DETECTION OF MICRO TOOL WEAR IN DIAMOND TURNING OF LARGE AREA MICRO-LENS ARRAY BY IN-PROCESS CUTTING FORCE MEASUREMENT

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INTRODUCTION
Diamond turning with fast tool servo (FTS) or fast tool control (FTC) is a promising tool for fabrication of optical components including micro-lens array [1][2]. The micro-lens array is used in various optical communication devices and imaging devices for improvement of the image quality. With the increase of fabrication area of micro-lens array, it is important to monitor the long time fabrication process influenced by tool damage, tool wear, etc. Micro tool wear is easily occurred while the material is being removed from the workpiece because the diamond cutting tool used for fabrication of micro-lens array is fragile with the small nose radius and large clearance angle. Micro tool wear is the reason to reduce both surface finish and accuracy of the micro-lens array. It also increases the cutting force, in turn increase of the tool wear [3]. The most popular method to detect micro tool by direct imaging the tool cutting edge is a scanning electron microscope [4] and an atomic force microscope [5]. However, it takes a long time for the imaging process. It is also necessary to remove the tool from the diamond turning machine for measurement. The aim of this research is to indirectly detect the micro tool wear by in-process measurement of cutting force. This is based on the fact that the cutting force is increased with the tool wear. Since the change of cutting force caused by tool wear is very small, it is necessary to make the in-process cutting force measurement with a high sensitivity. For this purpose, a stiff but sensitive piezoelectric force sensor is carefully integrated to the FTC unit used for cutting the micro-lens array. To observe the tool wear during the fabrication of micro-lens arrays, it is desired to monitor the generated cutting force at the interface between the cutting tool and the machined surface with the diamond turning process. This paper presents experimental results of detection of cutting tool wear by the FTC unit integrated with a sensitive piezoelectric force sensor, which is designed for in-process measurement of the cutting force.

DESIGN REQUIREMENTS OF FTC UNIT FOR FABRICATION OF MICRO-LENS ARRAY
Figure 1 shows a schematic of the micro-lens array fabricated in the experiment. The micro-lens has a parabolic profile and it is fabricated on the workpiece surface over a large area. The specific parabolic micro-lens designed for the experiment has a length of 190 μm, a width of 90.3 μm and a depth of 5.2 μm. The micro-lenses are fabricated as an array over a Ni-P plating roller surface with a diameter of 55 mm. Generally speaking, a FTC unit should be designed to satisfy the following requirements for fabrication of micro-lens arrays. First, the length of axial direction (width) of micro-lens is decided by the cutting tool profile. Therefore, for fabrication of a narrow lens, a cutting tool with a small nose radius down to 10 μm should be employed. If the contact between the small sized cutting tool and the workpiece is not well detected, the tool may be broken. Also, the fabrication process is influenced by a lot of factors such as tool damage, tool wear, etc. It is thus desired to detect the initial position of machining and monitoring of the long time fabrication process. Second, the depth along the Z-direction of micro-lens is relatively deep up to tens of micrometers and the maximum stroke of FTC unit should be longer than the depth of micro-lens. Third, because the length along the circumference direction (Pc) is short, the FTC unit is required a high dynamic characteristic.

FIGURE 1. Profile of the micro-lens array
### DESIGN OVERVIEW OF FTC UNIT

The structure of FTC unit is shown in Figure 2. The hollow-type piezoelectric actuator is installed in the casing under the preload by the spring. The piezoelectric actuator has an outer diameter of 20 mm, an inner diameter of 14 mm and a stiffness of 117.5 N/μm. To get a higher dynamic performance of a piezoelectric actuator, a preload must be introduced in the FTC unit system because the piezoelectric actuator can only generate a pushing force. Generally, a lot of piezoelectric actuators are preloaded against the piezoelectric actuator in order to avoid backlash by alternating load force direction. And preload on the piezoelectric actuator must be higher than any inertial forces of moving parts [6]. In the FTC unit system shown in Figure 2, the piezoelectric actuator is preloaded by adjusting the thickness of spring with a force of 280 N for high dynamic way. The capacitance type displacement sensor with 125 μm range and 12.5 nm resolution is installed in the hollow-type piezoelectric actuator. The bandwidth of the capacitance type displacement is set at 20 kHz. Because the capacitance type displacement sensor is aligned with the axis of the piezoelectric actuator motion, the motion of piezoelectric actuator can be measured by capacitance type displacement without Abbe error.

