Modeling of a Creep Process between Rough Surfaces under Tangential Loading

B. Grzembia*

Technische Universität Berlin, Berlin, D-10623 Germany
*e-mail: birthe.grzembia@tu-berlin.de

Received February 17, 2014

Abstract—If two bodies with rough surfaces are brought into contact and an increasing tangential load is applied, there will be some relative tangential displacement of the bodies due to the contact stiffness and partial slip in the contact area. The sliding areas will increase with increasing load until the condition of complete sliding is fulfilled and macroscopic sliding starts. In this paper it is suggested that an essential part of the slow creep observed in many contact problems is due to this combined effect of elasticity and partial slip. To prove this hypothesis, tangential creep in contact of rough surfaces is simulated using the assumption of a constant coefficient of friction. The results of the simulation are compared with high resolution experimental measurements of creep between steel samples. In the most cases, the surface parameters can be adjusted to achieve a good description of the experimental data.

DOI: 10.1134/S1029959914030072

Keywords: tangential contact, creep, rough surfaces, stick-slip, Coulomb friction, method of dimensionality reduction

1. INTRODUCTION

Creep in contacts is a universal phenomenon, which is observed in contacts of all scales, from nanoindentation [1] to earthquake dynamics [2, 3], both in the normal [4] and tangential direction. In the literature, one can find different usage of the notion “creep”. The standard meaning of creep is a slow deformation or displacement occurring under conditions of constant load. However, in rolling contact mechanics, the slow relative movement of bodies due to their elastic deformation and partial slip in the contact area is also called “creep” [5]. In a pure tangential contact under a constant load, elastic deformation and partial slip do not lead to progressive slow motion. However, if the load is increasing, it is not possible to differentiate between the “true” creep due to plastic deformation and due to elastic deformation and partial slip. In the present paper we suggest that an essential part of the “creep” in tangential contacts under unsteady loading conditions may be due to the mentioned effects of contact stiffness and partial slip.

To prove this we consider a contact of rough surfaces under constant normal and increasing tangential load. This is a contact setup often used for experimental investigations especially in the field of earthquake dynamics. Such systems tend to a stick-slip movement, where creep occurs in the sticking phase prior to sudden slip events.

For moderate normal loads, a rough surface will usually not come into complete contact. When a tangential load is applied, some regions of contact will be still sticking whereas others will be already in sliding state. Because of the increase of tangential load, there will be an increasing relative displacement of bodies, which macroscopically looks like slow “creep”. In the following, we will investigate this relative displacement and call it “creep”.

The maximum displacement due to this creep before macroscopic sliding is a characteristic length parameter of the contact configuration. It depends on the surface and material properties and the normal force [6].

Instable frictional processes as the considered ones are often described using rate-and-state friction laws [7–9]. This class of friction laws represents microscopic creep processes using three or four empiric parameters in the global friction law. In contrast, in this paper the microscopic effects are represented by a resolution of the surface roughness and a local Coulomb friction law.

In the area of rock friction the considered surfaces are fractal and self-affine in their roughness [10]. This con-
cept for roughness can also be used in other engineering areas [11]. The surface topography is then characterized by two to three parameters: the Hurst exponent, rms roughness and cutoff wavelength. The normal contact problem for such fractal surfaces has been studied extensively over the last years [12, 13].

For fractal rough surfaces, the accurate representation of normal contact stiffness by the method of dimensionality reduction (MDR) has been proven in [14, 15]. The validity of the method of dimensionality reduction for tangentially loaded contact has been shown for rotational symmetric bodies [16] and the corresponding proof for fractal surfaces is in progress.

2. CREEP MODEL

Consider a 3D contact of two bodies with rough self-affine, fractal surfaces which can be characterized by rms roughness \( h_{\text{rms}} \) and the Hurst exponent \( H \). In the present model, it is assumed that the surface roughness has no cutoff wavelength, which means the longest present wavelength is the size of the system itself. In a series of recent papers, it has been shown that the contact problems of three-dimensional rough bodies can be described equivalently by one-dimensional contacts with elastic foundations (method of dimensionality reduction) [14–18]. In the frame of the method of dimensionality reduction this problem is replaced by a problem of contact of a rough line generated accordingly to [17] with an elastic foundation having the following normal and tangential stiffnesses [18]:

\[
c_n = \frac{E}{2(1-v^2)} \Delta x \Delta x, \quad c_t = \frac{2G}{2-v^2} \Delta x \Delta x, \quad (1)
\]

where \( E \) and \( G \) are the Young’s and shear modulus, respectively, \( v \) is the Poisson’s ratio and \( \Delta x \) represents the distance between two springs.

An example of such fractal line is given in Fig. 1. The phasing of all created fractal lines is random. Congruously, all numerical calculations where performed for hundred sample lines and the results are given by the mean values.

The simulation proceeds in the following steps. First, the rough line is brought into normal contact with the elastic plane until the desired normal force is reached. Then step by step a tangential displacement is forced upon the system and the according tangential force is deduced as the sum of all spring forces. The Coulomb friction law

\[
F_t \leq \mu_0 F_n \quad (2)
\]

is applied for each single contact point \( i \) at the end of each spring. The tangential spring forces \( f_{t,i} \) are then given by

\[
f_{t,i} = \begin{cases} c_t u_t & \text{for } c_t u_t < \mu_0 f_{n,i}, \\ \mu_0 f_{n,i} & \text{for } c_t u_t \geq \mu_0 f_{n,i}. \end{cases} \quad (3)
\]

Here \( \mu_0 \) is the friction coefficient and \( u_t \) is the global tangential displacement which is the same for all points, \( f_{n,i} \) is the normal force of spring \( i \).

This is performed as a static process, equilibrium is assumed at all times. Since each single state of the system is unique, fixing the displacement or fixing the force is equivalent. The static approach is valid if the considered creep processes proceed slowly.

A plot of the global tangential displacement \( u_t \) on the global tangential force \( F_t \) for different surfaces shows the influence of the Hurst exponent on the creep process (Fig. 2). The normalization is applied: The maximum tangential displacement is given by the displacement where the last spring goes into sliding state; the spring with maximum normal deflection \( d_{\text{max}} \) located beneath the highest asperity; \( d_{\text{max}} \) is also equivalent to the macroscopic indentation depth. The complete sliding state is reached when

\[
c_t u_{t,\text{max}} = \mu_0 f_{n,\text{max}} \Rightarrow u_{t,\text{max}} = \frac{\mu_0 f_{n,\text{max}}}{c_t} = \frac{c_n}{c_t} d_{\text{max}}. \quad (4)
\]