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TECHNICAL PAPER

Development of a new meso-scale machine tool for fabricating micro V-grooves

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Abstract This work presents the development of a meso-scale machine tool with a nanometer resolution. The newly developed meso-scale machine tool consists of a pagoda structure for Z-axis, four HR8 ultrasonic motors, three linear encoders with a resolution of 2 nm, a coaxial counter-balance system, a XY coplanar positioning stage, a rotary stage, a Galil 4-axis motion control card, an industrial PC and a CCD camera system. The optimal geometrical dimensions of the pagoda structure have been determined by ANSYS software. The designed meso-scale machine tool is equipped with an X–Y coplanar positioning stage with nanometer resolution. The coplanar stage developed by National Taiwan University was integrated with two linear encoders, so that a two-axis closed-loop control was possible. A circular positioning test with the radius of 1 mm using the developed stage was tested, and the overall circular positioning error was about 83 nm based on the test results. The micro V-grooves and the micro pyramid cutting tests of the polished oxygen free copper using a single crystal diamond tool on the developed meso-scale machine tool have been performed. The cutting tests under various combination of the depth of cut and cutting speed have been carried out. It revealed that the cutting speed had no great influence on the cutting force. The measured cutting forces for the depth of cut of 5, 10, 15 μm were 1.2, 1.6 and 2.4 N, respectively. The results showed the meso-scale machining tool can be used in micro pyramid structures manufacturing.

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1 Introduction

Industrial demands on the micro-mechanical parts, such as digital cameras, mobile phones, sensors, and actuators etc., have been greatly increased in the past decade (Dornfeld et al. 2006). The precision manufacturing processes could be applied to fabricate microstructures with 3D complex shapes or freeform surfaces (Kong and Cheung 2012). As a result, more and more researches focus on high precision machine tool design and manufacturing, such as ultra-precision turning machine (Thompson et al. 1982), precision grinding machine (Kim et al. 1997), and micro-milling machine (Dornfeld et al. 2006). Performing the design of a precision machine, four major subsystems have to consider, including the mechanical structure analysis, the driver system, the spindle system and the control system. The ultra-precision machine tools structure design and analysis have been discussed in (Luo et al. 2005). Regarding diamond tool machining, Lee et al. (2004) used diamond tool to fabricate the V-groove on an optical fiber connector using a miniaturized machine tool. Yan et al. (2009) used single crystal diamond tool for machining V-groove on an electroless-plated Nip surface and used as molds for hot-press glass, and also using finite element method simulation to make sure the experiment result. (Kim and Loh 2007) discussed the new method using a single crystal diamond tool to manufacture micro V-groove, in which two piezoelectric actuators were integrated to generate an ultrasonic elliptical vibration cutting device to reduce the burrs formation and reduce the cutting force.

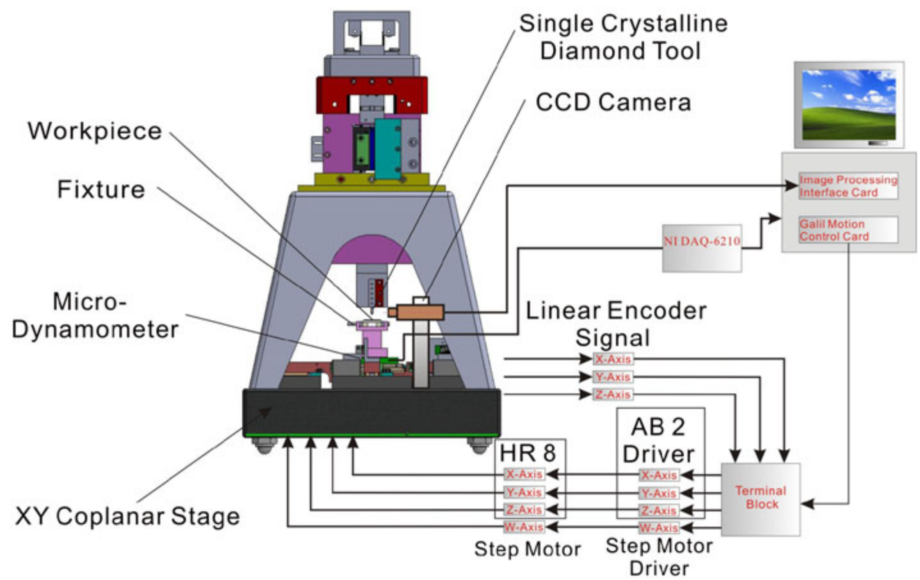

Fig. 1 Schematic of the meso-scale machine tool and its control system

The development of an economic meso-scale machine tool with a nanometer resolution is to be introduced in this paper. Moreover, the applications of the developed meso-scale machine tool to manufacture the micro V-grooves on a polished oxygen-free high conductivity copper (OFHC) material using the single crystal diamond tool are to be discussed. The cutting forces under different cutting speed and depth of cut have also been investigated.

