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Manufacturing and testing of X-ray imaging components with high precision

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Abstract: In the latest 20 years, X-ray imaging technology has developed rapidly in order to meet the needs of X-ray photo-etching, spatial exploration technology, high-energy physics, procedure diagnosis of ICF, etc. Since refractive indices of materials in the X-ray region are lower than 1, and X-ray is strongly absorbed by materials, the characteristics of X-ray increase greatly difficulty to obtain X-ray image. Conventional imaging methods are hardly suitable to X-ray range. In general, grazing reflective imaging and coding aperture imaging methods have been adopted more and more. We have designed a non-coaxial grazing reflective X-ray microscope which is composed of four spherical mirrors, in order to satisfy the requirement of the diagnosis of inertial confinement fusion (ICF). The four mirrors have the same radius of curvature. The radius of each mirror is 29 000 mm and the aperture is 30 mm×15 mm. Allowable tolerance of the radius is $\leqslant 0.2\%$ and one of surface roughness (rms) is $\leqslant 0.6$ nm. Evidently it is very difficult to fabricate and test such mirrors. In order to obtain eligible mirrors, we choose 18 mirror roughcasts and array them on a round disk according to format. The combined manufacturing method can ensure high accordant quality. The fabricated mirrors are tested by both templet and double round aperture methods. Radius errors of the mirrors is about 53 mm. The surface roughness (rms) of the mirrors is inspected by the relative interferometric equipment (WYKO) and atomic force microscope. Before and after coating the measured surface roughness is averagely 0.52 nm and 0.4 nm, respectively.

Key words: X-ray imaging; quality evaluation; manufacturing and testing; nanometer precision; nanometer component

1　Introduction

X-ray imaging technology has been one of the most important research contents since Roentgen discovered X-ray in 1895. Initially, X-ray was used to study the internal structure of substances by contact radiography. The specimen is placed in contact with a photographic film during the X-ray exposure. The image of the specimen is displayed after developing. The method has been used until now, and it is widely applied in medical treatment and inner flaws detection of industrial materials.

Since the refractive indices of materials in X-ray range are lower than or very close to unity, and X-ray almost can not reflect from a smooth surface, conventional refractive and reflective imaging methods are not suitable for X-rays, which confine the development of X-ray imaging and diagnosis technologies.

Now grazing reflective imaging technology and coding aperture imaging technology are major imaging methods in X-ray range.

In 1922, Compton discovered that under grazing conditions X-rays can reflect from pol-

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ished surfaces, and even total external reflection is observed[1].

Kirkpatrick and Baez developed a method to eliminating astigmatism of single concave mirror under grazing condition in 1948, as shown in Fig. 1. Two perpendicular spherical mirrors (or cylindrical surface) are used in the method, that is later so called KB microscope. Although this microscope removes astigmatism, there also exist strong field obliquity and coma, and spherical aberration is not corrected also. With the decreasing of grazing angle, these aberrations will become more and more severe, so people didn't pay enough attention to KB in a long time.

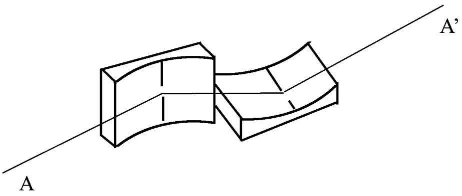

Fig. 1 KB microscope

Entering 90's of last century, X-ray imaging technology has developed rapidly for the needs of X-ray photo-etching, spatial technology, high energy physics, process diagnosis of the inertial confinement fusion (ICF). KB microscope is paid attention to afresh. In 1989, Yosihio Suzuki etc. substituted elliptical-cylindrical mirrors for perpendicular spherical mirror in KB microscope in order to eliminate spherical aberration[2]. Therefore the imaging quality of the system is greatly improved, but severe coma and field obliquity are still not corrected. In 1995, R. Kodama et al. designed a system called as AKB X-ray microscope. They used four mirrors, a pair of the mirrors was hyperboloid-cylinder surfaces, the other pair of the mirrors was ellipsoid-cylinder surfaces, as shown in Fig. 2. Since there are two mirrors in meridian plane and sagittal plane, respectively, the structure decreases field obliquity remarkably, and increases effective field. Since aspheric surface is used in the system, difficulty of manufacturing and assembling is increased once again.

