CONTACT MECHANICS AND NEEDLE LIKE SURFACES FOR MICRO-NANO INTEGRATION

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Abstract — Understanding the adhesion mechanisms between nanostructured surfaces is essential for using such surfaces for bonding based on the Velcro®-principle. This paper reviews the current contact mechanics based adhesion models between needle like surfaces for micro- nano integration. The focus is made on multi-asperity contact interaction where the involvement of each asperity is estimated individually and the overall adhesion is calculated by summing all single contributing asperities. A new approach to express multi-asperity contact interaction by considering the neighboring influence is also suggested and discussed. The theoretical evaluation is compared to experimental results obtained for nanostructured Silicon surfaces.

Keywords: Adhesion, contact mechanics, bonding, nanostructured surfaces

I - Introduction

Further miniaturization of microsystems and microelectronic devices will require new bonding techniques especially with self-alignment capability to replace conventional pick-and-place mounting techniques. Bonding via nanostructured surfaces (Velcro®- or Gecko-principle) is one possible approach [1]. Here, surface forces and nanoscale surface interactions play a significant role. The surfaces of real solid materials, regardless of their preparation methods possess morphological irregularities defined as surface roughness or asperities [2]. In reality, the contact between two supposed flat surfaces is restricted to a huge amount of asperities which are randomly spread on the surfaces. As a result, the real contact area is a lot smaller than the apparent one. The propensity of the asperities at or close to contact area results in adhesion forces due to their inter-atomic interactions [3]. In general, several interactive forces such as Van der Waals forces, electrostatic forces, capillary forces, and hydrogen bridging can be observed between two solid surfaces [1]. However, when the distance between the involved surfaces is less than 3nm, the Van der Waals forces are dominant in dry environment [4,5]. However, the capillary forces also contribute to bonding with a significant influence in the hydrophilic surfaces or wet environment [6].

A. Single asperity adhesion model

For deformable bodies, the Van der Waals adhesion force between an elastic sphere and a flat surface was first introduced by Johnson, Kendall and Roberts (JKR) in 1971, and then followed by Derjaguin, Muller and Toprov (DMT) [7]. Both JKR and DMT models altered the Hertz adhesionless contact model by taking the total surface energy $\Delta \gamma$ of involved surfaces, the contact radius $a$, the asperity radius $R$ (Fig. 1) and the composite Young’s modulus $E$ into the consideration. The composite $E$ is defined as: $1/E = (1-v_1^2)/E_1 + (1-v_2^2)/E_2$ with $E_1$ and $E_2$: Young Moduli and $v_1$ and $v_2$: Poison ratio of involved materials.

The JKR model assumes the surface force acts only over the contact area, and causes a deformation at the contact point [7]. For a single asperity in contact with a flat surface, the JKR model defines the contact force $F_{JKR}$, corresponding deformation $\delta$ and pull-off force $F_P$ as follow:

$$F_{JKR} = \frac{4 \pi a^3}{3R} - \sqrt{8 \pi a^2 \Delta \gamma E} \quad (1)$$

$$\delta_{JKR} = \frac{a^2}{R} - \frac{2}{3} \sqrt{\frac{\pi a^2 \Delta \gamma}{E}} \quad (2)$$

$$F_{P(JKR)} = 1.5 \pi R \Delta \gamma \quad (3)$$

However, in the DMT model, the authors introduced non-contact forces which act across the gap between two bodies [3]. For the DMT model the contact force is defined as:

$$F_{DMT} = \frac{4 \pi a^3}{3R} - 2 \pi R \Delta \gamma \quad (4)$$

and the corresponding deformation and pull-off force are:

$$\delta_{DMT} = \frac{a^2}{R} \quad (5)$$

$$F_{P(DMT)} = 2 \pi R \Delta \gamma \quad (6)$$

B. Multi-asperity adhesion model

The contact between two rough surfaces can be modeled as one bumpy surface in contact with a perfectly flat surface. Under this hypothesis, the effect of each asperity is local and considered separately from other asperities and the total contact force is the summation of contribution of individual asperities [8].

