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Extraction of thermal contact conductance of metal–metal contacts from scale-resolved direct numerical simulation

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ABSTRACT

The thermal contact conductance (TCC) between two conforming metallic rough surfaces was extracted from scale-resolved direct numerical simulation (DNS) of thermal transport across the interface. To compute thermal transport across the interface, microscale models of the interface geometry were created by stochastically reconstructing the topography of the two metallic surfaces, followed by generation of meshes that resolved all fine-scale features of the interface, including the air pockets. Steady state conjugate heat conduction computations were then conducted, and the TCC values were extracted and expressed as a function of the applied pressure (which translates into a mean separation distance) and the mean interface temperature. When compared with experimental data, the extracted TCC values were found to be in good agreement, thereby validating the approach. To lend practical value to the methodology and data presented in this paper, a relationship was also established between the extracted TCC and the number of contacts between the two surfaces. Further, it was shown that the number of contacts generated using surface reconstruction (numerically computed) correlates well with the theoretically calculated number of contacts using the joint probability distributions of the asperity heights on the two surfaces. The implication of these relationships is that irrespective of the actual topography of the surface, for a given pressure (separation distance) and metallic pair combination, the TCC can be estimated from the correlations presented in this paper (TCC versus number of contacts) without the need to conduct any additional numerical computations.

1. Introduction

Engineered surfaces are never perfectly smooth. When viewed microscopically, they exhibit irregularities from the prescribed geometrical form, known as surface roughness. As a result of this microscopic surface roughness, when two surfaces are placed in contact, tiny air pockets reside within the interface and the actual contact area is only a small fraction (<2%) of the nominal contact area, even at high pressure [1]. The miniscule air pockets interspersed between the few discrete contact spots impede heat transfer by conduction between the surfaces. This is because the thermal conductivity of air is 3 orders of magnitude smaller than that of most metals. Owing to the high thermal conductivity mismatch, heat is constricted to flow through the regions where the two surfaces actually come in contact. The resistance to heat flow resulting from the imperfect nature of contact gives rise to a relatively high temperature drop across the interface. The effective thermal conductivity of an interface is often measured in terms of the thermal contact conductance (TCC), which, essentially, is the conductive heat transfer coefficient across the interface. Since contact between metallic surfaces is ubiquitous, accurate prediction of the TCC is critical to the effective modeling of thermal behavior and design of machine components.

The prediction of the TCC involves determining the actual area of contact from all the contact spots at the interface, and the heat flow through each contact spot. Contact occurs when the highest asperities of the two surfaces touch and deform under the influence of an external pressure. Therefore, in addition to surface topography, the actual contact area depends on the pressure applied across the interface. As the pressure increases, new asperities come in contact, which increases the contact area and consequently increases the heat flow across the interface. As shown in Fig. 1, the prediction of contact conductance is a tightly coupled problem with two parts, namely, a mechanical part to predict the real area of contact from the deformation of the contacting asperities, and a thermal part to predict the heat transferred across all

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Nomenclature

A	apparent area of contact (m^2)
d	separation distance (μm)
erf	error function
f	cumulative distribution function
h	thermal contact conductance ($W/m^2/K$)
k	thermal conductivity (W/m/K)
L	sampling length (μm)
P	probability
Q	heat transfer rate (W)
R_a	arithmetic mean roughness (μm)
R_z	random number
s	piecewise cubic polynomial
u	coefficients of cubic spline fit
z	surface profile height (μm)
Δt	temperature difference

Greek symbols

σ	standard deviation of surface heights (μm)
μ	profile heights measured from a reference plane (μm)
δ	dimension in direction of heat flow (μm)
η	knots of the cubic spline fit

the contact spots. The focus of this study is the thermal part of the aforementioned modeling framework.