2 Design and analysis of the meso-scale machine tool

The conceptual design of a meso-scale machine tool, including a pagoda structure, four HR8 ultrasonic motors (Nanomotion, Israel), three linear encoders with a resolution of 2 nm (Renishaw Ltd., UK), a coaxial counter-balance system, XY coplanar positioning stage, a rotary stage mounted on the XY coplanar stage, a Galil 4-axis motion control card (Galil Motion Control, USA), an industrial personal computer (PC) and a charge-coupled device (CCD) camera system (The Imaging Source Ltd., Germany) is shown in Fig. 1. Table 1 shows the specification of the designed meso-scale machine tool.

Table 1 Specification of the developed machine tool

Machine size (LWH)	500 × 500 × 600 mm
Working range (XYZ)	25 × 25 × 10 mm
Drive system	Ultrasonic motor
Maximum speed	6.8 mm/s
Resolution	2 nm

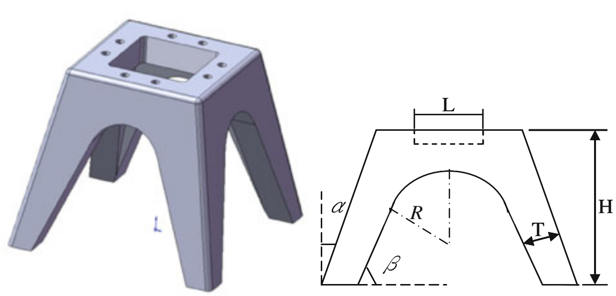

Fig. 2 CAD model of the pagoda structure and its design parameter

2.1 Z-axis design and analysis

Considering the design of the structure of meso-scale machine tool, the rigidity of the Z-axis must be taken into account to endure the weight of the spindle system. According to the former design of several different shapes of the machine tool structure, and using ANSYS (ANSYS Inc., USA) finite element analysis software to analyze the best machine structure, the result of the pagoda-type structure was the most stable one (Fan et al. 2007). Considering the previous pagoda-type structure design was designed for micro measurement machine tool, therefore this work follows previous design, and makes some design improvement to clamp and integrate the new Z-axis for the

Table 2 Optimal geometrical dimensions of the pagoda structure

Design parameter	Dimension
R	90 mm
β	78°
T	50 mm
H	430 mm
L	130 mm

micro v-groove shaping machine tool. The optimal geometrical dimensions of the pagoda structure have been determined by ANSYS software. Figure 2 shows the new design of the granite pagoda structure for Z-axis. The optimal geometrical dimensions of the newly designed pagoda structure parameters are listed in Table 2. According to the simulation results, the maximum static deformation along the z-axis of the pagoda, under the weight of 17.5 kg, was about 5.05 nm, as shown in Fig. 3.

2.2 Design of diamond tool clamp and driving mechanism in Z-axis

There are four main parts in the design of diamond tool clamp and driving mechanism, including the counterbalance system, linear encoder, ultrasonic motor, and diamond tool clamp, as shown in Fig. 4. The design of the diamond tool clamp and driving mechanism consists of two ultrasonic motors to drive the tool clamp with a seesaw motion.

