Effect of AFM Cantilever Geometry on the DPL Nanomachining process

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Abstract: With the development of micro and nanotechnology, machining methods at micro and nanoscale have now become interesting research topics. One of the recently-proposed methods for sub-micron machining, especially nanomachining, is dynamic plowing lithography (DPL) method. In this method an oscillating tip is used for machining soft materials such as polymers. The geometry of the oscillating beam and its vibrational properties are the most important parameters in this nanomachining process. In this study, effects of the AFM beam geometry on its stiffness coefficient, resonant frequency, beam stability, and the maximum stress created in the beam structure were investigated for 12 different general shapes using the finite element method. The obtained results indicate that circular and square membranes are the most favourable AFM cantilever geometries because these structures provide higher machining force and speed; while for noisy conditions and environments, straight and V-shaped beams are recommended (because of their higher stability factor) for the DPL nanomachining process.

Keywords: AFM Beam, AFM nanomachining, DPL nanomachining, Dynamic plowing lithography, Nano lithography, Oscillating tip

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1 INTRODUCTION

Atomic force microscopy (AFM) machining is one of the few methods that can create small nanoscale features. This method has been widely studied in recent years. Intensive efforts have been made for AFM nanomachining like different techniques such as Dip-Pen Nanolithography (DPNL) [1], thermal affecting [2], mechanical nanomachining [3], and the field emission.

Due to their widespread use in macroscale, mechanical machining methods have attracted particular attention. The implementation of computer numerical control (CNC) techniques using SPM at the nanoscale has been investigated in a number of studies [4], [5]. Two methods that are used in mechanical AFM nanomachining are as follows: plowing the sample surface using the static force-displacement indentation (FDI) method and using the dynamic plowing lithography (DPL) method. The later method is used for creating groove on the surface of soft and polymer samples [6]. The advantage of the static method lies in its capability in machining a variety of materials, whereas its disadvantage is low tool life and low machining speed compared to the dynamic method (DPL). The dynamic method can only be used for machining polymers and other soft materials. The ridges formed along the grooves are much larger in the dynamic method compared to the static method, and the ridge density in the DPL method is much lower than that in the FDI method. A number of techniques have been proposed to eliminate them or reduce their size, which are not applicable in the FDI method [6], [7]. Thus, higher speeds and longer tool life have made the dynamic method a better choice in the nanomachining of polymers compared to the static method. Accordingly, several researches have been conducted to optimize this method, through studying damping, force, and beam stiffness coefficient, duration of the contact between the tip and the sample surface, as well as the beam deformation [8-20].

One of the main components of this nanomachining process that directly affects the machining results is the cantilever that acts as a spring to which the tip is attached. The most important parameter in a beam is its stiffness. The higher the stiffness, the greater force exerted by the tip to the surface (considering a constant displacement) and, consequently, the greater the plastic deformation (the amount of material removed from the sample surface) [21]. The beam stiffness is also directly related to its natural frequency (which is the beam working frequency). Increased beam stiffness increases the machining speed. Increasing the machining speed is very important especially in top-down manufacturing, which is generally slow, and can further expand its applications. Beam stability is another important parameter in the DPL process. Beam stability can be evaluated through calculating the ratio of the second mode frequency to that of the first mode. Higher frequency of the second mode compared to the first mode means that second vibrational mode is distant from the first mode which causes the beam to remain in the first vibrational mode. The final parameter is the maximum stress induced in the beam. The nanomachining depth (groove depth) is determined by the vibration amplitude of the beam, which is known and constant. It is desired to have less stress in the beam structure for a constant deflection (vibration amplitude) because lower stress causes increase in the beam's life or allows the nanomachining depth to be increased. In this research, effect of the AFM beam geometrical shape on its stiffness coefficient, resonant frequency, stability and maximum stress was studied using the finite element method.

