Efficiency-enhanced elastic emission machining on the basis of processing mechanism

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Abstract

Elastic emission machining (EEM) is well known as a high-precision processing technology, and its high smoothing effect has been successfully demonstrated for the fabrication of hard-X-ray focusing mirrors, by which sub-30 nm focusing was established under diffraction-limited conditions at an X-ray wavelength of 0.08 nm [1]. Recently, EEM has been expected as a technology which can achieve the required surface accuracy of the optical mirrors used in an extreme ultraviolet (EUV) lithography system. The required surface accuracy is 100 pm root-mean-square (rms), which is as high as that of the X-ray focusing mirror surface. Through various examinations, the application potentiality of EEM to EUV mirrors has been demonstrated [2]. It is well known in the semiconductor market that an increase in integration density is absolutely required, by which the optical performance of the lithography system is obliged to be improved. Consequently, processing accuracy is necessarily required to be higher than the present one. In this study, the improvement potentiality of EEM accuracy was investigated on the basis of the processing mechanism. EEM is carried out by utilizing the chemical reactions between the optical surface to be processed and the fine powder particles supplied by pure water. The processing mechanism was clarified from the viewpoint of powder particle behavior, and a method of enhancing the EEM smoothing effect was suggested. On the basis of this suggestion, the process test of enhanced EEM was examined. Consequently, an unprecedented high surface accuracy was successfully achieved.

1 Smoothing mechanism of rotating-sphere elastic emission machining

Rotating a sphere made from an elastomer on a workpiece surface, an elastohydrodynamic lubrication state is generated, by which a non-contact state is maintained between both surfaces, and powder particles can be supplied to the workpiece surface by a pure water flow. The distribution of water flow can be calculated using the elastohydrodynamic lubrication (EHL) theory [3], and accordingly the particle behavior which is strongly affected by a fluid drag force is assumed. In this section, the roughness reduction mechanism of EEM is investigated from the viewpoint of the particle behavior.

1.1 Powder particle behavior

Figure 1 shows the fluid flow distribution calculated based on the EHL theory, which is a section view of the EEM processing point. The sphere rotates in a counterclockwise direction in the figure, and the center of the rotating sphere is on the *z*-axis. With respect to the fluid flow in the lubrication area, the velocity component of the *x*-axis is four orders of magnitude larger than that of the *z*-axis, indicating that powder particles strongly tend to flow parallel to the workpiece surface. Moreover, an approximately linear shear flow exists in the lubrication area as follows. When $z \sim 0$ μm (near the workpiece surface) and $z \sim 1$ μm (near the rotating sphere surface), the fluid flow velocities are 0 m/s and 1 m/s, respectively. According to the shear rate, when a powder particle with a diameter of 100 nm is used in EEM, which is a typical condition, the particle velocity near the workpiece surface is calculated to be approximately 0.1 m/s. In this situation, the kinetic energy of the flowing particles near the workpiece surface is equivalent to 3.6×10^{-2} eV, which is two orders of magnitude lower than the binding energy of silicon. This finding indicates that the powder particles which flow in proximity to the workpiece surface do not have a sufficient energy to remove surface atoms physically, and that EEM is consistently promoted chemically.

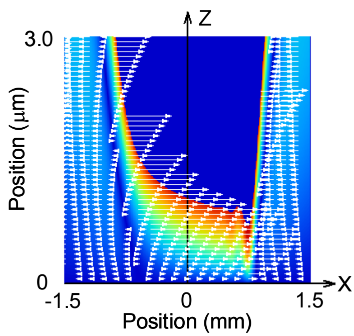
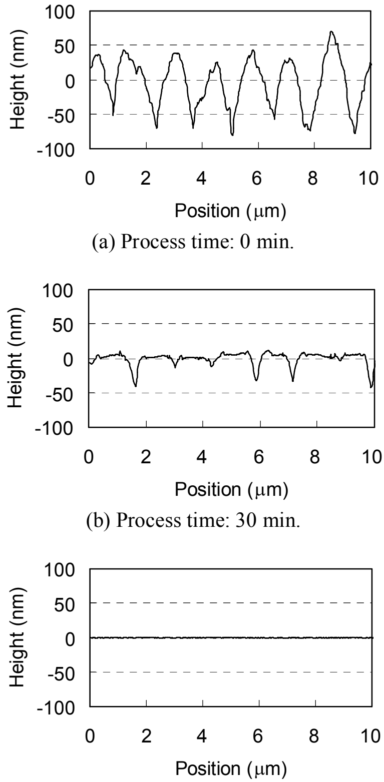