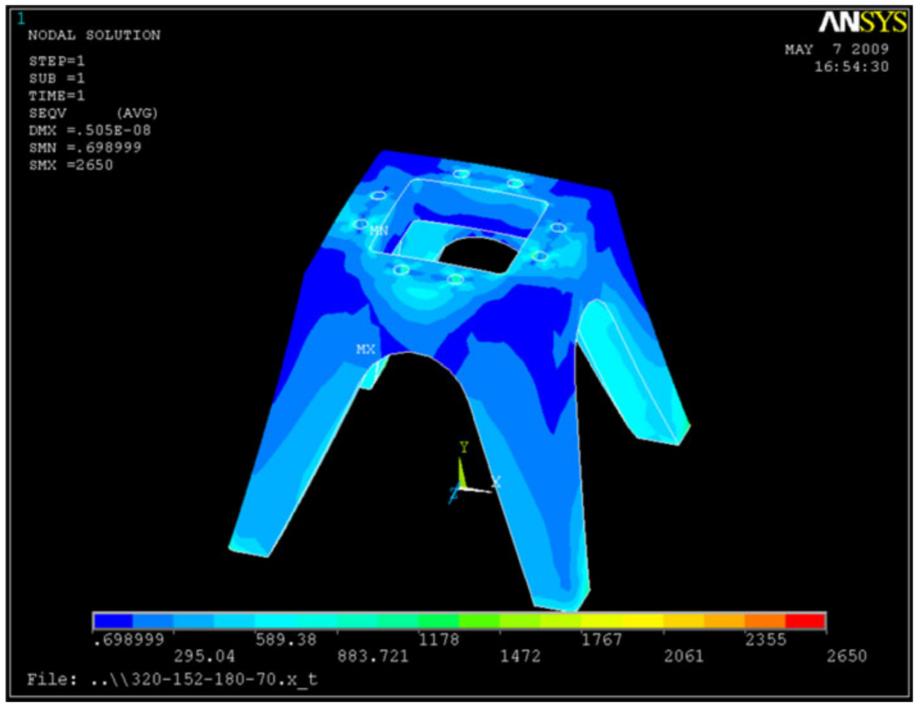

Fig. 3 The maximum displacement of the pagoda structure analyzed by the ANSYS software

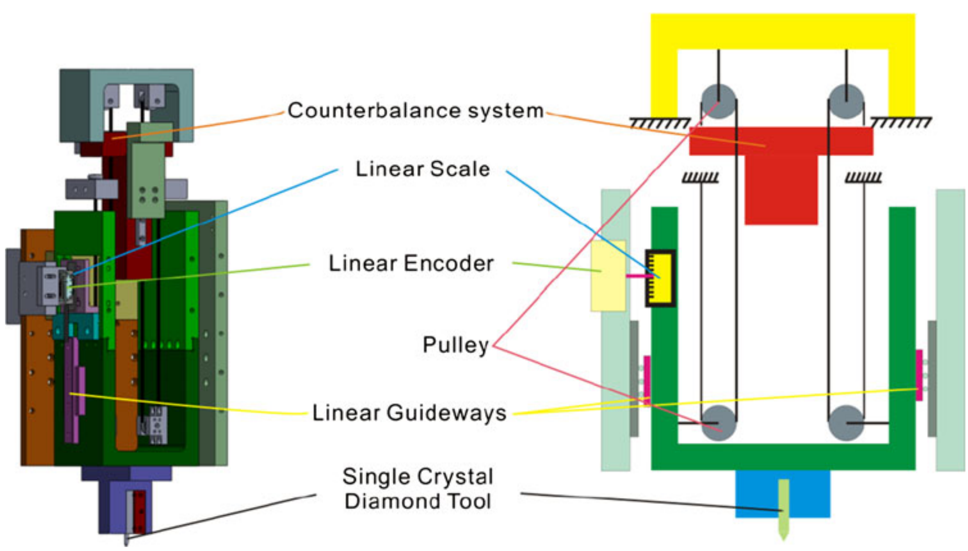

Fig. 4 The Z-axis structure and its driving mechanism

Furthermore, a set of linear encoder with a resolution of 2 nm is used as displacement feedback sensor for the movement of Z-axis, so that the execution of the close loop control is possible.

2.3 XY coplanar positioning stage design

The coplanar stage developed by Nation Taiwan University was integrated with two linear encoders as the displacement feedback sensors. Two HR8 ultrasonic motors are used as actuators, and eight linear guides are used to perform the coplanar movement without Abbe's error (Abbe 1887). The design of the XY-coplanar stage is shown in Fig. 5 and the assembled coplanar stage is shown in Fig. 6.

2.4 System integration and test results

The newly developed meso-scale machine tool was assembled with a pagoda structure for the Z-axis, four HR8 ultrasonic motors, three linear encoders with a resolution of 2 nm, a coaxial counter-balance system, a XY coplanar positioning stage, a Galil 4-axis motion control card, a rotary stage, an industrial PC and a CCD camera system, is shown in Fig. 7. A micro dynamometer has been integrated with the developed machine tool to measure the cutting force. With regard to the positioning accuracy of the used XY coplanar positioning stage, the laser interferometer system (SIOS MI-5000, SIOS Technology Inc., Germany) has been used to measure the circular positioning test with the diameter of 1.000 mm of the XY coplanar positioning stage. The XY stage was driven by two HR8 ultrasonic motors using a circular step by step command and two laser interferometer systems were set on the X-axis and Y-axis, respectively, as shown in Fig. 8. According to the test result, the roundness error of the circular positioning test was about 83 nm, as shown in Fig. 9. A CCD camera system has been integrated with the developed machine tool to monitor the positioning of the diamond tool tip along the Z-axis and to inspect the wear of the tool tip, as shown in Fig. 10.

