Development of focusing mirror for X-ray free electron laser

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Abstract – We describe the fabrication of a long mirror for focusing hard X-rays to nanometer dimension. We established the figuring system with an accuracy of nanometer-level for X-ray mirror optics. Electrolytic in-process dressing grinding is used for first-step figuring and elastic emission machining is employed for final figuring and surface smoothing. The focusing mirror has an elliptical curved shape with a length of 400 mm and focal length of 550 mm. Figure accuracy with a peak-to-valley height of 2 nm is achieved. A focusing test was performed at BL29XUL of SPring-8 and found the focused beam size to be approximately 75 nm at 15 keV, very similar to the theoretical value.

***Key Words*:** XFEL, X-ray mirror, ELID grinding, EEM, On-machine measurement, MSI, RADSI

1. Introduction

Focusing X-rays to a small spot is a greatly desired technology for increasing photon density at a sample position. Such extremely narrow beams would provide a high spatial resolution for X-ray microscopy. Recently, nanofabrication technologies have advanced rapidly and high performance focusing optical components for X-rays are now readily available. Focusing optics can be divided into three classes, (1) reflective, (2) refractive and (3) diffractive. Each with advantages and drawbacks depend on the specific application, photon energy, achievable spot size and aperture and robustness. Currently, these optics can achieve focused beam sizes of less than 100 nm[1-5].

Since total reflection mirrors have high efficiency and no chromatic aberration, mirrors are permanently installed in many beamlines in synchrotron facilities, typically set in Kirkpatrick–Baez (KB) geometry[6]. Two mirrors, with elliptical curve figures, are required for two-dimensional focusing. To obtain an ideal focused beam size and focusing efficiency, unprecedented figure accuracy and smoothness are demanded for the mirror surfaces. In the past decade, mirror fabrication technology has greatly progressed and mirror surface figure accuracy of 1-nm level can be achieved. The best spot sizes are of the order of 25-nm at 15 keV[3]. Hence, the performance is limited not by mirror surface figure errors, but by the optical design, which is determined by the geometrical optics and/or wave-optical theories.

Hard X-ray free electron laser (XFEL) facilities are currently under construction in Germany, the US and Japan[7-9]. Soft XFEL are already available[10]. An XFEL produces high-intensity ultra-short X-ray flashes with the properties of laser light. This excellent new light source will open up a range of new perspectives for the natural sciences. Many researchers consider focusing mirror optics to be a key technology for the effective use of XFELs. In focusing devices, reflective optics are considered to be more promising, because mirrors have overwhelming advantages with regard to X-ray radiation hardness and focusing efficiency[3].

To date, the lengths of the employed mirrors in reported studies are shorter than 100 mm. One reason for this short length is the difficulty in machining and measuring long mirror optics. Considering the risk of damage to a mirror surface under XFEL illumination[11] and the requirement of a wide acceptance aperture, the employment of longer mirrors is indispensable. In this report, we describe the design, fabrication and evaluation of a 400-mm-long mirror for hard X-ray focusing. The focusing mirror has an elliptical curved shape with a length of 400 mm and focal length of 550 mm. Electrolytic in-process dressing (ELID) grinding was used for first-step figuring. Elastic emission machining (EEM) was employed for the final figuring and surface smoothing.

2. Optical system

We designed a two-dimensional focusing system with two long mirrors. The lengths of the vertical and horizontal focusing mirrors are 400 mm and 200 mm, respectively. The focal lengths are 550 mm and 200 mm. The working distance is 100 mm. The incident X-ray energy and glancing angle are set at 15 keV and 1.4 mrad, respectively. Elliptical shapes are employed to realize a hard X-ray beam with a size less than 100 nm at the 1-km-long beamline (BL29XUL) of SPring-8[12), 13)]. The figure profile and employed ellipse parameters are shown in Fig. 1 and Fig. 2, respectively. Figure 3 shows the wave-optically calculated intensity profile of a beam focused by the ideally shaped ellipse of the 400-mm-long mirror, for an incident slit width of 100 μm. The FWHM and the interval between the first two minima are found to be 75 nm and 150 nm, respectively.

