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Adhesive contact between solids with periodically grooved surfaces

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ABSTRACT

This paper presents a study on adhesive contact between a periodically grooved surface and a flat surface. The effect of interfacial adhesion is included through the use of the Maugis–Dugdale adhesive contact model. The contact problem is reduced to a singular integral equation with Hilbert kernel for a height of the interface gaps and a system of two transcendental equations for widths of the gaps and the adhesion zones. Solutions are obtained for three different equilibrium states of the contact pair involving loading and unloading. The effects of the dimensions of the initial grooves and the adhesive stress on dimensions of the interface gaps, pull-off stress and adhesion hysteresis are investigated.

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1. Introduction

The surfaces of components in modern devices have very various shapes that are often created artificially by special processes (Etsion, 2005; Stepien, 2011). In particular, grooves and dimples are the most common geometric features used for modification of smooth surfaces. Many studies have shown that surface roughness affects the adhesion (Fuller and Tabor, 1975; Li and Kim, 2000; Persson, 2002; Persson and Tosatti, 2001; Sviridenok et al., 1990; Zhao et al., 2003). One effective approach for controlling adhesion between bodies is to create regular microrelief of contacting surfaces through micro texturing techniques. This approach is especially beneficial for MEMS/NEMS devices (Komvopoulos, 2003) that normally have smooth surfaces and are subjected to small applied forces.

The theoretical investigation of adhesive interaction between surfaces having regular microrelief is restricted to contact between a spherical indenter and a wavy surface (Guduru, 2007; Jin et al., 2011; Waters et al., 2009) and contact between semi-infinite solids with wavy surfaces (Adams, 2004; Carbone and Mangialardi, 2004; Goryacheva and Makhovskaya, 2010, 2011; Johnson, 1995; Wu, 2011) and rough surfaces (Hui et al., 2001; Zilberman and Persson, 2002) when the roughness is described by some periodic function.

In a previous paper (Chumak et al., 2014), a solution was given for the problem of adhesive contact between a half-space with a single surface micro-groove and a flat half-space. The effect of adhesion was taken into account by utilizing the Maugis–Dugdale model (Maugis, 1992). The solution covers both the case of incomplete (partial) contact and the case of complete (full) contact.

In this paper, based on the Maugis–Dugdale model, we will investigate the adhesive contact between a periodically grooved half-space and a flat half-space. The contact of solids with such surface texture is characterized by the presence of a periodic array of gaps at the interface. The solution of the corresponding contact problem can be constructed by means similar to those used in the previous paper (Chumak et al., 2014). Therefore, we give here only the essentials.

2. Statement of the problem

Fig. 1 shows two half-spaces prior to loading. It is assumed that the solids are made from isotropic and dissimilar materials with Poisson's ratios ν_1, ν_2 and shear moduli μ_1, μ_2. The surface of the lower half-space S_1 is perfectly flat, while the surface of the upper half-space S_2 has regular texture in the form of periodically arranged grooves. The width of each groove is equal to $2b$, and its shape is described by the smooth even function $r(x)$ $(r(\pm b) = 0,\ r'(\pm b) = 0)$. The grooves are spaced with the period d $(d > 2b)$. The contact problem is posed in the framework of linear elasticity, assuming plane strain conditions.

The solids are pressed together by a uniform pressure p applied at infinity (Fig. 2). Due to the regular surface texture of the upper solid, the interface consists of a periodic array of gaps and a periodic array of contacts. The interface is supposed to be frictionless. The adhesion between the surfaces is modeled by a tensile constant stress σ_0 acting in the regions $(-a + md, -c + md)$ and $(c + md, a + md)$, $m = 0, \pm 1, \pm 2, \ldots$, where the interface gaps are positive but less than a prescribed value h_0 (the Maugis–Dugdale model (Maugis, 1992)). For larger separations, the surface forces are zero. The adhesive stress