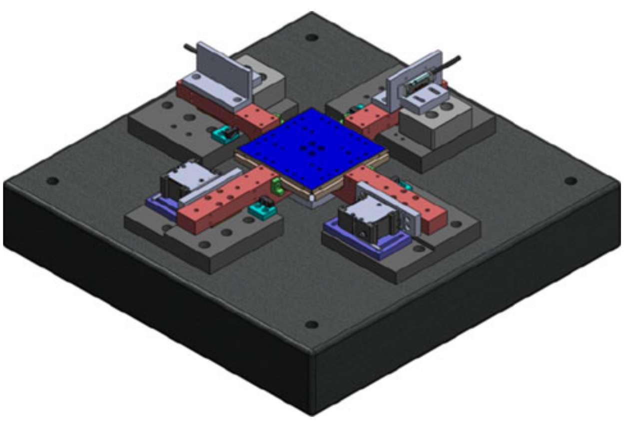

Fig. 5 Design of the XY-coplanar stage

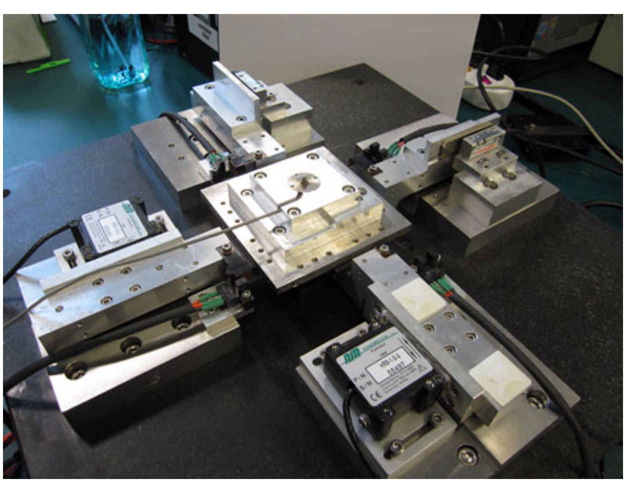

Fig. 6 Photo of the assembled XY-coplanar stage

Fig. 7 Photo of the developed meso-scale machine tool

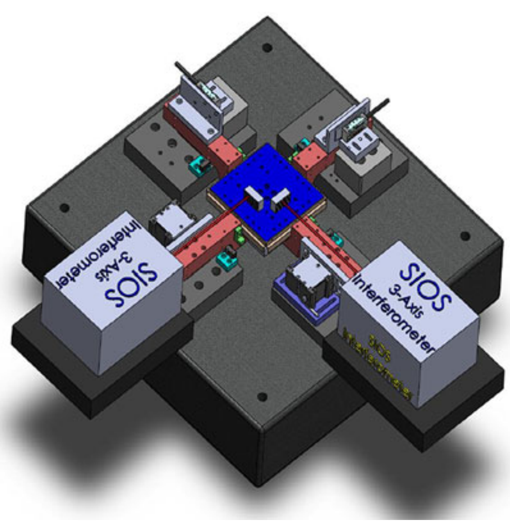

Fig. 8 Measurement setup for the circular positioning error test

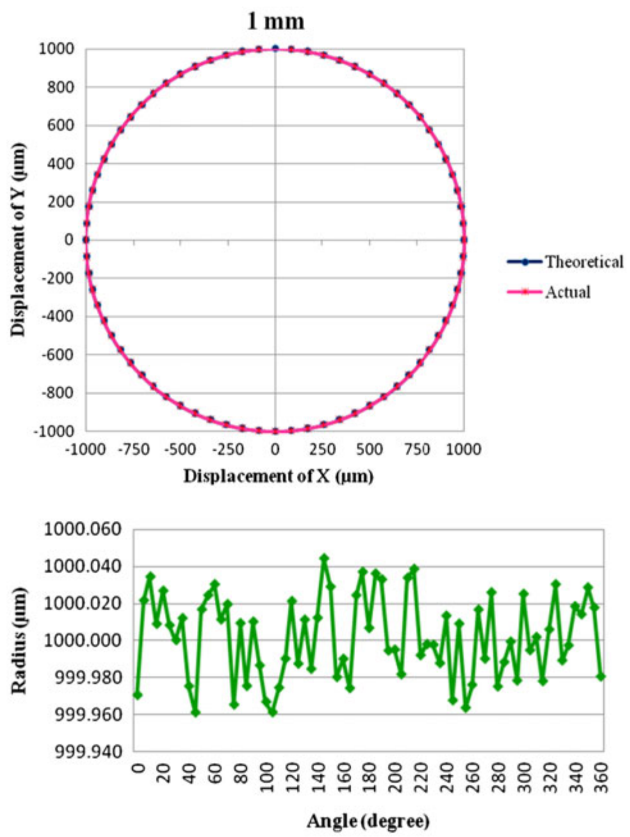

Fig. 9 Circular positioning test results with the radius of 1.000 mm

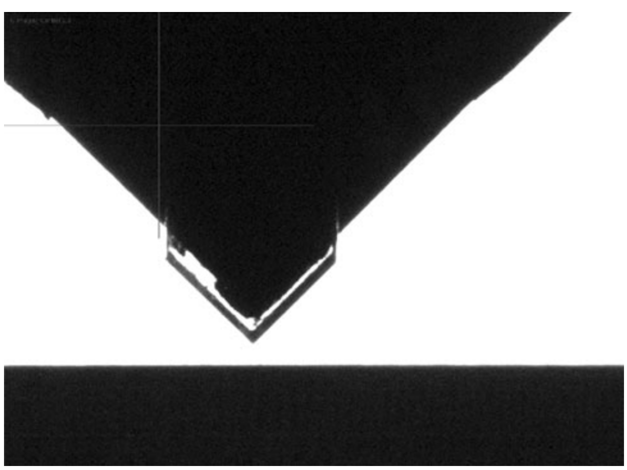

Fig. 10 Monitoring of the single crystal diamond tool tip using a CCD camera

3 Experimental setup

3.1 Design of the single crystal diamond tool

Some preliminary cutting tests on the different materials, such as alumina (AL 2024 and AL 5052), OFHC copper and bulk metallic glass (BMG) using different polycrystalline diamond tools on the developed machine tool have been investigated in (Shiou et al. 2012). A single crystal diamond tool has been used in this study to carry out the shaping tests on the polished OFHC. The designed geometry and the specification of the used single diamond tool are shown in Fig. 11; Table 3, respectively. Figure 12 shows the fabricated single crystal diamond tool, observed by a toolmaker microscope, made by Lu Sung Diamond Industrial Co. Ltd in Taiwan.

3.2 Preparation of the oxygen-free high conductivity copper

The OFHC copper was selected for the cutting test in this study. After doing the milling and grinding preprocess, the material has been polished to improve the flatness and surface roughness, as shown in Fig. 13. After polishing process, the measured mean surface roughness of the specimen was Ra 0.02 μm.

