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Strain gradient plasticity analysis of elasto-plastic contact between rough surfaces

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ABSTRACT

From a microscopic point of view, the real contact area between two rough surfaces is the sum of the areas of contact between facing asperities. Since the real contact area is a fraction of the nominal contact area, the real contact pressure is much higher than the nominal contact pressure, which results in plastic deformation of asperities. As plasticity is size dependent at size scales below tens of micrometers, with the general trend of smaller being harder, macroscopic plasticity is not suitable to describe plastic deformation of small asperities and thus fails to capture the real contact area and pressure accurately. Here we adopt conventional mechanism-based strain gradient plasticity (CMSGP) to analyze the contact between a rigid platen and an elasto-plastic solid with a rough surface. Flattening of a single sinusoidal asperity is analyzed first to highlight the difference between CMSGP and J_2 isotropic plasticity. For the rough surface contact, besides CMSGP, pure elastic and J_2 isotropic plasticity analysis is also carried out for comparison. In all cases, the contact area A rises linearly with the applied load, but with a different slope which implies that the mean contact pressures are different. CMSGP produces qualitative changes in the distributions of local contact pressures compared with pure elastic and J_2 isotropic plasticity analysis, furthermore, bounded by the two.

1. Introduction

The well-known Coulomb friction law states that the friction force F depends linearly on the normal load N through the friction coefficient μ: $F = \mu N$. Alternatively, Bowden and Tabor (1950) have argued from a microscopic point of view that friction can also be interpreted as $F = \tau A$, where τ is the shear strength of the contact and A is the real contact area, the latter being a small fraction of the apparent contact area A_0 because of the inevitable roughness of the surfaces. Consistency of the two types of description requires a linear dependence of the real contact area A on the normal force N. This is far from being trivial: for instance, the Hertzian elastic contact model gives a dependence of $N^{2/3}$ between a sphere and a flat. A nearly linear dependence was first obtained by Greenwood and Williamson (1966). They performed a statistical analysis of a rough surface with a distribution of asperity heights, based on the simplifying assumption that all peaks are spherical asperities with the same radius. Bush et al. (1975) generalized the Greenwood–Williamson model by incorporating paraboloidal asperities and a distribution of asperity size; yet, they still obtained a linear dependence.

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The fact that the generalized Greenwood–Williamson model predicts that a linear relationship between A and N is far from being obvious, in view of the numerous underlying assumptions. Over the years, several of the simplifications have been criticized and, partially, mended. For example, the Greenwood–Williamson model assumes that the asperities deform independently, whereas in reality asperities will interact through the very fact that they are connected by a common substrate; a possible correction for this has been proposed by Ciavarella et al. (2008). A much more fundamental assumption is that the asperities respond elastically. However, since contact happens at the highest peaks or asperities, it is to be expected that the local contact stress gets so high that plasticity is initiated. Indeed, the real contact area measurements in polymeric magnetic media by Bhushan (1985) had already revealed that a significant portion of the deformation was not recovered after unloading.

Gao et al. (2006) were the first to systematically study plastic deformation in asperity contact. Based on the behavior of an elastic-perfectly plastic two-dimensional (2D) sinusoidal asperity under contact, they computed the real contact area between a rigid flat surface and a deformable rough surface (Gao and Bower, 2006). However, these studies did not provide any information about the connection between contact area and normal force for a real 3D rough surface in the presence of both asperity interaction and asperity plasticity. A conceptually straightforward attempt was made by Pei et al. (2005), who performed a large numerical study of a 3D elasto-plastic contact problem of self-affine rough surfaces. Their model intends to address all issues of the Greenwood–Williamson model. Besides predicting a linear dependence of contact area on normal load, these authors also provide the contact pressure distribution and contact patch size distribution, both of which are very important information for wear. A distinct limitation of this study, however, is the use of J_2 isotropic plasticity at all length scales, down to asperities that are inevitably single crystalline.