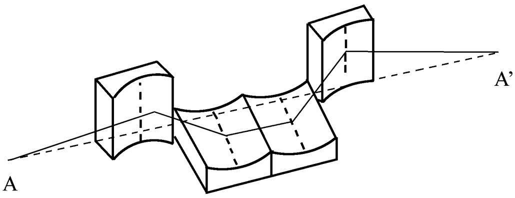

Fig. 2 AKB microscope

R. Saunenf etc. developed KBA type microscope in 1997[4]. The microscope is composed of two pairs of mirrors perpendicular to each other, two mirrors in each pair are parallel as shown in Fig. 3. It is well known that if the angle between two parallel mirrors is η, then the angle between the incident light and the exit light from second surface is 2η. And the angle doesn't change with the altering of the grazing incident angle. Thus field obliquity is essentially corrected, and effective field is expanded also. The resolution of 5～7 μm is obtained in 2 mm field.

According to requirements of National Key Laboratory of Laser Fusion of the Chinese Academy of Engineering Physics, Mianyang, Sichuan province, we have designed a KBA X-ray microscope working at grazing incident, in order that the system implements diagnosis of ICF exploded by high power laser. Nowadays the equipment is manufactured and assembled[5-6]. The emphasis of the paper is on the manufacturing and assembling of the KBA microscope. The key components of the microscope are four mirrors with very large radius of curvature (29 000 mm). The requirement of radial error is lower than 0.2%, this is equivalent to $\Delta R \leqslant 60$ mm and the surface roughness (rms) of the mirrors is lower than 0.6 nm. It is greatly difficult to manufacture and test the components. The paper will principally discuss methods of manufacturing and testing the mirrors.

2 KBA X-Ray microscope

We have known that off-axial thin rays near pseudo axis can be calculated from Young's equations[7].

$$\frac{n'\cos^2 I'_p}{t'}-\frac{n\cos^2 I_p}{t}=\frac{n'\cos'_p-n\cos I_p}{r}\ ,\qquad(1)$$

$$\frac{n'}{s'}-\frac{n}{s}=\frac{n'\cos I'_p-n\cos I_p}{r}\ ,\qquad(2)$$

Where t, s, t' and s' are object distance and image distance formed by meridian and sagittal rays respectively, I_p, I'_p are incident angle and refractive (reflective) angle of principle ray, n is the index of the front medium, n' is that of the back, and r is curvature radius. If the imaging component is a mirror, $n'=-n=-1$, $I'_p=-I_p$, equations (1) and (2) become

$$\frac{1}{t'}+\frac{1}{t}=\frac{1}{f'_t}=\frac{2}{r\sin\theta}\ ,\qquad(3)$$

$$\frac{1}{s'}+\frac{1}{s}=\frac{1}{f'_s}=\frac{2\sin\theta}{r}\ ,\qquad(4)$$

Here θ is the grazing angle, $\theta=90-I_p$. f'_t, f'_s are the focal length in meridian plane and sagittal plane, respectively.

KBA X-ray microscope is developed on the basis of KB microscope[4]. It's purpose is to eliminate or reduce field obliquity and off-axial aberration in order to increase effective field of KB microscope.

As we have shown, if the angle between two mirrors is η, then the angle between incident light beam and emergent light beam from the second mirror is 2η, and whatever incident angle is, the angle doesn't change. This is the natural characteristic of double mirror system as shown in Fig. 4.

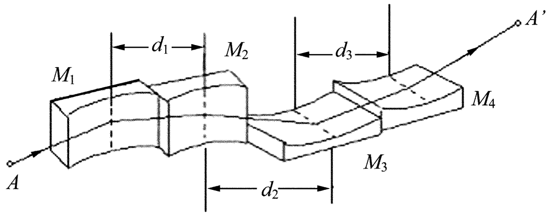

Fig. 3 KBA microscope

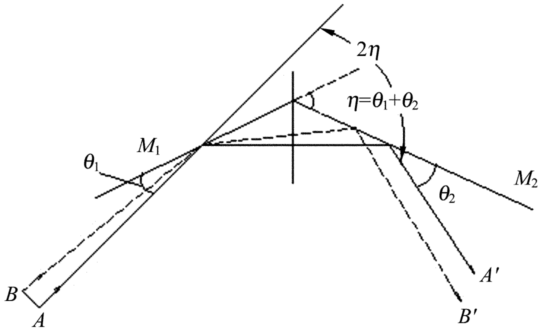

Fig. 4 Reflective characteristic of the double parallel mirrors

We assume the grazing angle of incident light is θ_1, and the grazing angle of the ray entering into the second mirror is θ_2, then $\eta=\theta_1+\theta_2$, as shown in Fig. 4. The angle between incident light and emergent light from the second mirror is $2\eta=2(\theta_1+\theta_2)$. Thus, the focal length of the system is nearly same for both A and B at different fields in object plane. Now we calculate the combined focal length and power of the two parallel mirrors.

