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Influence of the elasto-plastic adhesive contact on Micro-Switches

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Abstract

Undesirable stiction, which results from contact between surfaces, is a major failure mode in micro electro-mechanical systems (MEMS). In previous works, a statistical rough surfaces interaction model, based on Maugis and Kim formulations has been presented to estimate the adhesive forces in MEMS switches. In this model, only elastic adhesive contact has been considered. However, during the impact between rough surfaces, at pull-in process for example, plastic deformations of the rough surfaces cannot be always neglected especially for the MEMS with metallic contact surfaces.

In the present work, a new micro-model predicting the adhesive-contact force on a single elastic-plastic asperity interacting with a rigid plane is presented. This model will be used later on for the interaction between two elastic-plastic rough surfaces. The MEMS devices studied here are assumed to work in a dry environment. In these operating conditions only the Van der Waals forces have to be considered for adhesion.

1 Introduction

Due to their reduced sizes, one of the most common failure mechanism of MEMS is stiction [1], which results from surface forces (capillary, van der Waals (VDW) or electrostatic). Stiction happens when two components entering into contact permanently adhere to each-other due to the importance of these surface forces. This can happen either during the fabrication process at etching or during normal use, in which cases one will respectively talk about release or in-use stiction.

Recently stiction of a structure was predicted by considering two scales [2, 3]: a finite-element model of the structure at the higher scale, and a micro adhesive-contact model at the lower scale. In order to easily implement such a micro model in a finite element framework, the authors recently proposed a model predicting the micro adhesive-contact curves, *i.e.* the adhesive-contact force *vs.* surface separation distance, for two interacting micro-surfaces, [4]. This analytical model, accounting for elastic deformation of the asperities and for van der Waals forces, is based on classical adhesion theories.

Most common theories of adhesion between two elastic spheres are the Johnson-Kendall-Roberts (JKR) model [5] and the Derjaguin-Muller-Toporov (DMT) model [6]. As the JKR model is ideal for soft materials with a large contact curvature surface and with a high surface energy, while the DMT theory is well suited for hard materials with a reduced contact curvature and with a low surface energy, Maugis [7] provided a transition solution for intermediate cases, solution which was improved to account for the adhesion in the non-contacting parts of the spheres by Kim *et al.* [8]. In order to account for the roughness property of real micro-surfaces, these former analytical theories based on a single asperity model can be generalized using the statistical approach introduced by Greenwood and Williamson (GW) [9], where the rough surfaces are simulated by multi-asperities with a random height distribution [10].

When used in a two-scale framework, the micro-model previously presented by the author [4] has been shown to predict accurate results for elastic material in dry environment [3]. However to improve

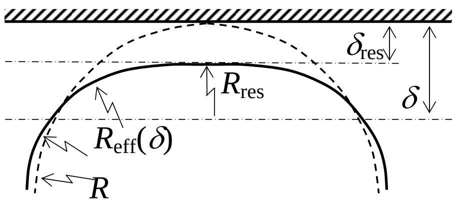


Figure 1: Schematics of the single elastic-plastic asperity problem.

the accuracy in other environment, this micro-model requires enhancements, and in particular its extension to the elasto-plastic behavior of the asperities. As a first step toward this end, this paper presents an improved model for the single elastic-plastic asperity-plane interaction problem.

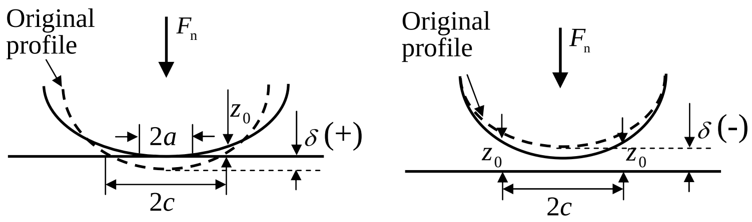
During contact, as a critical yield stress is reached, part of the material within the asperity yields gradually and some materials is deformed plastically, while the surrounding material can remain elastic (elastic-plastic interim regime) or not (fully plastic regime). Chang-Etsion-Bogy (CEB) model of a single sphere pressed by rigid flat [11] considers a constant volume when plasticity occurs. In their model Sahoo and Banerjee [12] assume that the asperity keeps the Hertz contact profile even under plastic behavior, allowing to evaluate the adhesive forces from the DMT adhesion model. Maugis-Dugdale theory [7] is used in Peng and Guos work [13] to consider the adhesive interaction in the fully plastic regime. In these last cases, the interim elasticplastic regime cannot be modeled.

