Removal properties of low-thermal-expansion materials with rotating-sphere elastic emission machining

Masahiko Kanaoka\textsuperscript{a,}\textsuperscript{*}, Hideo Takino\textsuperscript{a}, Kazushi Nomura\textsuperscript{a}, Yuzo Mori\textsuperscript{b}, Hidekazu Mimura\textsuperscript{b}, Kazuto Yamauchi\textsuperscript{b}

\textsuperscript{a}Sagamihara R&D Center, Extreme Ultraviolet Lithography System Development Association (EUVA), 1-10-1 Asamizodai, Sagamihara, Kanagawa 228-0828, Japan
\textsuperscript{b}Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

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Abstract

Optical mirrors used in extreme ultraviolet lithography systems require a figure accuracy and a roughness of about 0.1 nm rms. In addition, mirror substrates must be low-thermal-expansion materials. Thus, in this study, we processed two low-thermal-expansion materials, ULE [K. Hrdina, B. Hanson, P. Fenn, R. Sabia, Proc. SPIE 4688 (2002) 454.] (Corning Inc.) and Zerodur [I. Mitra, M.J. Davis, J. Alkemper, Rolf Müller, H. Kohlmann, L. Aschke, E. Mörsen, S. Ritter, H. Hack, W. Pannhorst, Proc. SPIE 4688 (2002) 462.] (SCHOTT AG), with elastic emission machining (EEM) in order to evaluate the removal properties. Consequently, we successfully calculated the respective removal rates, because removal volumes were found to be proportional to process times in EEM. Moreover, we demonstrated that the surface roughness of Zerodur is reduced to 0.1 nm rms in the spatial wavelength range from 100 \textmu m to 1 mm.

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1. Introduction

Extreme ultraviolet (EUV) lithography utilizing a 13.4 nm wavelength allows the patterning of lines with less than 50 nm dimensions. However, there are many technical difficulties. For one thing, EUV light is strongly absorbed in virtually all materials. Thus, mirrors coated with Mo/Si multilayers must be used instead of lenses. In an EUV lithography system, mirror substrates have to be low-thermal-expansion materials and be fabricated with an absolute figure accuracy and a roughness of about 0.1 nm rms \cite{[1,2]}. Elastic emission machining (EEM) is known for its high-smoothing performance. The surface roughness of single-crystal silicon is reduced to 0.1 nm rms or less with EEM \cite{[3]}. However, EEM has not been utilized for low-thermal-expansion materials. In this study, we evaluate the removal properties of low-thermal-expansion materials with rotating-sphere elastic emission machining. Two low-thermal-expansion materials (ULE and Zerodur) are used as specimens.

2. Rotating-sphere EEM

EEM is a machining method utilizing the chemical reaction between two solid surfaces. EEM is carried out in a fluid mixture of pure water and fine powder particles. Fine powder particles with submicrometer diameters are supplied to a workpiece surface along with a flow of pure water. When transported powder particles come in contact with the workpiece surface, a chemical reaction between the two surfaces occurs. There are two methods of generating the flow of pure water. One utilizes a jet nozzle \cite{[4]}, and the other utilizes a rotating sphere \cite{[5]}. In this study, we employ the latter method. Fig. 1 shows a schematic view of the EEM apparatus.

By utilizing a state of fluid lubrication between a rotating sphere and a specimen surface, a fluid film can be
maintained during EEM. The thickness of the film is submicrometer. Thus, the rotating sphere does not come into contact with and does not scratch the specimen surface. The diameter of powder particles is smaller than the fluid film thickness, thus the accelerated powder particles are able to flow through the film with chemisorbing surface atoms.

3. Removal properties

3.1. Removal rate

Four areas of the two low-thermal-expansion materials were processed with EEM in order to evaluate the removal rates. Each area (5 × 5 mm) was processed by a raster scan for a different length of time. The depth of each processed area was measured using a 3D optical profiler (ZYGO NewView). Table 1 shows the experimental conditions. Fig. 2 shows the relationship between process time and removal volume. Removal volume is found to be proportional to process time. On the basis of this finding, EEM for ULE and Zerodur can produce the desired shape by numerically controlling the speed and location of the rotating sphere. In the experimental conditions shown in Table 1, the removal rates of ULE and Zerodur are $0.83 \times 10^{-4}$ and $1.0 \times 10^{-4}$ mm$^3$/h, respectively.

3.2. Smoothing performance

A flat Zerodur surface was processed with EEM in order to evaluate the smoothing performance. An area of 5 × 5 mm was processed uniformly by a raster scan, and was observed using the 3D optical profiler (ZYGO NewView) in three different fields of view. Figs. 3(a) and (b) show the profiles of the preprocessed and EEM-processed surfaces. The preprocessed surface was prepared by conventional pitch polishing. EEM was carried out under the experimental conditions shown in Table 2. In the three measurement ranges, surface roughness was reduced to 0.1 nm rms. Fig. 4 shows the power spectrum density (PSD) curves of preprocessed and EEM-processed surfaces. Surface roughness was reduced in the spatial wavelength range from 100 μm to 1 mm. This result shows that EEM is very effective for reducing the detrimental effect of scattering EUV light, which we refer to as flare [6].
4. Conclusion

In the EEM of two low-thermal-expansion materials (ULE and Zerodur), removal volume is found to be proportional to process time. This result shows that we can apply both materials to a numerically controlled EEM system. The processed surface was evaluated using a 3D optical profiler in three fields of view. Surface roughness is found to be reduced to 0.1 nm rms in the spatial wavelength range from 100 μm or less to 1 mm. In an EUV lithography system, the mid-spatial frequency roughness (spatial frequencies in the 1/mm to 1/μm range) scatter light within the imaging area. Thus, EEM is effective for fabricating high-precision optical mirrors for EUV light.

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