As shown in Fig. 4, if the interval between the two parallel mirrors is d, the assembly focal power is

$$\begin{aligned}\varphi&=\varphi_1+\varphi_2-d\varphi_1\varphi_2\\&=\frac{2}{R_1\sin\theta_1}+\frac{2}{R_2\sin\theta_2}-\frac{4d}{R_1R_2\sin\theta_1\sin\theta_2}\ ,\end{aligned}\qquad(5)$$

Here $\varphi_1=\frac{2}{R_1\sin\theta_1}$, $\varphi_2=\frac{2}{R_2\sin\theta_2}$, R_1 is curvature radius of mirror M_1, and R_2 is curvature radius of mirror M_2. If $R_1=R_2=R$, $\theta_1=\theta_2=\theta=2/\eta$, then the above equation becomes

$$\varphi=\frac{2}{R^2\theta_1\theta_2}[R\eta-2d]=\frac{8\left(1-\frac{2d}{R\eta}\right)}{R\eta}\ ,$$

$$f'=\frac{R\eta}{8\left(1-\frac{2d}{R\eta}\right)}\ . \tag{6}$$

When $d \ll R\eta$, the equation (6) can be further simplified as

$$\varphi\approx\frac{8}{R\eta}\ , f'\approx\frac{R\eta}{8}\ . \tag{7}$$

According to requirements of National Key Laboratory of Laser Fusion of the Chinese Academy of Engineering Physics, Mianyang, Sichuan, we have designed a KBA X-ray microscope working at grazing incident, in order that the system implements diagnosis of ICF exploded by high power laser. The structure parameters of the KBA microscope are as follows. The target distance is $L=-200$ mm. The grazing angle on front two mirrors is 1.6° ($\theta_1=\theta_2=1.6°$), and one on back two mirrors is 1.9° ($\theta_3=\theta_4=1.9°$). The solid angle of the system is $\omega=4\times10^{-6}sr$. The aperture angle in object space is 0.0065°. The radius of each mirror is $R=29\ 000$ mm. The intervals between the mirrors are $d_1=27$ mm, $d_2=29$ mm, $d_3=25$ mm, respectively. The image distances in the meridian plane and sagittal plane are 1786.71 and 1786.73. The magnifications of meridian and sagittal dimension are $7.925^{\times}$ and $6.2316^{\times}$, respectively.

3 Manufacturing and testing of X-ray mirrors with high precision

We have designed a non-coaxial grazing reflective X-ray microscope which is composed of four spherical mirrors, named as KBA. The four imaging mirrors in KBA X-ray microscope are key components. They decide imaging quality of the whole system. Manufacturing and testing the components with high precision is required. In order to acquire sufficient reflectivity of the imaging system working at 1.6° grazing angle, the surface roughness of the mirrors should be lower than 0.6 nm. For the sake of convenient for fabrication, the four mirrors with the same radius are designed. Since the radius of curvature is very large ($R=29\ 000$ mm), and that the apertures of the components are quite small, maximal aperture of them is 30 mm × 15 mm. Through analysis and calculation, allowable tolerance of the radius is ≤0.2%, that is to say, $\Delta R\leqslant 60$ mm. Evidently, it is awfully difficult to fabricate and estimate the mirrors with such high precision.

If test plate (templet) of a plane is used to test the manufactured mirrors, the maximal interval between the plane templet and the surface of a mirror is .

$$x=\frac{D^2}{8R}\ , \tag{8}$$

where D is the maximal aperture of mirrors, R is the radius of the mirrors.

If $R=29\ 000$ mm, $D=30$ mm, from above equation we can obtain $x=0.00\ 388\ \text{mm}=7\lambda$ ($\lambda=550$ nm). The value is equal to 14 Newton rings. Each Newton ring corresponds to about radius error of 2 000 mm.

If the requirement of $\Delta R\leqslant 60$ mm is satisfied, which shows that the error of surface form of the mirrors is lower than $\lambda/67$. Thus conventional templet testing or interferometric methods can not reach the precision.

