A stand-alone scanning force and friction microscope

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We present a new design for a compact stand-alone force and friction microscope. Both the force sensor and the scanning unit are mounted on the microscope head, thus allowing the investigation of virtually all surfaces, independent of thickness and size, and minimizing the geometrical dimension. The beam deflection method in a collinear arrangement is used to detect the normal force and the friction force. The cantilever is fixed to the scanning piezo. The influences of the scanning motion on the force signal and the compensation schemes are discussed. The new design of the SFM allows a combination of optical surface manipulation and real-time detection of the stimulated processes with the scanning force microscope. The set-up also makes it possible to work under fluids.

1. Introduction

The scanning force and friction microscope (SFM) [1-4] allows the measurement of two forces simultaneously through the bending and twisting of the cantilever in the imaging process. The first one is due to the normal force between probe and sample. The second one is the lateral or friction force arising from the scanning motion in the repulsive mode or contact mode. A four-quadrant detector is used to measure the deflection of the cantilever independently in two orthogonal directions [4]. It was shown that atomic resolution is achieved in the friction signal and that soft samples may be imaged at a higher resolution in the friction mode. For further details, see ref. [4].

2. Design of the stand-alone scanning force microscope

The concept for the new SFM arose from the idea to separate the sample from the scanning piezo to accommodate any kind and size of samples. It allows surface manipulations while scanning. Therefore, the microscope head incorporates the force sensor, the scanning unit and the detection system.

For the sake of compactness we choose a collinear set-up shown schematically in fig. 1. As light source we use a commercial laser diode module with a built-in focusing lens [5]. The polarized laser light passes a polarizing beam-splitter cube and is adjusted such that it is rotated 90° and directed through a quarter-wave plate towards the end of the cantilever. Part of the light is reflected back from the lever and passes again the quarter-wave plate. Now the polarization axis of the incident and reflected light are perpendicular. The reflected light passes therefore straight through the first beam-splitter cube. Above the first beam-splitter cube is a second one which is adjusted such that the return beam is deflected at a right angle into the position-sensitive detector. The four-quadrant detector [6] allows the simultaneous measurement of the bending and twisting of the cantilever.

The mechanical design of the microscope is outlined in fig. 2. The microscope head is built out of cast steel with a lamellar graphite distribution and has a size of 60 mm × 75 mm × 60 mm. The material has the advantage of efficiently damping external vibrations coupled into the sys-
position sensitive detector

parallel plate

laser diode

piezo tube

cantilever

optical microscope

polarising beam splitter cubes

quarter wave plate

Fig. 1. Schematics of the collinear detection system. Two polarizing beam-splitter cubes and a quarter-wave plate are used for the beam-deflection method in a collinear arrangement. The orientation of the beam splitters and the polarization of the laser diode are adjusted so that the incoming and reflected beam are separated.

The head is held by three fine-pitch thread screws [8]. Two of them are used for the coarse approach and the third with a mechanical reduction of 10:1 for the fine approach. This yields a resolution better than about 0.1 μm, allowing a manual approach. In future the screw will be replaced by one driven by a stepper motor. The scanning piezo, a segmented tube for the x, y and z displacements, is fixed at the bottom of the microscope block. The holder can be tilted along the direction of the cantilever. A lid on the end of the piezo moves on a sphere when scanning in the x–y plane. The change of the orientation of the cantilever is interpreted by the read-out electronics as a variation of the force on the cantilever, since the beam-deflection method is sensitive to the change in the angle of the cantilever rather than to the distance from the probe to the sample. At small scan ranges the angular errors are negligible, whereas at large ranges a linear voltage ramp derived from the scanning motion can compensate the error in the force measurement. Only the scan axis parallel to the cantilever axis has to be compensated on line since the force signal is used for the feedback loop to control the z-piezo. The same error in the friction signal may be corrected by the software.

The maximum scan range of our microscope is 5 μm, generated by a piezo tube of 10 mm in diameter and 16 mm in height [8]. The maximum additional angle caused by the bending of the piezo is approximately given by (fig. 3).

\[ \alpha = \Delta x / L, \]  

3. Influences of the scanning motion

In this design the force sensor is mounted on the scanning piezo. The top end of the piezo moves on a sphere when scanning in the x–y plane. The change of the orientation of the cantilever is interpreted by the read-out electronics as a variation of the force on the cantilever, since the beam-deflection method is sensitive to the change in the angle of the cantilever rather than to the distance from the probe to the sample. At small scan ranges the angular errors are negligible, whereas at large ranges a linear voltage ramp derived from the scanning motion can compensate the error in the force measurement. Only the scan axis parallel to the cantilever axis has to be compensated on line since the force signal is used for the feedback loop to control the z-piezo. The same error in the friction signal may be corrected by the software.

