Size-dependent plasticity in contact/friction: from discrete dislocation dynamics inside an asperity to statistical summation over asperities

Song, Hengxu

1

General introduction

1.1. Technological background

The inclination towards smaller scales has been going stronger all the time. For example, smaller and smaller integrated circuits make our computers lighter, smaller and portable; the development of microelectromechanical systems (MEMS) provides explosive functionality: from navigation systems, smart phones to personal health monitors and other bio-medical devices [1, 2, 3]. Currently, the biggest obstacle for the development of such small systems resides in the manufacturing process: being smaller brings more problems. First of all, materials at small length scales —from several micrometers to nanometers— behave in a significantly different way compared to bulk behavior. Therefore, for example, precision forming of a piece of material at small length scale cannot be acquired by simply scaling the conditions that are required at large length scale. Secondly, there are more details (higher resolution) exposed and dominating the phenomenon at small length. Because of the limited size, the responses are different with the macroscopically observed ones which are essentially the macroscopic space- and time- averaged values. For example, a smooth surface at large length scale turns out to be a rough surface at small length scale; a smooth frictional response (friction force versus time or friction force versus loading displacement) at large scale can become stick-slip at atomic scale [4].

Overall, much of the knowledge that have been applied successfully in the conventional industry may not work properly for MEMS at small length scales. Based on the fact that the manufacturing process usually involves contact/friction problems at very small length scales, in this thesis, we intend to gain a better understanding of contact/friction problem at small length scales.

1.2. Physical mechanisms of friction

The well-known Coulomb friction law describes friction force as the product of the normal force and friction coefficient. The latter is an empirical parameter, but it is not a constant. It is material dependent, surface morphology dependent and humidity dependent, etc.. Furthermore, there are instances where Coulomb friction law fails, such as strong adhesion (tape on glass). The Coulomb friction law is actually the description of macroscopic space- and time- averaged values [5]. The lack of microscopic details and understanding even results in imprecise conclusion, for example, the friction force does not depend on the area of contact between moving surfaces. However, we know that because of the roughness, there is a big difference between the apparent contact area and real contact area (shown in Fig. 1.1) where the former is actually referred to in the friction law. Strictly speaking, the friction force does not depend on the apparent contact area, it depends on the real contact area which depends on the normal load.

With the development of experimental techniques, we are able to observe more details. For example, nowadays, it is commonly accepted that surfaces in nature are always rough, containing peaks (termed asperities) and valleys; the real contact area consists of many small contact patches. These details not only provide us the opportunities to gain a better understanding of contact/friction, but also bring us challenges to characterize friction at small length scales where macroscopic space- and time- averaged friction law fails.

Recently developed friction models based on pure elasticity [6, 7, 8] have made great progress in understanding contact behavior of rough surfaces. However, the complexity does not only reside in topography, but also in the mechanical response of asperities, especially plasticity. The surface roughness gives rise to the fact that the true contact area A is only a small fraction of the apparent contact area A_0 [9]. Given the contact force N, the nominal contact pressure $p_0 = N/A_0$ can be smaller than the material yield strength σ_Y. However, the real contact pressure on asperities $p = N/A = p_0A_0/A$ can be much larger than σ_Y. So contacting asperities on metallic surfaces usually contain plastic deformation [10, 11].

Some contact models [12, 13, 14] have incorporated plasticity, all of them are based the classical size independent plasticity theory."Unfortunately", it is already quite clear for decades that plasticity is size dependent at length scales of microns or below. The origin of the size dependence has been attributed to the plastic strain gradient [15, 16, 17] and material micro-structures [18, 19], both of which exist for contacting asperities at small length scale. Therefore, it is necessary to incorporate size-dependent plasticity in the analysis of contact/friction problems at the micro/sub-micron length scale in order to gain a better understanding.

1.3. Research questions

As shown in Fig. 1.1, the friction involves two steps: contact and shearing. The friction force can be interpreted as $F = \tau A$ [9], where A is the real contact area and τ is the shear strength of the contact. In order to predict the friction force, we need to address two quantities: A and τ.