In order to obtain eligible mirrors, we choose 18 mirror roughcasts and array them on a round disk according to 3 × 6 format. Fused quartz is selected as material of the mirrors. The combined manufacturing method can ensure high accordant quality of the mirrors. Total aperture of the set of the mirrors approaches 100 mm.

We apply double round apertures to test the radius of the fabricated mirrors. The 18 mirrors arranged on a round disk are illuminated by collimated laser beam, the aperture of the beam is larger than 100 mm. Location of focal point of the mirrors is measured time and again. Thus average value of the radius can be obtained. Furthermore, in order to acquire reliable value of the radius, a screen with accurate scale is located before and after the focus, as shown in Fig. 5. When aperture of the laser beam is 30 mm, the distance from the focus before and after the focus is measured repeatedly. The average value is finally obtained. Through these measurements, the radius value with high precision is achieved. The error of the radius is about $\Delta R=53$ mm.

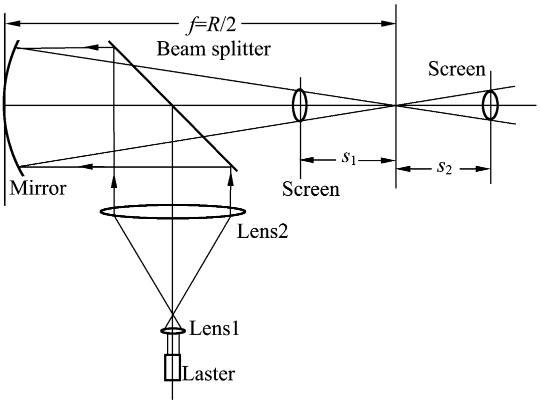

Fig. 5 Measurement scheme of mirror's radius

In order to obtain high form precision of the components, a spherical templet with super high precision is manufactured in advance. The templet is tested by ZEGO interferometer, The form precision of the test plate is close to $\lambda/70$. We estimate the fabricated mirrors using the test plate, The Newton ring is not observed, which indicate that radius precision of the mirrors is identical with one of the test plate.

The surface roughness (rms) of the mirrors is inspected by the relative interferometric equipment (WYKO) before coating. The measured surface roughness (rms) is lower than 0.52 nm. Afterwards the chromium and nickel films are coated on the fabricated mirrors. The coated mirrors are measured by atomic force microscope made in South Korea. The roughness of resultant mirrors is equal to or lower than 0.4 nm. The Fig. 6 indicates measured result on surface area of a mirror using the atomic force microscope.

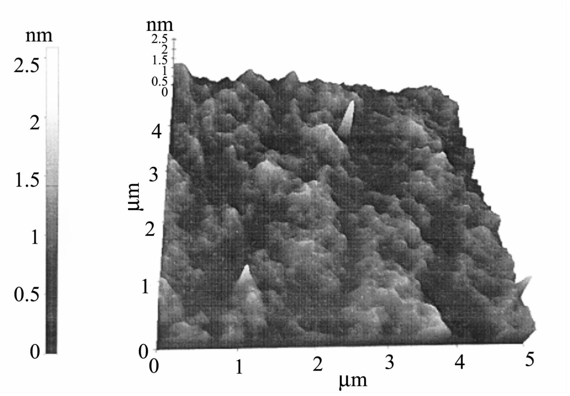

Fig. 6 Surface roughness inspected by atomic force microscope

4 conclusion

We have successfully manufactured and assembled the KBA X-ray microscope with high precision. The radius error of the four imaging mirrors is lower than 0.2%, i. e. $\Delta R=53$ mm. Before coating the surface roughness (rms) of the mirrors is lower 0. 52 nm, The mirror′s roughness of 0.36 nm is obtained after coating.

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Brief professional biography of the author:

HU Jia-sheng received his MS degree in applied optics from Changchun Institute of Optics and Fine Mechanics,in 1966 and became a professor in 1988. He was a visiting scholar and a visiting professor at the University of California,Santa Barbara,in 1980 to 1982 and in 1993,and he is currently a professor at the Dalian University of Technology. He has received various awards from administration of China and Chinese Academy of Sciences,including the first award for research and design of an optical processor for synthetic aperture radar and two second awards for a laser scanning microscope and a multi-spectral imaging microscope. He was also named as an excellent scientist in 1996 by government of China. His main interests are novel imaging techniques,image processing,pattern recognition,and optical system design. He has published over 100 papers in these areas. He is a member of SPIE.