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Influence of the mechanical behaviour of cantilevers on the topography of nano-scale grooves during AFM tip-based machining

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Abstract

Probes used for Atomic Force Microscopy (AFM) can also be employed as nanoscale tools to generate features on the surface of specimens via ploughing or through chip formation. Compared to single point precision machining, which essentially aims at the fabrication of relatively large surfaces with nanoscale form accuracy and surface finish, the AFM tip-based nanomachining process is focussed on the generation of discrete features with high spatial resolution. In this paper, such nanomachining operations were conducted on a commercial AFM system when processing single crystal copper using a range of applied normal loads. As with most AFM tip-based nanomachining studies, the experiments reported here were conducted under the force-controlled mode of the AFM instrument. In this case, a feedback loop ensured that the voltage output of a position sensitive photodiode (PSPD) was kept constant during the trials. More specifically, this voltage signal corresponds to the projection of a laser beam reflected from the back of the probe cantilever onto the PSPD. Based on the analysis of different output signals monitored during processing, combined with the inspection of the topography of the produced grooves, a particular phenomenon was observed when the tip was cutting in a direction pointing in front of the AFM cantilever. In this case, the experimental evidence suggests that the deflection of the probe at its free end may change from a convex to a concave shape during the groove formation process. The consequence of this change from a convex to a concave orientation was observed to be significant with respect to its effect on the topography of the machined grooves. In particular, both the depth and width of the grooves increased by more than 50% following this change in the cantilever shape. Thus, for the considered processing direction, conducting tip-based nanomachining operations using the force-controlled mode of the AFM instrument does not necessarily lead to constant cutting conditions.

Atomic force microscope, Tip-based nanomachining, Cantilever deflection

1. Introduction

AFM tip-based nanomachining is a method, which may be used to generate micro- and nanoscale cavities on the surface of a processed workpiece [1, 2]. The existing body of research studies in this field demonstrated the implementation this technique along different processing directions. Figure 1 illustrates two of the main machining directions, which are typically found in the literature.

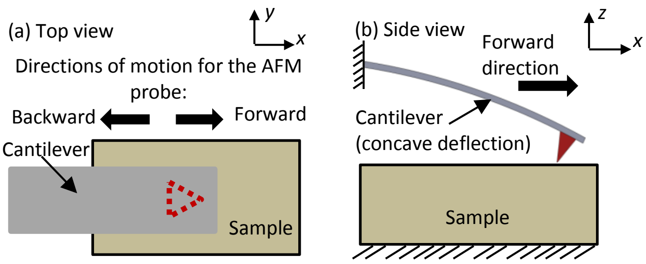

Figure 1. (a) Top view for backward and forward AFM scratching; (b) side view of the commonly assumed concave cantilever deflection when processing in the forward direction.

For the so-called "forward direction" [3], it is generally assumed, such as in [4-6], that the bending of the cantilever is concave, as illustrated with Figure 1(b), where this direction is oriented along the positive *x* axis. However, the deformed shape of the cantilever along this direction, and also along a direction at an inclined angle with respect to such a pure forward configuration should depend on load conditions acting on the tip. Thus, there is no a-priori justification to assume concave bending by default. In this context, the aim of this work is to demonstrate experimentally that both deformed shapes of the cantilever can be observed during actual nanomachining tests along an inclined forward direction.

2. Experimental methodology and cutting conditions

An XE-100 AFM instrument from Park Systems was employed in all experiments. The tests were performed on a single crystal copper sample using a DNISP probe from Bruker. A data acquisition system was developed to capture three voltage signals as described in Table 1. The cutting speed and length of the produced grooves were 5 µm/s and 15 µm, respectively. As specified in Figure 2, the machining tests were conducted along an inclined forward direction, which was at an angle of 22.5˚ with respect to the *x* axis but still within the (*x*, *y*) plane. The normal loads applied by the tip onto the sample ranged between 14 µN and 40 µN.

Table 1 Monitored signals

Name	Physical description
A-B signal	This is given by a position sensitive photodiode (PSPD). It is commonly used by the feedback loop of the AFM to monitor the cantilever deflection at its free end.
Z-detector signal	This voltage is provided by a strain gauge sensor. It allows the monitoring of the vertical motion of the cantilever at its support.
Y stage signal	This signal enables the monitoring of the lateral motion of the AFM stage.

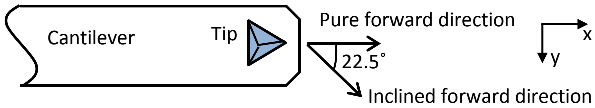

Figure 2. Considered inclined forward cutting direction with respect to the cantilever orientation and tip geometry.

