Friction and Adhesion at Atomic and Nanometer-Scale

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INTRODUCTION: Scanning probe microscopy was used to investigate the tribological properties of nanoscale contacts on a Pt(111) single-crystal surface under ultrahigh vacuum (UHV) conditions. The electrically conductive tip made it possible to alternate between contact measurements and noncontact scanning tunneling microscopy. Several types of interfaces were found depending on the chemical state of the surfaces. In addition, a comprehensive nanotribological study of a hydrogen-terminated diamond(111)/tungsten carbide interface has been performed using UHV atomic force microscopy.

METHODS: By using atomic force microscope (AFM) and scanning tunneling microscope (STM) with the same conductive cantilevers[1-3], we were able to study the tribological and electronic properties of nanocontacts and to correlate these properties with the degree of passivation of the interface. Contacts could be classified as clean, half-passivated, and fully passivated, depending on whether none, one or both of the participating surfaces are covered with chemically inactive layers. While it would be desirable to obtain detailed information on the specific chemistry and structure of these contaminant species, no technique currently exists for obtaining such information at a confined nanoscale interface. Rather, we are restricted to rely on wide-scale AES measurements of the surfaces. Based on these measurements, we propose that the passivating materials for the WC tips consist mostly of strongly bound O and C species. On the tip, they could be removed by sliding contact under high load on the Pt substrate. In the case of Pt, the contaminants were C species. The clean Pt(111) surface could be imaged in STM mode with cantilevers stiff enough to avoid the jump-to-contact instability[1]. When such a surface is brought into contact with a clean tip, strong bonds are formed that cause rupture of the contact in the bulk part of the tip and/or substrate upon separation.

RESULTS: With passivated tips, low adhesion energy contacts (~1 J/m2) are formed. The friction properties of such contacts depend on whether additional adsorbate layers are also present on the Pt surface. Passivated areas of the surface give rise to low-friction and sigmoid-type $I-V$ characteristics, typical of poorly conductive or semiconducting materials. Clean Pt areas produce ohmic contact characteristics. Clean Pt can be imaged in contact mode with passivated tips and gives rise to atomic lattice stick-slip friction with the Pt(111) lattice periodicity. Thus, chemically active metal surface has been imaged in UHV in contact revealing stick-slip with atomic lattice periodicity, and indicating that the passivating layer on the WC tip is bound strong enough to the tip that material is not transferred to the active Pt even under the conditions where substantial energy dissipation takes place during friction. The results indicate that even in UHV conditions, transfer of low-conductivity, passivating material can easily occur in nanoscale contacts.

Many AFM friction experiments are carried out under atmospheric or inert gas conditions, where contamination and water meniscus formation significantly affect the results. With diamond, for example, sliding can catalyze a phase change in moderately evacuated chambers due to residual oxygen and water vapor. UHV experiments are therefore necessary to provide a reliable and fundamental insight into the relation between friction and contact area.

Using an AFM, we have studied the nanotribological behavior of a well-defined hydrogen-terminated diamond(111) /tungsten carbide contact in UHV as a function of applied load[4,5]. Contact conductance measurements provided a direct and independent way of measuring the area of contact. Current (contact area) *versus* load curves for a variety of voltages were unambiguously fit by the DMT model, in agreement with the finding that $\mu = 0.019 < 0.1$. The load dependence of the friction was also found to be in excellent agreement with the DMT model, verified by an independent measurement of the pulloff force. Therefore, we conclude that, for this ideal single asperity contact, i.e., one of the hardest, stiffest known heterocontacts involving materials of a great tribological importance, friction is proportional to A: $F_f = \tau A$, where $\tau = 238$ MPa for loads up to 12 nN.

DISCUSSION & CONCLUSIONS: Several types of interfaces were found depending on the chemical state of the surfaces. We demonstrate for the first time the load dependence of the contact area in UHV for this extremely hard single asperity contact as described by the Derjaguin-Müller-Toporov continuum mechanics model. Furthermore, the frictional force is found to be directly proportional to the contact area.

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