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Three-dimensional modeling of elasto-plastic sinusoidal contact under time dependent deformation due to stress relaxation

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ABSTRACT

In the current work, the effect of stress relaxation in contact between sinusoidal surfaces is studied using FE simulations. There are a few works on the elastic and elasto-plastic contact between sinusoidal surfaces, but the transient effects such as creep and stress relaxation are not considered in these works. Stress relaxation causes significant change in the contact area and pressure between the contacting surfaces. The Garofalo formula is used to model the transient behavior of stress relaxation. The results for the contact area and contact pressure are presented and discussed. Empirical equations are developed to predict contact area and pressure by fitting to the FEM results. The equations are dependent on the initial surface separation, aspect ratio, and the Garofalo constants.

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1. Introduction

The contact between rough surfaces has been a popular topic to researchers for many years. Most of the previous models on the contact between rough surfaces assume a cylindrical or spherical/ellipsoidal shape for the geometry of the asperities on the surfaces [2–11]. More recent models consider a sinusoidal shape for the asperities because it models the geometry of real surfaces better especially for heavily loaded contacts [1,12–16]. It is shown for the two-dimensional sinusoidal contacts [14] and three-dimensional sinusoidal contacts [15] that the maximum average pressure increases past the conventional hardness, H, limit of $3S_y$ obtained assuming spherical geometries [17]. Several works have shown experimentally measured contact pressures much higher than three times the yield strength, $3S_y$ [18,19]. Furthermore, the interaction between adjacent asperities is addressed by applying symmetric boundary condition in a sinusoidal asperity contact model which is overlooked in works based on spherical asperities. Also, most of the multi-scale rough surface contact models consider the multi-scale nature of surface roughness by transforming a rough surface into sums of sine and cosine functions using a Fourier series or Weierstrass profile [13,20–22]. Therefore, it is logical to use a sinusoidal instead of a spherical shape in modeling the asperities.

The elastic contact between two-dimensional sinusoidal surfaces was analytically solved by Westergaard [12] for the whole range of contact. Johnson et al. [1] presented two asymptotic solutions for the elastic contact of three-dimensional sinusoidal surfaces, but no analytical solution is available for the entire load range. Jackson and Streator [22] developed an empirical equation based on the JGH data [1] for the whole range of contact from early contact to complete contact. However, plastic deformation is practically inevitable in most cases of contact between metallic rough surfaces due to high loads. Gao et al. [14] considered plastic deformation in their contact model. They modeled a two-dimensional elastic-perfectly plastic sinusoidal contact using the finite element method (FEM). Krithivasan and Jackson [15] and Jackson et al. [16] considered both elastic and elasto-plastic sinusoidal contacts in three-dimensions in their work, and presented empirical equations for the contact area as a function of contact pressure for the whole range of contact. Their equations are used in this work to verify the developed model. Rostami and Jackson [23] also presented empirical equations for the surface separation in elastic and elasto-plastic sinusoidal contacts in three-dimensions. These elastic and elasto-plastic contact models between sinusoidal surfaces have been used in several multi-scale contact models [13,20–22,24–26] to predict the real contact area between two rough surfaces.

Stress relaxation and creep are time dependent phenomena which cause a change in the stress and strain in a material over time. For contacting surfaces, Stress relaxation and creep cause a change in the contact area and contact pressure over time. Stress relaxation refers to the stress relief of a material under constant

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Nomenclature

A	area of contact
B	aspect ratio (ratio of the sinusoidal asperity amplitude to its wavelength)
B'	creep constant of the power law
B''	creep constant of the exponential law
β	creep constant of the exponential law
C	critical yield stress coefficient
$C_i, \tilde{C}_i (i = 1-4)$	creep constants of the Garofalo, strain hardening, and modified time hardening laws
d	material and geometry dependent exponent
E	elastic modulus
E'	reduced or effective elastic modulus
E_T	tangent modulus
e_y	yield strength to effective elastic modulus ratio, S_y/E'
f	spatial frequency (reciprocal of wavelength)
F	contact force
$\overline{g}$	average surface separation
h	height of the sinusoidal surface from its base
H	hardness
n	creep constant of Garofalo law
p^*	average pressure for complete contact (elastic case)
p^*_{ep}	average pressure for complete contact (elasto-plastic case)
$\overline{p}$ or p_{ave}	average pressure over the nominal area of contact
S_y	yield strength
t	contact time
τ	dimensionless contact time
Δ	amplitude of the sinusoidal asperity
λ	wavelength of the sinusoidal asperity
ν	Poisson's ratio
σ	stress
ε	strain
δ	interference between the sinusoidal asperity and the rigid surface
a, b	curve-fitting constants for contact area
a', b', c', d'	curve-fitting constants for contact pressure