Prokopovich et al. (2011) presented an adhesion model for multi asperity system based on JKR and DMT models [2]. According to her model (Fig. 1), the
overall contact force for a rough surface approaching an ideal rigid flat surface (at a distance \(d\)), is the summation of all the forces generated by the asperities whose heights \(h_i\) goes beyond \(d\) or are within their respective critical deformation \(\delta_i\); where, “the critical deformation is defined as a critical distance of asperity \(i\) according to equation (7) [3].

\[
F_{\text{adh}}(d) = \sum_i \delta_i^{\frac{3}{2}} n(\delta_i, R_i)
\]

For each asperity, the pair of Eqs. (1) and (2) or Eqs. (4) and (5) represents a system which gives the relation for JKR and DMT adhesion forces as a function of deformation and radius of the curvature as:

\[
F = fn(\delta_i, R_i)
\]

and the total contact force can be expressed as:

\[
F_{\text{adh}}(d) = \sum_i \delta_i^{\frac{3}{2}} n(\delta_i, R_i)
\]

where \(\delta_i = h_i - d\) and \(\delta_{ci} = \frac{1}{3} R \left( \frac{27 \pi R^2 \Delta y}{E} \right)^{2/3}\) is the critical distance of asperity for JKR model and equal to 0 for DMT mode [2].

The main objective of this work is to investigate the current adhesion models and to develop a new accurate model to express the interaction mechanism of two needle like surfaces for micromanufacturing based on contact mechanics theories.

II - Experimental Details

A. Surface preparation

The needle like surfaces which have been used in this investigation (Fig. 2) were made based on porous silicon in a simple fabrication process by anodizing the surfaces of low doped p- Si wafer at 70 mA/cm² in 7 wt.% HF in (water) electrolyte concentration for 40 minutes [1]. Then the needle density, needle curvature diameters and needle heights were measured (Table 1) based on optical observation using SEM technique since the surface structures could not be investigated by AFM technique due to large interaction between AFM tip and needle like surfaces [1].

B. Measurement process

The needle like surfaces are attached to each other at room temperature by pressing the surfaces together with different applied weight ranging from 1 to 10 Kg. Then, the pull-off force characterization is carried out by a special pull-off force meter. The pull-off force measurement unit is consisted of a force sensor and exhibits a high dynamic range from 1 mN to 20 N.

![Figure 1: Schematic representation of Prokopovich adhesion model, modified from [2].](image1)

![Figure 2: SEM pictures of needle like surfaces with different magnifications based on electromechanical etching of porous Si.](image2)

**Table 1: The Surface properties of a specific needle like surface**

<table>
<thead>
<tr>
<th>Wafer Type</th>
<th>p−Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needle density (N/cm²)</td>
<td>6.001 x 10⁶</td>
</tr>
<tr>
<td>Needle curvature diameter (µm)</td>
<td>1-5</td>
</tr>
<tr>
<td>Surface Energy (mN/m)</td>
<td>32.22 [3]</td>
</tr>
<tr>
<td>Young’s modulus (Mpa)</td>
<td>165 [9]</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.22 [9]</td>
</tr>
</tbody>
</table>

III - Results and Discussion

A. Measurement results

The bonding of the surfaces is carried out by pressing them together with a weight. From the results (Fig. 3), it is clear that bond strength (Pull-off force) between bonded surfaces initially increases by increasing applied weight.

![Figure 3: Pull-off strength results at varying bonding force in terms of applied weight for effective active bonding area of 0.1 cm². Solid line: measured values and dash line: curve fitted values.](image3)

B. Simulation results

For better understanding the interaction mechanism between two needle like surfaces in a multi-asperity adhesion model and comparison to experimental results, the required parameters are obtained and fed into the given equations using MATLAB software. To be able to compare the simulation results with experimental results, the set of the data in Table 1 is used as input parameters. For the measured effective bonding area of
0.1 cm², the number of 6.001 × 10⁵ needles are generated with random uniform distribution by assuming height and radius of curvatures ranging from 10-15 µm and 1-5 µm, respectively. The overall simulated pull-off force in respect to the distance between two surfaces is shown in Figure 4. In this calculation, the overall pull-off force is obtained by total pull-off force of one needle like surface with a flat surface multiplied by 2. The linear increase of pull-off force is a result of more needles being involved for bonding when reducing the distance between the surfaces. Saturation corresponds to fully interlaced needle like surfaces.

![Figure 4](image)

**Figure 4:** The overall simulated pull-off force vs. distance between two surfaces.

C. Discussion

From both simulation and measurement results, it can be observed that any increase in the applied bonding weight causes a nearly linear increase in bonding strength which can be also interpreted as an increase in the area of the contact. The applied bonding weight shows inversely proportionality relation to the distance between surface and directly proportionality to the area of the contact. Since the Van der Waals force or pull-off force equations in both JKR and DMT models (Eqs. (3) and Eqs. (6)) show independently relations from deformation and the force which contribute a deformation, we can interpret that applied bonding weight decreases the distance between two surfaces and consequently causes an increase in the area of the contact by involving shorter needles in the adhesion mechanism. To support this idea, the obtained total pull-off forces with DMT approach from both measurement and simulation are fed into equations 1 and 4 to find the real area of the contact (Fig. 5).

