HILL PUBLISHING

Engineering Advances, 2023, 3(6), 483-487
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

Innovation and Development of Micro- and Nano-machining Technology in Mechanical Manufacturing

Yongfeng Gu*, **Qian Sun**, **Yang Liu**

School of Mechanical and Electrical Engineering, Qingdao City University, Qingdao, Shandong, China.

How to cite this paper: Yongfeng Gu, Qian Sun, Yang Liu. (2023) Innovation and Development of Micro- and Nano-machining Technology in Mechanical Manufacturing. *Engineering Advances*, 3(6), 483-487.
DOI: 10.26855/ea.2023.12.008

Received: November 30, 2023
Accepted: December 27, 2023
Published: January 19, 2024

***Corresponding author:** Yongfeng Gu, School of Mechanical and Electrical Engineering, Qingdao City University, Qingdao, Shandong, China.

Abstract

Based on the application research of micro and nano machining technology in mechanical manufacturing, a micro and nano machining device was built for the contact mode of AFM, and its maximum machining range and maximum normal load were increased to 50mm and 100uN. At the same time, custom trajectory machining and variable force control machining subroutines were written, and vibration assisted machining modules were integrated to improve the machining capability of the whole machine. On this basis, the working performance test and machining experiment of the whole machine are carried out. Finally, the machining experiment was carried out using micro - and nano-mechanical machining device. The function test of the custom trajectory machining and the variable force control machining subroutine was carried out to verify the reliability of the machining subroutine, and the influence of different process parameters on the machining results was analyzed based on the nano-corrugated structure with the machining cycle controllable by the variable force control method. Based on the vibration-assisted machining module, the auxiliary machining technology was studied to explore the advantages of auxiliary machining compared with conventional machining: large-scale micro-nano structure machining experiments were conducted to verify the large-scale composite machining capability of the machining device.

Keywords

Atomic force microscope, Nano-machining technology, Mechanical manufacturing, Custom trajectory, Composite machining

1. Introduction

As an instrument used to characterize the morphology and characteristics of samples, atomic force microscopy (AFM) has the advantages of high resolution, non-destructive samples, and diverse working environments. The atomic force between the tip of the probe and the measured sample is sensed by an atomic arm of the atomic force microscope, and the force is kept constant during the scanning process by controlling the expansion of the piezoelectric ceramics, and the morphology of the sample is detected in real-time according to the expansion of the piezoelectric ceramics. When the force is increased to produce plastic deformation of the sample or even material removal, nanomechanical machining similar to traditional machining can be achieved [1]. Compared with the mainstream nanomachine technology, the nanomachine technology based on AFM has the advantages of simple processing technology, a diverse processing environment, and wide range of processing materials. At the same time, it can achieve the removal of nano-scale materials that cannot be completed by micromachining technology. The processing characteristics of its force control can be used to process nano-structures with the same depth on inclined, curved, or even complex surfaces. It can be applied to the fields of superhydrophobic surface and optical property control. The working range is small, the normal force that can be applied is limited, the secondary development is difficult, and it is not suitable for machining. Therefore, it is necessary to develop the AFM for micro and nano machining [2], expand its maximum machining range and maximum normal load, write a custom trajectory machining and variable force control machining subroutine, integrate vibration-assisted machining module, and improve the machining capability of the whole machine.

