FRICTION FORCES ON THE LUBRICATED SURFACES IN MICRO AND NANO SCALE

Krzysztof Wierzcholski

Maritime University Gdynia
Morska Street 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901348, fax: +48 58 6901399
e-mail: wierzch@am.gdynia.pl

Andrzej Miszczak

Maritime University Gdynia
Morska Street 81-87, 81-225 Gdynia, Poland
tel:+48 58 6901348, fax:+48 58 6901399
e-mail: miszczak@am.gdynia.pl

Abstract

The present paper determines static and dynamic friction forces and friction coefficients using atomic force microscope during the hydrodynamic viscoelastic liquid flow in the thin boundary layer around the cells of two cooperating bodies. Atomic force microscope is necessary in performed experimental investigations and measurements of friction forces. Therefore proper parameters of microscope are described and illustrated in specific enlargement.

The use of microscope of atomic forces AFM for complex technical investigations to a large extent has facilitated carrying-out the measurements of tissue surface features and control of its growing process in human joint and deforming process in micro-bearing alloy.

During conventional nano-scale measurements of surface topography, the AFM microscope makes it possible to simultaneously map local lateral forces and oscillatory phases of translations which may be interpreted as a representation of local friction forces and local adhesive forces as well as values of elasticity modules.One of the important advantages of the AFM microscope application in the area of investigations with the use of bio-reactors is the possibility of carrying out measurements directly in liquid, namely that which surrounds the cells or micro-bearing gaps.

Keywords: *AFM, experimental data, dynamic friction forces*

1. Afm measurements

The use of microscope of atomic forces AFM for complex technical investigations to a large extent has facilitated carrying-out the measurements of tissue surface features and control of deforming process in micro-bearing alloy. During conventional nano-scale measurements of surface topography, the AFM microscope makes it possible to simultaneously map local lateral forces and oscillatory phases of translations which may be interpreted as a representation of local friction forces and local adhesive forces as well as values of elasticity modules [1-2]. The spectroscopic forces determined by means of the AFM provide information on local values of elasticity modules as well as those of dynamic viscosity of the liquid contained in the thin layer on tissue surface [3, 6]. The complex data derived by applying the AFM microscope may be used for imaging the investigated surfaces [4-5] that simultaneously makes it possible to visualize and characterize qualitative geometrical and local physical - chemical diversities of joint surface superficial layer.

In Fig. 1 and Fig. 2 the AFM is presented. The problem of manual assembly of nanotube probes can largely be solved by directly growing nanotubes on the AFM tips by method catalyzed CVD (Chemical Vapor Deposition). The tips presented in Fig. 3 and Fig. 4 have approximately the cone shape [7-8]. The radius of the tip has values from 2 to 40 nm.

Fig. 4a shows various conical surface-growth nanotube tip fabrication. The upper pictures in Fig. 4b from left to right show the steps of nanotube tip fabrication. The lower picture in Fig. 4b from left shows an SEM (scanning electron microscopy) image of such a tip with a small nanotube protruding from the pores (scale bar is 1 nm). The lower picture in Fig 4b from right presents a TEM (transmission electron microscopy) of a nanotube protruding from the pores (scale bar is 20 nm). Nanotubes grow perpendicular to a porous surface containing embedded catalyst. This approach was exploited to fabricate nanotube tips by CVD with the proper alignment, as illustrated in Fig. 4. A flattened area of approximately 1-5 m^2 was created on Si tips by scanning in contact mode of high load 1 N on a hard, synthetic diamond surface.

During the measurements the tip has the contact with the boundary superficial layer of cartilage or with the other hyper-elastic material and works as the micro or nano conical bearing or gear. Between conical surface and super thin liquid layer stand up the hydrodynamic or elasto-hydro-dynamic pressure in nano or micro level.

The prospect is expected for investigations with the use of the AFM microscope is deemed in determining the tissue surface or micro-bearing surface friction forces that makes it possible - from a general point of view - to ensure a greater stability of measurement results.

After some modification of the AFM scanning microscope units such measurements could be performed directly in a bio-reactor or in micro-mechanism devices. The proposed technique will make it possible to characterize more precisely friction features in the conditions very close to those usually met in natural joints [3].