Greenwood and Williamson (GW) [20] assumed that the rough surface consists of circular asperities with the same radius curvature and that the height of the asperities follows a Gaussian distribution. Given the mechanical response of a single asperity (purely elastic in the original GW model, elasto-plastic in subsequent works [21, 22]), the response of the rough surface is the summation of all

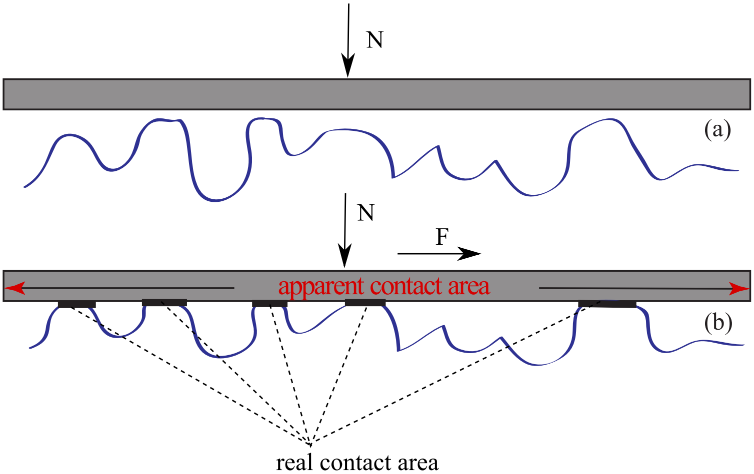

Figure 1.1: 2D sketch of a friction process: contact (flattening) of a rough surface by a rigid flat followed by horizontal shearing. The apparent contact area is the length of the rigid flat and the real contact areas are indicated by black bars.

individual asperities.

However, we also note that asperities are not isolated, but are mechanically connected through the substrate. Therefore, deformation of a higher asperity will shift all its neighbors down. This phenomenon is termed as asperity interaction, and influences the subsequent contact evolution. So the first research question is:

- ⊠ what is the role of asperity interaction in rough surface contact problem?

The mechanical response of a single asperity in all existing GW type contact models is based on size independent plasticity theory. It is well known that plasticity becomes size dependent at length scale of micron/sub-microns. Therefore, it is necessary to investigate asperity contact problem by means of size dependent plasticity.

Understanding the behavior of simple geometries paves the way to the study of more complex real surfaces. Asperities (in 2D) are usually simplified into simple geometries, such as sinusoidal [23] or rectangular [24]. If an asperity is idealized as the latter (rectangular), the flattening (contact) of the asperity is similar to the compression of a pillar. So the second research question is:

- ⊛ what is the response of micron/sub-micron pillar-like asperity under compression?

Finite element (FE) simulation of a 3D rough surface contact is the straightforward attempt to address complex contact problems either caused by topography or by plasticity. Size independent plasticity has been implemented to study rough surface contact [25], and the model provides important information such as the linear dependence of the real contact area A on the normal load N and contact pressure distribution. However, it is clear that, due to roughness, asperities on the surface have different sizes where size dependent plasticity play a role. Therefore, the third research question is:

⊞ what is the effect of size dependent plasticity in rough surface contact problem?

Large-scale FEM simulations of rough surface contact problems put high requirements on computing resources and time. By contrast, a GW-type statistical model is a very efficient method to deal with complex rough surfaces. Unfortunately, existing GW-type models do not incorporate size dependent plasticity. So the forth research question is:

⊖ Given the size dependent behavior of a single asperity, is GW-type model able to provide a reasonable prediction for the whole rough surface under contact?

Beside the contact area A, the Tabor-Bowden expression $F = \tau A$ also requires information about the friction strength τ. The tangential relative motion of contact pairs can be caused either by interfacial failure, for example de-cohesion, or by plastic deformation of contacting asperities. However, in the original Tabor-Bowden theory [9], τ is a just constant for the given materials in contact. Our fifth research question is:

⊛ what is the value of τ for different sizes of the contact and different loading rates?

When dealing with rough surface contact/friction problem, two rough surfaces are usually equivalently mapped (based on pure elasticity) into one rigid flat surface in contact with a deformable rough surface [26]. Regardless of whether the equivalence works for plasticity, this simplification ignores the other kind of asperity contact that exists in two rough surface contact/friction: interlocking asperities, shown in Fig. 1.2 indicated by blue circle while the intimate contact pair is indicated by red circle.

