AFM ANALYSIS OF TRIBOLOGICAL PROPERTIES OF AMORPHOUS CARBON FILMS*

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A tribological investigation of nanostructured carbon films performed with atomic force microscope is presented. Surface morphology is self-affine, with different correlation lengths corresponding to an inhomogeneous distribution of deposited carbon clusters. After reducing topographical effects, the friction coefficient μ turns out to be ~ 0.15 (in air), with a slight dependence on the cluster distribution.

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Friction at nano- and micrometer scale presents a considerable interest in the development of nanotechnological devices. The contact area of the sliding surfaces at such scales is formed by few junctions. With the introduction of the atomic force microscope (AFM) it became possible to study the frictional properties of an isolated tip sliding over a surface [1]. The frictional force F_L acting on the tip of an AFM can be deduced from the lateral bending of the elastic cantilever supporting the tip [2]. The procedure is not straightforward in the case of rough surfaces, which are commonly used in nanotechnology. In such cases the bending is produced by frictional forces coupled with topographical effects. Furthermore, cantilevers are often not rectangular shaped and their characteristic lengths are not known with satisfying accuracy, which introduces serious problems in the evaluation of frictional forces.

In this paper, we consider a recently developed kind of nanostructured carbon films of considerable interest in nanotechnology [3, 4]. Films are produced by deposition of supersonic cluster beams generated with a pulsed microplasma source; clusters are deposited by intercepting the beam with a substrate and they give rise to an amorphous structure with a rough surface. The distribution of clusters in the incident beam is inhomogeneous, because of inertial separation effects. The central part of the beam is rich in heavy close–cage diamond–like clusters, while the lateral part is formed by linear and planar graphite–like clusters [5].

With an AFM operated in air at room temperature [Park Scientific Instruments AutoProbe CP] we have examined both the morphology and the tribological properties of regions with different cluster population. The morphological analysis of the samples, performed on topographies

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acquired in tapping mode, is described in details elsewhere [6]. It was found that the height-height correlation function

$$G(r) = \frac{1}{L^2} \int \left(z(\mathbf{r}' + \mathbf{r}) - \mathbf{z}(\mathbf{r}') \right)^2 d^2 r', \tag{1}$$

where $\mathbf{r} \equiv (\mathbf{x}, \mathbf{y})$ and L is the scan length, behaves as

$$G(r) \sim \begin{cases} r^{2\alpha} & (r \ll \xi) \\ \text{const.} & (r \gg \xi) \end{cases} \tag{2}$$

Eq. (2) states that the examined nanostructured carbon films are self–affine [7]. The lateral correlation length ξ is comprised between 20 and 1000 nm, depending on cluster distribution. The film roughness, given by the asymptotic constant value of $G(r)$ in Eq. (2), is comprised between 30 and 100 nm, also depending on cluster distribution. On the contrary, the scaling exponent $\alpha = 0.64 \div 0.68$ is not influenced by the composition of the incident beam, although isolated clusters significantly larger than surrounding ones might have an important role in the film growth.

In the present article we describe the tribological characterization of the amorphous carbon films. The frictional forces between the AFM silicon tip and the film surface were determined in contact mode with a triangular shaped cantilever [ThermoMicroscopes ULNC B] with length $l = 180$ μm, width $w = 38$ μm and thickness $t = 2$ μm. The quantitative relation between the bending of the cantilever and the lateral forces acting on the tip might be determined analytically following the procedure suggested by Neumeister *et al.* [8]. However, the position and the length of the tip and the thickness t of the cantilever are not known with satisfying accuracy. For this reason, we calibrated the lateral forces with a different method, exploiting the fact that normal forces are well known. Our method is resembling that suggested by Ogletree *et al.* [9].

We scanned the tip across a commercially available silicon grating [Silicon-MDT TGG01] formed by alternated planes tilted $\pm 55^o$. The force perpendicular to the horizontal plane, $F_\perp$, is kept constant by the feedback loop of the AFM. The force parallel to the horizontal plane, $F_\|$, is different on the alternated planes of the grating. It can be proven that the difference between $F_\|$ measured on $\pm 55^o$ tilted planes is given by $\Delta F_\| = 2.86 F_\perp$,, independent of the friction coefficient μ between the AFM tip and the grating. The "perpendicular" force $F_\perp$ is calibrated with the normal elastic constant furnished by the constructor. Thus, the conversion ratio A between the lateral signal $V_\|$, acquired with the photodetector, and $F_\| = AV_\|$ can be evaluated. In our case, $A = 200$ nN/V. We point out that with such method no SEM imaging of the cantilever is required.