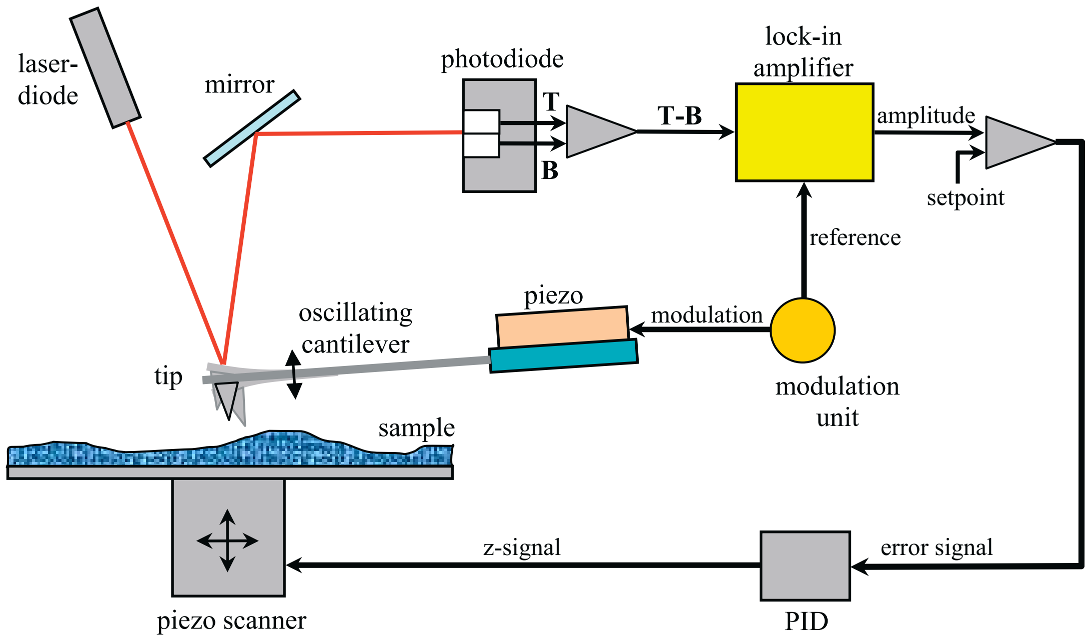

Fig. 1. Basic scheme of (AFM) with the run of measurement process [8]

One of the important advantages of the AFM microscope application is the possibility of carrying out measurements directly in liquid, namely that which surrounds the cells or micro- bearing gaps. The mean statistical height of the roughness of tissue amounts to 20 nm. In the cross-section of biobearing gap the characteristic vertical and lateral asperities of the roughness, reaching the dimensions of 15–25 nm, can be observed on the cartilage. The values correspond to the dimensions of collagen fibres.

In mechanical micro-bearing the roughness reading the dimension 20 nm can be observed on the sleeve surface.

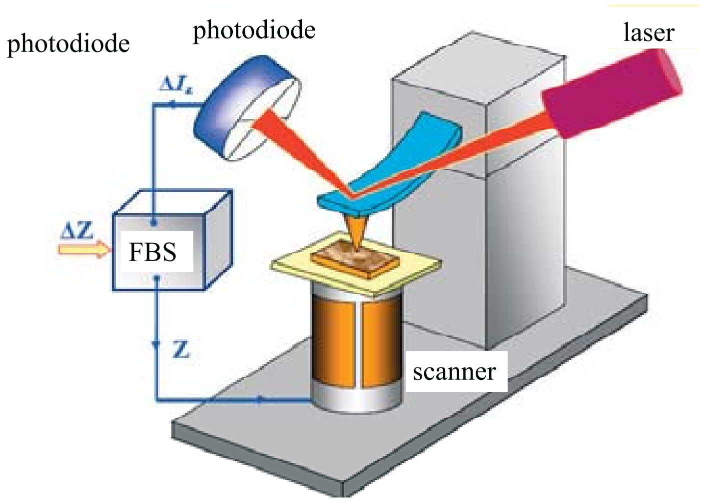

Fig. 2. Detection system in modern Atomic Force Microscope [8]

