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

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Summary

The overall objective of this work is to gain a better understanding of contact/friction at micron/sub-micron length scales with an emphasis on the potential role of size-dependent plasticity.

The roughness of natural surfaces emerges in the form of surface asperities at length scales of micrometers or smaller, where plasticity is known to be size dependent: smaller is harder. However, existing contact/friction models, such as Greenwood-Williamson (GW) statistical model and its extended models, Persson's contact model for fractal surfaces, FEM models, either ignore plasticity or, at best, adopt size-independent plasticity. Therefore, there is a need to incorporate size-dependent plasticity into contact/friction models.

The size-dependent plasticity in this work is described by two-dimensional discrete dislocation plasticity (2D DDP), or, in three dimensions, by conventional mechanism-based strain gradient plasticity (CMSGP), given their capability of predicting size effects and successful applications in various problems.

In 2D DDP, plasticity is the outcome of the collective motions of discrete dislocations, which are modeled as line singularities in an isotropic linear elastic medium. The material lengths in the DDP framework –Burgers vector, average source/obstacle/dislocation spacing– allow the framework to capture plasticity size effects.

CMSGP is an extension of conventional J_2 plasticity theory by incorporation of the effect of geometrically necessary dislocations (GNDs) which are related to the plastic strain gradient. The intrinsic material length, which is on the order of microns, endows the framework with the ability to capture plasticity size effects.

Using discrete dislocation plasticity, chapter 3, 6, 7 study the contact/friction of a single asperity in two dimensions.

In Chapter 3, a simplified geometry (pillar) is used to study the compression of an asperity. With increasing pillar size, the model naturally transitions from size-dependent plasticity to size-independent plasticity. It is found that the size effect is connected to large flow stress fluctuations and critical avalanches which can be understood through the concept of depinning. When obstacles for dislocation motion are much stronger than dislocation sources, depinning controls the behavior, leading to size-dependent yield and avalanches of plastic slip. In contrast,

when the dislocation source strength becomes comparable to that of the dislocation obstacles, yield strength size effects are absent and plasticity avalanche dynamics is strongly universal.

Chapter 6 focuses on the friction strength between a rigid flat and a deformable crystal under shear. The interface is simulated by a cohesive zone while the plasticity of the crystal is described by discrete dislocations. It is found that the friction strength is determined by the competition between interfacial failure and crystal plastic deformation. The competition is influenced not only by the crystal material property and the interfacial strength, but also by the loading rate.

Chapter 7 is devoted to the analysis of how an interlocking asperity pair deforms under shear. It is found that the initial ploughing depth does not have a strong influence on the force that is needed to plastically deform the asperity. An even more surprising result is that for different sizes of self-similar asperities, the force that is needed to plastically deform the asperity is size *in*dependent.

In Chapter 2, 4, 5, the focus is on the rough-surface contact of three-dimensional rough surfaces.

In Chapter 2, we relax one of the key limitations –namely, asperities deform independently– of the GW statistical model for rough surface contact. Asperity interaction is caused by contacting asperities and is transmitted by the substrate. The consequence is that a contacting asperity shifts neighboring asperities down by a magnitude that depends on the distance from the contacting asperity and the magnitude of its deformation. By computing the change of the asperity mean height by statistical summation, it is found that asperity interaction reduces the contact force compared to the contact force if the asperities would deform independently. The asperity interaction effect depends on the surface characteristics: mean radius of curvature of the asperities, the standard deviation of the surface height, and the areal density of asperities.

However, the response of a single asperity, which is the input of the GW statistical model, is based on the size-independent J_2 plasticity theory. Therefore, in Chapter 5, we provide the size-dependent single asperity response calculated by CMSGP. The intrinsic length l in CMSGP for asperity flattening is obtained by comparison of a 2D simulation with DDP. It is found that the roughly linear dependence of the real contact area on the normal load, predicted by the statistical model, is universal regardless of material's plastic property and surface roughness. These characteristics only influence the slope of the roughly linear dependence, i.e. the mean contact pressure. This is consistent with the findings of full-detail FEM simulations of rough surface contact in Chapter 4. In chapter 4, also the dependence of the asperity pressure distribution on the material properties

and on the surface roughness is analyzed in detail.