2 MODELING OF THE AFM CANTILEVER

In this research, finite element analysis method was used to evaluate effect of the AFM beam geometry on the DPL nanomachining process through the following parameters: 1. Stiffness coefficient of the beam: An increased stiffness coefficient increases the beam stiffness and the force is exerted on the sample surface and consequently allows machining of the harder materials. 2. The natural or resonance frequency: the greater the resonance frequency, the higher the machining speed. 3. Beam stability: Increase in the beam stability raises accuracy and repeatability of the machining process and the tool life. 4. The stress induced in the beam: a low stress value ensures longer beam life and allows for increasing the depth of nanomachining. A 225×35×7 commercial cantilever (Pointprobe NCL, Nanosensors, Wetzlar-Blankenfeld, Germany) with a natural frequency of 156 KHz and spring constant of 30 N/m [7] was used for modelling as the base dimensions. As it is shown in the Fig. 1, Effect of the different beam geometries including base cantilever, cantilevers with half and twice the width of the base cantilever, V-shaped beam with angles of 30, 60, 90 and 120°, X-shaped beam, square beam (membrane) with four constrained sides, and circular beam (membrane) with constrained circumference was studied.

3 RESULTS AND DISCUSSION

3.1. Stiffness Coefficient

Stiffness coefficient or spring constant of the AFM beam is an important parameter in DPL nanomachining process. Several studies have measured the spring constant and evaluated its impact on machining [9], [19], [22]. According to Eq. (1), stiffness coefficient (K) is directly related to the force applied by the beam on the sample surface. An increased stiffness increases the applied force (F) and the deformation generated in the sample, as well as machinability of the process, and allows for machining of the harder materials [9].

$$F = Kx \tag{1}$$

Where, x is deflection of the beam. According to Eq. (2), an increased stiffness coefficient increases the natural frequency of the beam which, in turn, increases the nanomachining speed.

$$\omega = \sqrt{\frac{K}{m}} \tag{2}$$

In order to calculate the stiffness coefficient of different beam geometries, a known 10^{-4} N force was applied to the free end of the beam, and the displacement was determined through the finite element method. The spring constant was then calculated using Eq. (1).

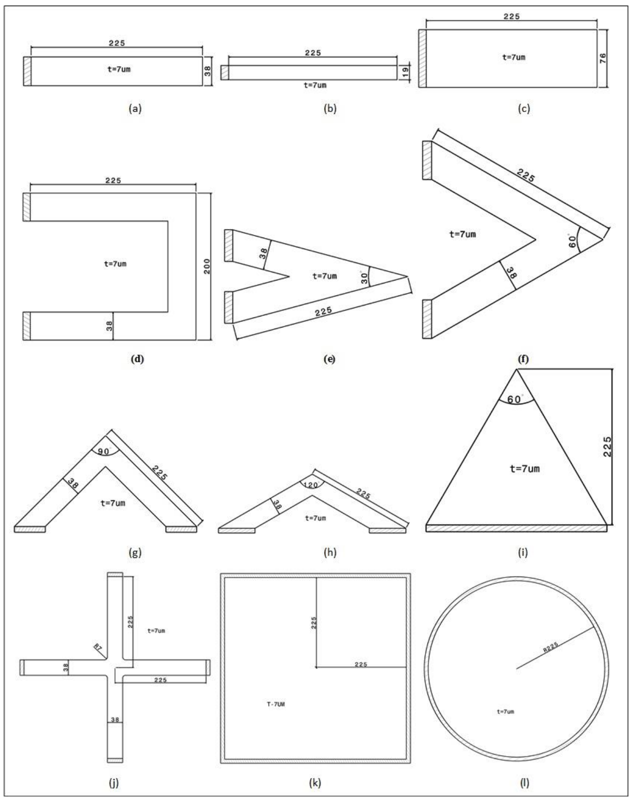

Fig. 1 The studied AFM cantilevers; straight cantilever (as base dimension): a, cantilever with half of the width of base cantilever: b, and twice the width of base cantilever: c, U-Shape cantilever: d, 30, 60, 90, and 120 degree V-Shape beams: e, f, g, and h, respectively, triangular beam: i, X-Shape beam: j, square membrane: k, and circular membrane: l

The results are presented in Fig. 2. The stiffness coefficient calculated for the straight beam with dimensions similar to the base dimensions was 36.11 N/m which is very close to the value reported by [7]. This validates the presented model in this research.