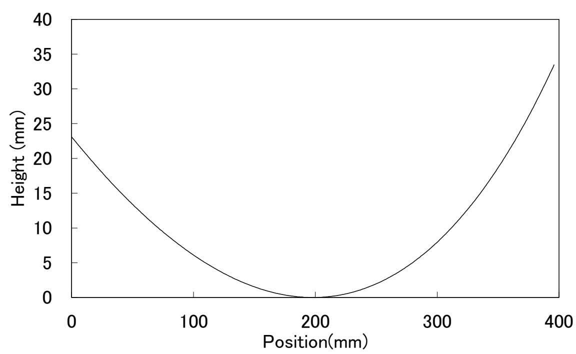

Figure 1 Figure profiles of focusing mirrors with lengths of 400 mm. The optical system is diagramed in Fig. 2

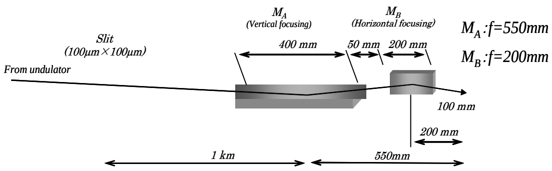

Figure 2 Hard X-ray focusing system with long mirrors

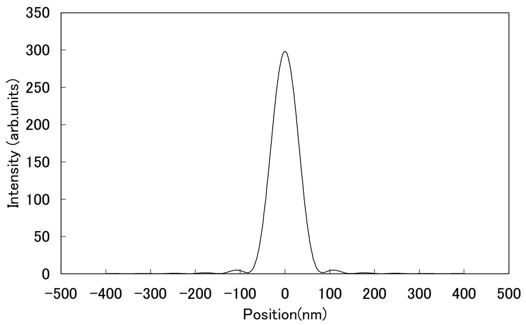

Figure 3 Intensity profiles of focused beam obtained by wave-optical simulations

3. Elastic Emission Machining

In the past decade, accuracy of the order of nanometers has been achieved for both flat and elliptical mirrors having lengths shorter than 100 mm[14), 15)]. The primary machining method for figuring ultra-precise X-ray mirrors is EEM. EEM is a surface preparation method utilizing the chemical reaction between the surfaces of fine powder particles and the process surface. In EEM, silica powder particles are typically employed as a reactive species. They are uniformly mixed with ultrapure water and are applied to the process surface via a controlled flow. When the powder particle surface and process surface come into contact and then separate, there is a significant probability that the atoms on the workpiece surface will adhere and move onto the surface of the powder particles. Observations of the surface structure after the EEM process using scanning tunneling microscopy (STM) clarified that the processed Si (001) surface is composed of almost three atomic layers. However, there is an obstacle in fabricating a 400-mm-long mirror. Since EEM can achieve removal rates of only about 10-15 m^3/h, a preliminary figuring method is required to prepare the mirror shape with figure accuracy of the order of at least 100 nm (P-V).

4. Electrolytic In-process Dressing Grinding

In ELID grinding, a mirror surface can be easily and rapidly fabricated from a substrate[16), 17)]. ELID involves dressing a metal bond diamond wheel by the electrolytic effect in the process of grinding. A large ultraprecision aspheric grinding system with ELID has been developed for the fabrication of large optical elements. The machine table size of this system is 1500 mm in length and 550 mm in width. Rectangular X-ray aspherical mirrors such as toroidal or cylindrical shapes can be fabricated. The machine slide ways use double-V rollers for 3-axis dimension. An air hydrostatic bearing is installed for the grinding wheel spindle. An ultraprecision contact-type form measuring probe was equipped for on-machine measurements. Alternation of the surface profiles after each process can be measured without separating the work from the stage table, which allows high productivity[18)]. The measuring force is so light that the probe does not scratch the mirror surface. The vertical measurement resolution is 1 nm.

Figuring is performed by precisely controlling the z-position of the grinding tool during the back and forth motion of the stage. Figure accuracy of the order of 10 nm is possible using this machine. Figure 4 shows a photograph of the X-ray mirror before and after machining, showing that a non-mirrored surface is turned into the mirrored surface.

(a) Before Machining

(b) After Machining

Figure 4 Photograph of a mirror substrate before and after ELID processing

5. Interferometric metrology -

The final surface figure testing is based on interferometric stitching technology. Surface profiles, measured by combining microstitching interferometry (MSI)[19)] and relative angle determinable stitching interferometry (RADSI)[20)], are employed as profiles before and after processing for surface figure correction with EEM. In MSI, by stitching small area surface profiles having a spatial resolution of 0.03 mm, which are measured by a Michelson-type microscopic interferometer, acquisition of the surface profiles of the entire area of a mirror is possible with the same resolution. In RADSI, by stitching partially measured profiles of curved mirrors, using a stitching angle accurately measured as the time profile data are acquired, elliptically curved profiles can be obtained. By mixing these two stitching interferome-try methods, surface figure measurement is possible with measurement accuracy matching surface figure accuracy required for ideal performance. These surface testing systems were upgraded for the measurement of 400-mm-long X-ray mirrors[21)].

