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A mechanical model for the adhesive contact with local sliding induced by a tangential force

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ABSTRACT

Adhesion has been demonstrated to play an important role in contact and friction between objects at small scales. While various models have been established for adhesive contact under normal forces, studies on the adhesive contact under tangential force have been far fewer, which if any, are mostly confined to the non-slipping situations. In the present work, a model has been proposed for adhesive contact with local sliding under tangential forces. Herein, the onset of local sliding in adhesive contact has been addressed by assuming the nucleation of dislocations. By analogy with the emission of dislocations at a crack tip, the critical tangential force for the onset of sliding has been determined, and its effect on the evolution of contact size has also been studied. Comparison with relevant experiments has verified the validity of the present model.

1. Introduction

Adhesion has been demonstrated to play an important role in the contact and friction between small dimensioned or soft objects [1–4]. Continuum models such as Johnson-Kendall-Robertson (JKR) [4], Derjaguin-Muller-Toporov (DMT) [5], Maugis-Dugdale (MD) [6], and the more recent double Hertz [7-9] models have been well established and widely used, which are only applicable for the situations of contacting bodies under normal forces. However, in many circumstances, tangential forces may be imposed as well on the contacting objects. Deposited particles under viscous flow and sliding of particles are typical examples. Indeed, only a few studies [10–15] have focused on the adhesive contact under the simultaneous action of normal and tangential forces, which can be considered as the extension of the JKR model. In those studies, either explicitly or implicitly the non-slipping conditions have been assumed. A question naturally arises with respect to when local sliding may occur in such a context. Determination of the onset of local sliding between contacting objects is important for understanding the friction and failure mechanisms under tangential forces. Conventionally, account of local sliding in contact mechanics models has been achieved in some investigations [16–18] by adopting the Cattaneou-Mindlin's approach [19,20] where onset of local sliding is determined by the Amonton's law. However, there have been debates over the validity of the law at both small scales where adhesion comes into effect and macroscopic scales [21,22]. According to the existing studies on adhesive contact under tangential forces, shear peeling, i.e., reduction of the contact size by tangential forces, occurs before sliding onset. Recently, Adams [23] has proposed that sliding may take place when the shear peeling renders the adhesive force vanishing and developed a model for plane strain adhesive contact under tangential forces. However, for negative normal loading, i.e., adhesive contact under pulling, the model may yield

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meaningless results since negative contact size may arise. So how to determine the sliding onset remains an open question and study on adhesive contact under arbitrary forces is far from adequate. Given the facts that some experiments [24,25] have revealed that sliding between contacting objects may be initiated by the nucleation and propagation of various defects such as cracks and slip pulses, and that sliding induces displacement jumps at the contacting interface, which can be approximated by dislocations, the present work is attempted to address the sliding onset by considering the nucleation of dislocations in adhesive contact under both normal and tangential forces.

2. Model for the onset of local sliding through dislocation nucleation

2.1. Summary of existing studies

According to the previous studies [10–15] that dealt with the adhesive contact between spherical bodies within the JKR model under non-slipping condition, the contact tractions at the interface may be expressed as

$$p(r) = \frac{2E^*}{\pi R}\sqrt{a^2 - r^2} - \frac{P_1 - P}{2\pi a\sqrt{a^2 - r^2}},\quad P_1 = \frac{4E^* a^3}{3R} \tag{1}$$

$$\tau(r) = \frac{T}{2\pi a\sqrt{a^2 - r^2}} \tag{2}$$

where R is the effective radius for the two contacting bodies, a the contact radius, P and T respectively the applied forces in the normal and tangential directions. $P_1 - P$ in Eq. (1) is termed as adhesive force. Since the stresses are singular of square root at the contact edge, one may define stress intensity factors as

$$K_{\mathrm{I}} = \frac{P_1 - P}{2a\sqrt{\pi a}},\quad K_{\mathrm{II}} = \sqrt{\frac{2-\upsilon}{2-2\upsilon}}\frac{T}{2a\sqrt{\pi a}} \tag{3}$$