A comparison between the stiffness coefficients calculated for different beam geometries showed that the circular membrane has the highest stiffness coefficient. Further investigations showed that the beams that were constrained in more than one side have higher stiffness coefficients compared to those that were constrained in only one side. Therefore, they can be used to increase the stiffness coefficient of the vibrating beam and improve the machining efficiency. Among the beams constrained at one side, the 90° V-shaped beam geometry is the best geometry that has the highest stiffness coefficient. Another point observed in this study was that in straight beams, an increased beam width increases the stiffness coefficient and, consequently, the machining force.

However, it should be noted that increase in the stiffness coefficient reduces the sensitivity in sensing applications of the AFM cantilever because this would require higher interatomic forces to overcome the spring constant for maintaining optimal performance of the AFM in topography applications. Therefore, this issue should be noted in applications other than nanomachining.

As it can be seen in Fig. 2, the stiffness coefficient increases in the following order with beam shape: the straight beam with half-width of the base cantilever (b), straight cantilever (a), 30° V-shaped beam (e), straight beam with twice-width of the base cantilever (c), U-shape cantilever (d), 60° V-shaped beam (f), triangular beam (i), 120° V-shaped beam (h), 90° V-shaped beam (g), X-shaped beam (j), square membrane (k), and the circular membrane (l).

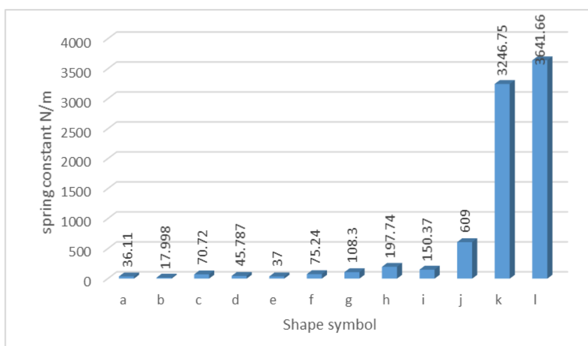

Fig. 2 The Stiffness coefficients calculated for different beam geometries

3.2. Resonant frequency

In order to improve efficiency in both machining and surface evaluation modes, the AFM beam must vibrate at its natural frequency. Considering the importance of this issue, several studies have been conducted on AFM beam vibration [11], [12], [18], [20]. In the present study, vibrational analysis of the AFM beam with various geometric shapes was performed using the finite element method and the natural frequency of the beams was determined. Results of this simulation including the first mode shape of the studied AFM beams are shown in Fig. 3. As previously mentioned, an increase in the natural frequency is desirable since it can increase the nanomachining speed.

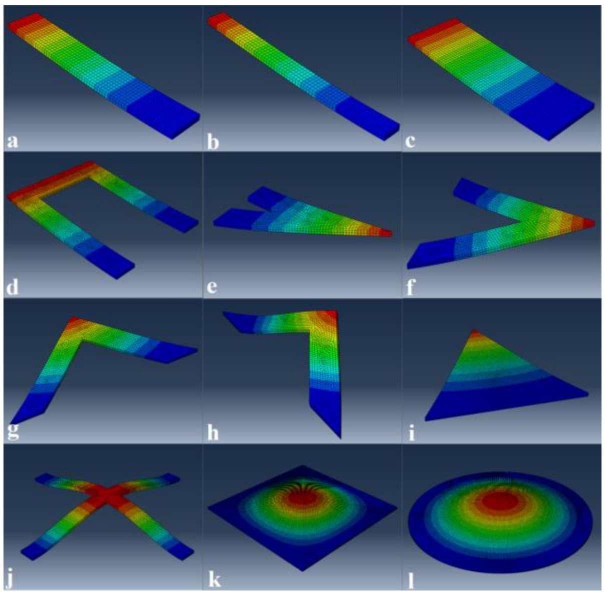

Fig. 3 First mode shape of the studied AFM beams

Figure 4 represents the natural frequency of the beams calculated for different geometric shapes. In straight beams, increasing width enhances the stiffness; however, it does not considerably affect the natural frequency. Unexpectedly, using two straight beams connected via a joint to form a U-shaped beam significantly reduces the natural frequency of the beam as a whole. It was observed that the circular membrane has the highest natural frequency. Among the beams constrained on one end (side), the 120° V-shaped beam has the highest frequency. It was observed that the natural frequency calculated for the base cantilever (base dimensions) is in a good agreement with the natural frequency computed by reference 7. This also shows the validity of the modeling performed in this research.

