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Development of a novel vibration-assisted ultraprecision cutting system for fabricating hierarchical micro/nanostructures

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Micro/nanostructures can afford unique functions in the electrical, optical, mechanical, and thermal properties, which have attracted more and more interest in recent years. The common machining methods, such as photolithography and laser ablation, face the drawbacks of high machining cost and low machining quality. To solve these problems, a novel vibration-assisted ultraprecision cutting system is proposed to fabricate the micro/nanostructures in this study. Firstly, a mechanical structure of this cutting system was designed. Then, a finite element model was established to evaluate the working performance of the developed cutting system. Next, a test platform of the working performance was built to identify the bandwidth of the developed cutting system. Finally, a preliminary machining experiment was performed. The hierarchical micro/nanostructures with the high aspect ratio were successfully machined on workpiece surfaces, demonstrating the effectiveness of the developed cutting system. This study provides a highly efficient cutting system, which can be directly applied in the machining industries.

NOMENCLATURE

l_1 = whole length of the mechanical structure
l_2= whole length of the inner mechanical structure
w= whole width of the mechanical structure
h= whole height of the mechanical structure
r= radius of the hinge
n= the number of the level of the micro/nanostructure

1. Introduction

Micro/nanostructured surfaces with various functions are drawing increasing interest because of their outstanding performance in a range of modern industries. For example, the micro-dimple surface can decrease the friction as much as 80% in comparison with untextured surfaces [1]. The heat transfer is dramatically enhanced by using the micro-channel in the heat exchangers [2]. Although the micro/nanostructured surfaces have excellent functions, how to machine these micro/nanostructured surfaces with low cost and high efficiency faces many challenges. Lithography is commonly applied to create micro/nanostructures, but it has the drawbacks of low efficiency and high machining cost [3]. Laser ablation is another process to machine micro/nanostructure on different engineering materials, but its surface quality is not high [4].

To solve these problems, the vibration-assisted machining technique based on the vibration of the cutting tool was developed, which has been a promising method for improving machining efficiency and surface quality. In recent years, many researchers have designed different cutting systems based on this technique. Kim et al. [5] designed a long-stroke cutting system to machine the optical freeform mirrors with a form accuracy of 0.15μm in peak-to-valley value error. Zhu et al. [6] developed the decoupled two-degree-of-freedom flexural mechanism using the Z-shaped flexure hinge. Du et al developed [7] a high-bandwidth vibration-assisted cutting system with high output stiffness. However, there is very limited knowledge available in the existing research database on the machining of the hierarchical micro/nanostructures with the high aspect ratio.

In this study, a novel vibration-assisted ultraprecision cutting (VAUC) system is developed to machine hierarchical micro/nanostructures with the high aspect ratio. Firstly, the mechanical structure of the VAUC system was introduced based on the circular-type flexure hinge. Subsequently, a finite element method was conducted to simulate its working performance. In order to more precisely evaluate the bandwidth of the VAUC system, a test plat was established. Finally, a preliminary machining experiment was performed to verify the cutting system's capability for machining the hierarchical micro/nanostructures.

2. Mechanical Design

Normally, the natural signal-crystal diamond insert always has an arc-shaped cutting edge, as shown in Fig. 1(a), which has nearly no chance to machine the high aspect ratio micro/nanostructures. But the single-crystal diamond facet tool has the straight-line cutting edge, as shown in Fig. 1(b), which offers the possibility of machining this kind of micro/nanostructures.

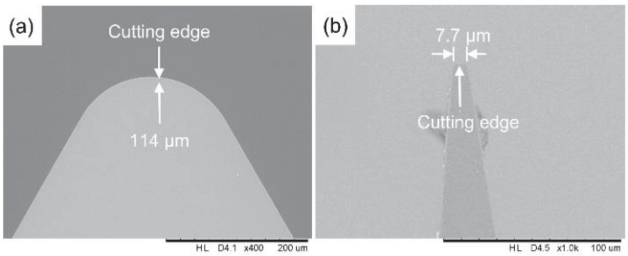

Fig. 1 Scanning electron microscopy images of the tooltip of (a) the insert, and (b) the facet tool

There are many flexible hinges to transfer the vibration motion of the piezoelectrical actuator (PEA) into the cutting tool, such as circular-type, corner-type, and elliptical-type. Considering the convenience of the electrical discharge machining, the circular type was chosen to transfer the motion of the PEA. Besides, the whole mechanical structure of the VAUC system adopts a symmetrical layout to improve the stability. As shown in Fig. 2, the facet tool, PEA, and the supporting block are located in the centreline of the mechanical structure to decrease the displacement disturbance along the cutting direction. The single-crystal diamond facet tool is fixed to the mechanical structure via the fixing bolt. The preload bolt is used to adjust the preload force of the PEA. The key parameters are listed in Table 1**Error! Reference source not found.**.

