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Numerical modelling of contact heat transfer problem with work hardened rough surfaces

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ABSTRACT

A numerical model of heat conduction in vacuum through contact between two rough bodies made of commercial-purity AD1 aluminium is developed. To this end, the elastic–plastic contact deformation problem is solved accounting strain hardening. A method for consideration of surface initial cold work hardening and indentation size effect (ISE) is provided. Plastic characteristics of surface micro-volumes of material were taken from indentation results. Numerical realisation of the model in ANSYS finite element software is considered. Fractal surface models of two levels of roughness were used. Introduction of the second level roughness (microroughness) to the model was found to have considerable effect on the real contact area only when ISE is taken into account. An attempt to compare simulation results with data obtained with Shlykov's semi-empirical model was made.

1. Introduction

With constantly raising precision in mechanical engineering, instrument engineering and electronics, thermal calculation of compound structures is an essential problem. For instance, errors due to thermal expansion are the ones most frequently ignored and difficult to understand in the field of mechanical engineering [1]. Temperature field of compound structures made of materials with high thermal conductivity heavily relies on thermal contact conductance. Thermal contact conductance estimation has always been one of the most difficult areas in the field of heat transfer [2].

Thermal contact conductance has been studied for more than 100 years, starting from the early studies [3–5]. No reliable method for contact heat transfer parameters prediction has been proposed so far. Experiments can provide only limited and insufficient information [6].

Shlykov's empirical model [7] which was developed as a generalisation of experimental data gathered before the 1970's for a wide range of materials, roughness parameters of contacting bodies and pressures is of particular interest in this respect. According to Shlykov, thermal contact conductance can be calculated with the following formula:

$$\alpha = 8000\bar{\lambda}\left(\frac{P}{C\sigma_U}K\right)^{0.86} \quad (1)$$

here $\bar{\lambda} = \frac{2\lambda_1\lambda_2}{\lambda_1+\lambda_2}$, $C = 3$, coefficient K is determined by the following formulae: $K = 1$, when $Ra_1 + Ra_2 \geqslant 30$ µm, $K = \left(\frac{30}{Ra_1+Ra_2}\right)^{1/3}$, when 10 µm < $Ra_1 + Ra_2$ < 30 µm, $K = \frac{15}{Ra_1+Ra_2}$, when $Ra_1 + Ra_2 \leqslant 10$ µm.

Model assumptions and drawbacks:

- Factor 8000 is derived on the assumption, introduced for the first time in [8], that the contact spot mean radius is 30 µm and that the real contact area is proportional to the number of such contact spots. Based on the bulk of experimental data gathered in 40–70's of the last century, this assumption allowed to a certain extent to link data on thermal contact conductance with compression force.
- Ultimate strength σ_U is used instead of yield strength σ_Y of the maximally cold work hardened material. However, paper [9] discloses that the hardened surface layer has a different and significantly higher stress–strain curve than that of the bulk material.
- $C\sigma_U$ represents contact pressure or hardness. The idea to calculate real contact area by division of normal force acting on the surface by material Brinell hardness was suggested in [10], and is based on the assumption from [11] of replacement of the contact pressure by the hardness detected by indentation. The hardness is considered to be linked to the yield strength by the equation $H = 2.8\sigma_Y$. Value 2.8 for coefficient C was

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Nomenclature

P	pressure (Pa)
C, K	coefficients
B	material constant (Pa)
B^*	constant B, modified to count for indentation size effect (Pa $\mu m^{1/2}$)
B^{**}	constant B^*, related to the roughness element properties (Pa $\mu m^{1/2}$)
l, d	characteristic size (μm)
l_{max}, d_{max}	maximum penetration depth values of l and d, respectively (μm)
H	hardness (Pa)
E	modulus of elasticity (Pa)
L	sample length (m)
G	fractal roughness (m)
D	fractal dimension (m)
Ls	cut-off length (m)
M	number of superposed ridges
n_{max}	upper limit of frequency index
q	thermal flow density (W/m^2)
Rz, Ra	standardized roughness parameters (μm)
T	averaged temperature of smooth surface under convection heating (K)
T_g, T_w	gas and wall temperatures (K)
u_z	displacement of the upper surface of the body N (m)
n	strain-hardening exponent
TCC	thermal boundary conductance at nanoscale set in ANSYS between contact finite elements (W/m^2 K)
R, R_m, R_{NO}	thermal resistances of the contact, of the model, of the contacting bodies N and O, respectively, (m^2 K/W)
h	heat-transfer coefficient (W/m^2 K)
x,y,z	coordinates