2. Related work

Nanomechanical technology based on AFM probes has been successfully applied to the preparation of one-dimensional, two-dimensional, and three-dimensional nanostructures on both planar and non-planar surfaces. The nanochannel structure is a typical structure processed by AFM machining technology and can be used as a nanochannel to prepare nanofluidic chips [3]. The nanogroove structure can be obtained by single scribbling machining, which mainly includes static scribbling based on contact mode, dynamic scribbling based on tapping mode, assisted scribbling by z-vibration, and assisted scribbling by XY vibration. The researchers combined the MEMS process with AFM nanocrystalline technology and processed a 30um long, 20nm deep, and 200nm wide nanochannel on the surface of a MEMS silicon chip with microreservoir and electrode by static scribing [4] to prepare a nanofluidic device. The transverse friction generated in the static scribing process will cause the cantilever beam to twist and bend, leading to the deviation between the theoretical normal load and the actual normal load, and the larger transverse friction and normal load will also aggravate the wear of the probe. The researchers used dynamic engraving to process grooves at depths of 0 to 25nm on the PMMA surface, achieving smaller feature sizes than static engraving, while reducing transverse friction and probe wear. However, dynamic scratching based on tapping mode requires the cantilever beam to be operated near the resonant frequency [4], the processing mechanism is unclear, the structure size control is complicated, and the force between the probe and the sample in tapping mode is small, the processing efficiency and material removal rate are low, and the structure with greater depth cannot be obtained. This dynamic cutting mode can reduce the transverse friction and reduce the wear of the probe. Therefore, some scholars refer to ultrasonic vibration-assisted machining in traditional machining and put forward the vibration-assisted marking method [4]. The researchers carried out 3MH Z-direction ultrasonic vibration-assisted scratching on the surface of the aluminum and PMMA [5]. Compared with the static scratching method, the ultrasonic vibration-assisted scratching method has a high material removal rate, high machining depth, low friction force, and low probe wear, and the machining depth is mainly controlled by the vibration amplitude and the applied normal load. In addition, the vibration-assisted machining platform built [6] by the researchers can also carry out high-frequency vibration (10kHz) in the XY plane, processing principle, and processing results.

3. Development of micro and nano machining device based on AFM

3.1 Structural design of micro and nano machining device

3.1.1 Component selection of the overall structure

Before the mechanical design of the overall structure, it is necessary to select the various components according to the needs and determine the geometric size of each component. The components mainly include XYZ piezoelectric positioning platform, Z electric moving platform, XY large-scale precision moving platform, position sensitive detector, laser, optical lens, manual displacement platform optical adjustment frame, visual aid system, etc.

The XYZ piezoelectric positioning table is used to control the movement of the sample. It is also the core part of the force closed-loop control system, which should have a large stroke, a high resolution and a certain load capacity. The SPM3 three-dimensional piezoelectric positioning platform made by PIEZOCONCEPT [7] of France is selected, as shown in Figure 1. Piezoceramics and strain gauge displacement sensors are integrated inside the platform, which has the advantages of small size, high resolution, fast response speed and good stability. It has a maximum stroke of 75umX75umX50um, a closed-loop resolution of 0.05nm and a maximum horizontal load of 0.1kg.

3.2 Optical path design of micro-nano machining device

According to the force detection principle of the micro and nano machining device, the bending deformation of the cantilever is caused by the force of the probe tip, and the position of the spot on the PSD will be offset, and the offset is proportional to the cantilever deflection of the probe and the length of the reflected light path. The length of the reflected light path determines to a certain extent the maximum normal load that can be applied and the magnification of the bending amount of the probe suspension arm [8], so it is necessary to determine the appropriate reflected light path length before designing the mechanical structure. It shows the change of the reflected light path when the probe cantilever is bent and deformed. According to the geometric relationship in the figure, the offset of the light spot on the PSD can be approximated as equation (1).

$$\Delta \mathrm{z} \approx L \times 2\Delta\theta \tag{1}$$

Where, L is the length of the reflected light path, and $\Delta\theta$ is the bending Angle of the probe cantilever. Meanwhile, the calculation formula of the reflected light path length can be obtained as formula (2).

$$L \approx \mathrm{lk}\Delta z / 3F \tag{2}$$

4. Experiment and analysis

4.1 Experimental equipment and experimental samples

In this paper, a micro - and nanomechanical device has been built to process the nanostructures on the surface of the sample. In addition to the self-developed device [8], the following equipment and samples are also required; Atomic force microscope: Dimension Icon atomic force microscope produced by Bruker of Germany is selected. The maximum working range of the scanner is 80umX80um, and the three-dimensional morphology of nanostructures is detected by ScanAsyst intelligent imaging mode. Probe: RTESPA-52 and RTESPA-300 monocrystal silicon probes produced by Bruker [9] of Germany were selected. The cantilever elastic coefficient of the RTESPA-525 probe is about 200N/m, and the resonance frequency is about 525kHz. It is used for the processing of nanostructures in the established micro and nano machining device, and its tip shape is a quadrangular pyramid symmetrical along the long axis. The cantilever elastic coefficient of the RTESPA-300 probe is about 40N/m and the resonance frequency is about 300kHz. Rtespa-300 probe is used for three-dimensional morphology detection of nanostructures in ScanAsyst mode of Dimension Icon atomic force microscope.

