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A study of the mirror design and the fabrication for an X-ray microscope

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Abstract

One of the exciting research areas of the X-ray microscope is the observation of a living cell. In order to study a living cell with high resolution, the order of the several tens nm , we need to improve the efficiency of mirrors which are components of an X-ray microscope system.
In this paper we present the mirror design and manufacture to give a high resolution and reflectivity. We designed Wolter type I the condenser and objective mirror with the several tens of nm resolution. According to mirror design, we made the program using the visual basic. Using the new processing method as well as the ultra-precision diamond cutting, we directly processed the inside of an aluminum bulk in order to manufacture mirrors. From the experimental result, we think that the new processing method will improve a high reflectivity through the improved cutting tools and optimum cutting conditions.

Keyword : X-ray microscope, Wolter type I, condenser mirror, objective mirror, ultra-precision diamond cutting.

1. Introduction

X-ray microscope systems are applied to organisms as well as industrial and electronic materials. One of applications of the them is the observation of living cells that is an active research area in the world. X-ray microscope enables us to observe dynamic specimens, living cells, with several tens nm resolution. Also developments are progressing to analyze the elements without destruction.

To concentrate the X-ray in one point, there are largely two methods such as diffraction and reflection. Because of the refraction index $n \leq 1$ for X-ray range, many researchers use the reflection. So the optical components are not lens but mirrors for X-ray microscope. The total reflectivity is commonly used in order for improving the reflectivity that is connected with the roughness of surface of mirrors and grazing incidence angle.

We need reflective mirrors with several nano-meter surface roughness. It is very difficult to process the mirrors with the precision at present. There are a variety of methods to manufacture. One of them is a replica method. The mold is made through grinding and polishing. We deposit Au or Pt to the mold by coating. Using this replica, we can make mirrors and then polish the inner surface of the mirror to reduce the roughness. Many mirrors can be made in principle but actually only a few possible. It is necessary to several steps in the replica method so that there are a lot of factors inducing errors[1]. We need to a new technique to obtain the Wolter type I mirror in the inside of the bulk material.

In this paper, we will present the mirrors, the Wolter type I condenser and objective, designed and fabricated to give a high resolution and reflectivity in order to observe the living cell in the range of the water window. We design Wolter type I mirrors with the resolution about tens nm. Using the ultra-precision diamond cutting, We will directly process the inside of an aluminum bulk to produce mirrors used in the X-ray microscope by computer numerical control. Fig.1 represents to the procedure of the mirror design and fabrication diagram.

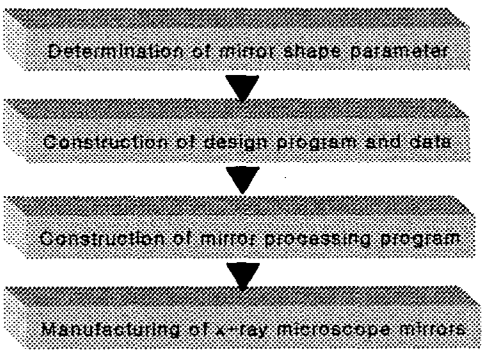


Fig.1. The procedure of the mirror design and fabrication diagram.

2. The optical mirror design of the X-ray microscope

Because the refractive index is below one in the X-ray range, so we use the reflection property. In order to obtain the high reflection, we use the total reflection. The critical angle (radian)[2] is represented by

$$\Theta_c = 1.6 * 10^{-3} \lambda \text{ root } \{\rho\}. \quad (1)$$

Where λ and ρ represent the wavelength of the incidence wave with Å unit and the density of the material, respectively.

Fig.2 represents the reflectivity of various materials according to the grazing incidence angle for 560ev photons. Where the Al stands for high reflectivity than others below about 50mrad. Al show that the reflectivity is rapidly tend to decrease above 50mrad. To get high reflection, it is necessary to select proper material and control a grazing incidence angle.