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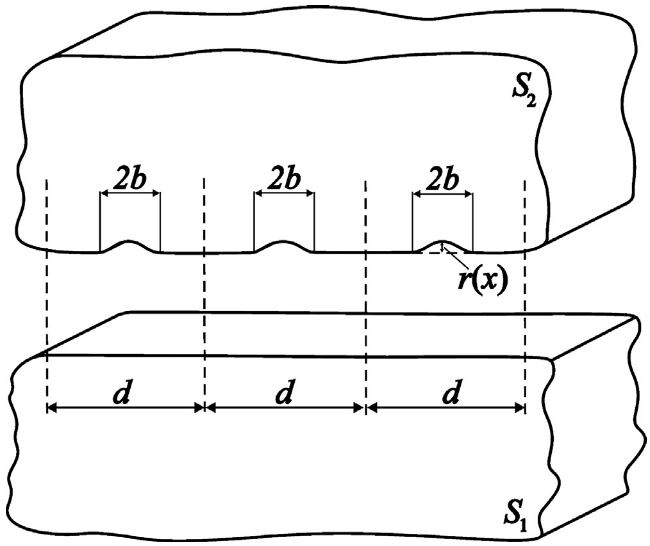

Fig. 1. The solids prior to loading. The surface of the lower half-space is flat. The surface of the upper half-space has a periodic array of grooves.

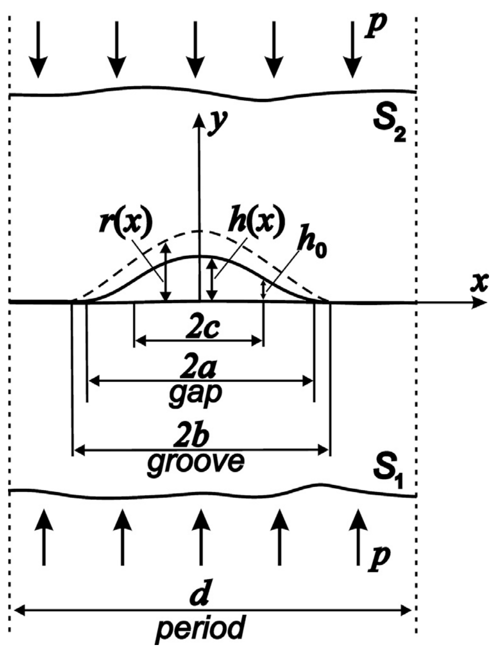

Fig. 2. Contact between the solids within the period $[-d/2, d/2]$: the constant adhesive stress σ_0 acts in the regions $(-a, -c)$ and (c, a). In the periods $[-d/2 + md, d/2 + md]$, $m = \pm 1, \pm 2, \dots$, the contact model is the same.

σ_0 is the maximum adhesion force approximately equal to $1.03\gamma/\varepsilon$ (γ is the work of adhesion, and ε is the equilibrium distance), and $h_0 \approx 0.97\varepsilon$. A height $h(x)$ and a width $2a$ of the gaps are unknown and depend on surface interaction as well as the applied load.

In addition, we assume that the maximum height of each groove is small in comparison to its width. This assumption justifies the approach in which the boundary conditions are not imposed on the curved surfaces but, as customary for contact problems in linear elasticity, written rather at the interface $y = 0$.

Because of the periodicity of all field quantities, the boundary conditions need only be considered in the interval $-d/2 \le x \le d/2$. The boundary conditions at the interface ($y = 0$) are:

$$\sigma_{yy}^-(x, 0) = \sigma_{yy}^+(x, 0), \sigma_{xy}^-(x, 0) = \sigma_{xy}^+(x, 0) = 0, |x| \le d/2, \tag{1}$$

$$\sigma_{yy}^+(x, 0) = \sigma_0, c < |x| < a, \sigma_{yy}^+(x, 0) = 0, |x| \le c; \tag{2}$$

$$u_y^+(x, 0) = u_y^-(x, 0) - \begin{cases} r(x), & a < |x| \le b \\ 0, & b \le |x| \le d/2 \end{cases}. \tag{3}$$

The boundary conditions at infinity ($|y| = \infty$) are:

$$\sigma_{yy} = -p, \ \sigma_{xy} = 0. \tag{4}$$

Here, the superscripts $^+$ and $^-$ denote the boundary values of the function on x-axis in the upper and lower solid, respectively; $\sigma_{xy}(x, y)$ and $\sigma_{yy}(x, y)$ are stress components; and $u_y(x, y)$ is a normal displacement.

