

Adhesion of Cleaned Nanoscopic Metal Contacts

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Nanoscopic metal contact in this context means Atomic Force Microscope (AFM) tips in contact with cleaned, flat, smooth surfaces in UHV. Such idealized contact conditions become more and more of relevance for friction in Micro-Systems-Technology. Additionally such contacts can be theoretically described by MD simulation. The comparison of experiment and simulation results will enhance the understanding of the elementary processes and mechanisms causing friction. The final goal is to develop a systematic chart of adhesion between all kinds of material contacts, because adhesion is beside the deformation the other main mechanism of friction.

Adhesion measurement with an UHV – AFM

For adhesion measurements the approach and retraction of the AFM-tip is recorded as shown in Fig.1 for a commercial Au-coated Si₃N₄-tip brought in contact with a clean Ag-surface. This type of diagram is called a force-distance curve.

According to the JKR model [Johnson, K.L., Kendall, K., and Roberts, A.D., Proc. Roy. Soc. London A, 324 (1971) 301] the pull-off force F_c is proportional to the energy of adhesion per unit area of both the tip with radius R and the flat.

$$\text{Pull-off force } F_c \propto \sqrt{\frac{3}{2} \gamma R} \quad (1)$$

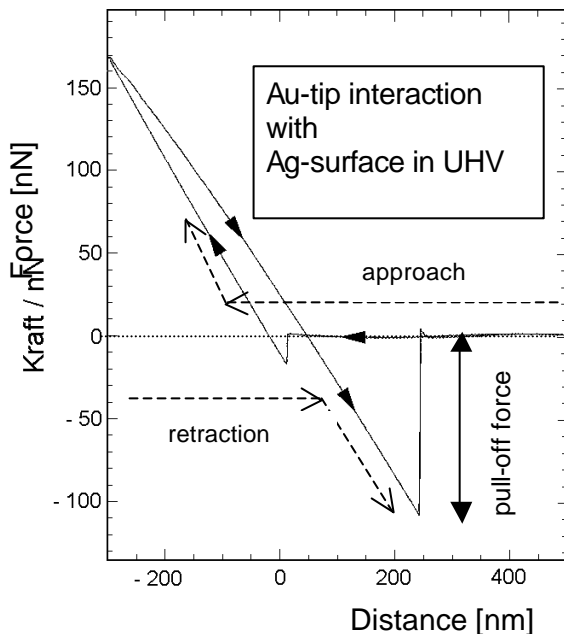


Figure 1 Force-distance curve for an Au-tip on an Ag-surface in UHV

A number of conditions must be fulfilled to evaluate adhesion energies for material contacts from force-distance curves.

- First, the surfaces must be clean before brought into contact. Material surfaces stored without protection are covered by contamination, reaction, and adsorption layers which hide the real properties.
- Second, the force constant of the AFM-cantilever must be known to measure the pull-off force correctly.
- Third, according to equation (1) the radius R of the cantilever tip is needed to calculate the energy γ from the measured pull-off force F_c .

If these three main conditions are fulfilled adhesion energies in relation to lattice type, bonding type, and different mechanical material properties can be evaluated.

The AFM was operated in UHV of about 10^{-11} mTorr. Until now the force constant of the cantilever and the tip radius have been taken from the specification of the manufacturer. To overcome these two uncertainties we always performed series of measurements with the

same cantilever and tip. The results obtained in this way are only correct for relative adhesion values of the different contacts measured in one series.

Another effect influencing the force-distance curves is the velocity of approach and retraction. In Fig. 2 force-distance diagrams for three approach velocities $v_1 > v_2 > v_3$ of a Si-tip onto an Al- surface are shown. With decreasing approach velocity, which is equivalent with increasing contact time, the pull-off forces increase. This time effect was only encountered for Al-surfaces which were not cleaned by sputtering in UHV. Similar effects are reported by Johnson and by Tsui et al [Tsui, O.K.C., Wang, X.P.,

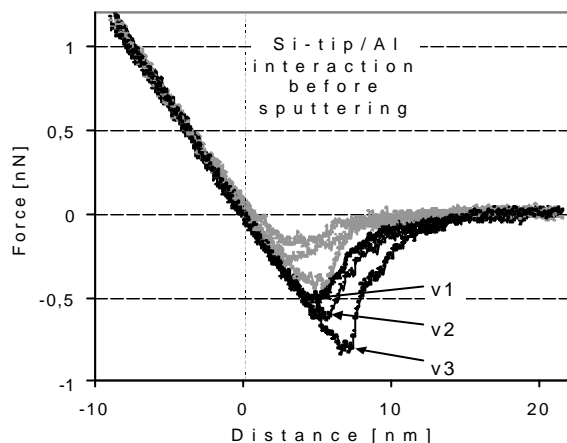


Figure 2 Force/distance curve of a Si-tip on Al-surface in UHV before sputtering for different approach velocities $v_1 > v_2 > v_3$ ($600 \text{ nm/s} > 120 \text{ nm/s} > 60 \text{ nm/s}$)