6. Mirror fabrication

In this study, the 400-mm-long mirror was fabricated by combining ELID grinding and EEM. The non-mirror surface was shaped directly into an elliptical shape with figure accuracy of the order of 100 nm (P-V) by using an NC ELID grinding system. The surface was simultaneously smoothed to a mirrored surface. Final figuring and surface smoothing were then performed by EEM. Figure 5 shows the figure error profiles after several EEM figuring processes. The surface quality is gradually improved after each figuring. Finally, we achieved figure accuracy of 2 nm (P-V).

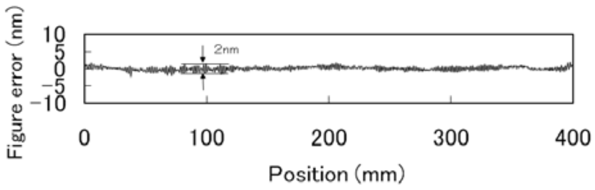

Figure 5 Figure error profile after EEM figuring process

7. Evaluation

Figure 6 shows a photograph of the experimental set-up for a one-dimensional focusing test. The experiment was performed using the 1-km-long beamline of SPring-8. The distance between the incident slit placed behind the monochromator and the mirror was 950 m. The average incident angle was 1.4 mrad. Monochromatic 15-keV X-rays were one-dimensionally focused. The mirror was supported by only the three Bessel points on the rigidly structured table to minimize the change in the overall length. The mirror shape determined using X-rays was the same as that determined by RADSI profiling during fabrications. The focused X-ray beam was probed by inserting a gold wire and analyzing the relationship between the vertical height and the intensity passing though the wire. The passing X-ray photons were counted using an avalanche photodiode, because of its high linearity in photon counting.

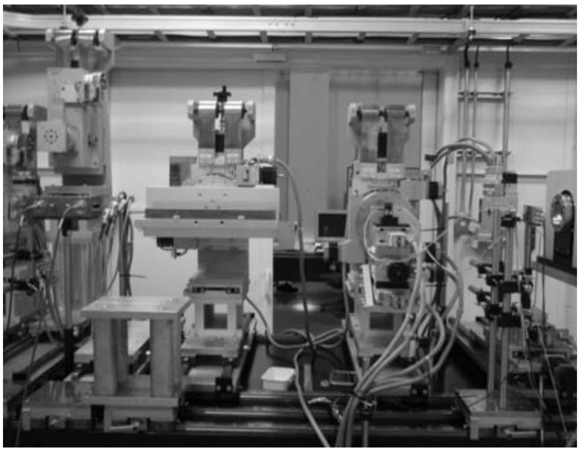

Figure 6 Experimental setup for investigating the focus of the fabricated mirror

Attention was paid to accurately aligning the mirror. The incidence angle is sensitive to the deformation of the shape of the focused beam. This angle was adjusted using a goniometer, monitoring the intensity profile of the focused beam, and optimizing the angle so that the minimum beam size was attained. Other parameters, such as the yaw angle relative to the incident X-ray beam, were finely adjusted when the mirror was inserted on the stage. Figure 7 shows the measured and ideal intensity profiles of the focused beam. The focused beam size was 75 nm, as defined by the full width at half maximum of the profile. This size is almost equal to the ideal size under diffraction-limited conditions at 15 keV.

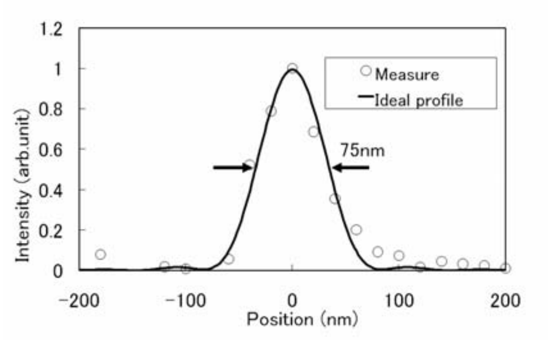

Figure 7 Intensity profile of the focused X-ray beam

8. Discussion

In this study, a 400-mm-long mirror for hard X-ray focusing was designed, fabricated and evaluated. The mirror will not only be useful at XFEL facilities, but may also be used at current third-generation synchrotron radiation facilities, due to the fact that when using a long mirror, a long work distance can be selected with a small focused beam size. This advantage promises breakthroughs in X-ray microscopy. The various systems for analysis can be set around samples.

Prior to this study, there were two obstacles in producing long mirror optics. The first was the difficulty of measuring a curved surface profile. The second was the requirement for improved production efficiency. In this report, we describe the effective solutions to these obstacles. This technological development will make available highly accurate mirror optics of long length, which will be of great use to many researchers.

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