Influence of surface topography in electrostatic forces simulations for microassembly

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***Abstract*— Micro manipulations of objects between 10μm and 1mm by contact are often disturbed by adhesion between the handled object and the gripper. This is due to the presence of the surface forces which overcome gravity and prevent the release of the object. Capillary, electrostatic and van der Waals forces are the main surface forces responsible for this adhesive phenomenon. Several factors may influence these forces such as the materials in contact, the fabrication process, the surface treatments or the surface contaminations. All of these factors contribute to shape the topography of the surface. In this paper simulations are performed on the electrostatic forces for smooth surfaces and for rough surfaces in order to study the influence of surface topography. The results are compared with analytical models for the smooth case and show a good correlation. The rough case simulations use a sphere ended conical tip-plane contact. The discussed roughness models are mainly elementary protuberances and fractal representation using the Weierstrass-Mandelbrot model. The simulations using fractal representation show an influence of the surface topography at small separation distances. A comparison is also performed with experimental results from the literature.**

I. Introduction

Micro manipulations of object between 10μm and 10mm by contact are often disturbed by the sticking of the handled object on the manipulator. Capillary, electrostatic and van der Waals forces are the main surface forces responsible for this adhesive phenomenon. They have already been studied in previous works [1]–[4]. This paper deals with the electrostatic forces. They may be influenced by several factors such as the materials in contact, the fabrication process, the surface treatments and the surface contaminations. All of these factors contribute to shape the topography of the surface. No matter how carefully or expensively the surface is manufactured it can never be perfectly smooth. It has been observed that this roughness may decrease the adhesion forces due to the reduction of the surface of contact [5]. The aim of this paper is to perform simulations on the electrostatic forces in order to determine the importance of roughness in the phenomenon. Simulations are performed for smooth and for rough surfaces using the finite element software Comsol. The paper is divided into two main sections. The first one deals with roughness, starting with a state of the art about its influence in micromanipulations, then with a review of different models and finally with a discussion about the fractal representation (which is the one chosen in this work). The second section deals with the simulations showing their correlation with analytical models and then early results including roughness and compared with experimental results from the literature. We finish with the conclusions and prospective works.

II. Roughness and surface forces

A. State of the art: Influence on surface forces

Due to capillary condensation, a liquid film can form between two objects in contact (e.g. the gripper and the handled object in micromanipulation experiments). From the formation of this meniscus results a capillary force that can make a large contribution to the total adhesion force [6]. With hydroplilic surfaces the meniscus force increases for smoother surfaces so that the adhesion of ultrafat surfaces can be extremely strong [7]. A significant decrease in the magnitude of the adhesion force with an increase in roughness in the low relative humidity regime has been observed [8] so that we can state that capillary adhesion is substantially lowered in the presence of nanoscale roughness.

The Van der Waals forces are due to the instantaneous polarization of the atoms and molecules due to quantum mechanical effects. In the case of two rough surfaces the average interplanar distance would be large and the van der Waals forces would be small [7]. These forces thus depend greatly on the roughness of the surface.

Electrostatic forces appear due to Coulomb interaction when the electrostatic charges are generated. We limit our study to the contact between conducting materials which is well understood. How does surface roughness influence these forces and how can we integrate the roughness factor in simulations are the questions we will try to answer.

B. Roughness representation

Many authors agree that even a nanoscale roughness should be taken into consideration when performing simulations on adhesion [9]. Finding accurate models for surface topography representation is of crucial importance. The most often encoutered models in the literature are presented in the following.

The simplest case is given by [10] and only considers the roughness peaks. The roughness profile is assumed to be equivalent to a smooth profile located at a separation distance

d+R/2, where *R* is the height of the highest peak and *d* is the distance between the plane and the highest peak (Fig.1a). This model is however not accurate since it does not take into account the density of protrusions.