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where $\Delta x$ is the maximum scan range of the piezo and $L$ its length. This yields an apparent deflection of the lever of

$$h = \frac{1}{2}a_1,$$  \hspace{1cm} (2)

where $l$ is the length of the cantilever. Taking the dimensions of our microscope ($\Delta x = 2.5 \, \mu m$, $L = 16 \, mm$ and $l = 100 \, \mu m$) we get an angle of $1.5 \times 10^{-4}$ rad and an apparent change in the lever displacement of 10 nm. The actual change in height of the lever position given by

$$\Delta h = \frac{1}{2} \Delta x^2 / L$$  \hspace{1cm} (3)

is 0.2 nm which is the limit in the resolution. A typical cantilever with a spring constant of 0.1 N/m thus shows a force error of 1 nN. Hence if the force microscope is operated with a tip loading large compared to this force no correction is necessary. On soft samples, however, which are imaged at tip loadings smaller than $10^{-9}$ N, a linear correction voltage derived from the scanning voltage will keep the force of the cantilever constant.

Another error is due to the lateral movement of the cantilever, reflecting a position-dependent amount of the incoming light. The minimum size of the laser spot in a focal plane at 30 mm is 25 $\mu m \times 19 \, \mu m$ as given by the manufacturer of the laser diode module [5]. In our design the distance from the laser diode to the lever is 50 mm. The minimum spot size is calculated to be 50 $\mu m$, using the propagation laws for Gaussian beams. The width of the cantilevers is $w = 10 \, \mu m$ and $w = 20 \, \mu m$, respectively. The laser spot has a Gaussian profile with $\sigma = 25 \, \mu m$. The reflected intensities are then calculated with the probability integral $\Phi_0$ of the normalized Gaussian distribution. With an initially well centered beam on the lever the reflected portion is $2\Phi_0(w/2\sigma)$. If

![Fig. 2. Front view of the SFM. At the bottom of the microscope head the piezo tube is seen; the lid at the end holds the cantilever. The scanning unit is inclined $20^\circ$ with respect to the plane. On the left side the laser diode is mounted. The view is in the direction of the reflected beam.](image)
we take the whole piezo range (\( \Delta x = \pm 2.5 \text{ \mu m} \))

we have a relative intensity of

\[
\Phi_0\left(\frac{w - 2\Delta x}{2\sigma}\right) + \Phi_0\left(\frac{w + 2\Delta x}{2\sigma}\right).
\]

This yields a relative change in the reflected intensities due to the lateral movement of

\[
1 - \left[\Phi_0\left(\frac{w - 2\Delta x}{2\sigma}\right) \right. \\
+ \left. \Phi_0\left(\frac{w + 2\Delta x}{2\sigma}\right)\right] / 2\Phi_0\left(\frac{w}{2\sigma}\right).
\]  

In our case this is about \( \pm 0.4\% \) over the whole scan length, giving a smooth variation of the signal.

These corrections, however, are only of importance when a large scanning area of the order of \( \mu \text{m} \) is taken. If imaging at atomic resolution the errors are negligible.

Alternatively, to get rid of the curvature of the piezo in the scanning process one may use a tube where the tube segments are cut at half-height, forming eight segments. Corresponding segments are then driven with voltages of opposite sign to realize an S-shaped deformation of the piezo, compensating any bending of the piezo. However, in this mode the piezo range is reduced.

Additionally, due to the inclination of the scanning piezo with the force sensor relative to the sample, scanning in the \( y \) direction causes a movement in the \( z \) direction. The scanning is with respect to the \( x'y'x' \) frame whereas the \( xyz \) frame refers to the sample (fig. 4). The scanning in the \( y' \) direction leads to a change in the \( z \) position, and a displacement in the \( z' \) direction controlled by the feedback loop results in a shift in the \( y \) direction. The correction follows from simple geometrical considerations:

\[
y' \rightarrow y' - z' \sin \alpha,
\]

\[z' \rightarrow z' + y' \tan \alpha.\]  

Thus, to compensate, the voltages applied to the \( y \)- and \( z \)-piezo segment have to be mixed. In our set-up this means a correction of about 34% of the voltage change in the \( z \) direction.

We also must account for different calibration of the piezo in the \( z \) and \( y \) directions. Furthermore, the actual scanning length in the \( y \) direction is enlarged by a factor which is the inverse of the cosine of the tilt angle.
4. Conclusions

A stand-alone scanning force and friction microscope has been designed with the scanning unit, detection system and force sensor in one unit. The geometrical dimensions were minimized using a collinear beam deflection method. The size is limited by the optical components. The design allows a convenient adjustment of the laser beam which can be controlled from the top opening with an optical microscope. With the mechanical reduction the fine-thread screw allows a proper fine approach of the cantilever without a stepper motor.

The first measurements with the new SFM showed a correct operation of the microscope. We have imaged samples with an optical grating with a grid spacing of 420 nm [10]. The force and friction signals are shown in figs. 5a and 5b on the maximum scan area of about 5 μm. It is clearly seen that the displayed grid spacing varies over the scan range in both modes. This is due to the nonlinearities of the piezo material. The piezo is driven with ±150 V; the response is dependent on the polarity of the applied voltage and thus shows an asymmetry in the image. The influences of the scanning motion, however, are negligible because the images are taken with a much higher tip loading than the critical one, as discussed above.

The good operation of the SFM promises the achievement of imaging at atomic resolution in the near future. This then combines high-resolution imaging with the advantages of a compact and handy instrument.

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References

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