Figure 1: Distribution of fluid flow under lubrication state.

1.2 Roughness improvement

The improvement in surface roughness is investigated. EEM is processed on a workpiece surface with a periodic structure of 1.5 μm dimension, which is made of SiO_2, and the changes in surface roughness are observed. Figure 2 shows the surface profiles measured by atomic force microscope (AFM) with changes in process time. It is found that roughness improvement occurs selectively at the topmost site of the workpiece surface. To realize the phenomenon that particles with a dimeter of 100 nm reduce the roughness in the wavelength range of 1.5 μm, particles should move straight parallel to the workpiece surface and come in contact with the topmost site. Therefore, the validity of the powder particle behavior assumed above can be considered sufficient.



(a) Process time: 0 min.

(b) Process time: 30 min.

(c) Process time: 150 min.

Figure 2: Changes in surface roughness with periodic structure.

2 Enhancement of smoothing property

In a conventional rotating-sphere EEM, a sphere rotates in a constant direction on a workpiece surface, which shows that only the powder particle flow with a constant direction induces surface removal. As shown in section 1, the particle powder behavior strongly affects surface roughness improvement, therefore the constant powder particle flow has a possibility to generate anisotropic surface error. The directionally averaged powder particle flow can be suggested as a method of resolving the anisotropic error and is expected to enhance the smoothing effect of EEM.

As shown in figure 3, the directionally averaged powder particle flow can be realized by rotating a workpiece under the condition that a rotating sphere position is fixed and the processing point is the workpiece rotation center. Figure 4 shows the surface profiles obtained by normal polishing (a), conventional EEM (b) and enhanced EEM (c). A surface roughness of 50 pm rms, which is an unprecedented high surface accuracy, can be successfully achieved.

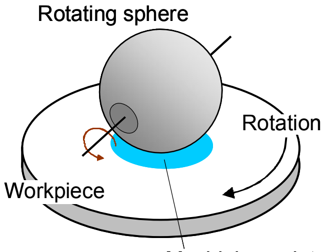
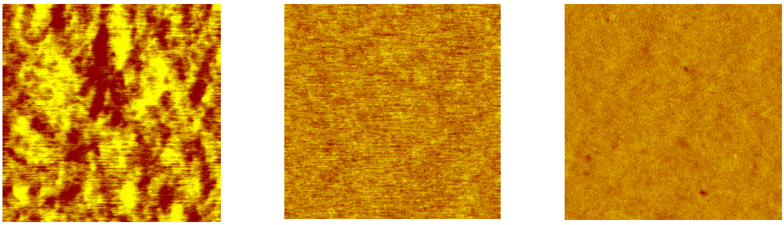


Figure 3: Schematic of enhanced EEM (particle flow is directionally averaged).



(a) Preprocessed
Roughness: 220 pm rms

(b) Conventional EEM
Roughness: 110 pm rms

(c) Enhanced EEM
Roughness: 50 pm rms

Figure 3: Surface profiles obtained under three different conditions.

3 Conclusions

As the result of improvement of EEM fluid flow method on the basis of the processing mechanism, enhancement of EEM smoothing performance can be realized. Unprecedented high surface accuracy of 50 pm rms was successfully achieved, which indicates that EEM is a candidate for next-generation technology of optical surface fabrication.

Acknowledgement

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References:

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