4.2 Experimental research on custom trajectory machining

In this section, a custom trajectory machining subroutine of micro and nano machining devices is tested to verify the reliability of the machining subroutine. First of all, Matlab is used to generate and save the custom trajectory coordinate points to the text file, the processing subroutine reads the custom trajectory coordinate points in the text file and then machines the chrysanthemum, spiral, four-leaf clover, and spiral line shape patterns according to the custom trajectory. As shown in Figure 1, the geometric features of each pattern obtained by processing are clear, and the processing is well carried out in accordance with the predetermined trajectory.

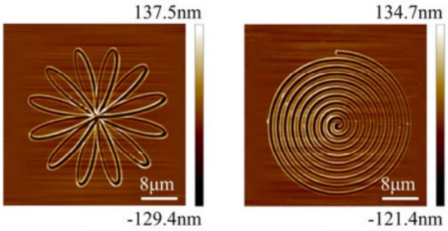


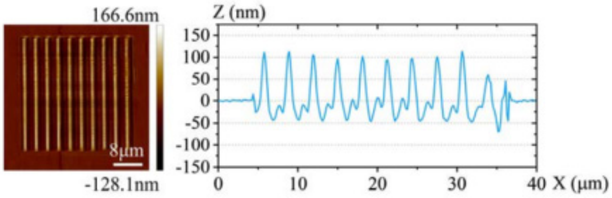
Figure 1. Special patterns.

4.3 Influence of the number of ripples on the nano-ripple structure

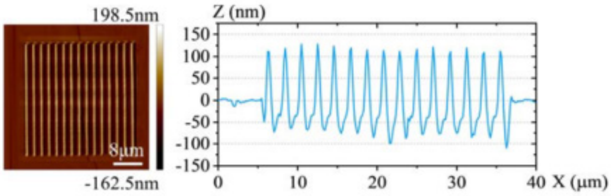
By changing the period of the applied variable load, the nano-ripple structure with a controllable number of ripples can be machined theoretically within the processing range of 30um. In order to verify the theoretical feasibility, nano-corrugated structures with different numbers of ripples were processed. The scanning line number, processing speed, minimum normal load, and maximum normal load were set to 20, 30um/s, 8.29uN, and 33.15uN respectively, and five groups of ripples with equal spacing from 10 to 30 were selected for the experiment.

Figure 2 shows the morphology and cross section of nanoripple structures processed with different number of ripples. As can be seen from the figure, the shape of the nanoripple structure is clear, there is no inclination and other phenomena, the period is consistent with the period of the applied variable load, and the number of ripples is completely controllable, which verifies the theoretical feasibility. However, when the number of ripples in the nano-corrugated structure is small, the quality of the corrugated structure is poor, and the cross-section does not conform to the characteristics of the sine curve, especially for the number of ripples is 10, forming a corrugated structure composed of two types of bumps. When the number of ripples increases to 20, the quality of the ripple structure is greatly improved, and the amplitude of each bump is consistent. The cross-section is fully in line with the characteristics of the sine curve. When the number of ripples increases further, the quality of the ripple structure decreases slightly. The amplitude consistency of each bump becomes slightly worse, and the cross-section diagram conforms to the characteristics of sine curve.

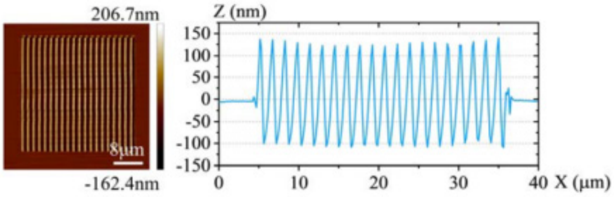
The morphology and cross-section of nanoripple structures processed under different maximum normal loads show that the amplitude of the ripple structure increases with the increase of the maximum normal load, which is because the increase of normal load will push the tip of the probe deeper into the surface of the PC sample during processing. When the tip of the probe begins to scratch, more materials will be removed from the surface of the sample, resulting in deeper troughs. At the same time, more material is deposited in front of the probe, resulting in a higher wave crest, resulting in an increase in the amplitude of the ripple structure. Among them, the nanoripple structure processed with a maximum normal load of 33.15uN has the best amplitude consistency, as shown in Figure 3.



a) Surface morphology and cross section of the sample after processing with the maximum normal load of 24.86uN



b) Surface morphology and cross section of the sample after processing with maximum normal load of 41.44uN



c) Surface morphology and cross section of the sample after processing with maximum normal load 58.02uN

Figure 2. Morphology and cross section of nanoripple structures processed under different maximum normal loads.