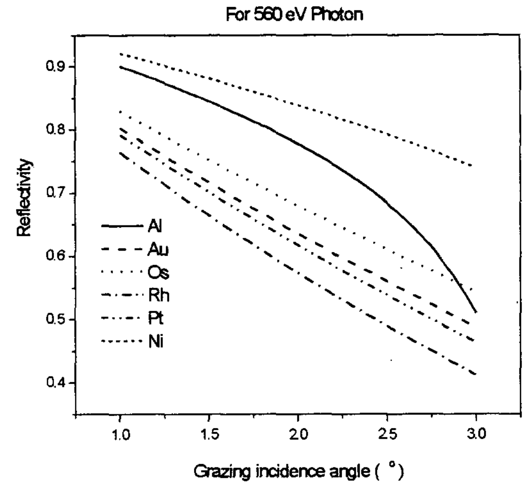


Fig.2. The reflectivity of various materials.

2.1. The design of the Wolter type I mirror

The Wolter type I mirror [3] which consists of an ellipsoid and a hyperboloid is used for X-ray microscope, as shown Fig.3,

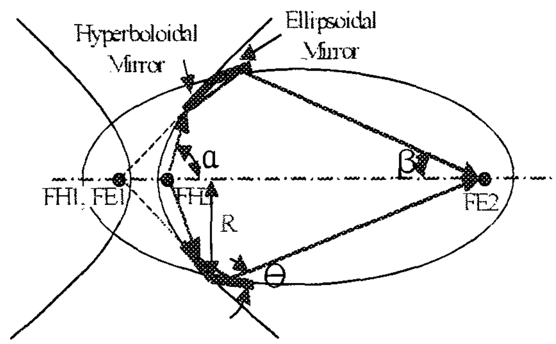


Fig.3. The concept of Wolter type I mirror

The Wolter type I (objective mirror) has the shape where one focal point (FH1) of the hyperboloid coincides with one focal point (FE1) of the ellipsoid, on the optical axis. The X-ray source is focused to the other focal point (FE2) of the ellipsoid. The sample is located at the another focus point (FH2). The X-ray is reflected on the hyperboloid at first and then the ellipsoid. The Wolter type I is approximately satisfied with the Abbe's sine condition and minimizes coma aberration.

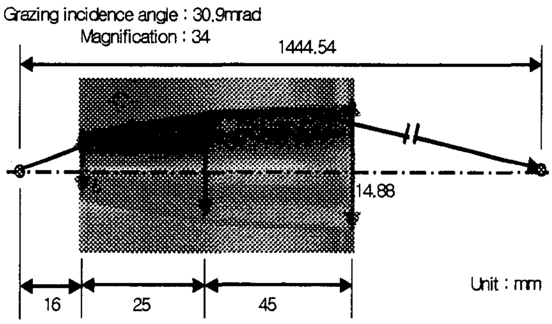


Fig.4. The parameters of the Wolter type I mirror.

In this study, Fig.4 represents the Wolter type I objective mirror with its parameters. The condenser mirror is also similar to objective mirror. According to its parameter of mirror design, we made the program using the visual basic.

2.2. Reflectivity and imaging of the Wolter type I objective mirror

Though the Wolter type I objective mirror in theory has a high resolution, the real mirror doesn't have the theoretical value. The shape deviation by fabrication occurs to a drop of reflectivity, contrast, resolution, penumbral blurring and so on.

The reflectivity in the ideal reflective surface of mirror can be written by

$$R=|\{\Theta-\mathrm{root}(n^2-\cos^2\Theta)\}/\{\Theta+\mathrm{root}(n^2-\cos^2\Theta)\}|^2 \quad (2)$$

Where R , n, and Θ represent the reflectivity, the refraction index, and the grazing incidence angle, respectively. But a real mirror surface has surface roughness after fabrication. The reflectivity of the mirror surface is

$$R = R_0 \exp\{-(4\pi\ \sigma\ \sin\Theta\ /\ \lambda)^2\} \quad (3)$$

Where R_0, R, σ , and λ represent the reflectivity at the ideal surface, the reflectivity of real surface, the root mean squares (RMS), and the wavelength of the incidence wave, respectively.

