. Figure.1 and Figure.2 show the measured surface topographies of a stainless steel sample and an Al sample respectively.

Based on the analysis of the profile measuring results, the thermal contact conductance (or resistance) can be predicted by used the models above-mentioned.

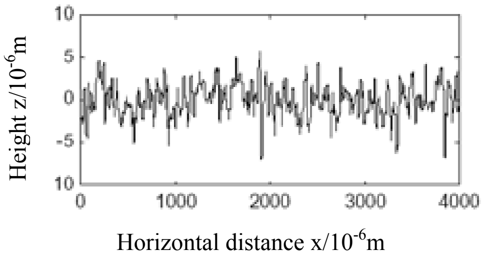

Figure 2 The actual profile of stainless steel sample

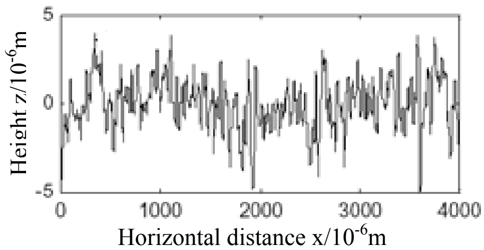

Figure 3 The actual profile of Al sample

EXPERIMENTAL MEASUREMENT

Experimental method and apparatus

The contact resistance of the solid material at low temperature and vacuum has been studied and measured widely, and a lot of experimental data has been obtained. But there are some common defects remain. Some of the experimental apparatus can only measure rod shaped samples, and some can only measure thin-disk-shaped samples, but hitherto no apparatus can measure both sample shapes. In some experiments, the input power had been regarded as the sole heat flux to the sample. In fact, many factors cause a heat leakage.

In our research, a new apparatus that overcomes these defects is introduced [4]. In this experimental apparatus, double heat flow meters were used and the heat flow through the sample and the temperature different between the interfaces can be obtained by the outer-expansion method. The apparatus can measure not only rod-shaped samples but also thin-disk-shaped samples. Also, the thermal conductivity of the materials at low temperature can be measured on this apparatus.

The relative error of the temperature difference ΔT between the contact surfaces is less than 9%, and the total relative error is less than 12.21%.

Experimental results and discussion

The experimental results about the two pairs of samples were shown in Figure 4 ~5. In order to compare with the prediction data, the data predicted by the profile discretization method, the G-W model and Y model were shown in the figures also.

It can be seen from Figure 4~5 that predicting values of the G-W model are usually less than the experimental values, and the predicting values of the Y model are far more than the experimental values. From the results of the stainless steel samples in Figure 4, it can be seen that the maximum error of the predicting values of Y model is exceed 100% of experimental values; the maximum error of the predicting values of G-W model is more than 50% of experimental values. In the mean time, the maximum error of the values predicted by discretization method is only about 10% to experimental values. As for the Al samples (see Figure 5), the maximum error of the predicting values of Y model is exceed 200% of the experimental values; the maximum error of the predicting values of G-W model is more than 50% of the experimental values. In the mean time, the maximum error of the values predicted by discretization method is less than 50% of the experimental values. However, the data predicted by Profile discretization method is in good agreement with the experimental results.

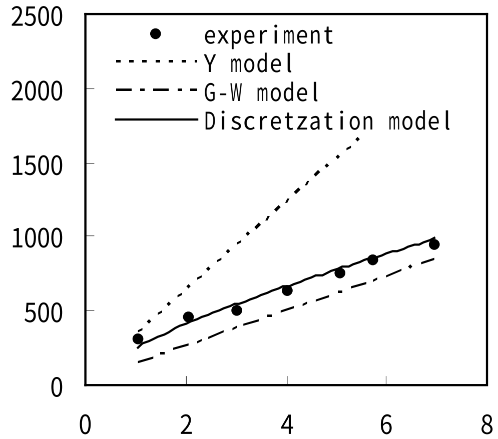

Figure 4 Experimental and theoretical predictions data of the stainless steel samples (T=155K)

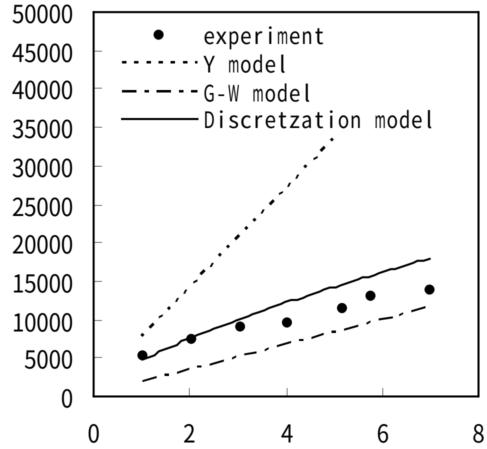

Figure 5 Experimental and theoretical predictions data of the Al samples (T=155K)

Compared Figure 5 with Figure 4, it can be found that the error of the values predicted by discretization method for Al samples is more than it for stainless steel samples. For an easily oxidable metal, the oxidation will cover the machining surfaces of the Al samples inevitably. The thick of the oxidation layer is about 0.075~.236 μm and on influence on the profile of the samples, but it harder than the main body material and the conductivity is smaller. So the actual deformation and thermal conductance between the interfaces is different in theoretical. The detail mechanism about this phenomenon is waiting for more research.

CONCLUSIONS

Based on the measurement of the profile of the surfaces, it is discovered that the height distribution of micro-heaves on the rough surfaces is random. Then the profile discretization model without any assumption was put forward to predict the thermal contact conductance (or resistance) between the metal interfaces.

The thermal contact conductances between two pairs of samples were researched experimentally. The experimental results were compared with the predicting values of G-W model, Y model and the discretization model. It shows that simulated results of the discretization model are in best agreement with experiments.

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