By reviewing the main assumption of the JKR and DMT models, it can be observed that these theories are modeled based on standalone interaction of an elastic spherical object in contact with a flat rigid surface, and does not consider the influence of neighboring objects. In the needle like surfaces, a needle is mostly looks like a cone, and the spherical object (tip) is a small portion of it. By looking at the side view of two bonded needle like surfaces (Fig.6), it can be observed that the interaction between two needles are mostly happen at the side contact not at the tip contact. Hence, it can be concluded that the side contacts has much more influence in the adhesion mechanism compare to the tip contacts. Since a needle can be surrounded by several needles, the neighboring needles will have a huge influence in adhesion by increasing the area of the contact. This phenomenon can be observed easily by comparing the Simul. and 4.6N (Maximum pull-off force) graphs at distance of 10 µm in Fig.5. The difference shows the effect of the side contacts in adhesion since the simulation result shows the maximum area of the contact in the tip contact mode.

![Figure 5](image)

**Figure 5:** The real area of the contact as function of the distance between two surfaces for both measured and simulated pull-off forces with DMT approach. Measured pull-off force in N, and Simul. stands for maximum simulated pull-off force (0.728N) for an effective bonding area of 0.1 cm².

Therefore, a more accurate adhesion model to express the adhesion between needles like surfaces can be obtained by considering both tip contact and side contacts of needles in accordance to penetration depth. In this case, a conical shape needle can be represented as combination of cylindrical body and half sphere head for the simplicity of estimation and calculation [10]. Then to express the tip contact, and the side contact, the JKR and DMT adhesion models for an elastic sphere with a flat surface, and two cylinders can be used, respectively. Since a needle can have a side contact with several needles at the same time, the overall side contact should be considered. In this case, the pull-off force for a single needle can be represented as follow:
\[ F_p = F_{tip(sphere)} + \sum_{n} F_{side(Cylinder)} \]  \hspace{1cm} (9)

and the total adhesion force can be obtained as:

\[ F_{total} = \sum_{n} F_p \]  \hspace{1cm} (10)

where \( n \) and \( m \) are the number of side contacts and needles, respectively. Since \( F_p \propto A_{contact} \), we can also say \( F_{side} \propto A_{side} \). In this case, the side area of the contact for one needle can be obtained through:

\[ A_{side} = N. A_{cyl-cyl}. d \]  \hspace{1cm} (11)

where \( N, A_{cyl-cyl}, \) and \( d \) are the number of side contacts, area of the contact between two cylinders and the penetration depth, respectively.

Since the needles have different heights and can be deformed, the interaction at side contact may be varied from two parallel cylinders to two crossed cylinders in contact which result in changing the side contact area from rectangular to elliptical shape. The rectangular area can be calculated from \( A_{rec} = 2a. L \) where \( a \) is the one-half the width of contact strip and can be obtained from [11]:

\[ a = 2 \sqrt{\frac{2(1-v^2)p}{\pi EL} \frac{R_2 R_3}{R_1 + R_2}} \]  \hspace{1cm} (12)

where \( p \) is the force of pressing of two cylinders together, \( L \) is the height of cylinder, \( E \) is the modulus of elasticity, \( V \) is Poisson’s ratio of the material, \( R_1 \) and \( R_2 \) are the radius of cylinders.

In the case of elliptical contact, the area of the contact can be obtained from [12]:

\[ A_{ell} = \pi mn \left( \frac{6n(1-v^2)R_3^2 Y}{E. sn\theta} \right)^{2/3} \]  \hspace{1cm} (13)

where \( m \) and \( n \) are functions with respect to spatial angle (\( \theta \)) between two cylinders and can be found in [12, 13].

**IV - Conclusion**

The current adhesion models based on contact mechanics theory are investigated for expressing the adhesion in needle like surfaces. Both experimental and theoretical results show a linear relation between the area of contact and adhesion force. A new adhesion model is suggested to express the adhesion in more accurate way by taking the side contacts of needles and the number of neighboring needles into account. To support the idea, further theoretical and experimental investigations are required. Measuring the needle densities, needle heights, and needle radius of curvature and their corresponding distributions profile with high accuracy are very important since they have a huge influence in calculations. Also, measuring the pull-off and shear forces in accordance to the penetration depth and finding a solution to calculate the number of the side contacts and corresponding adhesion forces are the key points and future work of this model.

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**References**


