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Short Communication

Thermal boundary conditions in sliding contact problem

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ABSTRACT

If two rough surfaces slide against each other, the typical contact event is a transient interaction of a pair of asperities. A recent finite element solution of the heat conduction through such a contact is used to develop an expression for the heat transferred between the bodies as a function of the surface statistics, the nominal contact pressure and the sliding speed. Simple curve fits are provided to permit these results to be implemented as a macroscopic heat transfer condition in numerical simulations.

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1. Introduction

When two bodies slide against each other, frictional heat is generated, leading to a non-uniform temperature field. Also, since the sliding surfaces are almost inevitably rough on the microscale, contact occurs only near the higher parts of the contacting surfaces. As a consequence (i) we get very high local temperatures known as 'flash temperatures' [1] and (ii) the contact being restricted to a small fraction of the nominal contact area imposes an effective thermal contact resistance between the surfaces and therefore permits the 'bulk temperature' at points immediately below the surface in the two bodies to differ [2].

The complex geometry of most engineering problems generally necessitates numerical (typically finite element [FE]) solution, but in creating an FE model of a real system, it is not feasible to include the geometric details of the microtopography. Instead, we need to homogenize the discrete nature of the localized asperity contact so as to define appropriate boundary conditions for a macroscale formulation of the problem. In particular, we need to define an effective thermal contact resistance under sliding conditions, and determine how its value is affected by nominal (i.e. average) contact pressure, sliding speed, and the parameters characterizing the surface roughness.

Numerous models have been proposed for the steady-state thermal contact resistance in static contact [3,4], but these are not appropriate for the sliding problem except at very slow sliding speeds. Liu and Barber [5] developed a model based on the assumption that the two surfaces can be characterized by Gaussian height distributions of identical asperities and that the typical contact event comprises the transient elastic contact between two such asperities, one on each surface. However, their analysis used a simplified geometry for the underlying contact problem and was restricted to the case where the Peclet number at the asperity scale is large compared with unity. In this paper, we shall use a recent finite element solution of the individual asperity interaction problem [6] to extend their results to the full range of Peclet number, as well as using a more accurate description of the contact geometry. In particular, we shall develop accurate curve fits that can be used to define appropriate thermal boundary conditions in macroscopic FE models.

2. Stochastic distribution of asperity interactions [5]

We characterize each of the two sliding surfaces $(i = 1, 2)$ as comprising a set of N_i $(i = 1, 2)$ identical spherical asperities per unit nominal area, each of radius R_i $(i = 1, 2)$, and whose summits exhibit a Gaussian height distribution,

$$\phi_i(h_i) = \frac{1}{\sigma_i\sqrt{2\pi}}\exp\left(-\frac{h_i^2}{2\sigma_i^2}\right), \tag{1}$$

where h_i $(i = 1, 2)$ is the height of a typical asperity above a datum plane and σ_i $(i = 1, 2)$ is the standard deviation, respectively. The

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assumption of a distribution of identical spherical asperities is an idealization, but many authors [7–10] have shown that at least in the static problem, the precise details of the asperity shapes and so forth have a relatively small effect on the ensemble predictions. If the datums in the two surfaces are separated by a distance h_0 and the bodies slide over each other at speed V, the typical asperity interaction event then comprises the transient contact of two asperities with a maximum contact radius a given by

$$a(h_1, h_2) = \sqrt{\frac{R_1R_2(b_0^2(h_1, h_2) - b^2)}{2(R_1 + R_2)^2}}, \tag{2}$$

where b is the closest approach of the summits in the interfacial plane and

$$b_0(h_1, h_2) = \sqrt{2(R_1 + R_2)(h_1 + h_2 - h_0)} \tag{3}$$

is the largest value of b for which a contact interaction can occur. The maximum contact radius a depends on the height of an asperity above a datum plane, h_i $(i = 1, 2)$.

2.1. Heat exchange rate

Liu and Barber [5] showed that the total heat exchange rate per unit nominal area, per unit sliding distance for this model can be written as

$$Q_c = 2N_1N_2 \int_{-\infty}^{\infty} \int_{h_0-h_2}^{\infty} \int_0^{b_0} \phi_1(h_1)\phi_2(h_2)Q(a)dbdh_1dh_2, \tag{4}$$

where $Q(a)$ is the total heat exchange through a single asperity interaction with maximum contact radius a.

A recent finite element solution of the heat conduction problem for a single asperity interaction [6] has shown that $Q(a)$ is very well approximated by the expression

$$Q(a) = \frac{2\pi a^2 K\Delta T}{V}\sqrt{2 + 0.9Va/k} \tag{5}$$

where V is the sliding velocity, and K and k are thermal conductivity and diffusivity respectively.