3.3 Experimental parameters

The experimental setup for machining the micro V-grooves using a single crystal diamond tool on the developed meso-scale machine tool is shown in Fig. 1. Three shaping parameters, namely the depth of cut, the pitch, and the feed rate, have been investigated in this study. The configured paths for the experiments were driven by a Galil 4-axis motion control interface card to drive ultrasonic motors of the XY co-planar stage. After conducting the micro machining experiments, the structures of grooves were observed by an optical microscope. Figure 14 shows the photo of the cutting test using a single crystal diamond tool.

The selected primary cutting parameters for shaping the micro V-grooves were the feed rate and the depth of cut. The feed rate was configured as 1.5, 3.0, 4.5 and 6.0 mm/s, respectively. The depth of cut was configured as 5, 10 and 15 μm, respectively. The shaping travel was 5.0 mm. The induced cutting forces were measured by a micro dynamometer.

In this study, a rotary stage was integrated with XY co-planner stage as shown in Fig. 15. To manufacture the micro pyramid structures, the workpiece was clamped by a modular fixture mounted on the rotary stage, the workpiece was rotated by a PC-based controlled rotary stage to decrease the positioning error. Regarding the cutting tests of micro pyramids, the depth of cut and feed rate were set as 10 μm and 1.0 mm/s, respectively. The cutting pitch was set as 28.2 μm based on the calculation. After the cutting test, a scanning electron microscope (SEM) was used to inspect the micro pyramid structures.