Elementary protuberances such as hemispheres and cones (Fig.1b) may also be used to model the asperities. Usually the roughness is modelled as hemispherical asperities characterized by the average asperity height and the density of asperities on the surface. This type of representation is found in works from [11]–[13].

A third technique uses sinusoidal functions. A cosine function is used in [14] which is an idealized periodic surface characterized by shape, height and wavelength to calculate the electrostatic repulsive energy between two rough colloidal particles.

Finally a last technique involves the use of fractals. The reader is refered to the next section for a description of this technique. It will be used for our own simulations. For [15] the topography of many engineered surfaces may be represented as fractals because similar features can be observed at different magnification of the same surface. It is moreover necessary to characterize rough surfaces by intrisic parameters which are independant of all scales of roughness such as the fractal parameters [16].

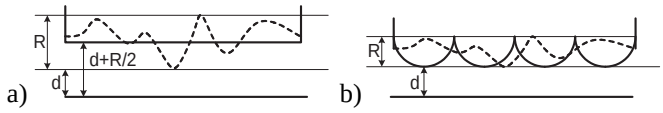

Fig. 1. a) [10], b) [11]

C. The fractal representation

Fractals are irregular objects possessing similar geometrical characteristics at all scales, i.e. self-similarity characteristics. The geometries of fractal surfaces are also continuous and non differenciable. Since the profile of rough surfaces z(x) (typically obtained from stylus measurements) is assumed to be continuous even at the smallest scales and ever-finer levels of detail appear under repeated magnificance, the tangent at any point cannot be defined. The profile has thus the mathematical property of being continuous everywhere but non-differenciable at all points. The Weirstrass-Mandelbrot function satisfies the properties of continuity, non-differenciability and self-similarity [17] and is therefore used to simulate two-dimensional profiles.

$$z(x) = L(\frac{G}{L})^{D-1} \sum_{n=0}^{\infty} \frac{\cos(2\pi\gamma^n \frac{x}{L})}{\gamma^{(2-D)n}} \qquad (1)$$

where *L* is the fractal sample length, *D* is the fractal dimension (1<D<2), *G* is the fractal roughness parameter and γ is a scaling parameter (γ>1). Eq.1 models the surface profile by a sum of cosine functions with geometrically increasing frequencies. In order for the phases of the different modes not to coincide at any given x position, the value of γ must be chosen to be a non integer (from [18] it is good to assume γ=1.5). As *D* becomes larger, the number of asperties increases (density increases) and their height decreases. As *G* increases, the peaks and the valleys are amplified. As the magnitudes of *D* and *G* increase, a rougher and more disordered surface topography can be generated. Fig.2 illustrates the influence of the fractal parameters *D* and *G* on the generated profile.

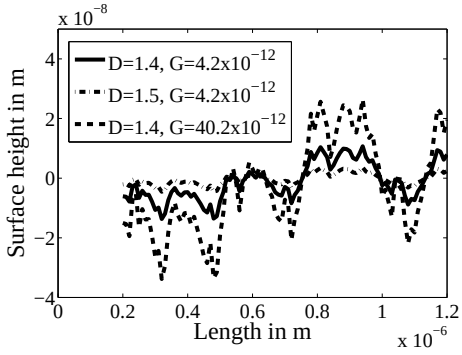

Fig. 2. Illustration of the influence of the fractal parameters *D* and *G* on the profile.

Fractal representation of surface roughness has however often been debated and authors do not all agree about its relevance. The main problem that has been suggested with using fractal representation for the topography of engineered surface is that not all of these surfaces are fractal. For [19] and [20] the fractal character of artificial surfaces depends on the processing method. For [21], fractals may not be applicable to very smooth surfaces. The scale independance of the fractal parameters has been questionned by [19], [21] and [22]. On the other hand, for [15] many engineered surfaces can be represented by fractals. It has been shown that surfaces of processed steel, textured magnetic thin film [23], and metallic surfaces produced by EDM, by cutting or grinding techniques, and even worn surfaces [24] are fractal. Arguments in favor of the fractal characterization can be summerized by the necessity to characterize rough surfaces using intrinsic parameters independent of all scales.