2.2. Flash temperature

Lee et al. [6] also showed that the maximum flash temperature at an elastic asperity interaction characterized by a maximum radius a is well approximated by the expression

$$T_{max}(a) = \frac{\pi a\mu p_0 V}{8K\sqrt{1 + 0.25Va/k}} \quad \text{where } p_0 = \frac{2E^*a}{\pi R^*}; \quad \frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}, \tag{6}$$

μ is the coefficient of friction and E^* is the composite elastic modulus.

The flash temperature varies from one asperity interaction to another, but a mean value can be determined as

$$T_0 = \frac{1}{N}\int_{-\infty}^{\infty} \int_{h_0-h_2}^{\infty} \int_0^{b_0} \phi_1(h_1)\phi_2(h_2)T_{max}(a)dbdh_1dh_2 \tag{7}$$

where

$$N = \int_{-\infty}^{\infty} \int_{h_0-h_2}^{\infty} \int_0^{b_0} \phi_1(h_1)\phi_2(h_2)dbdh_1dh_2. \tag{8}$$

2.3. Nominal contact pressure

The mean separation h_0 between the surfaces depends on the nominal contact pressure p_{nom}. If the asperity interactions are all assumed to be elastic, the mean nominal pressure is

$$p_{nom} = \frac{16N_1N_2E^*\sqrt{\pi R_1R_2(R_1 + R_2)}\eta^{5/2}}{15}I_f(\hat{h}_0), \tag{9}$$

where $\eta = \sqrt{2(\sigma_1^2 + \sigma_2^2)}$ and the integral

$$I_f(\hat{h}_0) = \int_0^{\infty} \exp(-(y + \hat{h}_0)^2)y^{5/2}dy \quad \text{with } \hat{h}_0 = \frac{h_0}{\eta} \tag{10}$$

can be regarded as a dimensionless measure of p_{nom}.

3. Results and discussion

The heat exchange rate Q_c can be obtained by substituting the finite element approximation (5) into (4), and a fairly general relation can be established by defining the dimensionless heat exchange rate $J_c(\hat{V}, \hat{h}_0)$ through the equation

$$Q_c = \left(\frac{4\sqrt{2\pi}N_1N_2(R_1R_2)^{3/2}\eta^2K\Delta T}{k\sigma_1\sigma_2(R_1 + R_2)}\right)J_c(\hat{V}, \hat{h}_0), \tag{11}$$

where

$$J_c(\hat{V}, \hat{h}_0) = \frac{1}{\hat{V}}\int_{\hat{h}_0}^{\infty} e^{(-\xi^2)}(\xi - \hat{h}_0)^{3/2} \times \int_0^1 (1 - x^2)\left(2 + \frac{0.9\hat{V}}{\sqrt{2}}\sqrt{\xi - \hat{h}_0}\sqrt{1 - x^2}\right)^{1/2} dxd\xi \tag{12}$$

and

$$\hat{V} = \frac{V\sqrt{\eta R^*}}{k} \tag{13}$$

is a Peclet number defined at the asperity scale. We recall that Q_c is the heat transferred per unit sliding distance, so an equivalent macroscale heat transfer coefficient h_c can be defined such that the mean heat flux $q_c = h_c\Delta T$, in which case

$$h_c = \left(\frac{4\sqrt{2\pi}N_1N_2(R_1R_2)^{3/2}\eta^2K}{k\sigma_1\sigma_2(R_1 + R_2)}\right)J_c(\hat{V}, \hat{h}_0). \tag{14}$$

A similar dimensionless measure of the mean flash temperature can be obtained by substituting (6) into (7) and defining the function $G_T(\hat{V}, \hat{h}_0)$ through the equation

$$T_0 = \left(\frac{\mu kE^*}{4K}\sqrt{\frac{\eta}{R^*}}\right)G_T(\hat{V}, \hat{h}_0). \tag{15}$$

where

$$G_T(\hat{V}, \hat{h}_0) = \frac{\hat{V}}{I\left(\hat{h}_0, \frac{1}{2}\right)}\int_{\hat{h}_0}^{\infty} e^{-\xi^2}(\xi - \hat{h}_0)^{3/2}\int_0^1 \frac{1 - x^2}{\sqrt{1 + \frac{\sqrt{2}\hat{V}}{8}\sqrt{\xi - \hat{h}_0}\sqrt{1 - x^2}}}dxd\xi \tag{16}$$

and

$$I\left(\hat{h}_0, \frac{1}{2}\right) = \int_0^{\infty} e^{(-(y+\hat{h}_0)^2)}y^{1/2}dy. \tag{17}$$

These equations show that the dimensionless heat exchange and the mean flash temperature are each characterized by a function of the two dimensionless parameters $\hat{V}$, $\hat{h}_0$, the second of which is in turn determined by the dimensionless nominal pressure I_f.

3.1. Limiting behavior at large and small Peclet number

Fig. 1(a) shows the dependence of the product $\hat{V}J_c$ on I_f at progressively reduced values of $\hat{V}$. A limiting curve is obtained

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