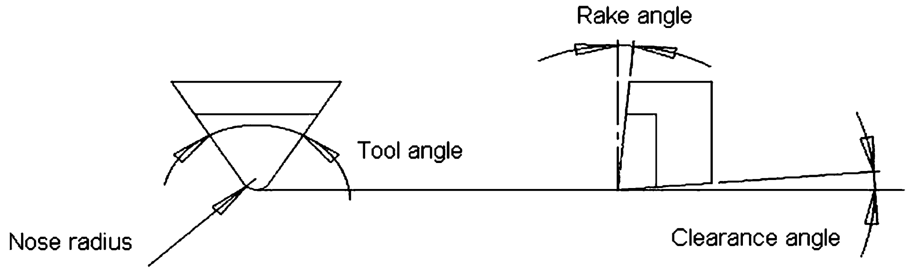

Fig. 11 Schematic of the single crystal diamond tool

Table 3 Specifications of the single crystal diamond tool

Tool angle	90°
Rake angle	0°
Clearance angle	5°
Nose radius	10 μm

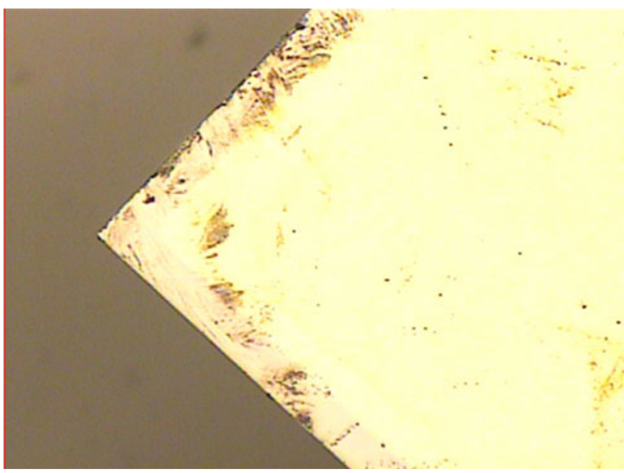

Fig. 12 The microscope photograph of the used single crystal diamond tool

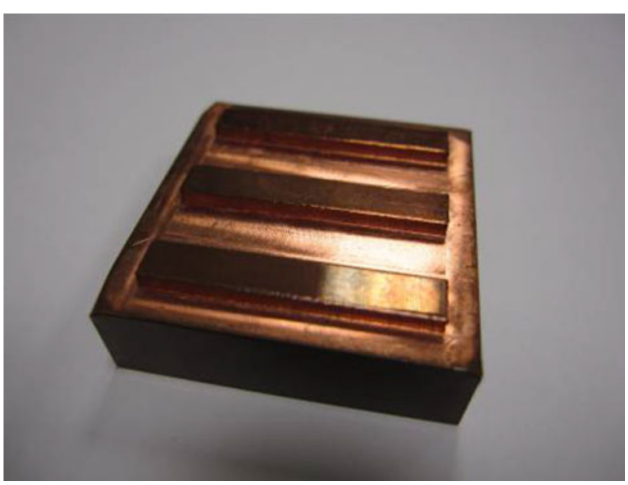

Fig. 13 Oxygen-free high conductivity copper after polishing

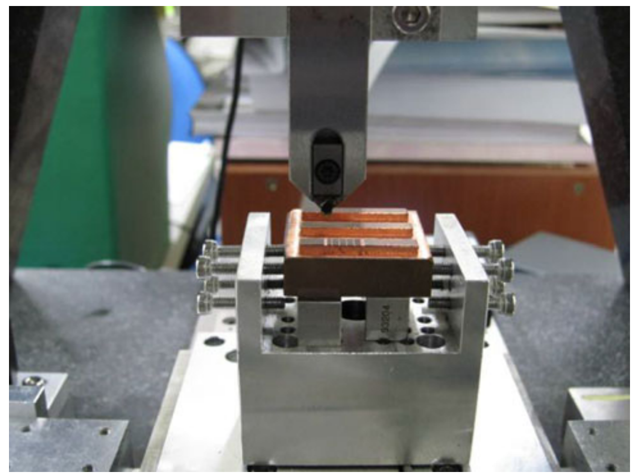

Fig. 14 Photo of the V-groove cutting test

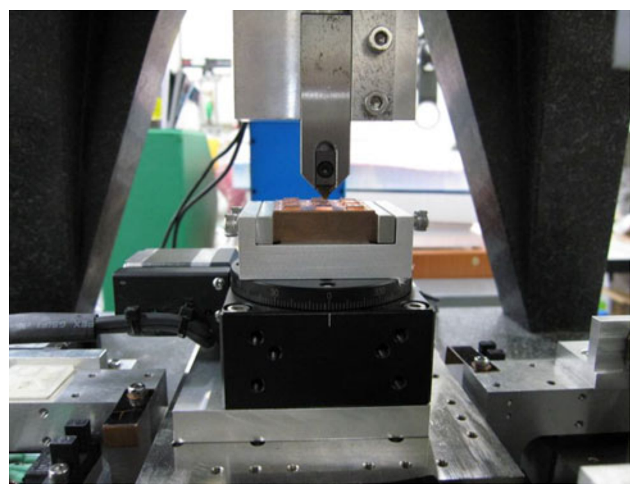

Fig. 15 Photo of the micro pyramid cutting test

4 Experimental results

The cutting tests for both the micro V-grooves and the cross V-grooves under various combination of the depth of cut and feed rate have been executed in this study. For the micro V-grooves shaping tests, the induced forces measured by a micro dynamometer at different cutting speed (1.5, 3.0, 4.5, 6.0 mm/s) under various depth of cut (5, 10,

