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CYCLIC LOADING OF AN ELASTIC-PLASTIC ADHESIVE CONTACT

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ABSTRACT

A numerical simulation is presented for several loading-unloading cycles of an adhesive contact between an elastic-plastic sphere and a rigid flat. The main goal of the simulation is to study the plastic deformation evolution in a contact bump material – the microscopic electrode found in a MEMS micro-switch for providing a good electric contact. This bump is subjected to a cyclic contact interaction with a harder substrate and cyclic plasticity of the bump material can lead to its wear and as result to a failure of the whole MEMS device.

INTRODUCTION

Elastic-plastic adhering contacts are widely found in modern micro/nano-scale applications such as MEMS micro-switch, for example. In this case the contact pair operates in a cyclic manner i.e. approach of two contacting bodies successively alternates with their separation.

“Stuck-closed” and “stuck-open” failures can be experimentally observed during micro-switch cycling [1]. In the first case, the adhesion at the micro-switch contact exceeds the restoring beam force after release of its actuation, and the device remains permanently closed. In the second case, the electric resistance of the micro-switch contact progressively increases, deteriorating its performance. Multiple physical mechanisms can be involved in these failures (e.g. electric heating or oxidation), however, the dominant mechanism is plastic deformation [1], which progressively destroys the micro-switch hemispherical contact bump, flattening its surface and causing material transfer from the bump to the contacting substrate.

Cyclic loading of non-adhesive elastic-plastic contacts was studied regarding various engineering applications. The erosive wear of ductile metallic substrate caused by repeated impacts of hard eroding particles [2], for example, was modeled as a repeated contact of a rigid sphere with an elastic-plastic half-space.

The adhesive attractive force plays an important role in a contact of micro/nano-bodies. The study of an adhesive contact has a long history [3] originating from the development of two classical elastic models, JKR [4] and DMT [5], based on limiting cases simplified analytical solutions. A dimensionless parameter, μ, having the form:

$$\mu = \left[\frac{R^* \, (\Delta\gamma)^2}{E^{*2} \varepsilon^3} \right]^{1/3} \tag{1}$$

was suggested by Tabor [6] as a criterion that characterizes the above two limiting cases (large values of μ correspond to the JKR case while small ones to the DMT case). In the case of a contact between an elastic sphere and a rigid flat, $R^* = R$, where R is the sphere radius, $E^* = E/(1-\nu^2)$ where E and ν are the Young's modulus and Poisson’s ratio, respectively, of the sphere material, $\Delta\gamma$ is the work of adhesion and ε is the inter-atomic equilibrium distance.

More recent studies of an elastic adhesive contact, based on the Lennard-Jones potential and various numerical solutions, provided universal models suitable for the entire range of μ (see e.g. [3]). These studies showed two possible stable states for the same value of the contact approach of two adhering bodies. This occurs for significantly high μ values, when the force-deformation relation becomes unstable and the sphere surface jumps into contact (jump-in instability) during loading, and jumps out of contact (jump-out instability) during unloading.

Several experimental works (see e.g. [7]) showed that adhesion alone is able to initiate plastic deformation. It is also known (see e.g. [8]) that the separation of adhesive elastic-plastic contacts can be purely elastic (brittle separation) or can be accompanied by certain amount of plastic deformation (ductile separation). Some simplified analytical solutions of an elastic-plastic adhesive contact are provided in [9] for the loading stage, generalizing the DMT model for the elastic-plastic material, and in [10] for the unloading stage, assuming a brittle separation of plastically loaded spheres.

A single load-unload cycle was studied by Finite Element simulations in [11] showing brittle and ductile separation for ruthenium (Ru) and for gold (Au) micro-contacts, respectively, when interacting with a rigid flat. Molecular Dynamic simulations studying a single load-unload cycle of an adhesive contact [12] showed that extremely large plastic deformations which occur during the unloading stage can induce material transfer from one contacting body to the other.

In a previous work [13] we studied a single load-unload cycle of adhesive contact between an elastic-plastic sphere and a rigid flat. In the current study we use the same model for the investigation of the load-approach curves evolution during subsequent loading-unloading cycles.

THE PHYSICAL AND NUMERICAL MODELS

Following the previous study [11], the contact of the micro-switch bump with contacting substrate can be assumed as a contact of a deformable elastic-plastic sphere and a rigid flat (see Fig. 2a). The undeformed shape of the sphere is shown by the dashed line. The parameter ω (which is used as the input parameter in the current model) denotes the approach between the summit of the undeformed sphere and the rigid flat. The interaction between the sphere and the flat is governed by the Lenard-Jones potential [3]. Hence, the local traction, $p(r)$, acting on the sphere surface is given by:

$$p(r)=\frac{8\Delta\gamma}{3\varepsilon}\left\{\left[\frac{\varepsilon}{h(r)}\right]^3-\left[\frac{\varepsilon}{h(r)}\right]^9\right\} \tag{2}$$

where $h(r)$ is the local distance between the deformed sphere and the flat. The reactive force, P, (the total force acting between two contacting bodies) holds the flat at the given input approach ω from the sphere.