Subscripts

0	initial or at t = 0
c	critical value at onset of plastic deformation
cr	creep dependent parameter
ep	elasto-plastic
JGH	from model by Johnson et al. [1]

strain condition, and creep describes how strain in a material changes under constant stress condition. In most works, the terms "creep strain" and "creep stress" are used for both cases of stress relaxation and creep.

Any material can experience stress relaxation or creep if certain conditions are met. It could be metals at high temperatures, polymers at room temperatures, and any material under the effect of nuclear radiation. It should be noted, although there is no recovered creep strain or reversible behavior under normal operating conditions, elastic deformations are still recovered. The stress relaxation or creep behavior depends on the temperature and the stress level to which the material is exposed and depends noticeably on the time duration of application of these conditions. There have been several works on modeling the stress relaxation and creep effects in the contact between single asperities [27–29]. Most of the earlier models on these effects have assumed a rigid spherical punch indenting an elasto-plastic flat surface [30–34]. Different effects in contact between rough surfaces such as the dwell-time dependent rise in static friction [35,36], the velocity dependent dynamic friction [37–40] or friction lag and hysteresis [41] can be explained by the creep theory. Many experimental studies concerning the increase of friction with dwell time are published i.e., [42–46]. Malamut et al. [35] studied the effect of dwell time on the coefficient of static friction in spherical contacts using FE simulations.

The previous works on the stress relaxation and creep effects in contact between surfaces used a cylindrical [38–40,47,48] or spherical [27–29] geometry for the asperities, but in the current work a sinusoidal asperity is considered in contact with a rigid flat surface under the stress relaxation effect. The change in the static friction between two solids with time is the main motivation for modeling the stress relaxation effect.

The current analysis uses the same geometry used in Johnson et al. [1] and Krithivasan and Jackson [15] in order to compare the static results to their works. The sinusoidal geometry is described by

$$h = \Delta\left(1 - \cos\left(\frac{2\pi x}{\lambda}\right)\cos\left(\frac{2\pi y}{\lambda}\right)\right) \quad (1)$$

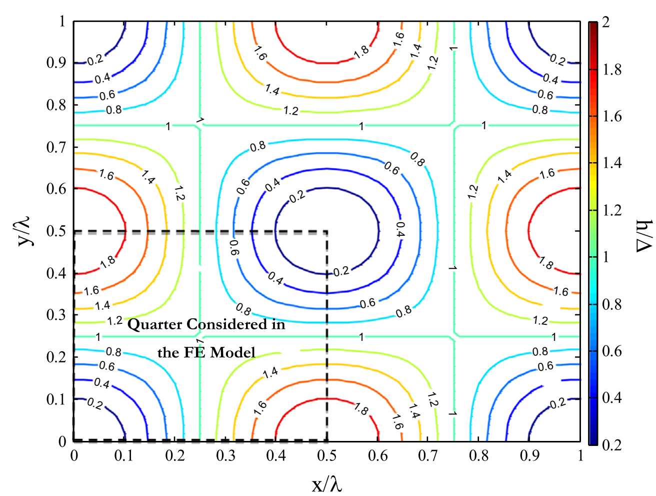

Fig. 1. Contour plot of the sinusoidal surface geometry.

where h is the height of the sinusoidal surface from its base, Δ is the amplitude of the sinusoidal surface, and λ is the wavelength of the sinusoidal surface. The contour plot of the sinusoidal surface is shown in Fig. 1.

2. Elastic sinusoidal contact

As mentioned before, Johnson et al. [1] developed asymptotic solutions for contact area of a perfectly elastic contact of three-dimensional sinusoidal shaped surfaces. In their work, $\overline{p}$ is defined as the average pressure on the surface (considering both contacting and non-contacting regions), and p^* is defined as the average pressure that when applied to the surface causes complete contact. p^* is given as

$$p^* = \sqrt{2}\pi E' \Delta f \quad (2)$$