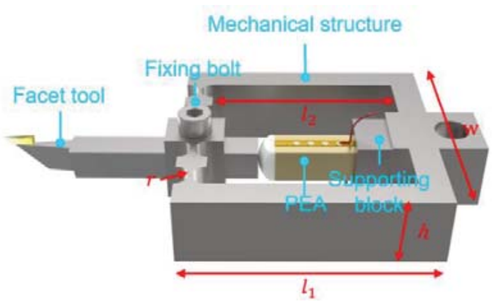

Fig. 2 Mechanical structure of the VAUC system

Table 1 Key parameters of the mechanical structure of the VAUC system

l_1	l_2	w	b	r
52 mm	40 mm	14 mm	50 mm	2.75 mm

The working performance, such as working frequency, directly determines the machining efficiency of the VAUC system. In general, the higher the working frequency, the higher the machining efficiency. A finite element model was established using the commercial software (ANSYS 19.0), as shown in Fig. 3. It aims to preliminary investigate the first two order resonant-frequency and first two order mode-shape. It can be found that the first-order resonant frequency is 1583.6 Hz. The first two order mode shapes are along the X-axis direction and Y-axis direction, respectively.

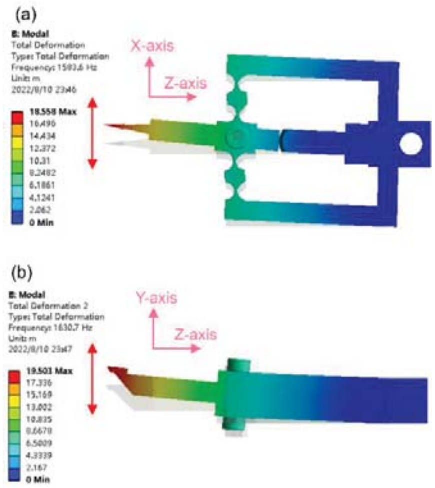

Fig. 3 First two order mode shape of the VAUC system

3. Test Platform of Working Performance

In order to obtain the real values of the maximal working frequency, a test platform of working performance was established, as shown in Fig. 4. This test platform contains a personal computer, a multifunction I/O device, and a high-performance piezo amplifier, and a capacitive displacement sensor. The personal computer offers the user interfaces and generates the digital signals by a graphical programming software, LabVIEW, and then the digital signals are converted into analog signals by the multifunction I/O device (NI DAQ USB-6341). The high-performance piezo amplifier (PI E617.001) is used to amplify these analog signals. The amplified voltage signals are inputted into the PEA (P-880.51, Polytec PI, Inc., Germany) to drive the VAUC system. The displacement of the facet tool along the X-axis direction can be precisely measured by the capacitive displacement sensor with peak-to-peak resolution of 58.17 nm (Elite, Lion Precision) and recorded by software LabVIEW at a sampling rate of 200 kHz. Besides, LabVIEW's user interface has the capability of observing and monitoring the frequency response in real-time to adjust the time of stopping the test. The sinusoidal excitation signal with the amplitude of 5V was applied to the PEA and the frequency was swept from 0 Hz to 3 Khz with a step size of 10 Hz. To efficiently reduce the external disturbance, the testing platform was carried out on a commercial anti-vibration table with air-bearing supports.

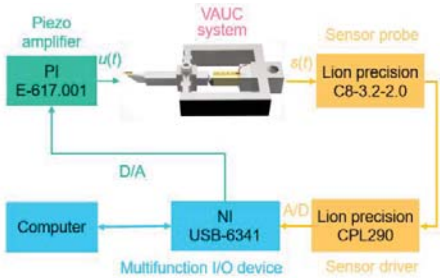

Fig. 4 Test platform of the working performance of the VAUC system

4. Experimental Setup

To demonstrate the effectiveness of the VAUC system for machining hierarchical micro/nanostructures with the high aspect ratio, the machining experiment was performed on the four-axis ultraprecision lathe (Moore Nanotech 350FG, USA). Basically, the developed VAUC system was fixed on the micro height adjust tool holder and the workpiece (the pure copper) was fixed on a fixture mounting on the spindle of the ultraprecision machine through the vacuum chuck, as shown in Fig. 5. The natural single-crystal facet tool with a nose width of 7.7 μm (Contour Fine Tooling Inc., UK) was selected for this kind of micro/nanostructures, and its included angle, clearance angle, and rake face angle are 15°, 5°, and 0°, respectively.

