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Figuring and smoothing capabilities of elastic emission machining for low-thermal-expansion glass optics

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The use of elastic emission machining (EEM) for fabricating optics from low-thermal-expansion glass for extreme ultraviolet (EUV) lithography is examined. EUV optics require figure accuracy and surface roughness of 0.1 nm root mean square (rms) or better. EEM using a rotating-sphere head is demonstrated to achieve this level of surface smoothness after a certain depth of removal dependent on the material being processed. In tests of continuous machining for 12 h, no increase in surface roughness is observed, demonstrating the high temporal stability of this noncontact processing method. EEM using a rotating-sphere head is thus confirmed to have sufficient figuring and smoothing capability for the fabrication of EUV optics. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2789440]

I. INTRODUCTION

Extreme ultraviolet (EUV) lithography is currently being developed as a fabrication technique suitable for printing features at design scales smaller than 50 nm, the limit of existing ultraviolet-based chip printing technology. This is achieved through the use of light at a wavelength of 13.5 nm, much shorter than the wavelength of 193 nm used today. Focusing light at such short wavelengths into the required image requires high-precision optics with absolute figure accuracy and a root mean square (rms) roughness of 0.1 nm. The optics used in EUV systems must also be made of low-thermal-expansion materials, since at least 30% of the light illuminating an optical surface is not reflected and converted to heat. ULE (Corning Inc.) and Zerodur (SCHOTT AG) are well-known examples of such low-thermal-expansion materials.[1,2]

The machining of low-thermal-expansion materials with the required precision and smoothness for EUV optics thus requires a suitably precise and stable processing method. In the present study, elastic emission machining (EEM) is examined as a potentially suitable machining process for this application. EEM is a noncontact machining method that involves passing a flow of fine powder particles in pure water across the workpiece surface. Removal of surface atoms occurs by the chemical reaction between the particles and the workpiece surface. The excellent smoothing performance of this method has already been reported.[3,4]

In the EEM process, fine particles are supplied to the workpiece in a flow of pure water generated by either a jet-nozzle or rotating-sphere head. Yamauchi *et al.* successfully fabricated high-precision x-ray condensing mirrors using the jet-nozzle head.[5] However, jet-nozzle EEM does not have sufficient processing efficiency for the fabrication of an optical effective area of EUV optics, which is markedly larger than that required for the x-ray condensing mirror. In a previous study, the present authors demonstrated the machining properties of rotating-sphere EEM.[6] The processing rate of rotating-sphere EEM is more than 1000 times greater than for jet-nozzle EEM, and since the removal volume is proportional to processing time, the method can readily be controlled by a numerical control system. Moreover, the spatial wavelength range in which the surface roughness can be minimized automatically is approximately 1 mm. For these reasons, the use of a rotating-sphere head is being considered as a working tool for EEM fabrication of EUV optics.

In this study, ULE and Zerodur surfaces are fabricated by rotating-sphere EEM, and the surface roughness and temporal stability of smoothing over extended continuous machining are evaluated in order to demonstrate the figuring and smoothing capabilities of rotating-sphere EEM for ULE and Zerodur materials.

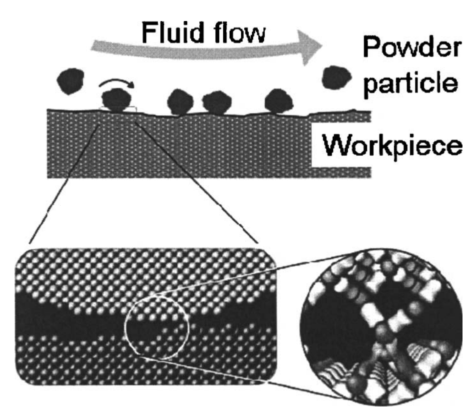

FIG. 1. Schematic representation of atom removal process in EEM.

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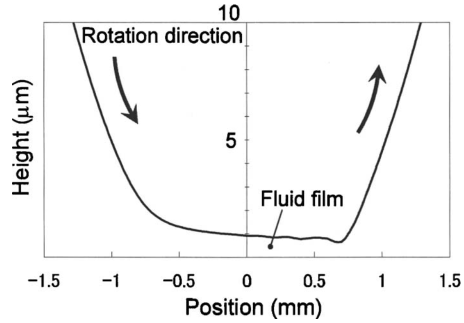

FIG. 2. Calculated fluid film thickness at workpiece.