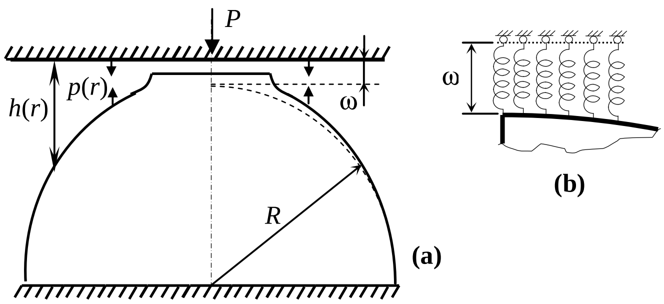

Figure 2. Schematic representation of an adhesive contact

A commercial ANSYS 9.0 Finite Element package was used to solve this axi-symmetric elastic-plastic problem. The non-linear relation between the local traction, $p(r)$, and the local separation, $h(r)$, is simulated by uniformly distributed imaginary nonlinear springs that connect the sphere surface to the rigid flat (see Fig. 2b). Each spring applies a pointwise force to the sphere in accordance to its extension (see [13] for more detailed explanation).

The material of the sphere is assumed elastic linear kinematic hardening with a tangent modulus E_T that is 2% of the Young's modulus E. The von Mises yielding criterion is used to detect local transition from elastic to plastic deformation, and the Hooke and the Prandtl Reuss constitutive laws govern the stress-strain state in the elastic and plastic deformation zones, respectively.

RESULTS AND DISCUSSIONS

Three main dimensionless parameters define the problem of the adhesive cyclic contact [13]; the Tabor parameter, μ, (see Eq. 1) and the plasticity parameter, $S=\Delta\gamma/\varepsilon Y_0$, where Y_0 is the virgin yield strength of the sphere material. A third dimensionless parameter, ω_{max}/ε, represents the maximum approach during the entire loading-unloading cycle.

In the current work we consider (as in [13]) a gold nano-sphere with a typical radius of 300 nm, and typical material properties: Young's modulus $E=80\,\text{GPa}$, Poisson's ratio $\nu=0.42$, energy of adhesion $\Delta\gamma=1\,\text{J/m}^2$, virgin yield micro-strength $Y_0=1.2\,\text{GPa}$ (see [14] where the yield strength is calculated according to Mackenzie's method) and an equilibrium inter-atomic distance $\varepsilon=0.3\,\text{nm}$. The dimensionless parameters of the contact pair are then: $\mu=1$ and $S=2.8$.

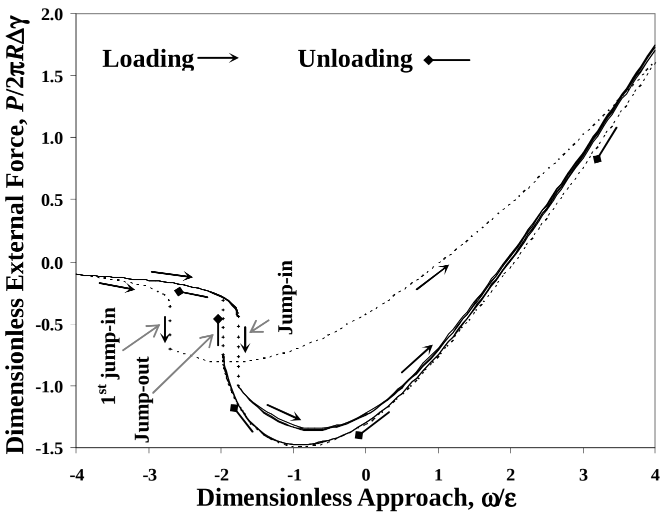

Figure 3. Dimensionless load-approach relation during the cyclic loading of the elastic-plastic adhesive contact

Figure 3 presents the total force, P, acting between the sphere and the flat, normalized by $2\pi R\Delta\gamma$, as a function of the dimensionless approach, ω/ε, for the case of $\omega_{max}/\varepsilon=4$. Negative values of force correspond to attraction between the sphere and the flat while positive values to repulsion between them. The results are shown for three subsequent load-unload cycles, where the dashed lines refer to the first load-unload cycle and the full lines to the following two cycles. As can be seen from Fig. 3 there is a clear distinction between the first load-unload cycle and the two subsequent ones. The difference exists mainly for the first loading half-cycle. It is also shown that the load-unload cycles that follow the firs cycle coincide and repeat themselves. This load-unload repeated loop contains both the jump-in and jump-out instabilities and exhibits a plastic hysteresis where, as is shown in Fig. 3, the loading half cycle does not coincide with the unloading one, especially in the range of $-2\varepsilon < \omega < 0$. It indicates alternative plasticity in which kinematic hardening material repeatedly undergoes plastic deformation during both the loading and unloading half-cycles, while the increment of plastic deformation during the whole load-unload cycle vanishes [14]. This phenomenon is called, plastic shakedown (also known as "plastic fatigue"), which leads to material failure. Similar failure is commonly observed during cyclic bending of paper clips that after a number of cycles can be fractured. The material of a contact bump undergoes similar damage process during the cycling of a micro-switch.

CONCLUSIONS

A numerical model for a cyclic adhesive contact between an elastic-plastic sphere and a rigid flat was developed. This model allows simulating the destruction of a MEMS micro-switch contact bump based on adhesion and kinematic hardening plasticity. The load-approach relation obtained from the numerical simulation shows the existence of plastic shakedown of the contact bump during the cycling of the micro-switch. Cyclic plasticity can lead to the flattening of the contact bump and to increase of its electric resistance by material destruction - e.g. wear particles transfer from the bump to the contacting substrate.

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