Machining characteristics with nanometer-cutting machine equipped parallel mechanism

Katsushi Furutani* and Michio Suzuki**

* Toyota Technological Institute
12-1, Hisakata 2-chome, Tempaku-ku, Nagoya 468-8511 Japan
E-mail: furutani@toyota-ti.ac.jp
** NSK Warner K. K. at present

1. Introduction
Today, fabrication of nanometer-scale structures using scanning probe microscope (SPM) instruments are actively investigated [1]-[3]. The authors have proposed a SPM type machine tool equipped a parallel mechanism with 6 degrees of freedom [4][5] for free form surface generation.
In this paper, the machining characteristics are investigated by using the nanometer-cutting machine. At first, a structure of the fine motion device employing the parallel mechanism is introduced. Then the dependence of machining direction to a cantilever is discussed.

2. Fine motion stage for nanometer-cutting machine
Fig. 1 shows an overview of a fine motion stage for a nanometer cutting machine [5]. The stage supported with 6 links with an elevation angle of 35° stands on a base platform. The machine measures 170 mm × 170 mm × 108 mm. A table weighs 103 g. The movable range of the table is 30 µm × 40 µm in the x- and y-directions and 100 µm in the z-direction. Stacked piezoelectric actuators with dimensions of 5 mm × 5 mm ×20 mm are used to change the link length. Displacement of the piezoelectric actuator is magnified over 8.6 times (approximately 100 µm) with a lever mechanism with flexure hinges made of ASTM S30400 stainless steel. Both ends of the links are connected with the base platform and the table by flexure joins.
The motion of the stage is controlled by a feedback of link displacements. A given posture of the table is resolved into the link lengths by inverse kinematics. Then, the link lengths are given as references in each servo systems with a proportional-integral (PI) controller. The controller is installed in a personal computer (80586, 100 MHz). The manipulation signal through a 12-bit D/A converter is given to the piezoelectric actuator through a voltage amplifier. The feedback signal is obtained with a 12-bit A/D converter. The displacement of each link is measured with an eddy current sensor with a resolution of 0.4 µm.
The displacement of the stage was calibrated by the least square fit with measured displacement in all directions. The repeatability (3σ) is 0.1 µm in translation and 10 µrad in inclination.

3. Machining characteristics
3.1 Machining conditions
Fig. 2 shows an experimental setup. The fine motion stage works as a part of an atomic force microscope (AFM) used as the nanometer-cutting machine in which the probe tip was used as a cutting tool. Table 1 shows the machining conditions. The probe is designed for a lateral force microscope. Acrylic resin was scratched with the probe. At the beginning of the machining process, an inclination of a workpiece was measured by scanning with a smaller contact force and a rough measurement pitch. Then the stage was moved in parallel to the inclined surface of the workpiece and the probe scratches it with a larger contact force on the same machine. Finally, the scratched area was observed with a commercial AFM.
3.2 Machining characteristics without vibration
Fig. 3 shows a result of machining in the case of
The shape error corresponded with the motion error of the stage. Because the cantilever is a strip, it was buckled in the \( x \)-direction. The frictional force between the tip and the surface of the workpiece as shown in Fig. 4. The normal and frictional forces shown in Fig. 5 (b) can be calculated by using the forces in both trace and retrace motions shown in Fig. 5 (a). Because the normal force was small at both ends and the frictional force was almost flat, no ridge was observed on the boundary of the machined area. Fig. 6 shows a contour map of 10 \( \mu m \times 10 \mu m \) area when the number of scratches was changed from 25 to 100. Although non-machined area
was decreased with an increase of the number of scratches, the bottom of the machined area was not flat. The non-machined area causes the viscoelasticity of the acrylic resin put to an end with the probe tip.

Fig. 7 shows a result of machining in the case of scratch in the $y$-direction. Some ridges with a height of 180 nm because of the viscoelasticity were observed on the boundary of the scratched area. The cantilever distorted during the $y$-scanning by the frictional force between the tip and the surface of the workpiece. Because the cantilever is stiffer in the $y$-direction than the $x$-direction, the normal force was not decreased at both ends which are the turning points of the scratches as shown in Fig. 8. Fig. 9 shows a contour map in the case of scratch in the $y$-direction. Although some ridges were observed, non-machined area was decreased and the bottom of the machined area was flat.

The error of the tip position in the $y$-scanning was smaller than that in the $x$-direction. Because the stiffness affected the scanning, machined shapes were
different between the scanning directions.

Fig. 10 shows the relationship between the machined depth and the number of scratches against the machining direction. In the $x$-direction, the machining speed decreases when the number of scratches exceeds 25. However, the depth of the pocket increases linearly for numbers higher than 25. Although the machined depth per scratch in the $y$-direction was smaller than that in the $x$-direction, it was proportional to the number of scratches. The machining error was small in the case of scratching in the $y$-direction. Therefore, scratching in the $y$-direction is preferable for the machining because of the anisotropic stiffness of the probe.

### 3.3 Machining characteristics with vibration

Then the vertical vibration with an amplitude of 59 nm and a frequency of 9.4 kHz was added to the stage motion with a piezoelectric actuator mounted on the stage to increase the relative velocity between the cantilever and the specimen. The piezoelectric actuator measures $5 \text{ mm} \times 5 \text{ mm} \times 10 \text{ mm}$. Fig. 11 shows a result of machining. Although the scratched area was $5 \text{ µm} \times 5 \text{ µm}$, the machined area measured $4 \text{ µm} \times 4 \text{ µm}$. The positioning accuracy of the stage and the distortion of the cantilever affects the decrease of the machined area. The depth of the pocket measured 20 nm after 100 scratches. No ridge was observed though the depth was decreased.

### 4. Conclusions

In this paper, the machining characteristics of the nanometer-cutting was described. The conclusions can be drawn as follows.

1. Pockets were machined by scratching acrylic resin with an AFM probe.
2. Because the stiffness of the probe is anisotropic, the machining accuracy depended on the scratch direction.
3. The additional vibration helps to decrease the ridges on the boundary of the machined area.

### Acknowledgement

The authors wish to thank Prof. Kazuyoshi Kondo of Toyota Technological Institute for his valuable advice. This study was financially supported by the Sasakawa Scientific Research Grant from the Japan Science Society and the Grant-in-Aid for High-tech Research Center for “Space Robotics” and for Scientific Research (C)(2)(13650289) of the Ministry of Education, Science, Sports and Culture of Japan.

### References