Study of Microcontact Model for Hard Particles Between Rough Surfaces

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ABSTRACT
Particles are often presented at contact interfaces. In this study, a three-body microcontact model Considering of hard particles and rough surfaces is proposed in order to understand the effects of particles between contact characteristics. Both transitional surface-to-surface and particle-to-surface two-body microcontact simulations can be obtained according to the simplification of this model. In the three-body contact situation, the curves of contact area ratio versus dimensionless load are located in the range between two straight lines. The surface-to-surface two-body contact situation is the upper bound and the particle-to-surface two-body contact situation is the lower bound. The contact situation will approach to the pure particle-to-surface two-body contact situation as the value of particle diameter over roughness value of surface increases. The total contact area ratio increases when particle size or particles density decreases, and contact load increases. Contrary to the results for contact area ratio, the dimensionless separation increases when particle density increases or contact load decreases.

INTRODUCTION
When two surfaces slide over each other, surfaces roughness and wear debris (or particle contaminants) cause contact to occur at discrete contact spots, including particle-to-surface and surface-to-surface contact spots. The sum of the areas of all the contact spots constitutes the real area of contact, which is only a small fraction of the apparent contact area. The real contact area plays a significant role in contact properties since it determines the states of wear, friction, lubrication, and frictional heating and signal transmission between two rough surfaces. In the last three decades several stochastic microcontact models of rough surfaces have been proposed [1-12]. All these approaches are two-body (surface-to-surface) microcontact models, generally falling into two approaches, the elastic model and the plastic model. The most widely used stochastic model is that proposed by Greenwood and Williamson (GW model) [1]. The GW model was later extended to include such aspects as curved surfaces [2] and nonuniform radii of asperity peaks [3]. Later, Bush et al. [4,5] used a spectral moment description of the rough surface and Hertzian contact equations to strongly anisotropic rough surfaces and the onset of plastic flow. McCool and Gaskell [6] used the Monte Carlo method to obtain results for the contact of two anisotropic surfaces as an alternative to the calculation of multiple integrals. Powierza et al. [7] experimentally confirmed the theoretical results of Greenwood and Williamson within the range of elastic deformation and for quasi-isotropic surfaces. However, their experimental values departed distinctly from the theoretical results in the plastic deformation range. The experimental observations of Pullen and Williamson (PW model) [8] showed that, in the plastic deformation state, volume is conserved by a uniform rise in the non-contacting surface under external load.

In common engineering situations the total contact area consists of a mixture of both elastic and plastic asperity contact. Chang et al. [9] proposed an elastic-plastic microcontact model (CEB model) based on the volume conservation of plastically deformed asperities for the contact of rough surfaces. Research using this model has shown that the GW model of fully elastic and the PW model of fully plastic surface microgeometry demonstrate two limiting cases of general elastic-plastic contact. Horng [10] proposed a generalized elliptic elastic-plastic microcontact model (H model), that takes into account the directional nature of surface roughness, for elliptic contact spots between anisotropic rough surfaces. This model can be simplified to become GW and CEB models. Recently, Zhao et al. [11] presented a plastic model of the microcontact model (ZMC model) to modify the shortcoming of transition from elastic deformation to fully plastic in the other models. This transition is modeled, replacing the plastic volume conservation of the experimental observations of Pullen and Williamson and it is based on contact-mechanics theories in conjunction with the continuity and smoothness of variables across different modes of deformation. Although to date, little work has been reported on the topic of a three-body microcontact model, the third particle, which participates in the relative motion of rough surfaces, is common situations in tribological interfaces. In this work, a three-body microcontact model of rough surfaces is proposed to describe this kind of contact characteristics. In addition, it is used to compare the difference between previous models and the present one.

METHODS
In this Analysis, we made the following assumptions.
1. All surface asperities are far apart and there is no interaction between them.
2. There is no bulk deformation. Only the surface asperities deform including elastic, elastoplastic and plastic deformation during contact.
3. Spherical particles of a uniform diameter D are much harder than both surfaces and the surfaces deform plastically during contact with particles.
4. Slopes of surface asperities are negligibly small.

Assumptions 1 and 2 above are the same made in many stochastic microcontact models (GW, CEB, H and ZMC models). Either polishing particle or wear debris due to work hardening during wear process is always harder than mating surfaces. Hence, assumption 3 does not appreciably limit the generality of the model. The work of Greenwood and Trapp [3] showed that the contact of two rough surfaces could be modeled by an equivalent single rough surface contacting a smooth plane. Fig. 1 shows the geometry of contacting three bodies including surface 1, surface 2 and the particles. Here, r and s denote the asperity height and separation of surfaces, respectively, measured from a reference of the model. The work of Poewiera et al. [7] experimentally confirmed the theoretical results of Greenwood and Williamson within the range of elastic deformation and for quasi-isotropic surfaces. However, their experimental values departed distinctly from the theoretical results in the plastic deformation range. The experimental observations of Pullen and Williamson (PW model) [8] showed that, in the plastic deformation state, volume is conserved by a uniform rise in the non-contacting surface under external load.