Moreover, at size scales below tens of micrometers, plasticity is now known to be size dependent, with the general trend of 'smaller being harder'. Size dependent plasticity at these scales has been convincingly demonstrated in torsion (Fleck et al., 1994), bending (Stolken and Evans, 1998) and microindentation experiments. In the latter, the indentation hardness decreases monotonically with increasing depth of indentation h, when h is in the range of sub-microns to microns (Nix, 1989; Ma and Clarke, 1995; Poole et al., 1996). Since classical plasticity theories, including J_2, do not include an intrinsic material length, size effects like these cannot be captured. The plasticity size effects mentioned above have been attributed to geometrically necessary dislocations (GNDs) associated with non-uniform plastic deformation in small volumes (Nye, 1953; Ashby, 1970; Gao and Huang, 2003). Strain gradient plasticity theories (e.g., Poole et al., 1996; Fleck and Hutchinson, 1993; Gao et al., 1999; Huang et al., 2000; Gurtin, 2002) have been developed to describe size dependent behavior for problems with an externally imposed strain gradient, such as bending, torsion and indentation (Fleck et al., 1994; Gao et al., 2015; Xue et al., 2002) as well as in problems where plastic gradients develop as a consequence of constrained plasticity, such as in void growth and composite materials (Liu et al., 2005; Huang et al., 2000; Bittencourt et al., 2003). As a few of these cited works already suggest, another approach to analyzing plasticity at these size scales is Discrete Dislocation Plasticity (DDP) in which plastic deformation emerges from the nucleation and motion of discrete dislocations in an elastic background. After 2D DDP simulations have confirmed the existence of size effects associated with GNDs in, e.g., bending and indentation (Cleveringa et al., 1997, 1999; Widjaja et al., 2005), this framework has been adopted to study contact and friction. Deshpande et al. (2004) analyzed the static friction strength through DDP together with a cohesive interface. Sun et al. (2012) carried out the plastic flattening of a sinusoidal asperity, while Song et al. (2015) investigated how interlocked asperities deform when the two surfaces slide relative to each other. All these studies focused on a unit process of a single asperity interacting with the facing surface, hence do not include information about the surface, such as surface roughness.

DDP simulations of a 3D rough surface are not feasible with the existing frameworks for 3D boundary-value problems. We therefore adopt a strain gradient plasticity theory in order to gain some understanding of how size dependent plasticity may modify the conclusions based on classical J_2 plasticity – such as a linear dependence of real contact area A on the normal force N. Because of its simplicity and success in fitting indentation results, we have chosen to adopt the conventional mechanism-based strain gradient theory (CMSGP) proposed by Huang et al. (2004). CMSGP is implemented through an ABAQUS user subroutine. When simplifying the contact between two rough surfaces, there are two options (Johnson, 1985). The first is to use a rigid flat surface to flatten the rough surface of a deformable solid with equivalent Young's modulus and Poisson ratio; this approach has been used in Gao and Bower (2006), Pei et al. (2005), and Sun et al. (2012). Alternatively, one could press a rigid rough surface into a deformable flat substrate, like in indentation; this is what Yin and Komvopoulos (2012) did. In the present paper, we utilize the former simplification and perform the simulation of elasto-plastic contact between a rigid flat and a rough surface. The height probability density function of the rough surface follows a Gaussian distribution, and the statistical correlation between heights at two random points on surface is also assumed to have a Gaussian distribution. These assumptions are used to treat surfaces as statistically homogeneous, i.e. the statistics are independent of location on the surface.

The remainder of this paper is organized as follows. Section 2 describes the methodology for generating the rough surface and a brief summary of the constitutive equations of CMSGP. Section 3 first presents results for the unit process of rough surface contact, namely that of a single sinusoidal asperity in contact. Subsequently, Section 4 presents the contact of a rough surface, checks the linear dependence, describes the distribution of contact pressures. Section 5 summarizes the key conclusions.