Several contact conductance models have been developed over the past decades. In the vast majority of models, the TCC is evaluated as the combined effect of the conductance of all the discrete contact spots across the interface. A method to compute TCC as the sum of the parallel conductance of all the contact spots, which have an assumed surface height distribution at the interface, was proposed by Greenwood [2]. Cooper et al. [3] developed a similar prediction method by extending the single circular contact hypothesis to multiple contacts with a distribution of asperity heights derived from surface topography measurements. Mikic [4] also proposed a simple correlation of the TCC of conforming rough contacts as a function of the root-mean-square (RMS) roughness and average of the absolute value of the asperity slope. The models in [2–4] assume that all the contact spots at the intersection of perfectly aligned asperities are circular with a constant radius. However, in reality, numerous contact spots of varying shapes and sizes are randomly distributed across the interface, which makes the distribution of heat flow through the contact spots complicated. Additionally, the distribution of contacts in real interfaces is not commonly measured and only surface topography descriptors, such as average surface roughness heights, are known. A nonlinear correlation for prediction of the TCC by constructing an interface comprised of contact spots of varying radii was proposed by Black et al. [5]. Hong et al. [6] developed an integrated thermo-mechanical model, which accounts for partial contact between asperities by accounting for the various degrees of misalignment between contacting asperities. However, in both of these studies [5,6], the TCC is described as a function of surface descriptors such as mean asperity slope, asperity density, and average asperity peak radius, which are not directly measureable, and can only be estimated from rigorous surface topography analysis. Singhal et al. [7] developed a coupled thermo-mechanical predictive model, which uses actual surface profile data, in conjunction with deformation analysis, to predict the actual contact area used in the computation of contact conductance. However, they approximated the contact between two rough surfaces with the contact between a single rough surface with equivalent characteristics and a perfectly smooth surface. While this assumption can be justified for the mechanical model (since the total force and deformation remains the same for the equivalent contact), it may be compromising some of the physical effects of the inhomogeneous interface on the heat flow. In addition, the surface topography model developed in their study is tedious and difficult to use.

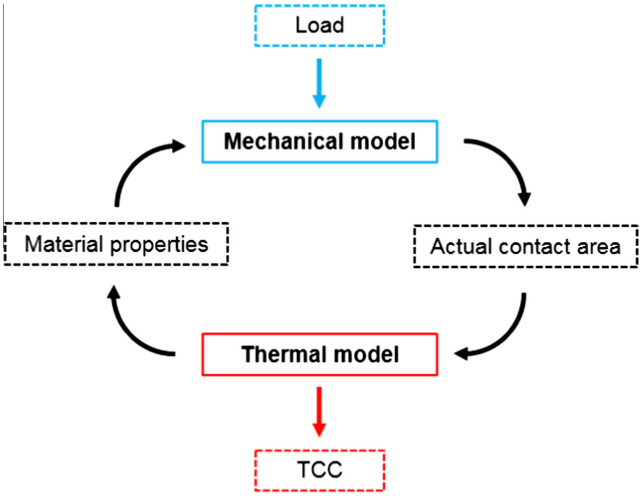

Fig. 1. Flowchart of steps involved in prediction of the TCC.

In the present study, a method is proposed in which the TCC is extracted from temperature and heat flux distributions obtained from direct numerical simulations of heat conduction across the interface. Rather than make any assumptions 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. In order to account for the physical effects of imperfect contact between surfaces at the microscale, scale-resolved direct numerical simulation (DNS) of thermal transport across the interface is then conducted. The complex interface geometry and all associated length scales are resolved using an unstructured mesh. The results obtained from the scale-resolved DNS are ultimately used to extract the TCC. Based on the preceding description of existing TCC models, it is clear that the methodology proposed here represents advancement over the state-of-the-art in modeling the TCC across metallic interfaces.

2. Research method

2.1. Surface topography reconstruction

Aside from the thermo-physical properties of the two materials that come in contact, the phenomenon of contact between two macroscopically flat metallic surfaces is dictated by two predominant factors: applied pressure (or load), and the surface topography. When two solids are pressed together by the application of a load, based on the distribution of the roughness features of the surface pair, contact occurs at the intersecting asperities. Therefore, for geometric reconstruction of contacting surfaces, parameters representing the applied load and surface topography must be first identified.