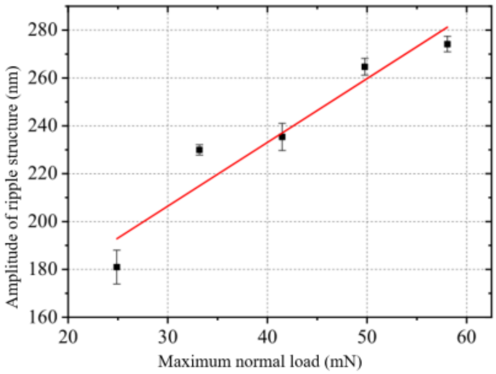


Figure 3. Influence of maximum normal load on the amplitude of corrugated structure

5. Conclusion

In the experiment of variable force control machining, the corrugated nanostructures were machined by combining the high viscoelastic material induction property of PC with the variable force control method. The nano-corrugated structure with a controllable number of ripples was obtained by changing the period of variable load applied by the pass size. The shape is green and there is no tilt. The section diagram conforms to the characteristics of the sinusoidal curve. With the increase of normal load, the tip of the probe is pressed deeper into the surface of the PC sample during processing, and more materials are stripped from the surface of the sample, resulting in more material accumulation, resulting in an increase in the amplitude of the corrugated structure: the larger the processing speed, the larger the dynamic stiffness of the probe, the smaller the tilt degree of the tip under the same force, and the smaller negative front Angle of the cutting edge. The more easily the tip of the probe is pressed into the surface of the PC sample, the more material is stripped off the surface of the sample, resulting in more material accumulation, resulting in an increase in the amplitude of the ripple structure.

References

[1] Geng Y, Yan Y, Wang J, et al. Fabrication of Periodic Nanostructures Using AFM Tip-Based Nanomachining: Combining Groove and Material Pile-Up Topographies [J]. Engineering, 2018, 4(6): 787-795.

[2] Deng J, Dong J, & Cohen P H. Development and Characterization of Ultrasonic Vibration Assisted Nanomachining Process for Three-Dimensional Nanofabrication [J]. IEEE Transactions on Nanotechnology, 2018, 17(3): 559-566.

[3] Geng Y, Wang Y, Yan Y, et al. A Novel AFM-Based 5-Axis Nanoscale Machine Tool for Fabrication of Nanostructures on A Micro Ball [J]. Review of Scientific Instruments, 2017, 88(11): 115109.

[4] Adams J D, Nievergelt A, Erickson B W, et al. High-speed Imaging Upgrade for A Standard Sample Scanning Atomic Force Microscope Using Small Cantilevers [J]. Review of Scientific Instruments, 2014, 85(9): 093702.

[5] Dukic M, Adams J D, & Fantner G E. Piezoresistive AFM Cantilevers Surpassing Standard Optical Beam Deflection in Low Noise Topography Imaging [J]. Scientific Reports, 2015, 5: 16393.

[6] An S, Jhe W. Nanopipette/Nanorod-Combined Quartz Tuning Fork-Atomic Force Microscope [J]. Sensors, 2019, 19(8): 1794.

[7] Kreith J, Strunz T, Fantner E J, et al. A Versatile Atomic Force Microscope Integrated with A Scanning Electron Microscope [J]. Review of Scientific Instruments, 2017, 88(5): 053704.

[8] Ge Weikun. Brief introduction of "Research Practice Base" of Ye Qisun Class of Physics Department of Tsinghua University [J]. Physics and Engineering, 2019, 30(01):23-25.

[9] Huang Jiaxu, Li Jun, Qiu Pei et al. Laser-Induced Two-Dimensional Patterning of Thin Film Materials [J/OL]. Acta Photonica Sinica, 1-8 [2023-12-07].

[10] Guo Xu. Research and Application of Nanopatterning Technology [D]. Nanjing University, 2015.

DOI: 10.26855/ea.2023.12.008