According to the JKR model, the equilibrium contact size is determined by equating the energy release rate $G = (K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2)/E^*$ with the work of adhesion w, which is analogous to fracture mechanics theory. So one may obtain the relationship between contact size and applied force as follows

$$\frac{4E^* a^3}{3R} = P + P_c + \sqrt{2PP_c + P_c^2 - (2-\upsilon)T^2/(2-2\upsilon)} \tag{4}$$

with $P_c = 3\pi wR/2$ being the pull-off force in the JKR model. In some studies [11,13], the mode-mixity-dependent work of adhesion has also been taken into account. From Eq. (4), it is found that the tangential force reduces the contact radius as compared to that merely under normal force. Such an effect has been referred to as shear-induced peeling. Nevertheless, for Eq. (4) to be valid, $T \le T_c = \sqrt{(2-2\upsilon)/(2-\upsilon)}\sqrt{2PP_c + P_c^2}$ should be satisfied. What happens otherwise remains controversial. Some researchers argued that when $T = T_c$, the onset of sliding may occur [10]. Thorton [11] suggested that sliding may begin well before T amounts to T_c and proceeded to propose that sliding actually takes place when the tangential force reduces the contact size to that within which compressive pressure is distributed. With the proposal, the critical tangential force for the onset of sliding has been derived and the results thus obtained agree well with some available data on friction. However, the physical implications are rather obscure. According to Adams [23], when the adhesive force becomes zero, from the balance of energy release rate, a critical tangential force and the corresponding contact radius under a given normal force can be obtained as

$$T_A = \sqrt{4(1-\upsilon)PP_c/(2-\upsilon)},\quad a_A = (3PR/4E^*)^{1/3} \tag{5}$$

Obviously, when the normal force is negative, expressions in the above equation no longer hold true.

2.2. Sliding onset via dislocation nucleation at the contacting interface

Intuitively, the onset of sliding represents the occurrence of displacement discontinuity along the tangential direction of the interface between two contacting bodies, which, as one may expect, can be well approximated by the generation of dislocations. In fact, both experiments [26] and simulations [27] have revealed nucleation and motility of dislocations during sliding. In the context of dislocation nucleation at a crack tip, Rice [28] has proposed an elegant model that relates the energy release rate to the unstable stacking fault energy γ_{us}. In the current context, the contact tractions are similar to the singular stress fields at a crack tip, and the potential interaction between contacting objects may yield a quantity similar to the unstable stacking fault energy in crystals. In fact, a sinusoidal potential has been frequently adopted in many studies [29–31] on atomic friction, which is exactly the same as that between atomic layers in crystals. Hence the adhesive contact under normal and tangential forces can be considered identical to a mixed-mode crack problem. If we consider a dislocation loop of pure edge nucleates close to the contact edge, which is similar to an edge dislocation generated along the slip plane coincident with the crack plane, the critical condition according to Rice [28] may be simply put as

$$K_{\mathrm{II}}^2 = \gamma_{us}E^* \tag{6}$$

Substituting Eq. (3) into Eq. (6) yields

$$u = 2\beta P_c P_1 \tag{7}$$

with $u = (2-\upsilon)T^2/2(1-\upsilon)$ and $\beta = \gamma_{us}/w$. By further using Eq. (4), it can be expressed as

$$\left(\frac{u}{2\beta P_c}\right)^2 - \left(\frac{P + P_c}{\beta P_c} - 1\right)u + P^2 = 0 \tag{8}$$

from which the critical shear force for dislocation nucleation can be solved as

$$\bar{T}_d = \sqrt{2\beta(2-2\upsilon)/(2-\upsilon)}\sqrt{\bar{P} + 1 - \beta + \sqrt{(2\bar{P} + 1 - \beta)(1-\beta)}} \tag{9}$$

where the over-bar represents the normalization by P_c. Indeed, one may also analyze the nucleation of dislocation from the perspective of free energy as done in [32] or that of the forces