In order to have the reflectivity damage below minimum 10%, the surface roughness(σ) must be about 2nm below for λ = 3.2nm and Θ = 30.9mrad.

The path difference of the reflected X-ray between the ideal surface and the real surface is

$$\Delta L = 2h \sin\Theta \quad (4)$$

Where ΔL, h, and Θ represent the path difference, the height between the ideal surface and the real surface , and the grazing incidence angle. If the path difference of them is smaller than λ/4, the difference of them give a small effect in imaging as the imaging condition of Rayleigh,

$$2h \sin\Theta < \lambda / 4 \quad (5)$$

For 3.2nm wavelength and 30.9mrad grazing incidence angle in this study, the result is h < 12 nm.

3. Experiment & Result

3.1. Manufacture of Wolter type I objective mirror

The Wolter type I objective mirror has 6mm in minimum diameter as shown Fig.5. The diamond tool has 5.5mm in diameter.

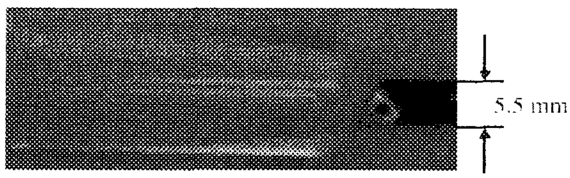


Fig.5. The machined Wolter type I objective mirror

We need to process the inner surface of small diameter from which the reflection arises, but it is very difficult to obtain the mirror with nm order without ultra-precision processing technique.

We here we try to get the mirror with nm order using ultra-precision diamond cutting[4]. Before ultra-precision diamond cutting, we first drill a cavity inside of the bulk. And then we put practice in the inner processing using single crystal diamond tool as shown in Fig.6.

Fig.6. A manufacturing of mirror using D.T.M

3.2 Suggestion new method in the mirror fabrication.

Fig.7 shows the surface roughness of the mirror which is about several 10nm order using ultra-precision diamond cutting.

The measured surface roughness value indicated RMS 37.935 nm for Al. It is hardly to use a mirror for X-ray microscope.

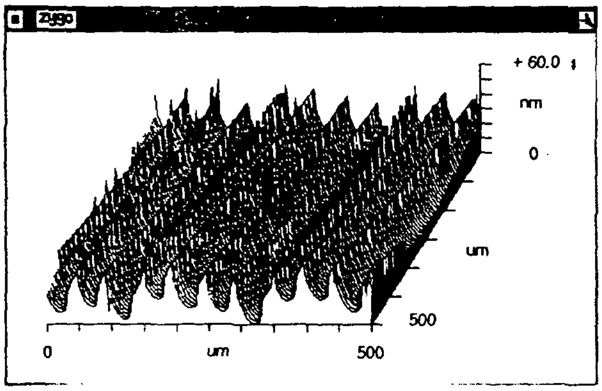
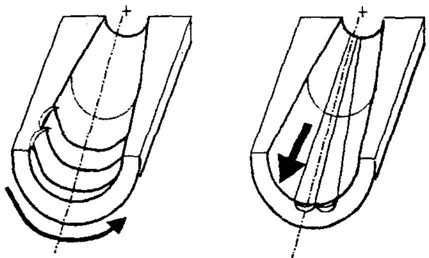


Fig.7. The surface roughness of mirror by the inner processing

To obtain the surface roughness with range from 1nm to 0.1nm in spite of the direct inner cutting, we need a well-designed diamond cutting tool and the study of materials of mirror with the high reflectivity in the water window wavelength and a good surface roughness. And we have to also consider the chip and vibration of diamond cutting tool during processing.