III. Simulations

A. Description

The potential difference between the geometries induces an electric field in the air. An electron transfer occurs resulting in the charging of the materials and an attractive electrostatic force. The electric potential *U* in the surrounding environment obeys Laplace's equation:

$$\Delta U = 0, \qquad (2)$$

The electric field is obtained from the gradient of *U*.

$$\vec{E} = -\nabla\vec{V} \qquad (3)$$

The two-dimensional axisymetric simulation is performed using the commercial simulation tool Comsol to model the geometry and to solve the partial differential equation Eq.2

using the finite element method. The outer boundary conditions insure the electric insulation of the domain. There is no normal component of the electric field on the outer boundaries. The potential U is applied on the boundary delimiting the tip in order to simulate the potential difference between the tip and the surface while the contacting flat surface is grounded (Fig.3). The electrostatic forces are calculated using Eq.4.

$$F_{elec} = \frac{\epsilon_0 E^2}{2} \tag{4}$$

Integrating the force for all the contributions brought by all of the elements in the model, we are able to calculate the total force acting on the two geometries.

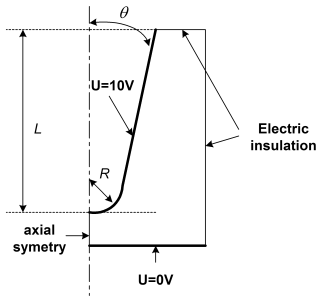

Fig. 3. Modelling of the problem.

B. Comparison with analytical results

The simulations have been validated using analytical models from the literature. In these models the main assumption is that the surfaces are completely smooth. The second assumption is that the materials are conductive which involves that the potential is uniformely distributed along the surface, the electric field is normal to the surfaces and the charges only carried by the surface of the materials (no volumic charges). No charge is present between the contacting objects meaning that the charges are only present at the surfaces of the materials. Two types of contacts have been used: sphere-plane and cone-plane because they are the most used in literature. For the sphere-plane contact we used the expressions developed by [25]–[27]. For the cone-plane contact we used the works from [28] and [29].

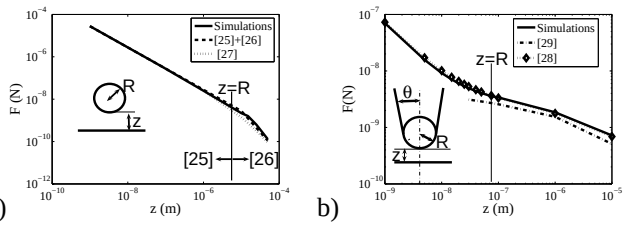

Fig. 4. a) Validation of simulations with the sphere models ([25] and [26] distinguish $z < R$ and $z > R$ while [27] is given for all distances), for a sphere of radius 10µm and a potential difference U=10V. b) Validation of simulations with the models using conical geometries for dimensions of the tip L=125µm, R=25nm, θ=9.46°(half aperture angle) and a potential difference U=10V with the asymptotic model from [28] and the uniformely charged line model from [29].

C. Comparison with a benchmark

Fig.5 gives a representation of the contact between a conical tip and a rough surface generated using a Weierstrass Mandelbrot function.