Topography and lateral force maps of the surface were acquired in both forward and backward direction on several regions of the inhomogeneous sample. Figs. 1a, b show a topography and a lateral force map acquired on a region formed by relatively small clusters (correlation length $\xi \approx 200$ nm). The local slope Θ was estimated from the first derivative of the topography in the scan direction (Fig. 1c). Within this approximation the roughness of the surface between two consecutive pixels of the maps is not taken into account. We define the "experimental" coefficient of friction μ_{exp} as

$$\mu_{exp} = \frac{\Delta F_\|}{2F_\perp} \tag{3}$$

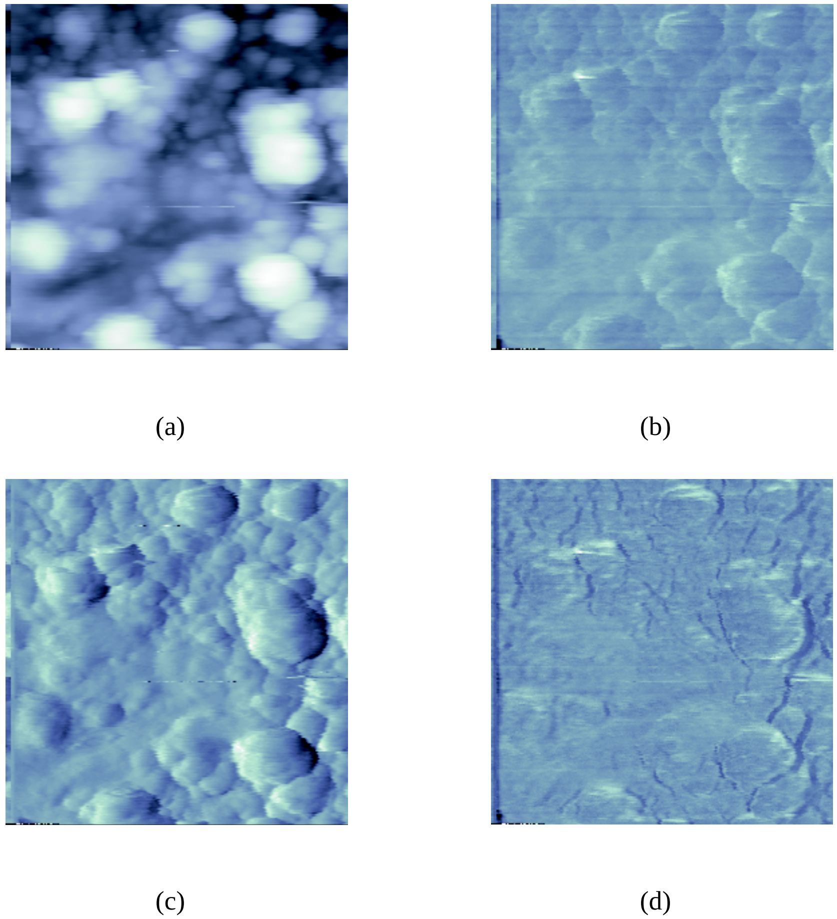

Fig. 1. Tribological analysis of a region formed by small clusters (scan size = 1 μm). (a) Contact-AFM topography; (b) Lateral force map; (c) First derivative of topography; (d) "Real" friction coefficient map.

The "real" coefficient of friction μ is related to the coefficient μ_{exp} through the relation

$$\mu = \frac{\mu_{exp}}{1 + \tan^2 \Theta}, \tag{4}$$

provided that $\mu \tan \Theta \ll 1$ [10]. Fig. 1d shows the map of local coefficient μ so evaluated. Excluding the border of the grains, where the condition $\mu \tan \Theta \ll 1$ is not satisfied, the friction coefficient turns out to be constant on the different grains of the same region. This procedure was repeated on several areas chosen on three regions with different cluster distributions ($\xi \approx$ 200 nm, 800 nm and 1 μm respectively). The corresponding values of friction coefficient are $\mu = 0.13, 0.17, 0.20$ respectively.

In conclusion, after removing the contribution of topographical effects, it is possible to evaluate the "true" coefficient of friction between the silicon tip and the nanostructured carbon films. The coefficient depends only on the materials in contact and not on their morphology. Higher friction is observed on regions with diamond-like clusters while lower friction is related to graphite-like structures, reflecting a weak dependence of frictional force on chemical composition of analysed materials.

References

[1] C.M. Mate, G.M. McClelland, R. Erlandsson, S. Chiang: *Phys. Rev. Lett.* **59** (1987) 1942

[2] E. Meyer, R.M. Overney, K. Dransfeld, T. Gyalog: *Nanoscience: Friction and Rheology on the Nanometer Scale*, World Scientific Publishing, Singapore, 1998

[3] L. Diederich, E. Barborini, P. Piseri, A. Podesta, P. Milani, A. Schneuwly, R. Gallay: *Appl. Phys. Lett.* **75** (1999) 2662

[4] A.C. Ferrari, B.S. Satyanarayana, J. Robertson, W.I. Milne, E. Barborini, P. Piseri, P. Milani: *Europhys. Lett.* **46** (1999) 245

[5] A. Libassi, P. Piseri, P. Milani, A. Ferrari, C.E. Bottani, C. Cepek, L. Giovanelli, E. Magnano, M. Sancrotti: *Surf. Sci.* **404** (1998) 441

[6] R. Buzio, E. Gnecco, C. Boragno, U. Valbusa, P. Piseri, E. Barborini, P. Milani: *Surf. Sci.* **444** (2000) L1

[7] A.L. Barabasi, H.E. Stanley: *Fractal Concepts in Surface Growth*, Cambridge University Press, Cambridge, 1995

[8] J.M. Neumeister, W. Ducker: *Rev. Sci. Instrum.* **65** (1994) 2527

[9] D.F. Ogletree, R.W. Carpick, M. Salmeron: *Rev. Sci. Instrum.* **67** (1996) 3298

[10] V.N. Koinkar, B. Bhushan: *J. Appl. Phys.* **81** (1997) 2472