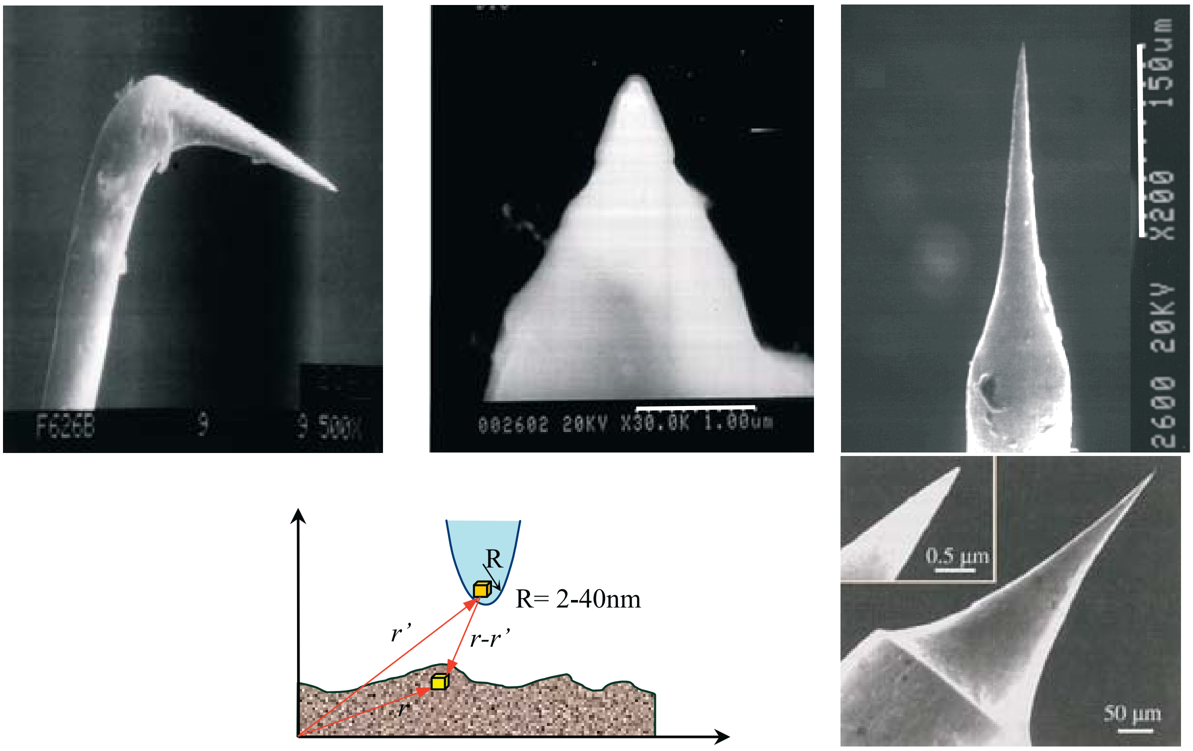

Fig. 3. Classical micro-tips of AFM for various conical shapes and its enlargement [7-8]

2. Geometry of cone tip

The geometry of cone tip is presented in Fig. 5. The tip has cone shape and is presented in cone coordinates system (φ, y, x). Coordinate φ indicates the circumferential direction of the cone tip, coordinate x is situated in cone generating line direction. Direction y indicates the height of the super thin liquid or superficial cartilage layer occurring in the contact area between tip and measured body. The height of the liquid thin boundary layer has values $\varepsilon_T(\varphi, x)$. Symbol γ denotes the angle between conical generating line and cross section plane of the cone bedplate. The cone tip generating line has the contact length $2b_c$ with the liquid or measured material. Radius of the cone R attains values about 20 nm. The dynamic viscosity η(φ, y, x) of the liquid flowing in the super thin boundary layer lying on the cone tip lateral surface depends on the gap height and on the mechanical properties of the measured material and shear rate. Hydrodynamic or elastohydrodynamic pressure p(φ, x) in the gap indicated in Fig. 5 changes in circumferential φ and longitudinal direction x.

In specific kinds of non-Newtonian liquids the pressure p(φ, x, y) depends moreover on variable y i.e., pressure changes in gap height direction.