Apart from these analytical models for plasticity, models can also be based on numerical results. Based on finite element analysis results and considering the variation in the curvature of the contact surface during the contact interaction, an analogous theoretical model is deduced by Li *et al.* [14]. Kogut and Etsion (KE) [15, 16] developed a model based on finite-element results for an elastic-perfectly plastic sphere-plane interaction. In this model, a very detailed analysis of the stress distribution in the contact region is performed and the empirical expressions are presented for the contact area and the contact force in a piece-wise form. In the work of Jackson and Green [17], a finite element analysis is also performed and the produced results appreciably differ from the KE model as more geometry and material effects (as hardness) are accounted for. Effect of contact condition (slip/stick) is described by Brizmer *et al.* [18]. In complement to these loading studies, unloading behavior is also studied by Etsion *et al.* [19].

In the present paper, following previous models [11, 17, 14, 18, 19], the evaluation of the elastic-plastic asperity profile during loading and unloading is first obtained without considering the adhesion effect. Thus, although it enables the modelization of hysteretic curves between loading and unloading, adhesion-induced plasticity which could happen for extremely soft materials as gold, see the criterion developed in [20, 21], will not be modeled. As we neglect deformation from the adhesion effect during the loading part, we consider the Maugis theory [7] completed by Kim extension [8] to evaluate the adhesion forces depending on the tip radius evolution during loading and unloading processes. As a main difference with previous models, adhesion forces are evaluated taking into account the effect of the non-constant asperity curvature after elasto-plastic deformation, which conducts to an accurate prediction of the pull-out forces when compared to full finite-elements simulations [22]. Only van der Waals forces are considered, which is a realistic assumption below 30 % humidity [1]. More details on the application of this model can be found in [23].

2 Elastic-plastic deformation of the single asperity

First, the evaluation of the elastic-plastic asperity profile during loading and unloading is obtained without considering the adhesion effect. Let us consider a single asperity of tip radius R interacting with a plane, at an interference δ, defined as the distance between the original profile of the asperity tip and the plane, see Fig. 1.



(a) Positive interference (b) Negative interference

Figure 2: Adhesion problem. (a) For a positive interference, a is the contact radius and c is the adhesive-contact radius. (b) For a negative interference, c is the adhesive-contact radius.

Following previous works [11, 17, 18], the critical yield interference δ_{CP} is defined as the interference at which the asperity starts yielding. These models [11, 17, 18] predicted the same expression

$$\delta_{\mathrm{CP}} = \left(\frac{\pi C_\nu S_Y}{2E}\right)^2 R\,, \tag{1}$$

where E is the asperity Young modulus, S_Y its yield stress, and where C_ν is a coefficient related to its Poisson coefficient ν. Although different in each model, the expressions of C_ν produce almost indistinguishably results in the Poisson ratio validity range, and in this paper, Jackson *et al.* [17] form $C_\nu = 1.295e^{0.736\nu}$ is adopted. The corresponding critical contact radius a_{CP} and contact force F_{CP} are respectively given by $a_{\mathrm{CP}} = \sqrt{\delta_{\mathrm{CP}} R}$ and $F_{\mathrm{CP}} = \frac{2}{3}\pi C_\nu S_Y \delta_{\mathrm{CP}} R$.

During the elastic-plastic loading phase, the interference reaches the maximal value $\delta_{\max}$, larger than the critical interference δ_{CP}, leading to plastic deformations. The effective asperity tip radius after unloading is different from its initial value R, and FE-based curve fitting achieved by Etsion *et al.* [19] predicts

$$\delta_{\mathrm{res}} = \delta_{\max}\left[1-\left(\frac{\delta_{\mathrm{CP}}}{\delta_{\max}}\right)^{0.28}\right]\left[1-\left(\frac{\delta_{\mathrm{CP}}}{\delta_{\max}}\right)^{0.69}\right], \tag{2}$$

$$R_{\mathrm{res}} = R\left[1+1.275\left(\frac{S_Y}{E}\right)^{0.216}\left(\frac{\delta_{\max}}{\delta_{\mathrm{CP}}}-1\right)\right], \tag{3}$$

for respectively the residual interference δ_{res} and the residual curvature R_{res} of the sphere after complete unloading, see Fig. 1.

