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Effect of temperature difference on the adhesive contact between two spheres

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ABSTRACT

In the present work, by considering the thermoelastic effect, the JKR model is extended to study the non-slipping adhesive contact between two spheres of different initial temperature under the normal applied force. The analytical expressions for the tractions within the contact area and the applied force as a function of the contact radius are derived, based on which some numerical results are given. It is found that the thermoelastic effect can significantly influence the adhesive contact behaviors such as the pull-off force and the contact radius at zero applied force. The present work may cast light on optimizing the strength of the adhesive contact interfaces in engineering like various thermal bonding technologies.

1. Introduction

Adhesive contact mechanics has been an active research topic for several decades. Since the pioneering works by Johnson, Kendall, and Roberts (1971) (JKR model) and Derjaguin, Muller, and Toporov (1975) (DMT model), there are many other adhesive contact models such as the MD model (Maugis, 1992) and the double-Hertz model (Greenwood & Johnson, 1998) have been proposed. In last two decades, based on those fundamental models, more complicated adhesive contact problems such as the non-slipping contact (e.g., Chen & Gao, 2006a, 2006b, 2007), the contact between bodies of materials other than the traditional isotropic and linearly elastic materials (e.g., Borodich, Galanov, Keer, & Suarez-Alvarez, 2014; Haiat, Huy, & Barthel, 2003; Jin, Guo, & Gao, 2013; Jin, Zhang, Wan, & Guo, 2016) and the contact between bodies of rough surfaces (e.g., Persson, 2002; Zhang, Jin, Guo, & Zhang, 2014) have been studied. However, to our best knowledge, almost all of the existing models are aimed at isothermal adhesive contact although the effect of temperature difference between the contact bodies on their adhesive contact behaviors are indicated by several experiments (e.g., Awada, Noel, Hamieh, Kazzi, & Brogly, 2011; Cappella & Stark, 2006) to be very significant. Actually, the adhesive contact between bodies with different temperature is commonly involved in many engineering technologies for instance the various thermal bonding technologies like cold spraying (e.g., Legoux, Irissou, & Moreau, 2007; Watanabe, Yoshida, Atsumi, Yamada, & Fukumoto, 2015). In those situations, the strength of the bonding strength is found to be sensitive to the change of temperature (e.g., Legoux et al., 2007; Watanabe et al., 2015), the mechanism behind which may be revealed from the view point of adhesive contact mechanics by considering the thermoelastic effect.

In fact, the Hertzian thermal contact problems without adhesion have already drawn much attention from many researchers. The seminal work in this field may be that done by Barber (1971a), where the contact between a heated rigid punch indenter and a semi-infinite elastic body is modeled. After that, based on the idea therein, Barber, Comninou and

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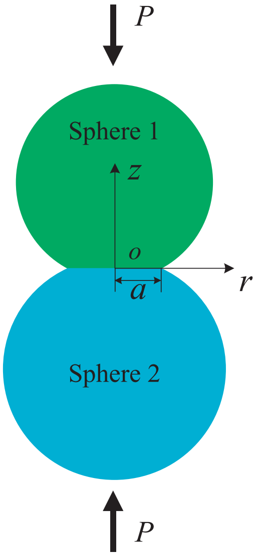

Fig. 1. Schematic representation of the contact between two spheres with different initial temperature under normally applied force *P*.

Dundurs (e.g., Barber, 1973, 1978; Comninou, Barber, & Dundurs, 1981; Comninou, Dundurs, & Barber, 1981) have done series of works to model the thermal contact between elastic bodies of various surface profiles. In those works, the main idea is to introduce the contact condition that the surface profile difference of the objects should be compatible with the thermal deformation and the mechanical deformation on the surface altogether, which is validated by the fact that the thermal constriction resistance predicted by the model (Barber, 1971b) can fit well with that from the experiment by Clausing (1966). From the results in those works, the contact pressure and the applied force required to achieve a specified contact size are sensitive to the change of temperature difference. Although in those models, adhesion is excluded and in essence only normal contact is considered, the idea therein to consider the thermoelastic effect may be followed in modeling adhesive thermal contact problems.

In Peng and Huang (2016), the non-slipping adhesive planar contact between two elastic cylinders subject to a temperature difference are studied by the JKR model (Johnson et al., 1971) with the consideration of thermoelastic effect, in which the adhesive contact behaviors are found to significantly depend on the temperature difference. In practice, the axisymmetric contact problem may be more common. Thus, in the present work, we study the non-slipping adhesive axisymmetric thermal contact between two spheres subject to a temperature difference.

2. Model formulation

As illustrated in Fig. 1, the adhesive contact between two spheres (labeled as 1 and 2) with initial temperature difference under a prescribed force P perpendicular to contact interface is considered here. A cylindrical coordinate (r, θ, z) with the z-axis pointing from the sphere1to the sphere 2 is placed at the center of the contact area.

For convenience, the normalized radial and axial coordinates $\rho = r/a$ and $\bar{z} = z/a$ is adopted in the rest text, where a is the contact radius. In the following, $\bar{z}$ will be simply denoted as z. The two spheres are of isotropic and linearly thermoelastic materials, and Young's modulus, Poisson's ratio, the thermal conductivity, the coefficient of thermal expansion, the initial temperature and the radius of the sphere i ($i = 1, 2$) are denoted as $E^{(i)}$,$\nu^{(i)}$,$k^{(i)}$,$\alpha^{(i)}$,$T_o{}^{(i)}$ and $R^{(i)}$ respectively.

Due to the existence of temperature difference, heat conduction will occur between the contacting spheres within the contact area. As a result, the initially colder sphere experiences heating while the initially hotter one experiences cooling, which results in the expansion and shrinkage respectively in the two spheres and hence the change in their surface profiles. Therefore, in the present problem, it is the thermal deformation and the mechanical deformation at the surface altogether that should be compatible with the original surface profile difference of the spheres within the contact area. Moreover, similar to the work by Chen and Gao (2006a, 2006b, 2007), the non-slipping condition is assumed here, and hence the total relative tangential displacement within the contact area should be zero. By combining the above two points and adopting the usual parabolic assumption of the local contact surfaces, the contact conditions for the present axisymmetric problem can be expressed as

$$u_z^{(1)}(\rho, 0) - u_z^{(2)}(\rho, 0) = d_{rig} - \frac{a^2\rho^2}{2R^*}, \tag{1}$$

$$u_r^{(1)}(\rho, 0) - u_r^{(2)}(\rho, 0) = 0 \tag{2}$$