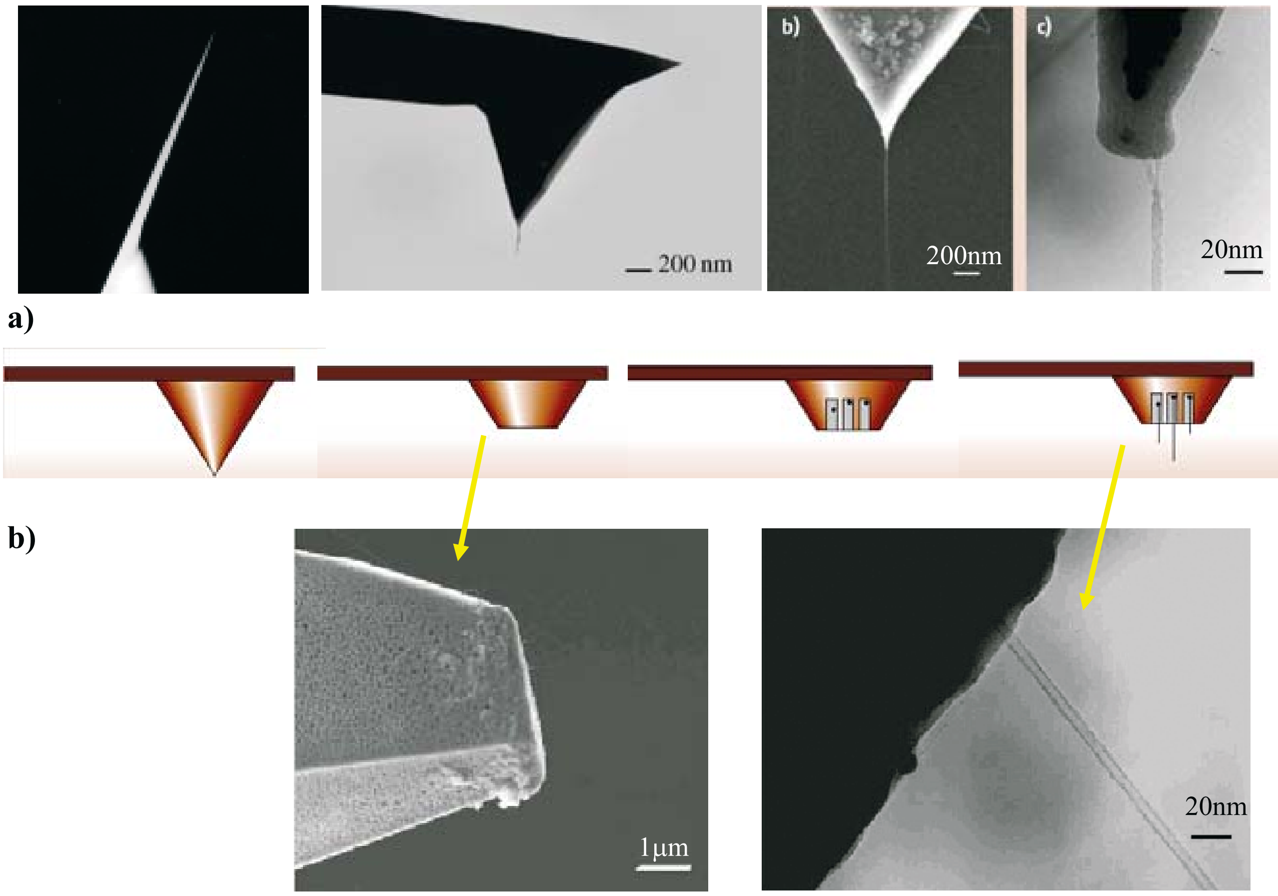

Fig. 4. Nano-tips of AFM for various conical shapes and various means of nano-tips fixing; a) enlargement of nano-tips with conical shapes, b) means of fix and nanotube tip fabrication [7-8]