According to the Fig. 4, among the AFM beams, the circular membrane (l) has the highest natural frequency, followed by 120° V-shaped beam (h), square membrane (k), 90° V-shaped beam (g), 30° V-shaped beam (e), triangular beam (i), X-shaped beam (j), 60° V-shaped beam (f), straight beam with twice-width of the base cantilever (c), base cantilever (a), straight cantilever with half-width of the base cantilever (b), and U-shaped beam (d).

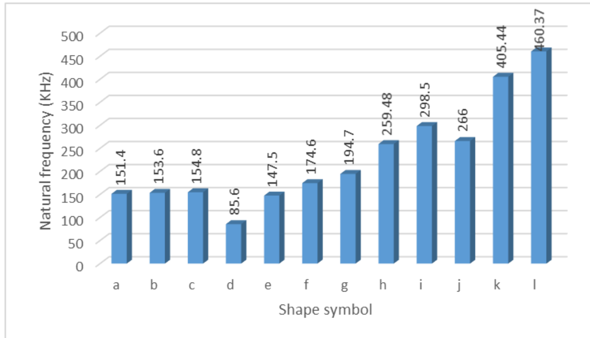

Fig. 4 The Natural frequency for different beam geometries.

3.3. Stability

Oscillators generally tend to vibrate around their natural frequency. However, in some cases, they may exit from their initial frequency mode and vibrate under undesirable conditions in other frequency modes. When beams vibrate at higher frequencies, the mode shape also changes, and the tip and the sample can be damaged. Therefore, in designing AFM beams, the second natural frequency is better than the first natural frequency.

To address this problem, the frequencies of the first and second resonance frequency modes were calculated using the finite element method. Then, ratio of natural frequency of the second mode to that of the first mode was obtained. As this ratio increased, stability of the AFM beam enhances.

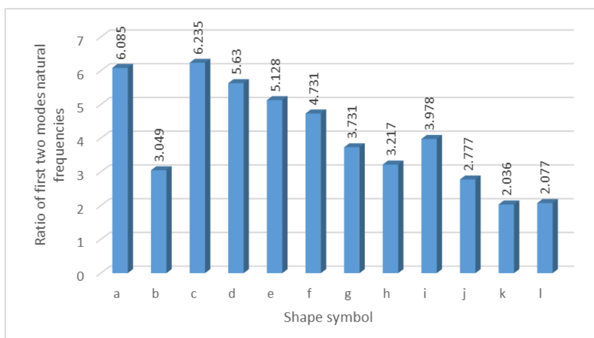

Fig. 5 Ratio of the second to first mode of the natural frequency for different beams.

Fig. 5 indicates ratio of the second to first mode of the natural frequency for different beams. It is observed that, in terms of stability, V-shaped beams are the best selection after the straight beams. Although square and circular membranes are better options considering stiffness coefficient and natural frequency, they have low stability. Therefore, they are not recommended for noisy environments. It was also observed that in straight beams, an increased width increases stability. As can be seen in Fig. 5, the straight beam with twice-width of the base cantilever (c) has the highest stability among the AFM beams, followed by the base cantilever (a), 60° V-shaped beam (f), 30° V-shaped beam (e), triangular beam(i), 90° V-shaped beam (g), 120° V-shaped beam (h), straight cantilever with half-width of the base cantilever (b), X-shaped beam (j), U-shaped beam (d), circular membrane (l) and square membrane (k).