Experiments are carried out to evaluate the static and dynamic performances of the FTC unit. The input voltage is applied to the piezoelectric actuator and it is magnified by a voltage amplifier. The piezoelectric actuator with the maximum voltage range of 150 V is used. Figure 3 shows the static response when the FTC unit is under the closed loop control. An analog PID controller is employed for servo control of the motion of FTC unit. As can be seen that the static response under the closed loop control become nearly linear. The developed FTC unit has a stroke of 48.3 μm and the linearity error is reduced to approximately 150 nm. The dynamic response is related to mechanical stiffness and mass of moving parts. The dynamic frequency response is measured with a FFT analyzer system. The FTC unit receives the command input signal (swept sine wave) corresponding to a displacement of 500 nm from the function generator. Then, it is compared with the output signal from the capacitance type displacement sensor measuring the position of the head. Figure 4 shows the obtained dynamic response result of the FTC unit along the in-feed direction. The measured resonance frequency in the in-feed direction is approximately 7837 Hz.

The FTC unit is integrated with a piezoelectric force sensor for measurement of cutting force during fabrication process in real time. The high stiffness of the piezoelectric force sensor is demanded in order to reduce the stiffness effect in the fabrication system. Also, the piezoelectric force sensor which has a high resolution and a high sensitivity is necessary for detecting of small cutting forces due to small removed material chips. For the measurement of cutting force by using the piezoelectric force sensor, a charge amplifier is employed. The piezoelectric force sensor has an outer diameter of 12 mm, an inner diameter of 5 mm, a stiffness of 953.3 N/μm. A piezoelectric force sensor should basically be preloaded in a mounting structure for measurement of process force including tensile force and compression force [7]. The developed FTC unit body has a dimension of φ35×100 mm.

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**FIGURE 2. Structure of the FTC unit integrated with piezoelectric force sensor**
IN-PROCESS DETECTION OF CUTTING FORCE

Figure 4 shows a schematic of the in-process cutting force measurement system. The In-process measurement system consists of a diamond turning machine, the FTC unit and a PC. The PC is used to generate output of depth of cut data and record the output signal of the cutting force from the piezoelectric force sensor. The FTC unit is mounted on the X-carriage of the diamond turning machine. A roller workpiece is mounted on the spindle. The micro-lens array is fabricated on the roller workpiece surface with a diameter of 55 mm. The fabrication of micro-lens array is started by responding to the trigger signal from the rotary encoder output of spindle. The depth of the micro-lens is controlled by the FTC unit along the Z-direction.

By using the FTC unit integrated with the piezoelectric force sensor, the cutting force can be measured in real time. The generated charge output of the piezoelectric force sensor in the fabrication process is proportional to the force output through the charge amplifier. This output is stored to PC memory through the A/D board.

FABRICATION OF MICRO-LENS ARRAY

First, a pre-cut is carried out to remove the out of roundness of the workpiece by a cutting tool with a 2 mm nose radius. Then the tool is replaced to a cutting tool with a nose radius of 0.2 mm for fabrication of micro-lens array. In order to exhibit the fact that the cutting force change depends on the tool wear, micro-lens arrays are fabricated on the Ni-P plating by a new tool and an used tool with the same nose radius of 0.2 mm, respectively. Figure 5 shows the microscope image of the tools. The contact between the tool and the workpiece is detected by the integrated piezoelectric force sensor. The tool is oscillated by FTC unit with a frequency of 380 Hz and an amplitude of 3 nm so that the piezoelectric force sensor output can be detected with a lock-in amplifier for high sensitivity detection [8]. The contact detection is decided from the output change of the piezoelectric force sensor when the tool is moved by the X-carriage of the diamond turning machine toward the workpiece with a step of 10 nm.
The piezoelectric force sensor outputs when the contact is detected between the tool and the workpiece by the new tool and the used tool are shown in Figure 6. The initial position of machining can be detected with a resolution of less than 10 nm for both the new tool and the used tool. The micro lenses which have depths of 5.2 μm and pitches of 190 μm, are then fabricated as arrays on the Ni-P plating surface by the two tools, respectively. The measured cutting forces by the FTC unit integrated with the piezoelectric force sensor are shown in Figure 7. The measured cutting forces are 0.9 N and 1.1 N, respectively. It can be seen that the cutting force with the new tool is smaller than that with the used tool. The results have confirmed the fact that the cutting force is increased with the tool wear and it is effective to monitor the tool wear by the piezoelectric force sensor output of the FTC unit. Figure 8 shows photographs and the sectional profiles of the fabricated micro-lens arrays by the two tools, respectively. The surface finish of the micro-lens cut by the new tool is better than that by the used tool.

CONCLUSION
The piezoelectric force sensor-integrated FTC unit has been developed to measure the cutting force in real time. The detection of tool wear can be determined from the monitoring of cutting force.

REFERENCES