The latter is factor generating large surface roughness. We consider the thickness, the length, and the diameter of shank when we design the diamond cutting tool.

To improve the reflective surface, we used electroless nickel as mirror material through experiments.[5]



(a) inner processing (b) new method

Fig.8. The traces in terms of inner processing and new method.

The cutting tool makes traces that are perpendicular to the optical axis on the reflective surface as shown in Fig. 8(a). Those give the scattering of the incidence X-ray and reduce the reflectivity of the surface.

Overcoming the weak point, we changed the method that the processing direction is the same that of the optical axis as shown Fig. 8(b). We believe the surface reflectivity will improve.

To test surface roughness as mentioned argument, we first experimented in plane processing for the each method in the case of an aluminium and an electroless nickel.

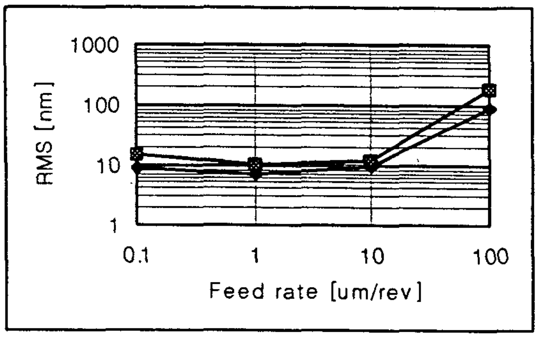


Fig.9. The surface roughness for aluminium.
(■ inner processing , ◆ new method)

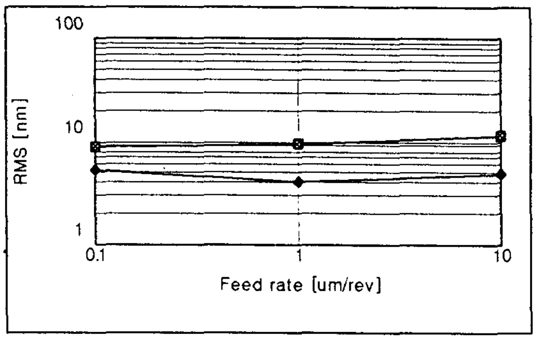


Fig.10. The surface roughness for electroless nickel.
(■ inner processing , ◆ new method)

The surface roughness was measured by the ZYGO New View 200, and result is Fig.9 and Fig.10.

In this tests, the aluminium and electroless nickel were measured almost similar tendency, but different values, for feed rates, and large surface roughness appeared at 100 (um/rev). We knew that the new method is possible to process the mirror. We experimented in new method in the case of an cylindrical Aluminium. From the results(Fig.11.) which measured from ZYGO New View 200, we verified the surface shape to be suitably machined.

4. Conclusion

In this paper we present X-ray mirror design and

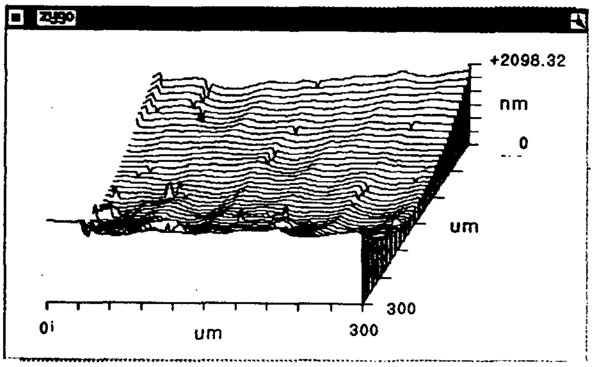


Fig. 11. The machined surface shape by the new method

manufacture to give a high resolution and reflectivity. We design Wolter type I the condenser and objective mirror with the several tens nm resolution. According to mirror design, we directly make the program using the visual basic. Using the processing method as well as the ultra-precision diamond cutting, we directly process the interior of bulk aluminum in order to manufacture mirrors. From experimental results we believe that the new processing method will improve high reflectivity.

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