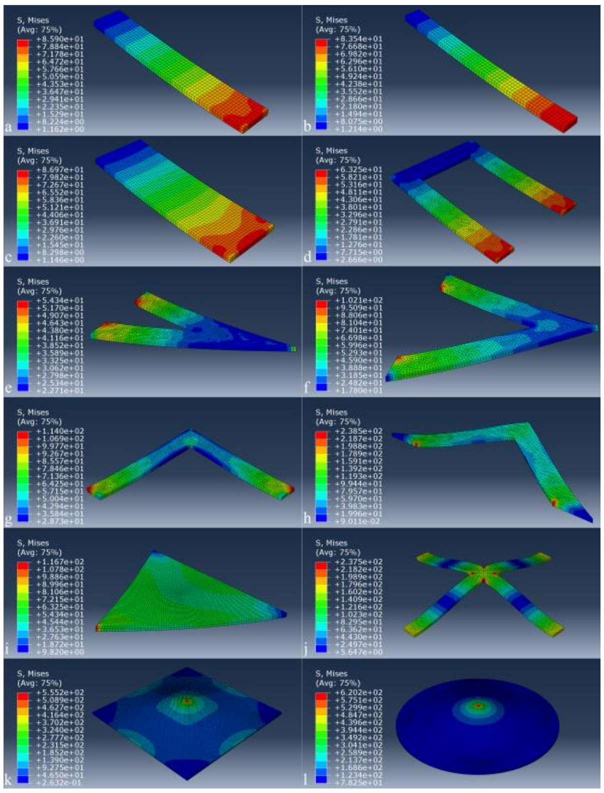

Fig. 6 The Von Mises stress induced in the studied AFM beams with different shapes

3.4. Von Mises Stress analysis

Oscillators in the atomic force microscope are set to a certain displacement amplitude. The displacement is in a way that it does not damage the beam; however, reducing the displacement excessively decreases the efficiency of AFM. At a certain tip displacement, lower maximum stress values are more desirable, because it increases the beam life, and the beam can be used in larger displacements. To measure this parameter, a fixed 5 µm displacement was applied to the free end of the beam (to the center of the X-shaped beam, square and circular membranes) and the maximum von Mises stress induced in the beam was calculated using the finite element method. Results of this simulation are shown in Fig. 6.

As it can be seen in Fig. 7, the circular membrane (l) has the highest maximum stress among the AFM beams, followed by the square membrane (k), 120° V-shaped beam (h), X-shaped beam (j), 90° V-shaped beam (g), 60° V-shaped beam (f), triangular beam (i), 30° V-shaped beam (e), U-shaped beam (d), straight beam with twice-width of the base cantilever (c), base cantilever (a) , straight cantilever with half-width of the base cantilever (b).

Therefore, the maximum and minimum stresses occurred in the circular membrane and straight cantilever with half-width of the base cantilever, respectively. As a result, the straight cantilever with half-width of the base cantilever is the best choice with regards to the beam life and the potential to be used in larger displacements.

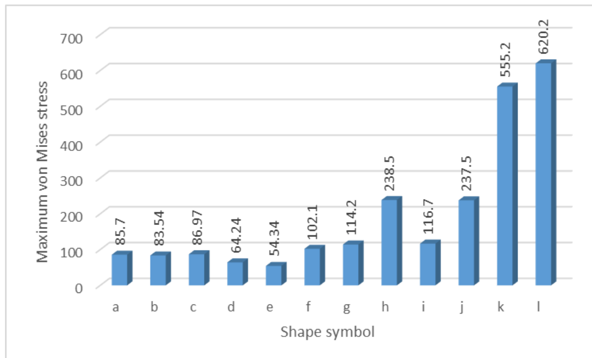

Fig. 7 Maximum von Mises stress induced in the studied beams for a constant displacement

7 CONCLUSION

In this paper, effect of the AFM beam geometry on the DPL nanomachining capabilities was analysed using the finite element method. The characteristics of stiffness coefficient, resonance frequency, stability, and maximum stress were investigated for 12 AFM cantilevers with different geometry shapes. This Analysis showed that the square and circular vibrating membranes are more suitable among the geometries constrained in the circumference, and 120° and 90° V-shaped beams among the beams fixed at one end with regards to stiffness and oscillation frequency. Using such geometries increases speed and efficiency of the DPL nanomachining. However, these oscillators are not desirable in terms of stability and maximum stress. Therefore, straight and V-shaped beams (rather than 120 and 90 degree) are recommended for the DPL nanomachining where unfavourable oscillations and noises exist. In straight beams, increasing the beam width improves nanomachining characteristics but decreases the beam life. In general, triangular beam is found to be more suitable for the DPL nanomachining applications considering the four parameters of stiffness coefficient, resonant frequency, stability, and maximum stress.

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