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Short communication

Observed transition from linear to non-linear friction–load behavior using a lateral force microscope

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Abstract

The most commonly observed friction behavior for sliding systems is that described by Amontons laws of friction. In this case, sliding friction is independent of the gross or apparent area of contact between the materials and a linear function of the applied normal load, where the constant of proportionality is called the friction coefficient. However, for dry sliding solids in contact via a single-asperity junction, Amontons (linear) friction–load behavior is not strictly relevant. In experiments measuring sliding friction between a silicon tip and a quartz surface using an atomic force microscope (AFM), a transition from linear to non-linear friction–load behavior has been observed. This is proposed to result from a nanoscale 'conditioning' of a multiple-contact tip–surface interface to form a single-asperity contact.

Keywords: Atomic Force Microscope; Contact mechanics; Adhesion; Friction; Wear

1. Introduction

Surface forces studies at nanometer length scales have progressed rapidly in the last decade or so, due in large part to experimental instruments such as the surface forces apparatus (SFA) and the atomic force microscope (AFM) [1]. When used to measure friction, an AFM instrument is often referred to as a lateral (or friction) force microscope (LFM). Investigation of frictional phenomena at sub-micron length scales has an impact not only in the development of small-scale technologies like microelectromechanical systems (MEMS) and magnetic storage devices, but can also offer new insight into the behavior of systems typically considered as 'macroscopic'. For example, contact between solid surfaces is generally made through a multitude of asperities that constitute the microscopic roughness of any 'real' surface. Clearly then, information about the frictional behavior of a single-asperity is useful in

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understanding how a multitude of asperities will behave. In the experimental work presented here, two distinctly different frictional behaviors are observed for a silicon AFM tip sliding on a crystalline quartz surface.

Macroscopic frictional behavior for sliding solids is frequently a linear relationship between friction and applied load. In this case, Amontons' laws state that sliding friction is directly proportional to applied load and independent of the apparent area of contact [2]. In an LFM friction experiment, linear friction–load behavior is often observed. In addition, adhesion between the tip and surface can be significant due to the small size of an AFM probe. In this case, the relationship between friction, F, and load, L, can be expressed as $F = \mu L + F_0$, where F_0 is the friction at zero applied load and μ is the coefficient of friction.

The concept that friction is proportional to the true (as opposed to apparent) area of contact between sliding solids was introduced by Bowden and Tabor in their plastic junction theory for sliding metals [3]. In this case, the relationship between interfacial sliding friction, F_f, and the true or 'interfacial' contact area, A, can be written as $F_f = \tau A$ where the constant of proportionality, τ, is the shear strength of the sliding contact junction. The interfacial contact area is directly proportional to the number of dissipative interatomic–molecular interactions occurring at the interface [4]. Sliding friction is, therefore, controlled by the variation in interfacial (or true) contact area, which is also a function of the normal load applied to the surfaces.

Due to the small size (nanometres) of an AFM tip, it is possible to form a single junction of contact between the tip and a surface, and during contact, a conically shaped AFM tip may be well approximated as a sphere-flat geometry [5]. The contact between two non-adhering spherical elastic solids, under a normal load, was first modelled by Hertz in 1881; in the case of a sphere on a flat rigid surface, the contact area is predicted to be proportional to $L^{2/3}$. The Hertz model has since been shown to accurately describe the contact area between elastic spheres for cases where adhesion between the bodies is negligible [6]. However, at very small scales, the surface-to-bulk ratio becomes significant, and the effect of adhesion arising from attractive surface forces acts to increase the contact area above that predicted by Hertz. To account for the effects of surface energy on the elastic deformation of spheres, JKR [7] and DMT [8] models were developed, with the JKR theory most applicable to large, compliant spheres, while the DMT model is most applicable to small stiff spheres. Considering that both theories represent limiting cases, it follows that many material pairs may not be suited to either of these models. One solution to this problem was formulated by Maugis [9], in which these extremes and any system lying between them could be analyzed. Using the so-called "Dugdale approximation," the Maugis–Dugdale (MD) model matches the effective range of surface forces to elastic deformation for interacting bodies by employing a so-called 'transition parameter', λ. The JKR case is when $\lambda \gg 1$, and DMT is when $\lambda \ll 1$ [10].

In studies of various material systems operating under different environmental and physico-chemical conditions, explanatory theories of frictional behavior are diverse. In several SFA and AFM studies using surfaces reportedly in contact via a single junction, both linear and non-linear friction–load behavior has been observed, depending on whether surfaces are dry, contaminated, lubricated, or whether damage has occurred during sliding [11–19]. For example, studies using the SFA have reported non-linear friction–load behavior for silica and also mica surfaces sliding in dry air [11,12]. In these studies, mica was sometimes subjected to damage during sliding, and once this occurred, a linear friction–load relationship was observed to be dominant. That is, the authors reported a 'wear-induced transition' from non-linear to linear friction–load behavior. In contrast, the focus of this report is the new observation of a wear-induced transition from linear to non-linear frictional behavior using an LFM instrument.

2. Experimental methods

2.1. Instrumentation and materials preparation

A commercial optical beam deflection AFM was used for experiments in this work (Nanoscope III, Digital Instruments Inc.). The cantilever was mounted in a 'fluid cell', which houses the cantilever and surface in a chamber containing dry high-purity nitrogen gas (maintained by a slight positive pressure).