3 Adhesive Contact

In this section, we briefly review the Maugis [7] and Kim expansion [8], of adhesive-contact theory for a single elastic asperity interaction. This includes the Hertz contact forces due to the elastic deformation of the asperity at micro contacts and the adhesion forces due to van der Waals attractive forces. Then we develop an enhanced model predicting the adhesive-contact forces for a single elastic-plastic asperity.

3.1 Maugis Theory

The inter-atomic attraction effect is modeled using a Dugdale assumption of inter-atomic attractions: within a critical value of separation z_0, two surfaces are attracted with a constant force per unit area σ_0, and if the separation z exceeds this threshold z_0, the adhesive traction immediately falls to zero. Thus the adhesive energy reads $\varpi = \sigma_0 z_0$.

In order to characterize the importance of the adhesive traction to the Hertz elastic deformation pressure, the Maugis transition parameter between the JKR and DMT regimes is defined as

$$\lambda = \frac{2\sigma_0}{\sqrt[3]{\frac{\pi\varpi K^2}{R}}} , \tag{4}$$

where $K = \frac{4}{3}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1}$ depends on the material properties of the two bodies. In Eqn. (4), R is the initial tip radius of an asperity interacting with a plane. The adhesive-contact force of the asperity F_n and the contact radius a, see Fig. 2(a), can be obtained from the interference δ, by solving the system

$$\begin{aligned}
1 &= \frac{\lambda A^2}{2}\left[\sqrt{m^2-1} + \left(m^2-2\right)\arctan\sqrt{m^2-1}\right] + \\
&\quad \frac{4\lambda^2 A}{3}\left(\sqrt{m^2-1}\arctan\sqrt{m^2-1} - m + 1\right) , && (5)\\
\Delta &= A^2 - \frac{4}{3}A\lambda\sqrt{m^2-1}\,, \text{ and} && (6)\\
\bar{F}_n &= A^3 - \lambda A^2\left(\sqrt{m^2-1} + m^2\arctan\sqrt{m^2-1}\right) , && (7)
\end{aligned}$$

in terms of the dimensionless values

$$\begin{aligned}
A &= a\sqrt[3]{\frac{K}{\pi\varpi R^2}} , && (8)\\
\bar{F}_n &= \frac{F_n}{\pi\varpi R} , \text{ and} && (9)\\
\Delta &= \delta\sqrt[3]{\frac{K^2}{\pi^2\varpi^2 R}} . && (10)
\end{aligned}$$

In these equations, $m = \frac{c}{a}$ and c is the adhesive-contact radius on which adhesive forces apply, see Fig. 2(a). The set of Eqs. (5-7), is completed by the interference evaluation

$$\delta = \frac{a^2}{R} - \frac{8\sigma_0}{3K}\sqrt{c^2 - a^2} . \tag{11}$$

Kim *et al.* [8] extended Maugis-Dugdale solution to the non-contact regime, *i.e.* $a = 0$ and $c \neq 0$, see Fig. 2(b), by the adjustment of Maugis governing Eqns. (5-7), see [4] for details. Practically, this expansion has to be considered when $\lambda < 0.938$.

From this theory, the determination of the contact force F_n in terms of the interference δ can be found be solving Kim expansion of Maugis theory for a given value of λ.

3.2 Adhesive Force on the Deformed Asperity

In the present work, we propose to account for a non-constant asperity radius in terms of the interference, see Fig. 1, and to perform the adhesive-contact theory on the assumed elastically deformed asperity which has an effective tip radius R_{eff} at a contact interference $\delta - \delta_{\text{res}}$. This is motivated by the fact that Maugis theory assumes a uniform asperity radius to apply Hertz theory. However, during the interaction, this case is only met at the limit case $\delta = \delta_{\text{res}}$.