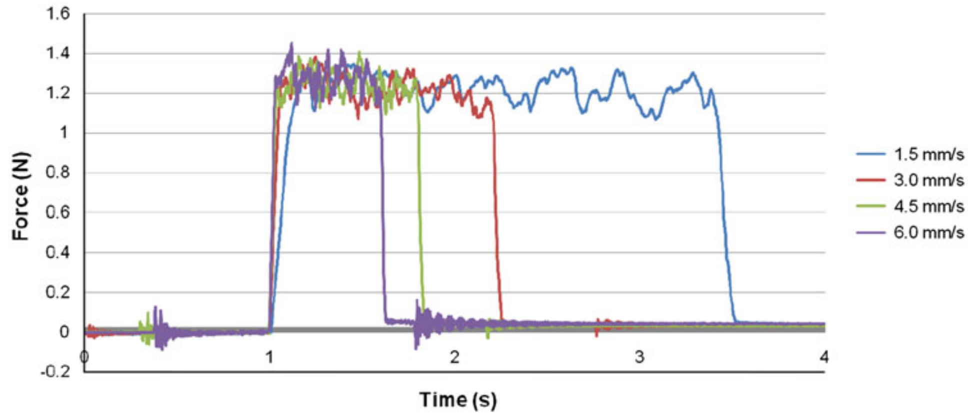

Fig. 16 The cutting force under the depth of cut of 5 μm at different cutting speed

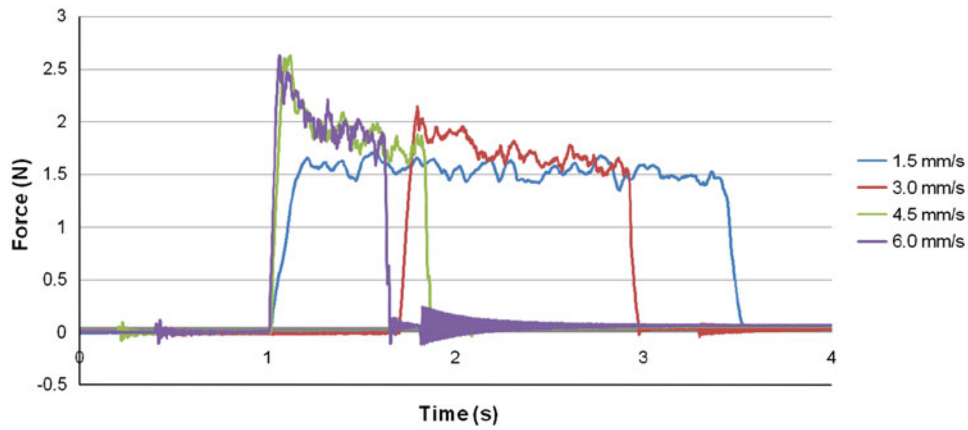

Fig. 17 The cutting force under the depth of cut of 10 μm at different cutting speed

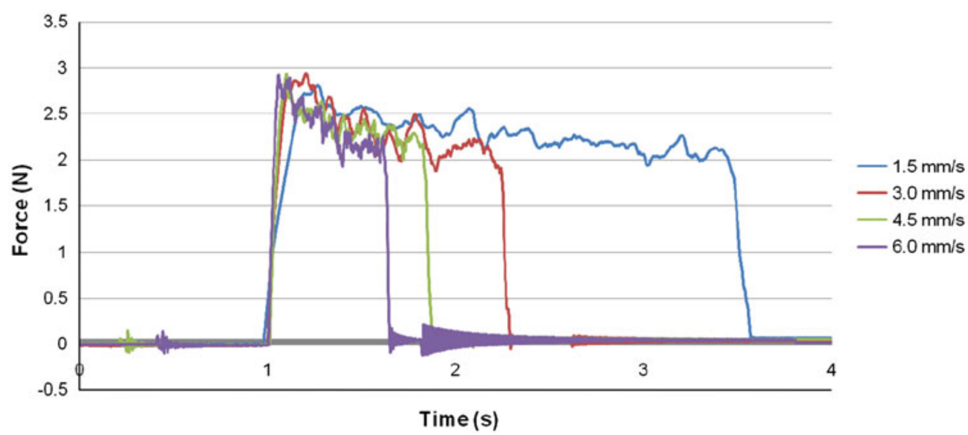

Fig. 18 The cutting force under the depth of cut of 15 μm at different cutting speed

15 μm) are shown in Figs. 16, 17, 18, respectively. It revealed that the cutting speed had no great influence on the cutting force. The measured cutting forces for the depth of cut of 5, 10, 15 μm were 1.2, 1.6 and 2.4 N, respectively. The larger the depth of cut, the greater the cutting force. The fabricated mean pitch of the V-grooves with the pitch of 100 μm was measured by a toolmaker microscope, as shown in Figs. 19, 20. The results showed the average pitch of the V-grooves was 100.347 μm.

