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Rougher is more slippery: How adhesive friction decreases with increasing surface roughness due to the suppression of capillary adhesion

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We systematically manipulate surface topography and use a fluorescence microscopy-based contact visualization technique to reveal the interplay between topography, contact formation and friction. We demonstrate good agreement between elasto-plastic boundary element method contact calculations and experimental visualization of the area of real contact. While the area of real contact and thus contact pressure could be varied by a factor of 4 through control of the surface topography, this had only a modest effect on the coefficient of friction. We do find a small but systematic increase in the friction coefficient with decreasing surface roughness that is attributed to capillary adhesion.
Keywords (from 3 to 5 max): topography, friction, capillary adhesion, area of real contact, contact visualization

1. Introduction

At almost all macroscopic interfaces the force of friction (Ff) is proportional to the normal force (Fn); the ratio of the two forces is constant and known as the coefficient of friction (CoF = Ff/Fn). Single contact experiments and simulations have demonstrated that the proportionality between frictional force and normal force can emerge due to the fact that increased normal force results in stronger atomic scale interlocking and thus proportionally more frictional force. Alternatively, if the atomic scale interlocking is dominated by adhesion rather than by externally applied force, the frictional force may scale with the area of real contact. At macroscopic, multi-asperity interfaces the contacting materials form asperity contacts and touch at the atomic scale within the area of real contact. Analytical theories such as the classical Greenwood and Williamson model and the Persson contact theory describe the process of contact formation. They attempt to explain why the area of real contact is proportional to the normal force, relating this to the surface topography, mechanical properties and in some cases adhesion. Alternatively, contact between rough surfaces can be understood through boundary element calculations and molecular dynamics simulations. However, these theoretical approaches towards describing multi-asperity contact formation are built on assumptions–such as idealized elasticity and plasticity or frictionless contacts–that do not necessarily hold in reality. The area of real contact is elusive and difficult to access experimentally because it is hidden from view by the contacting materials and defined by the deformation of small scale surface roughness variations. Therefore, it is challenging to compare multi-asperity contact theories to experiments at the appropriate length scales and even harder to assess the impact of the contact mechanics on friction. As a result, a key question remained unanswered: to what extent does adhesive multi-asperity friction really depend on the area of real contact?

Here, we use a fluorescence microscopy-based contact visualization method to reveal the local nanometric gaps at a multi-asperity interface. Through a detailed comparison between visualization experiments and boundary element contact calculations, we show that the observed deformations of nanoscale surface roughness are well-described by idealized elasto-plasticity. We show that a direct consequence of the contact mechanics is that the area of real contact will increase when the surface roughness is decreased, and decrease when the roughness is increased. Counterintuitively, the surface roughness and area of real contact do almost not influence the dynamic frictional force: smooth and rough surfaces have approximately the same coefficient of friction. However, when the interface roughness drops to values of just a few nm we do find increased coefficient of friction due to the large areas across which the interface is subject to capillary adhesion forces. These measurements give a comprehensive picture of how surface topography, elasto-plasticity and adhesion control the friction of multi-asperity contacts.

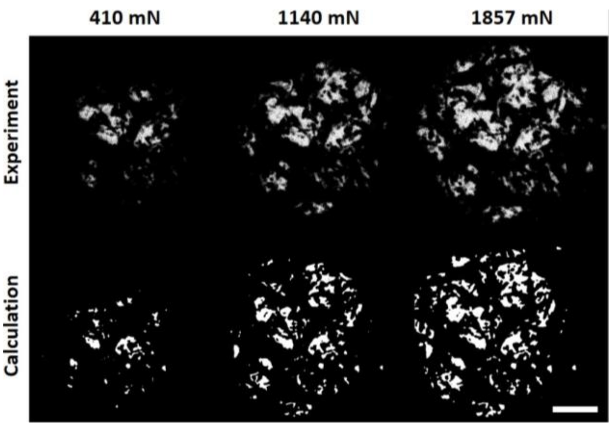

Figure 1: Si3N4-on-sapphire contact visualization and calculation.