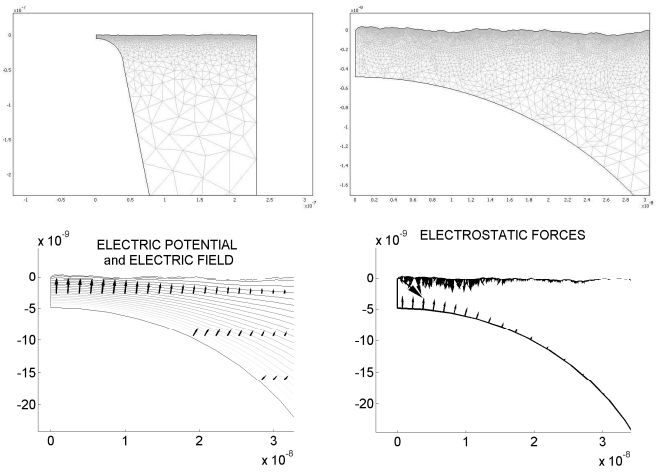

Fig. 5. Different representation of the geometries in contact (cone and plane) with a roughness for the plane simulated with D=1.55,G=1.5×10^{-12}, γ=1.5 and L=1µm.

The work from Sacha et al. [30] is used in order to compare their experimental results with results obtained using our simulation tool. They measured electrostatic forces for a sphere-ended conical tip of radius 40nm and half aperture angle 10° for different voltages(6, 8 and 10V). The characteristics of the tip were found using SEM images. The sample was a gold-coated glass slide. We compared their results with our simulations, first without and then with roughness included in the simulations (fractal representation). Results are presented in Fig.6.

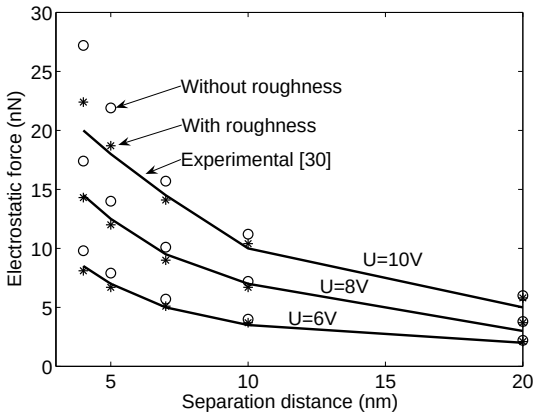

Fig. 6. Electrostatic normal force (nN) versus separation distance(nm) for different applied voltage for a sphere-ended conical tip of radius 40nm and half aperture angle θ=10°. Plot shows experimental results obtained by Sacha et al. [30], simulations results without roughness parameters and simulation results including roughness parameters $G = 1.5 \times 10^{-12}$ and $D = 1.55$ chosen in order to get a maximum asperities height of the order of 1nm.

We first observed that even though the results are in good

correlation for smooth simulations, our simulated forces are stronger than what was obtained experimentally. The difference between experimental results and simulation increases when the separation distance decreases. We attributed this observation to the fact that even though the spot of contact has been chosen to be smooth (atomic steps), it can never be perfectly smooth. A very small roughness may influence the results at such small separation distances.

We introduced roughness with the generation of a fractal surface using fractal parameters D=1.55 and $G = 1.5 \times 10^{-12}$ for the planar contacting surface in order to have a maximum high of asperity peaks of 0.8nm and an average roughness of 0.3nm (which is often assumed to be negligible). The first observation is that even a roughness as small as the one we simulated is influencing the results from simulations reducing the electrostatic forces. This is specially true when the tip gets closer to the surface. The influence of surface roughness is also more important at higher applied voltages. The results from our simulations including roughness are closer to the experimental measures.

IV. Conclusion

We have developed a reliable simulation tool for electrostatic forces which can be used to design microgrippers and develop micromanipulations strategies in order to minimize the disturbing effects of adhesive electrostatic forces. Comparison of the results with analytical models allowed to demonstrate the reliability of the simulations. Simulations performed including surface topography representation showed the importance of surface roughness at very close separation distances. It also brought into light the need to find an accurate model for this surface topography. Ideally the model should be adaptated to correlate the microfabrication process used for manufacturing the gripper. This is part of our prospective work. We also intend to perform experimental measures of the electrostatic forces in order to compare our simulations results with our own experimental measures after having characterized the roughness parameters of the sample.

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