The micro pyramid cutting tests have been carried out with the use of a rotary stage. The SEM image of the micro pyramid micro structures was shown in Fig. 21. The result showed the meso-scale machining tool can be used in micro pyramid structures manufacturing.

5 Conclusion

A prototype of the meso-scale machine tool with a nanometer resolution has been newly developed in this work. The optimal geometrical dimensions of the pagoda structure have been determined by ANSYS software. According

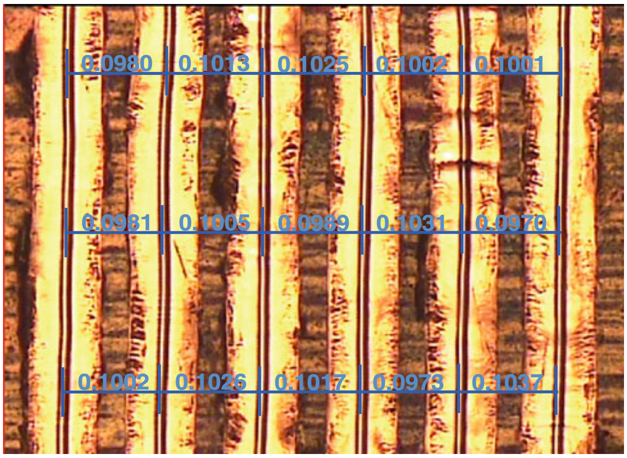

Fig. 19 Photo of the fabricated V-grooves with a pitch of 100 μm

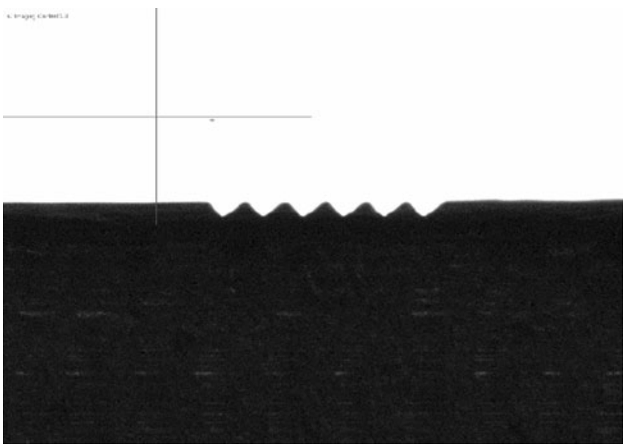

Fig. 20 End view of the fabricated V-grooves with a pitch of 100 μm (4.0×)

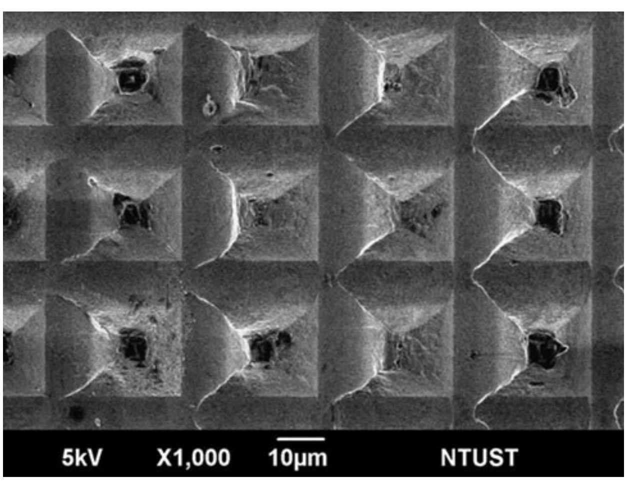

Fig. 21 The SEM image of the fabricated micro pyramid structures

to the simulation results, the maximum static deformation along the z-axis of the pagoda was about 5.05 nm. Regarding the performance test of the coplanar stage, the roundness error of the circular positioning test with the diameter of 1.000 mm was about 83 nm. The V-grooves cutting tests and the micro pyramids cutting tests on the polished OHFC copper using a single crystal diamond tool have been investigated on the developed meso-scale machine tool. The induced cutting forces measured by the micro dynamometer under various cutting speed and depth of cut have also been investigated. The measured cutting force for the depth of cut of 5, 10, 15 μm were 1.2, 1.6 and 2.4 N, respectively. The fabricated mean pitch of the V-grooves with the pitch of 100 was 100.347 μm. The result showed the meso-scale machining tool can be used to fabricate the micro pyramid structures.

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