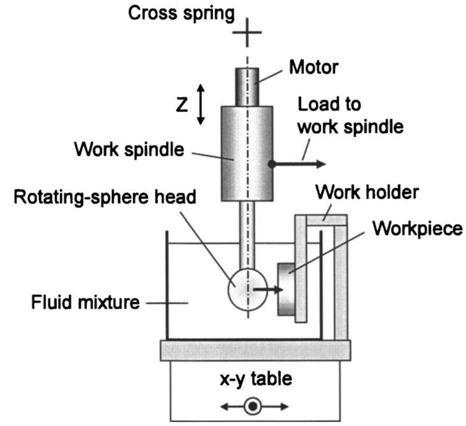

FIG. 3. Schematic of EEM apparatus.

II. EEM WITH ROTATING-SPHERE HEAD

A. Principle of EEM

EEM is a noncontact machining process, differing from conventional polishing which uses an abrasive pad. Fine powder particles are brought to the workpiece surface in a flow of pure water, and the chemical reaction between the workpiece surface and the particles results in the removal of surface atoms from the workpiece.[7] The powder particles thus act in a similar manner to reactive species in chemical machining. Figure 1 shows the general process of EEM. The particles supplied in a flow of pure water roll around on the processed surface along the streamlines, preferentially removing the topmost atoms on the surface. Smoothing thus progresses automatically.

B. Rotating-sphere head

The head supplying the mixture of water and powder particles does not contact the workpiece surface. Figure 2 shows the calculated fluid film thickness between the head and workpiece under the conditions listed in Table I. The fluid film is calculated to be thinner than 1 μm based on elastohydrodynamic lubrication theory.[8] Powder particles pass through in this fluid film.

The Reynolds number (Re) for the fluid flow in the fluid film is calculated to be 1.2 by the equation $\mathrm{Re}=UL/\nu$, where U is the mean fluid velocity (peripheral velocity of rotating-sphere head, 1.2 m/s), L is the characteristic length (fluid film thickness, 1.0 μm), and ν is the kinematic fluid viscosity (1.0×10^{-6} m^2/s for water at 20 °C). This Reynolds number indicates that flow in the fluid film is laminar, providing an efficient supply of powder particles to the workpiece surface.

TABLE I. Analysis conditions.

Diameter of rotating sphere	120 mm
Rotating speed	191 min^{-1}
Load	2.0 N
Viscosity	1.8×10^{-3} Pa s
Elastic modulus	0.072 GPa

C. Machining apparatus

Figure 3 shows a schematic of the rotating-sphere EEM system. This system consists of an x-y table to feed the workpiece, while the rotating sphere is scanned up and down on the z axis. This three-axis control system makes it possible to process any desired area on a workpiece surface. The work spindle with rotating-sphere head is suspended by a cross spring, similar to a pendulum, and the head is immersed in a tank of the fluid mixture. The rotating-sphere head is brought close to the workpiece surface by applying a load to the work spindle. By generating a state of elastohydrodynamic lubrication between the rotating-sphere head and the workpiece surface, a noncontact state can be maintained at the machining point during EEM.

III. TESTS OF FIGURING AND SMOOTHING CAPABILITY

A. Roughness improvement performance

The change in surface roughness with increasing removal depth was investigated by processing five discrete areas on the flat surfaces of the workpiece for different lengths of time using a raster scan process. The experimental conditions are listed in Table II. The depths and profiles for each of the processed areas were measured using a three-dimensional optical profiler (NewView, ZYGO). The measurement areas were 107×143 μm^2 in size.

Figure 4 shows the changes in the surface profiles with increasing removal depth. As the removal depth increases, the undulation of the surface becomes smaller. Figure 5

TABLE II. Experimental conditions for smoothing performance test.

Diameter of rotating sphere	60 mm
Rotating speed	840 min^{-1}
Load	3.3 N
Machining area	5×5 mm^2
Scan method	Raster
Scan speed	20 mm/min
Scan pitch	20 μm

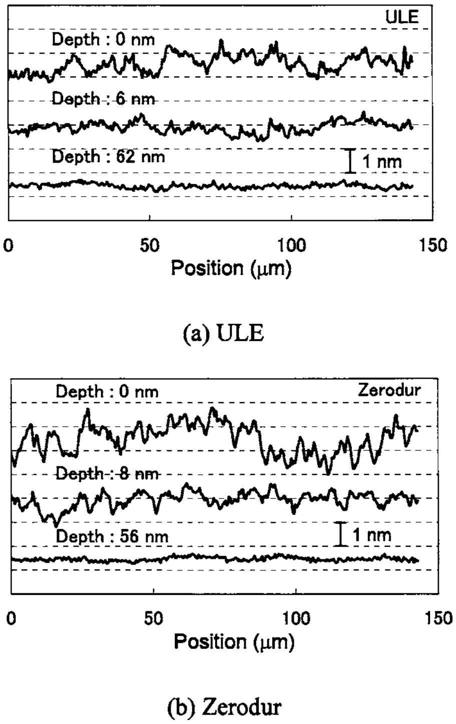

FIG. 4. Change in surface profile with increasing removal depth.

shows the relationship between removal depth and the rms surface roughness. The rms surface roughness becomes smaller with increasing removal depth, converging to a constant value of 0.1 nm at removal depth of 30 nm (ULE) or 40 nm (Zerodur). The approximate removal depth required to reduce the preprocessed surface roughness to 0.1 nm rms can thus be estimated, and this condition can be applied to control of EUV optics fabrication.