3. Solution to the problem

The initial stages of the solution are similar with Chumak et al. (2014) and will be omitted here in the interests of brevity. The stresses and displacements in the both solids are represented in terms of the height of the grooves $r(x)$ and the height of the gaps $h(x)$, and the problem is reduced to the following singular integral equation (SIE) for $h'(x)$:

$$\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{h'(t)}{t-x}dt = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{r'(t)}{t-x}dt + \frac{K}{2}(p + \sigma(x)), |x| < \infty, \tag{5}$$

where $h(x) = u_y^+ - u_y^- + r(x)$; $K = 2(1-\nu_1)/\mu_1 + 2(1-\nu_2)/\mu_2$; $\sigma(x) = \begin{cases}\sigma_0, & c < |x-md| < a \\ 0, & |x-md| \le c\end{cases}$, $m = 0, \pm 1, \pm 2, \dots$; $h'(t)$ represents the derivative of $h(t)$ with respect to t.

Taking advantage of the periodicity (Schmueser and Comninou, 1979), SIE (5) can be rewritten as

$$\frac{1}{d}\int_{-a}^{a} h'(t)\cot\frac{\pi(t-x)}{d}dt = \frac{1}{d}\int_{-b}^{b} r'(t)\cot\frac{\pi(t-x)}{d}dt + \frac{K}{2}(p + \sigma(x)), |x| < a. \tag{6}$$

Using the change of variables $\xi = \tan(\pi x/d)$, $\eta = \tan(\pi t/d)$, $\alpha = \tan(\pi a/d)$, $\beta = \tan(\pi b/d)$, $\chi = \tan(\pi c/d)$, we reduce SIE (6) with Hilbert kernel to SIE (7) with Cauchy type kernel:

$$\frac{1}{\pi}\int_{-\alpha}^{\alpha}\frac{h'(\eta)}{\eta-\xi}d\eta = R(\xi) + \frac{dK}{2\pi}\frac{p+\sigma(\xi)}{\xi^2+1}, |\xi| < \alpha \tag{7}$$

where $R(\xi) = \frac{1}{\pi}\int_{-\beta}^{\beta}\frac{r'(\eta)}{\eta-\xi}d\eta$, $\sigma(\xi) = \begin{cases}\sigma_0, & \chi < |\xi| < \alpha \\ 0, & |\xi| \le \chi\end{cases}$.

The function $h(\xi)$ satisfies the conditions (Chumak et al., 2014)

$$h(\pm\alpha) = 0, h'(\pm\alpha) = 0. \tag{8}$$

In addition, the following condition is imposed on the normal stresses $\sigma_{yy}^{\pm}(\xi, 0)$ in the contact regions:

$$\sigma_{yy}^{\pm}(\xi, 0) \le \sigma_0, |\xi| \ge \alpha, \tag{9}$$

where the normal stresses σ_{yy} are defined by the expression

$$\sigma_{yy}^{\pm}(\xi, 0) = \frac{2(1+\xi^2)}{dK}\left(\int_{-\alpha}^{\alpha}\frac{h'(\eta)}{\eta-\xi}d\eta - \pi R(\xi)\right) - p. \tag{10}$$

It is worth noting that SIE (7) for this problem differs from that in Chumak et al. (2014) only in the second term of their right-hand sides.

Let us describe the shape of the grooves in the new variables by the function $r(\xi) = r_0(1 - \xi^2/\beta^2)^{3/2}$ identical to that in Chumak et al. (2014). For such a function $r(\xi)$, $R(\xi)$ is evaluated analytically:

$$R(\xi) = \frac{3r_0}{\beta}\left(\frac{\xi^2}{\beta^2} - \frac{1}{2}\right).$$

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