Greek letters

α	thermal contact conductance (W/m^2 K)
$\bar{\lambda}$	effective thermal conductivity of the contacting bodies (W/m K)
σ_U, σ_Y	ultimate strength and yield strength (Pa)
λ	thermal conductivity (W/m K)
δ	nominal height of the bodies (m)
μ	Poisson's ratio
λ^*	thermal conductivity in case of equal materials (W/m K)
γ	scale factor
ϕ	random phase
ε^p	plastic strain

Subscripts

1	related to the upper body N
2	related to the lower body O

Lower indexes

n	frequency index
m	superposed ridge index

obtained by Tabor [12] for contact of spherical indenter with plane and based on the slip line field theory for the plane stress condition and ideally plastic behaviour of material. Before that, in [13] a value 2.84 was derived for the mean contact pressure to yield strength ratio. Value $C = 3$ in formula (1) was derived theoretically for an ideally plastic material [14]. For real materials this is often not true, and coefficient C can reach value up to 5 and more [15,16]. For a sinusoidal elastic-perfectly plastic fully closed (tight) contact [17] possible value for the coefficient calculated by finite element method reached up to 15.

Jackson and Green [18,19] showed that hardness or mean contact pressure, even at perfectly plastic contact, is not independent from the method of its obtaining and changes during deformation of the spherical asperity. It was confirmed experimentally in [20]. Song and Komvopoulos [21] demonstrated that mean contact pressure also continue to change after transition into fully plastic deformation regime.

Despite serious disadvantages of the model, the above-mentioned coefficients C, K, 0.86 and 8000 allowed to approximate the experimental data available at that time with an error of less than 20% [7]. Similar to (1) correlation models were proposed by other experimenters [22–27], but did not allow to clarify significantly the nature of the processes in the contact region.

From the end of the 19th century, it has been known [28] that rough surfaces do not mate ideally to each other, but contact by their peaks with air gap leaving between the surfaces. Thermal conductivity of air is much lower then that of the solid, so heat transfer is proportional not to the nominal, but to the real area of contact, i.e. to the area of direct contact of the hills. The experiments showed indirectly that the real contact area is in turn proportional to the contact compression force defining degree of mutual approach for the compressed surfaces. From the beginning of the 1930's, Holm [29] showed firm understanding of the fact that the real contact area of rough surfaces is only a small part (usually less than 1%) of the nominal area defined by geometry of the contacting bodies.

For prediction of thermal state, roughness structure of the contacting surfaces and features of heat transfer in the micron-size contact regions must be taken into consideration. Thus, there is a need for modelling of individual roughness element (hill) deformation.

In the 1960's with the advent of computers, attempts were made to calculate two-dimensional models of representative areas of rough surfaces with profiles derived either by 2D-profilometer or by stochastic modelling [30]. Due to lack of computational power of computers of that time even for such calculations in [30] proposed method of replacing the elastic contact of two rough surfaces by the contact of an equivalent rough surface with a rigid plane. In that case, the rough surface had an equivalent elastic modulus. Possible lateral interaction of the contacting hills is neglected, which is typical of the most of the discrete contact models described in the literature [31]. Attempts to include some interaction of asperities in statistical models [32–37] do not consider the plastic deformation of the bulk material and large deformations [38].

A fractal approach for surface modelling came into practise from the beginning of the 1990's [39,40].

In case of elastic deformation, the thermal contact conductance can be determined from the normal contact stiffness [41].

Multiasperity three-dimensional contact problems were solved for elastic [42–47], elastic and elastic-perfectly plastic [48–50], bilinear [38,51,52] and nonlinear [53] elastic–plastic material behaviour. In [54] asperity deformations were calculated from the creep constitutive relations. All these problems were solved assuming the contact of a rough surface with a rigid plane.

In the 21st century, two-dimensional roughness models (for multiasperity contact) are still in use [55–58]. Models of three-dimensional contact of two rough surfaces appeared within only last decade [59–61], i.e. those without the rigid plane assumption.