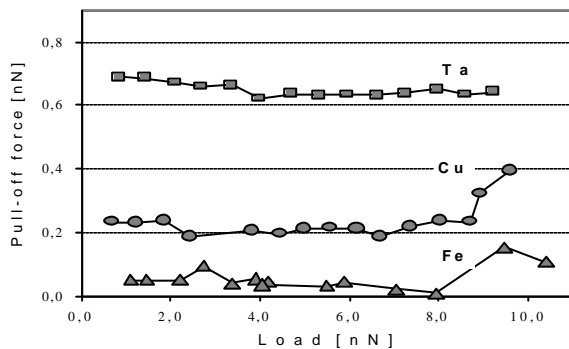


Figure 3 Pull-off forces for Si-tip from Fe-, Cu- and Ta-surfaces in UHV (after sputtering)

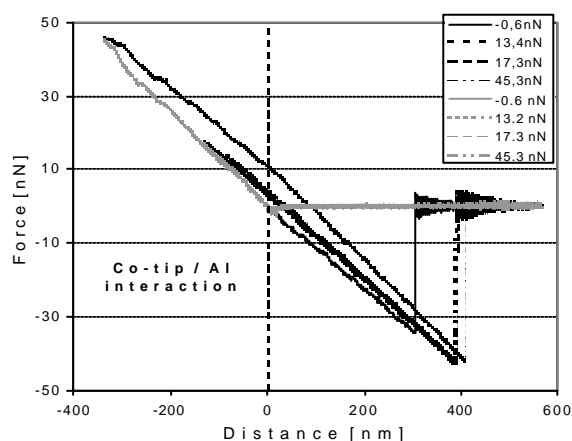


Figure 4 Force-distance diagrams of a Co-coated AFM-tip (Si) on an Al-surface for applied loads of -0.6 nN , 13.4 nN , 17.3 nN , and 45.3 nN

Ho, J.Y.L., Ng, T.K., and Xiao, X., *Macromolecules* 33 (2000) 4198] for rubber balls. To account for that further force-distance diagrams are taken with the same tip approach velocity. The first adhesion test series on Fe-, Cu-, and Ta-surfaces was conducted with an uncoated Si-Tip on a single beam cantilever (0.4 N/m). The metal surfaces were cleaned in UHV by Ar-ion bombardment before the measurement. The pull-off forces of the Si-AFM-tip are measured for increasing external loads. It can be seen from Fig.3 that there exists no dependence of the pull-off force F_c on the applied load. This is equivalent with an independence of F_c of the elastic moduli of the materials and of the contact

area. At a glance this may be surprising, but the JKR model predicts that the pull-off force is only depending on the tip radius R and the adhesion energy γ . The reason is, that both the surface energy and the elastic work (due to deformation) vary as the square of the radius of the contact area. Of course this holds only for elastic deformation.

For Fe and Cu above 8 nN load the pull-off force seems to increase, probably due to partly plastic deformation.

Due to the lack of force calibration mentioned earlier- and in this experiments not exact known radius of the AFM-tip - one cannot calculate the adhesion energies $\gamma(\text{Si/metal})$ from the values of pull-off forces F_c by equation (1). But because of the linear relationship between F_c and γ one can deduce a ranking of the adhesion energies

between Si and the metals

- $\gamma(\text{Si/Cu}) \approx 5x \gamma(\text{Si/Fe})$
- $\gamma(\text{Si/Ta}) \approx 3x \gamma(\text{Si/Cu}) \approx 15x \gamma(\text{Si/Fe})$.

Next, a series of force-distance diagrams was taken with a Co-coated AFM-tip on an Al-surface. The force-distance curves for this series are drawn in Fig.4. The pull-off forces are all between 42 nN and 43 nN for the three positive applied loads from 13 nN up to 45 nN .

Conclusion

The adhesion measurements performed with an AFM in UHV on metal surfaces confirmed the validity of the Johnson-Kendall-Roberts contact model in as far as the pull-off forces are independent of the applied loads.

To achieve progress in the development of an adhesion systematic a method to measure tip radii and spring constants of the AFM cantilevers has to be developed.