In this paper, we propose the expression

$$\frac{R_{\text{eff}}}{R} = \frac{R_{\text{res}}}{R} - 1.275\left(1-c_1\right)\left(\frac{S_Y}{E}\right)^{0.216}\left(\frac{\delta_{\max}}{\delta_{\text{CP}}} - 1\right)\left(\frac{1 - e^{c_2\frac{\delta-\delta_{\text{res}}}{\delta_{\max}-\delta_{\text{res}}}}}{1 - e^{c_2}}\right) , \tag{12}$$

where c_1 and c_2 are expressions determined by inverse analysis. In this paper, we propose the expressions

$$c_1 = 0.22 + 0.642e^{-0.092\frac{\delta_{\text{max}}}{\delta_{\text{CP}}}}, \text{ and} \quad (13)$$

$$c_2 = \frac{10}{1+\left(\frac{\delta_{\text{max}}}{10\delta_{\text{CP}}}\right)^2} - 5\,. \quad (14)$$

These expression were identified by inverse analysis, see next section, and are shown to be valid for at least Ruthenium material.

These expressions satisfy $R_{\text{eff}}\left(\delta = \delta_{\text{res}}\right) = R_{\text{res}}$, where for a given loading process characterized by δ_{max}, the residual interference δ_{res} and asperity tip radius R_{res} can be calculated from Eqs. (2-3). As the residual radius of curvature of the asperity profile is found to be larger at the summit than at other radial position [19], $R_{\text{eff}}\left(\delta_{\text{res}} < \delta < \delta_{\text{max}}\right)$ should be lower than R_{res}, and expression (12) predicts a monotonic decreasing profile with δ, until reaching $R_{\text{eff}}\left(\delta_{\text{max}}\right) = R\left[1 + c_1 1.275\left(\frac{S_Y}{E}\right)^{0.216}\left(\frac{\delta_{\text{max}}}{\delta_{\text{CP}}} - 1\right)\right]$. Due to the isochoric behavior during plastic deformations, R_{eff} should be larger than R, and $c_1 < 1$ characterizes the effective curvature radius of the asperity at δ_{max}.

Because of elasto-plastic behavior happening during contact, the theory developed here results in different adhesive-contact forces during loading $F_n^{\text{L}}(\delta)$ and unloading $F_n^{\text{U}}(\delta)$.

3.2.1 Loading Process

During the loading process, once interference δ becomes larger than the critical interference δ_{CP} (1), the current interference δ will be used as δ_{max} the maximum interference reached. Therefore $\delta_{\text{max}} = \delta$ and both the residual interference δ_{res} and asperity tip radius R_{res} are calculated from Eqs. (2-3). The adhesive-contact force during loading $F_n^{\text{L}}(\delta)$ can be directly evaluated from Maugis solution (5-11). This is achieved by substituting the asperity tip radius R by R_{eff} (12) and the interference δ by $\delta - \delta_{\text{res}}$. During the loading process δ_{res} keeps increasing.