Actually, the friction force should be expressed as $F = \tau A + F_\mathrm{p}$, where τA comes from intimate contact and F_p is the contribution from interlocking asperities. So the sixth research question is:

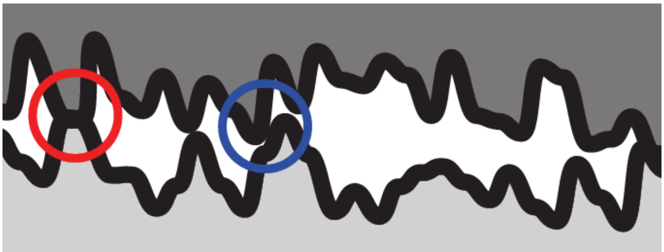

Figure 1.2: Two rough surfaces in contact. Red circle: intimate contact pair discussed above; Blue circle: interlocking contact pair (ploughing pair).

- △ how do interlocking asperities deform when two surfaces move relative to each other ?

Based on the above-mentioned research questions, the aim of this thesis is to use various kinds of simulations to gain a better understanding of the role of size dependent elasto-plastic behavior during contact/friction of rough surfaces .

1.4. Outline of the thesis

The thesis consists of a general introduction and six chapters which address the corresponding six research questions discussed above, organized as follows:

In Chapter 2 (⊠), for GW type models, a method is presented to account for asperity interaction through the statistical summation of asperities forces. Asperity interaction is found to reduce the contact force compared with the contact force if the asperities would deform independently. We also investigate the dependence of asperity interaction effect on material properties and surface roughness.

In Chapter 3 (⊛), a pillar-like asperity contact problem is studied through discrete dislocation plasticity simulations. A distinct size effect on the strength is observed. Special attention is focused on the connection between the observed size effect and critical avalanches during the loading process, and the mechanism behind is elucidated.

Chapter 4 (⊞) discusses finite element simulations of rough surface contact, in which size dependent plasticity is incorporated through the conventional mechanism-based strain gradient plasticity (CMSGP) theory. We focus on the difference between our predictions and those using size independent plasticity, including the linear dependence of the contact area on the normal load and contact pressure distributions.

In Chapter 5 (⊖), a GW-type statistical model in presented that incorporates size dependent plasticity. The size dependent plastic behavior of a single asperity is analyzed by CMSGP. The intrinsic length that is required as an input to CMSGP is fitted from simulations by discrete dislocation plasticity. The predictions of the statistical model are compared with FEM simulations of Chap. 4 to verify its effectiveness.

Chapter 6 (⊛) focuses on the friction strength τ of a contact pair. A two-dimensional model that incorporates both discrete dislocation plasticity inside an FCC crystal and adhesion in the interface is presented to investigate the dependence of τ on the size of contact and the loading rate. τ is shown to be the outcome of the competition between interface (adhesion) and material plasticity (discrete dislocation plasticity). A strong dependence of τ on the contact size and loading rate is observed.

Chapter 7 (△) aims to investigate interlocking asperities during friction. Part of the friction between two rough surfaces is due to the interlocking between asperities on opposite surfaces. In order for the surfaces to slide relative to each other, these interlocking asperities have to deform plastically. The unit process of plastic ploughing of a single micrometer-scale asperity is studied by means of two-dimensional dislocation dynamics simulations. Like in the other chapters, the focus is on the effect of the asperity size.

References

[1] Varadan, V.K., Vinoy, K.J. and Jose, K.A., 2003. RF MEMS and their applications. John Wiley & Sons.

[2] Eddy, D.S. and Sparks, D.R., 1998. Application of MEMS technology in automotive sensors and actuators. P. IEEE, 86(8), 1747-1755.

[3] Kim, D.H., Ahn, J.H., Choi, W.M., Kim, H.S., Kim, T.H., Song, J., Huang, Y.Y., Liu, Z., Lu, C. and Rogers, J.A., 2008. Stretchable and foldable silicon integrated circuits. Science, 320(5875), 507-511.

[4] Li, Q., Dong, Y., Perez, D., Martini, A. and Carpick, R.W., 2011. Speed dependence of atomic stick-slip friction in optimally matched experiments and molecular dynamics simulations. Phys. Rev. Lett., 106(12), 126101.