B. Time stability of smoothing performance

The fabrication of EUV optics by EEM can take a substantial length of time depending on the optical effective area and/or the removal rate. In extended continuous machining, there must be no temporal change in the smoothing performance. To investigate the stability of the present machining method for ULE and Zerodur, flat surfaces with roughness of 0.2 nm rms produced by conventional polishing were processed by rotating-sphere EEM for 13 h. It is expected from Fig. 5 that a removal depth of more than 15 nm is required to

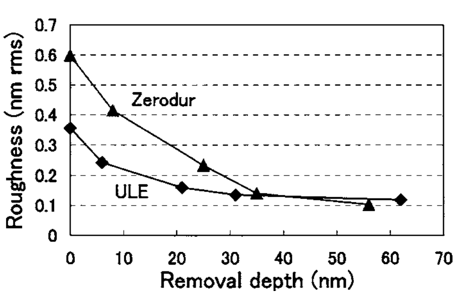

FIG. 5. Relationship between removal depth and surface roughness.

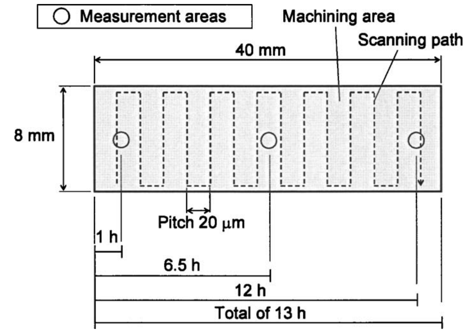

FIG. 6. Schematic of processing method and measurement area in extended machining test.

reduce the roughness of the prepared surfaces to 0.1 nm rms, corresponding to 13 h for areas of $8\times 40\ \mathrm{mm}^2$ on both material surfaces (Fig. 6). The experimental conditions are listed in Table III. These areas were processed by a raster scan at a scan speed of 20 mm/min in the direction of the 8 mm side. The temporal change in smoothing performance was determined by taking measurements at points on the raster path processed 1, 6.5, and 12 h into the machining process. Measurements were made using the optical profiler, evaluating a measurement area of $216\times 288\ \mu\mathrm{m}^2$.

Figure 7 shows the change in surface roughness at these time points during extended processing. At all of the measured points, the surface roughness was better than 0.1 nm rms. This demonstrates the high temporal stability of smoothing performance achievable by EEM using a rotating-sphere head.

IV. CONCLUSION

The smoothing performance of rotating-sphere elastic emission machining for processing ULE and Zerodur materials for EUV optics was investigated, and it was demonstrated that the rms surface roughness becomes smaller with increasing removal depth, converging to a constant value of 0.1 nm after removal of certain depth of material. The surface roughness can thus be reduced to 0.1 nm rms or better, suitable for the fabrication of EUV optics, if the removal depth is set at greater than this guideline value.

The temporal stability of the smoothing performance of EEM for ULE and Zerodur was also examined, revealing no increase in surface roughness even after 12 h of continuous processing. EEM thus has high temporal stability of smooth-

TABLE III. Experimental conditions for extended machining test.

Diameter of rotating sphere	120 mm
Rotating speed	300 min^{-1}
Load	9.8 N
Machining area	$8\times 40\ \mathrm{mm}^2$
Machining time	13 h
Scan method	Raster
Scan speed	20 mm/min
Scan pitch	20 μm

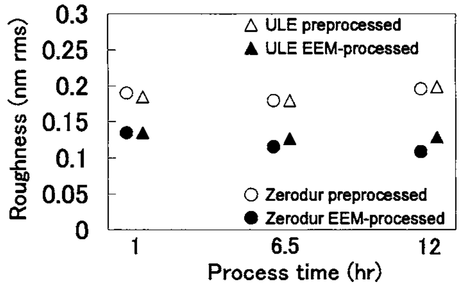

FIG. 7. Change in surface roughness during extended machining.

ing performance for extended continuous machining. This stability is attributable to the noncontact nature of this machining system. EEM using a rotating-sphere head is thus demonstrated to have excellent figuring and smoothing capabilities for the fabrication of EUV optics using materials such as ULE and Zerodur.

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