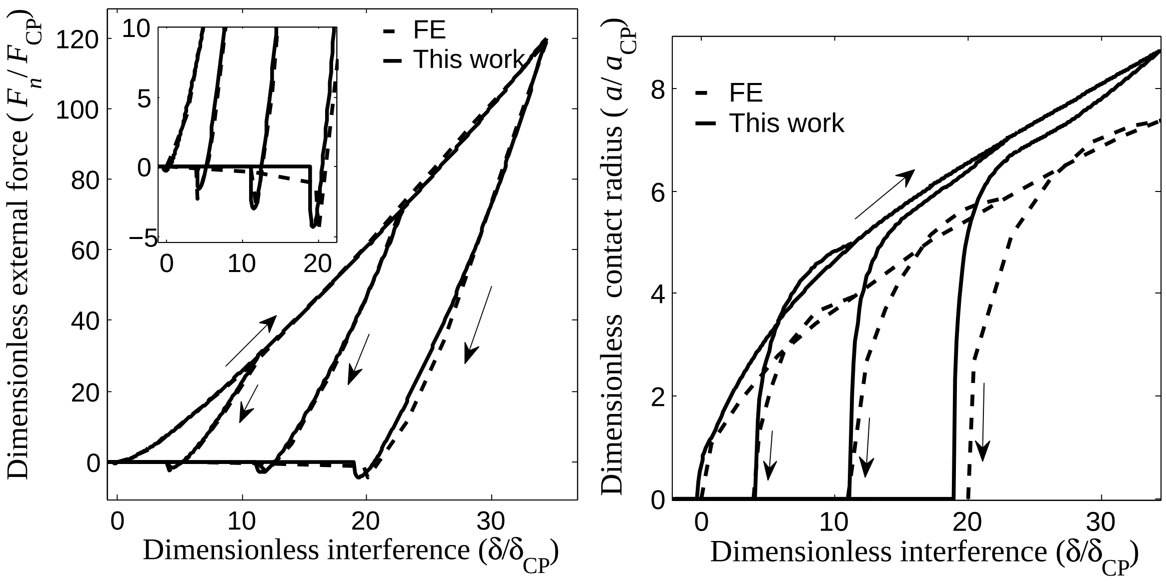
3.2.2 Unloading Process

During unloading, the maximum interference δ_{max} is a constant value determined at the end of the loading stage. The residual interference δ_{res} is derived from δ_{max} using Eq. (2) and remains constant during the unloading process. The adhesive-contact force during unloading $F_n^{\text{U}}(\delta)$ is obtained from the Kim expansion of Maugis theory after substituting the asperity tip radius R by R_{eff} (12) and the interference δ by $\delta - \delta_{\text{res}}$. Contrarily to the loading process, the effect of adhesion needs to be considered at the intermediate pull-out stage, which is achieved by using the Kim *et al.* [8] extended Maugis-Dugdale adhesive-contact theory [7].

4 Comparison with FE results

In this section, we compare our model results to the finite element results carried out for the single asperity problem by Du *et al.* [22]. In this work, the elastic-plastic adhesive contact of a micro sphere was studied for Ruthenium (Ru), which satisfies the elastic unloading assumption, see [20] for details. The surface and material properties considered in [22] are $R = 4\mu$m, E=410 GPa, ν=0.3, S_Y= 3.42 GPa, z_0=0.169 nm. The adhesion energy ϖ is set to 1 J/m^2 to account for the imperfect cleanness of the surface when the testing is not done under the UHV conditions [22]. To demonstrate the accuracy of the newly proposed method, we compare its predictions to the FE results for the loading and unloading adhesive-contact forces at three maximum interferences δ_{max} successively equal to 17, 20 and 30 nm.

Results for loading and unloading are illustrated in Figs. 3(a) and Fig. 3(b) in terms of the dimensionless external force *vs.* dimensionless interference, and in terms of the dimensionless contact radius *vs.* dimensionless interference, respectively. A really good prediction of adhesive-contact force can be



(a) Adhesive-contact force

(b) Contact radius

Figure 3: Comparison between the model and FE results

found, and the maximum adhesion forces obtained are rather close to the finite element results, within 1%, which is better than actual models, see comparison achieved in [22]. Although the predicted contact radius has the same trend as the finite element results, the difference increases with the increase of the maximum interference reached during the loading. This difference comes from neglecting plastic deformations resulting from adhesion. From the results comparisons, it is found that the coefficient c_1 has an obvious effect on the predicted adhesive-force, which is not sensitive to the coefficient c_2, which affects more the predicted contact radius.

The expressions of c_1 and c_2 are thus valid for Ruthenium material. Although new expressions should perhaps be provided for other materials, the methodology should remain valid under the assumption of elastic unloading.

5 Conclusions

With as final aim the development of 2-scale analyzes of MEMS structures able to predict stiction failure, we propose in the present work a micro-model for adhesive contact of elasto-plastic asperities.

First the deformed profile of the asperity is evaluated from literature models, which uncouple the plastic deformation from the adhesive effect. This assumption usually holds except for materials suffering from jump-in induced plasticity, as for gold, for which the sole adhesion effect can lead to plastic deformations.

Then, we use Maugis-Kim adhesive theory to evaluate the adhesive-contact forces. In order to account for the deformed shape of the asperity, assumed as spherical in Hertz contact of Maugis theory, we propose to evaluate an effective asperity radius which depends on the interference. With this method, we can predict the loading/unloading hysteresis curves of a single elastic-plastic asperity interacting with a rigid plane.

Finally predictions are compared to FE results from the literature, and excellent agreements are obtained on the adhesive-contact curves, and in in particular for the pull-out force.

Ongoing work is the generalization of the method to two rough surfaces interactions and application of the micro-model to MEMS structure analyzes.

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