MONITORING OF ULTRASONIC VIBRATION MICROMACHINING PROCESS

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1. Introduction
Glasses are preferred as the structural materials for bio/chemical analysis because of its superior stability. However, it is difficult to obtain smooth surface except etching processes. Abrasive jet machining can provide three-dimensional profiles, however, the geometrical accuracy is limited and random factor is introduced because of the fluctuation of the flow of the jet [1, 2]. Ultrasonic vibration machining can also provide deterministic three-dimensional profiles with smooth surface [3]. When the vibration machining is applied to micromachining, the monitoring of the process is essential because not only does a tiny tool easily break due to slight collision against the workpiece but large chippings deteriorate the finished roughness and generate sub-surface damages. One of the authors has already demonstrated the importance of monitoring using an acoustic emission (AE) sensor [4] and a force sensor [3] as well as the multi-axes tool vibration [5]. Applying appropriate control based on the sensor signal, a tiny tool as small as φ40µm can be used without breakage and also tool wear can be compensated [4]. However, the vibration frequency was limited to 20kHz. This paper extends this limitation up to 40kHz and the monitoring of the process during micromachining of glass is discussed to improve the quality.

2. Experimental setup
Figure 1 shows the schematic illustration of the experimental system. A tiny tool, just a cylinder made of sintered carbide, was set at the tip of an ultrasonic resonator (40kHz). The workpiece was set on a three-axis table that was numerically controlled by a PC. A force sensor set beneath the worktable measured the force that acted between a tool and a workpiece. The sensor signal was conditioned with an AC/DC converter or a spectrum analyzer to monitor the machining condition. This configuration enables the detection of tool-workpiece engagement (touch-sense for the reference of the depth of cut) and the process monitoring. Table 1 summarizes the specifications and the typical machining conditions.

![Fig.1 Experimental setup](image)

<table>
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<th>Table 1 Specifications and conditions</th>
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<td>Tool vibration</td>
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<tr>
<td>Tool</td>
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<td>Workpiece</td>
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Low-melting-temperature glass was used for the workpiece because smooth surface can be obtained with ultrasonic machining [3]. The overall size was 400mm in width, 400mm in depth, and 680mm in height. The experiments were carried out in a clean room (class 10000) where the temperature was controlled at 20°C.

3. Detection of tool engagement
Figure 2 shows the typical force measured during machining. To eliminate the effect of the noise due to electromagnetic interference (EMI), the background signal before machining was subtracted from the monitored signal. It was found that the distortion of sinusoidal waveform could be well observed. However, the first resonant frequency was 5kHz though the bandwidth of the amplifier and other processing equipments were high up to 100kHz, and thus it is difficult to discuss the quantitative value of the force due to the difficulty of calibration.

![Fig.2 Original waveform of the force sensor](image)

Figure 3 shows the time history of the measured force and the frequency components before and after the machining of 1μm depth of cut. It was found that the amplitude increased when the tool engaged in the workpiece. In addition, the waveform distorted because of the engagement during the partial period of each cycle. The distortion was well monitored with the power spectrum. It was found from Fig.3 (right) that the harmonics components, especially the first harmonics 80kHz, rapidly increased with the engagement. Both of these signals can be used for monitoring during the touch-sensing, the detection of engagement between the tool and workpiece.

![Fig.3 Changes in amplitude (left) and frequency components (right) before and after machining](image)

Figure 4 shows the monitoring signals during the touch sensing process. This process is important to ensure the machining accuracy. The horizontal axis shows the stepwise feed of the
Z-stage and the vertical axis shows the changes in peak-to-peak (P-P) value and RMS of 80kHz components. In this case, at 0.9µm, the tool engaged in the workpiece. At this point, the P-P value rapidly increased with the increase in position Z. Also, the RMS value rapidly increased from zero to 4mV in this case. It is not easy to determine which of these is suitable for the detection of tool engagement because the signal to noise ratio (S/N ratio) has not been evaluated. However, it was confirmed that the repeatability was good as less than 0.1µm.

4. Monitoring of the machining process
Figure 5 shows the correspondence between the monitoring results during the grooving process and the microscopic observation. The nominal depth of cut was 5µm, however, the actual depth of cut varied from 5µm (left edge) to 6.8µm (right edge) because of the inclination of the worktable. Due to this inclination, the process changed from mild (left) to severe (right) condition and the effectiveness of the monitoring could be well examined.
The left side of Fig.5 shows the results of smooth finish and it was found that the fluctuation of both of the P-P value and the RMS value were small, however, at the last part of machining (right end), the fluctuation became large due to the generation of chippings. The right side of Fig.5 shows the severe case in chippings. It was found that the fluctuation of RMS value was larger than that of P-P value of the force. These results suggest the possibility of the detection of chippings through the analysis of RMS value of 80kHz component. Such signal can be used for the adaptive control to prevent the generation of chippings. Actually, in the specific conditions using low-melting-temperature glass as a workpiece, smooth surface as shown in Fig.5 (left) can be obtained and thus the prevention of chipping is crucial [3].

5. Discussion
It was found from the above results that both of the P-P and RMS of the machining force could be used not only for the detection of the tool engagement but also for the monitoring of the process. However, before the actual application, the following items should be considered.
In this paper, the P-P value and RMS value are treated independently. However, any combination of these signals may give further valuable information. For example, any algorithm in sensor fusion should give a hint. In addition, another source such as an acoustic emission (AE) sensor will give additional information and other types of signal processing are also possible such as wavelet analysis.
In the above experiments, the FFT analysis was done with an optional function of the digital oscilloscope and the transmission to the PC was carried out through the GPIB interface. The transmission rate was limited up to 8 samples/s and it was not sufficient for practical use. If the frequency of the importance is fixed, another method can be possible such as the combination of band-pass filter, an AC/DC converter and an A/D converter.

6. Conclusions
A monitoring procedure was proposed for micromachining of glass with ultrasonic vibration tool. The force between the tool and the workpiece was measured and analyzed. The results are summarized as follows:
- Both of the peak-to-peak value and the RMS of harmonics of the thrust force well indicated the condition of the process.
- These signals can be used not only for the detection of the tool engagement but also for the monitoring of chip generation during the process.

References