RESULTS AND DISCUSSION
The materials used in this study were most commonly used polishing particle of synthetic monocrystalline diamond and steel, as listed in Table 1. Figure 2 shows results for the contact area ratio At/An versus the dimensionless load Fn/Fe for a 2-body model, predicted by the ZMC model, and a 3-body microcontact models for different particle sizes at W = 10.0 μm, W = 0.7 μm, and W = 1.6 μm. This figure shows a linear relationship between the contact area ratio and the dimensionless load for all cases. However, when the particle size is considerably small (D = 0.001 μm), the effect of particle on contact area is negligible for the large roughness value of surfaces (r = 1.6 μm). The contact area ratio predicted by the 3-body model with small particles is almost identical to that predicted by the 2-body model. When the particle diameter D increases to 10.0 μm, the contact area ratio decreases dramatically for the entire range of the dimensionless load studies. These results indicate that particles resulting from the wearing process or from the environment are an important parameter controlling contact characteristics at mating surfaces.

Figures 3(a) and 3(b) show the 3-body contact results for the contact area ratio and separation versus dimensionless load for different particle sizes while μ was held fixed at 0.40μm. For D = 9.0μm, the third body completely separates the mating surfaces due to D>>W. At these conditions of D = 9.0μm, a separation distance of about 9.0μm ~10.5μm, except for high load Fn/Fe≈1.0×10.3, is shown in Fig. 3(b). Therefore, the contact area between particles and surface 1 occurs at a plane placed at the asperity mean height, which is smaller than that the situation of small particles for the whole loading range. Contrary to the results for D = 9.0μm, the contact area ratio is upper bound for D = 0.12μm. Particles give rise to the negligible effect on contact area and
separation, as shown in Figs. 3(a) and 3(b). Irrespective of dimension loads, mating surfaces contact is the dominant factor in contact characteristics for large surface roughness and small particle size. When the particle diameter is in the range between 0.12 μm and 9.0 μm, the curves of contact area ratio versus contact load also located between the two straight lines. For the particle diameter D = 3.0 μm, the contact area between particles and surface 1 still comprises all the contact area when the dimensionless load is below 1.0×10^-3, and it is the particle-to-surface 2-body contact situation. The higher the loading, the smaller is the dimensionless separation. When the load is increased to 1.0×10^-2, all particles deposited on surfaces and the mating surface are much closer together. Meanwhile, the curve of contact area ratio versus dimensionless load cross from lower bound to upper bound. The tendency of area ratio curve at the D = 1.2 μm is similar to that at the D = 3.0 μm. However, at the smaller load of 1.0×10^-3 this curve crosses from lower bound (particle-to-surface) to upper bound (surface-to-surface) because the smaller load will be enough to produce contact between real surfaces for smaller particle size. For the same reasons, small particles also can cause relative small effect on contact area ratio at low loading. So, the contact area ratio is slightly smaller for the particle size D = 0.33 μm than that for the particle size D = 0.12 μm at low dimensionless load of 1.0×10^-5, as shown in Fig. 3(a). These results indicate that enough large wear debris between the surfaces will bring about decrease in real contact area ratio during the wear process. The contact temperature and pressure increase as the particle size increases. Relatively small wear debris between mating surfaces will produce negligible effect on contact area ratio and dimensionless separation. It is interesting to note that the contact area is the same for D = 3.0 μm and D = 9.0 μm when the load is below 1.0×10^-10. However, the difference of separation for two cases is considerably large. These facts indicate that, in pure 3-body contact situation, the effect of particles size on contact area is nil. However, the separation increases with increasing particle size.

**CONCLUSION**

In this paper, a three-body microcontact model that takes into account the effect of hard particles has been proposed. Plastic deformation between particles and surfaces, as well as elastic-plastic deformation between mating surfaces were considered in this study. Those transitional surface-to-surface 2-body microcontact simulations are special cases in this model. Results show that the third particle, resulting from wearing process or environments, is an important parameter controlling contact characteristics at mating surfaces. This model provides an efficient tool for solving the interfacial problems. The author gratefully acknowledges the National Science Council in Taiwan, R.O.C., which supported this research under grant NSC 91-2212E-150-008.

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**REFERENCES**


**Table 1. Material properties of contact system.**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Elastic Modulus (Pa)</th>
<th>Hardness (Pa)</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface 1</td>
<td>2.07×10^10</td>
<td>1.96×10^9</td>
<td>0.29</td>
</tr>
<tr>
<td>surface 2</td>
<td>2.07×10^10</td>
<td>1.96×10^9</td>
<td>0.29</td>
</tr>
<tr>
<td>particle</td>
<td>9.75×10^10</td>
<td>9.00×10^9</td>
<td>0.29</td>
</tr>
</tbody>
</table>

![Fig. 1 Geometry of three contacting bodies](image1.png)

![Fig. 2 Comparison of contact area ratio versus dimensionless load between two-body and three-body contact models](image2.png)

![Fig. 3 Effect of particle diameter on (a) contact area ratio and (b) dimensionless separation for different dimensionless loads](image3.png)