Before the machining of hierarchical micro/nanostructures, the workpiece was firstly rough turning with a spindle speed of 1500 rpm, and the depth-of-cutting and feed rate were set as 10 μm and 10 mm/min for the flatting, respectively. Subsequently, a finish turning with a spindle speed, depth-of-cutting, and federate of 1500 rpm, 2 μm and 4 mm/min were conducted to obtain the mirror surface.

In the machining experiments, the cutting velocity is 77.1 mm/min. The working frequency and working voltage are set as 500 Hz and 13 V. The computer provides the command signals. Then they can be converted into analogue signals by the multifunction I/O device and amplified by the high-performance piezo amplifier to drive the developed VAUC system.

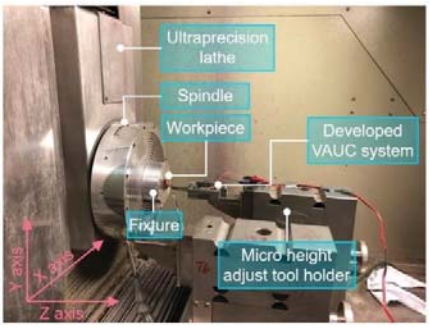

Fig. 5 Experimental setup of the micro/nanostructure machining

5. Results and Discussion

5.1 Characterization of Working Performance

The test result of the displacement response versus frequency is plotted in Fig.6. It can be found that the first order resonant frequency for the VAUC system is 1510 Hz. Before the first order resonance occurs, the displacements along the cutting direction are very stable and the corresponding working frequency range is from 0 Hz~1200 Hz, which is called the working area of the cutting system. The bandwidth, as the important index of the working performance, can be identified to be 1200 Hz.

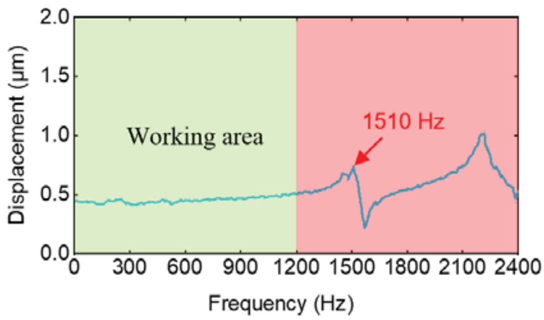

Fig. 6 Test result of the working performance

5.2 Characterization of Micro/nanostructured Surfaces

After machining, a white light interferometer with nanometre resolution (NexviewTM, Zygo Corp.) was used to characterize the three-dimensional surface topography of the hierarchical micro/nanostructures. It can be found that the hierarchical micro/nanostructures with high aspect ratio were successfully machined on the workpiece surface.

The number (n) can be used to define the number of the layer. For n=0, there are not any micro/nanostructures on the workpiece surface. n=1 presents that the micro/nanostructure has one layer. In this preliminary machining experiment, the two layers were generated on the workpiece surface, as shown in Fig.7. The first layer is the micro-groove with a high aspect ratio. More important, it has a right-angle cross-sectional profile, which cannot be realized by the common diamond insert. The second layer is the sinusoidal-shaped nanostructure with a height of 265 nm and a spacing of 2.7 μm, which demonstrates the effectiveness of the developed VAUC system.

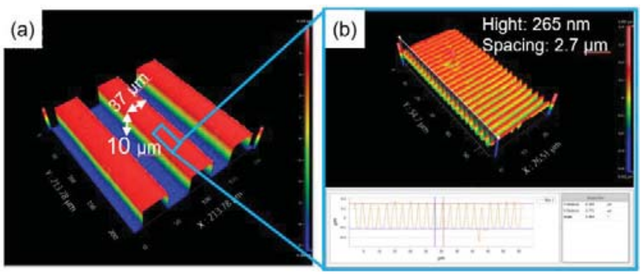

Fig. 7 Surface topography of the hierarchical micro/nanostructures

5. Conclusion

This study developed a novel vibration-assisted ultraprecision cutting (VAUC) system to machine hierarchical micro/nanostructures with the high aspect ratio. The main conclusions of this study are drawn as follows:

1) The mechanical structure of the VAUC system was designed based on the circular-type flexible hinge. The whole layout was symmetrical. A finite element model was established to simulate its mode. The results show that the first two order mode shapes are along the X-axis direction and Y-axis direction.

2) A test platform was established to evaluate its working performance. The test result shows that its bandwidth is 1200 Hz. It is a very higher bandwidth, which means that the developed VAUC system has a higher machining efficiency.

3) A preliminary machining experiment was conducted. Two-layer micro/nanostructures with a high aspect ratio were successfully machined on the workpiece surface, demonstrating the effectiveness of the developed VAUC system.

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