[5] Gao, J., Luedtke, W.D., Gourdon, D., Ruths, M., Israelachvili, J.N. and Landman, U., 2004. Frictional forces and Amontons' law: from the molecular to the macroscopic scale. The Journal of Physical Chemistry B, 108(11), 3410-3425.

[6] Persson, B.N., 2001. Theory of rubber friction and contact mechanics. J. Chem. Phys., 115(8), 3840-3861.

[7] Müser, M.H., 2008. Rigorous field-theoretical approach to the contact mechanics of rough elastic solids. Phy. Rev. Lett., 100(5), 055504.

[8] Yastrebov, V.A., Anciaux, G. and Molinari, J.F., 2015. From infinitesimal to full contact between rough surfaces: evolution of the contact area. Int. J. Solids Struct., 52, 83-102.

[9] F.P. Bowden., D. Tabor., 1950, The Friction and Lubrication of Solids, Part I, Clarendon Press, Oxford, UK. Chap. 5.

[10] Dieterich, J.H. and Kilgore, B.D., 1996. Imaging surface contacts: power law contact distributions and contact stresses in quartz, calcite, glass and acrylic plastic. Tectonophysics, 256(1), 219-239.

[11] Dwyer-Joyce, R.S., Drinkwater, B.W. and Quinn, A.M., 2001. The use of ultrasound in the investigation of rough surface interfaces. ASME J. Tribol., 123(1), 8-16.

[12] Li, H., Jiang, Z. and Wei, D., 2012. Crystal plasticity finite modeling of 3D surface asperity flattening in uniaxial planar compression. Tribol. Lett., 46(2), 101-112.

[13] Majumdar, A. and Bhushan, B., 1991. Fractal model of elastic-plastic contact between rough surfaces. ASME J. Tribol., 113(1), 1-11.

[14] Gao, Y.F. and Bower, A.F., 2006, January. Elastic–plastic contact of a rough surface with Weierstrass profile. Proc. R. Soc. A., 462, 319-348.

[15] Fleck, N.A., Muller, G.M., Ashby, M.F., Hutchinson, J.W., 1994. Strain gradient plasticity theory and experiment. Acta Metall. Mater. **42**, 475-487.

[16] Stolken, J.S., Evans, A.G., 1998. A microbend test method for measuring the plasticity length scale. Acta Mater. **46**, 5109-5115.

[17] Gao, H., Huang, Y., 2003. Geometrically necessary dislocation and size dependent plasticity. Scripta Mater. **48**, 113-118.

[18] Greer, J.R., Oliver, W.C. and Nix, W.D., 2005. Size dependence of mechanical properties of gold at the micron scale in the absence of strain gradients. Acta Mater., 53(6), 1821-1830.

[19] Uchic, M.D., Shade, P.A. and Dimiduk, D.M., 2009. Plasticity of micrometer-scale single crystals in compression. Annu. Rev. Mater. Res., 39, 361-386.

[20] Greenwood, J.A. and Williamson, J.B.P., 1966. December. Contact of nominally flat surfaces. Proc. R. Soc. A., 295, 300-319.

[21] L. Kogut, I. Etsion, 2002. Elastic-plastic contact analysis of a sphere and a rigid flat, J. Appl. Mech. ASME., **69**(5), 657-662.

[22] M. Ciavarella, J. A. Greenwood, M. Paggi, 2008. "Inclusion of "interaction" in the Greenwood and Williamson contact theory," Wear, 265, 729-734.

[23] Sun, F., Van der Giessen, E. and Nicola, L., 2012. Plastic flattening of a sinusoidal metal surface: A discrete dislocation plasticity study. Wear, 296(1), 672-680.

[24] Dikken, R.J., Van der Giessen, E. and Nicola, L., 2015. Plastic shear response of a single asperity: a discrete dislocation plasticity analysis. Philos. Mag., 95(34), 3845-3858.

[25] Pei, L., Hyun, S., Molinari, J.F., Robbins, M. O., 2005. Finite element modeling of elasto-plastic contact between rough surfaces. J. Mech. Phys. Solids. **53**(11), 2385-2409.

[26] Johnson, K.L., 1985, Contact Mechanics, Cambridge University Press, Cambridge, UK, Chap. 2.