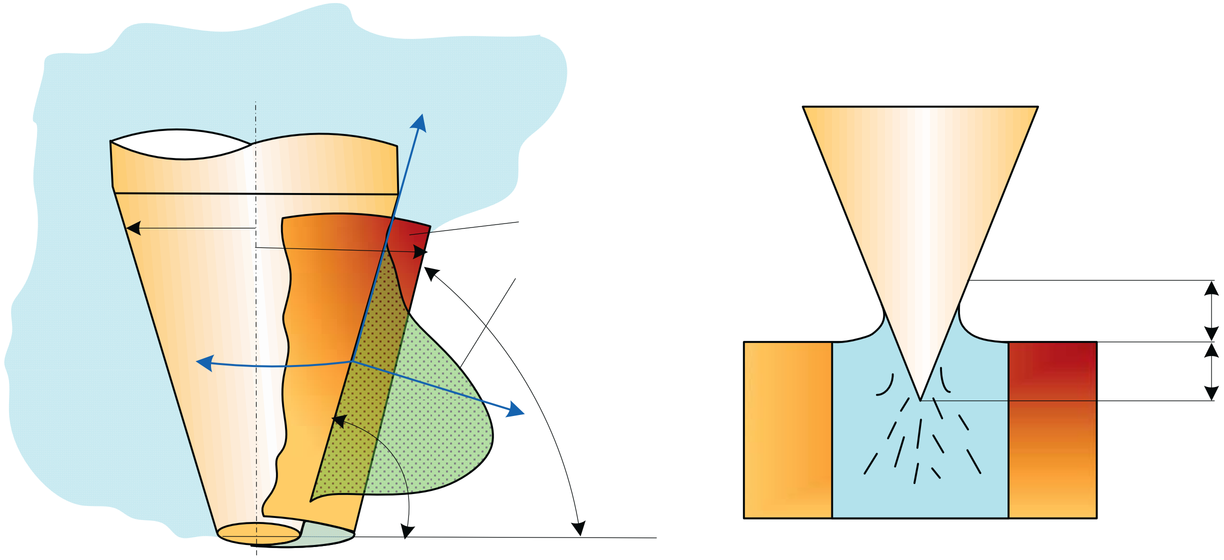

FIG. 5. Geometrical particularities of AFM tip with the cone shape a) and general view of cone tip b)

3. Friction forces

Two kinds of nano friction forces are associated during the AFM measurements on the micro surfaces. We have the micro friction forces caused by the liquid flow in material cells and friction forces caused by the contact of the cone tip with the thin boundary liquid layer or measured material.

The flow analysis of the lubricant liquid inside the super thin boundary layer will be performed by means of the equations of continuity equation, conservation of momentum equations, and energy equation [8], [9]. Moreover the equations of motion and heat transfer equation for elastic micro-bearing sleeve are applied.

By virtue of the hydrodynamic theory of lubrication we obtain finally the following form of friction force components caused by the contact of the cone tip with the thin boundary liquid in φ and x direction:

$$F_{R\varphi} = \iint_{\Omega} \frac{\partial p}{\partial \varphi} \left[\varepsilon_T(\varphi, x) - \frac{\int_0^{\varepsilon_T(\varphi,x)} \frac{y\,dy}{\eta(\varphi, y, x)}}{\int_0^{\varepsilon_T(\varphi,x)} \frac{dy}{\eta(\varphi, y, x)}} \right] d\varphi dx - \omega \iint_{\Omega} \left[\frac{(R + x\cos\gamma)^2}{\int_0^{\varepsilon_T(\varphi,x)} \frac{dy}{\eta(\varphi, y, x)}} \right] d\varphi dx, \tag{1}$$

$$F_{Rx} = R \iint_{\Omega} \left\{ \frac{\partial p}{\partial x} \left[\varepsilon_T(\varphi, x) - \frac{\int_0^{\varepsilon_T(\varphi,x)} \frac{y\,dy}{\eta(\varphi, y, x)}}{\int_0^{\varepsilon_T(\varphi,x)} \frac{dy}{\eta(\varphi, y, x)}} \right] (R + x\cos\gamma) \right\} d\varphi dx, \tag{2}$$

for $\eta=\eta(\varphi,y,x)$, $0\le y\le\varepsilon_T$, $0\le\varphi<2\pi\theta_1$, $0\le\theta_1<1.0 \le x\le 2b_c$. Symbol Ω denotes the real contact surface between the cone tip and liquid or measured material.

The first term of static friction forces indicated in equation (1) is caused by the pressure p. The second term of dynamic friction forces indicated in equation (1) is caused by the angular velocity ω of the cone tip or of the linear velocity if such motion during the measurements exists.
Friction coefficients has the following form:

$$\mu_{con} = \frac{\left| \mathbf{e}_{\varphi} F_{R\varphi} + \mathbf{e}_x F_{Rx} \right|}{C_{tot}^{(con)}}, \tag{3}$$

where: $\mathbf{e}_{\varphi}$, $\mathbf{e}_x$ are the unit vectors in conical φ and x coordinate directions.

4. Conclusions

1. By virtue of obtained experimental and numerical values we can see that friction forces caused by the contact of the cone tip with the measured material are to be about 10 percent of measured friction forces occurring on the cartilage surface about 20 μm × 20 μm.
2. If the angle γ between conical surface and the cross section plane increases in AFM tip then the capacity increases and friction force decreases.

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