3. Analysis of the Z-detector output signal

Given that it is obvious for the shape of the cantilever to be convex when processing in the backward cutting direction, an example is given here to interpret the Z-detector signal output in this configuration. The knowledge gained in this way can then be used to distinguish between the occurrences of convex and concave cases in the actual experiments along the inclined forward direction. During the nanomachining of a groove, the Z-detector signal can be divided into five stages as illustrated in Figure 3. For stage “A”, the tip is in static contact with the sample and the applied normal force is in the range of a few tens of nN. During stage “B”, the tip penetrates into the processed material as the probe is moved down vertically towards the sample until a pre-defined value is reached for the set normal load. Next, the stage lateral motion, which takes place in the (*x*, *y*) plane (c.f. Figure 1), is initiated. This defines the beginning of stage “C”, which results in a lateral cutting force being generated on the tip, in addition to the normal force. The time elapsed for stage “D” corresponds to the actual machining of the groove. Finally, stage E is reached when the motion of the stage is stopped. Thus, based on the example reported here, it is noted that, when the probe moves down towards the sample surface, the Z-detector voltage increases. In turn, when the probe moves away from the sample, this signal decreases.

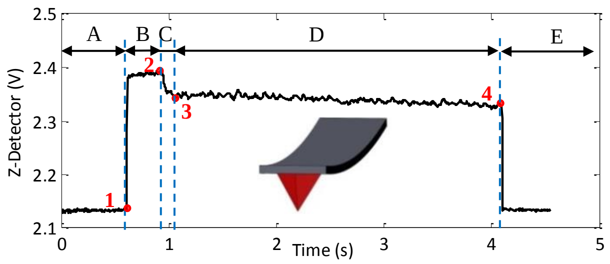

Figure 3. Example of Z-detector signal obtained during nano-machining in the backward direction for a set normal load of 34 µN.

4. Experimental results and discussion

For a set normal force comprised between 14 µN and 30 µN, the obtained results in the inclined forward direction showed that the Z-detector signal was similar to that reported in Figure 3. Hence, it is concluded that, for this range of force values, the cantilever shape stayed convex. However, when machining for set normal forces above 33 µN, the recorded data showed a different behaviour. Indeed, at one time point during the cutting of such grooves, the Z-detector signal always increased significantly. At the same time point, the PSPD voltage also started displaying more pronounced oscillations. For example, this particular observation is reported in Figure 4 for $t \approx 1.8$ s.

This rapid increase in the Z-detector signal showed that the feedback loop of the AFM suddenly drove the probe down as the groove was being cut. This was realised to ensure the A-B voltage output of the PSPD was maintained to a set target value. For the grooves where this phenomenon is observed, it is argued that the shape of the cantilever at its free end changes from a convex orientation to a concave one as illustrated in Figure 4. To support this, it is suggested that the lateral force acting on the tip is gradually increasing along the length of a machined groove. This increase results in a reduction of the deflection angle, which may eventually become negative and lead to feedback loop observed reaction. It is also argued that such an increase in the lateral force during the groove formation process could be the result of the possible occurrence of 1) strain hardening of the material ahead of the tip and 2) accumulation of piled-up material in front of it. Finally, the effect of this phenomenon on the topography of the produced groove is illustrated in Figure 5. Quantitative AFM measurements of such grooves show that their depth and width increased by just over 50% following such shape transition in the deformed cantilever.

5. Conclusions

In this study, it was observed that when an AFM is used to machine material along a direction pointing away from the AFM cantilever, the deflection of the probe may change from a convex to a concave shape during the actual groove formation process. The experimental results show that the occurrence of this phenomenon during machining significantly influences the resulting groove topography. Thus, this work highlights the importance of taking into account the non-rigid nature of AFM probes when studying AFM tip-based nanomachining.

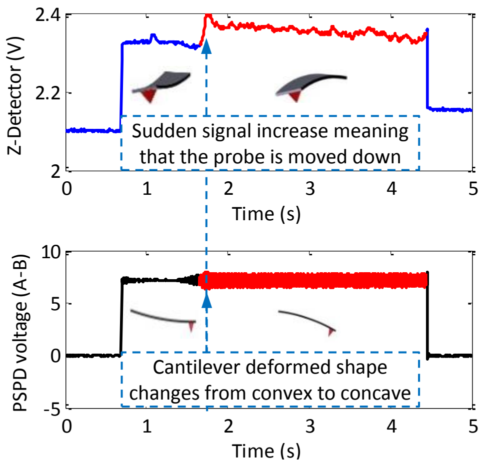

Figure 4. Z-detector and A-B signals recorded when using a set applied load of 33 µN

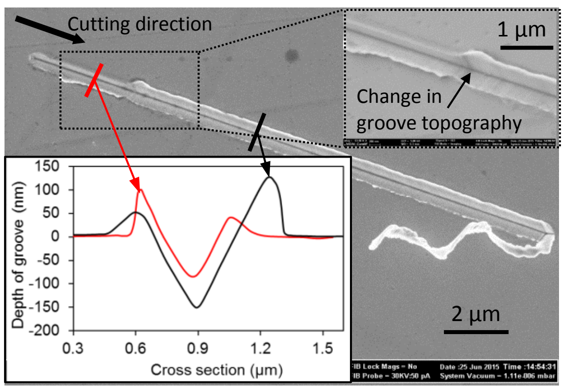

Figure 5. SEM micrographs of the grooves obtained when machining in the higher range of set normal loads considered (33 µN in this case).

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