Textbook for hard X-ray focusing with Kirkpatrick-Baez optics

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1. Background

Currently, grand-scale synchrotron radiation facilities, where high-quality X-ray sources are available in wide energy ranges from the soft- to hard- X-ray regions, have significantly advanced the performance characteristics of analytical technologies using the fluorescence, absorption and diffraction effects of X-rays in various materials. The application of X-ray microscopy with these exceptional X-ray characteristics has expanded in the fields of material, medical and biological sciences, due to the fact that this method is capable of nondestructive analysis of material characteristics for a variety of different samples including cells and proteins. Since focused X-ray beams are required to transmit spatially distributed information, X-ray focusing technologies are considered to be critical to the advancement of X-ray microscopy, with various methods based on diffraction (e.g. Fresnel zone plate) refraction (e.g. Compound reflective lenses) and total reflection (e.g. Kirkpatrick-Baez mirrors) being developed.

2. Kirkpatrick-Baez (KB) optics

In 1948, Kirkpatrick and Baez proposed an X-ray focusing optical system consisting of two total reflection elliptical mirrors, which aligned perpendicularly (Fig. 1). This focusing optical system is considered promising due to its potential to remarkably improve the performance characteristics of X-ray microscopy by enabling more efficient collecting of X-rays than in other methods. A further advantage is that the method maintains the focusing state with the same optical arrangement even if the wavelength of the X-rays is shifted. However, to realize X-ray beams with an ideal focal size, high efficiency and absence of background noise around a main peak, it is necessary to prepare elliptical mirrors having a very high degree of figure accuracy (approximately 2 nm peak-to-valley figure accuracy) and surface smoothness (approximately 0.2 nm RMS) over an entire reflective area, and position two mirrors accurately. Currently, such nearly perfect mirrors (so-called Osaka Mirror) are commercially available from JTEC (http://j-tec.co.jp/english/focusing/index.html).

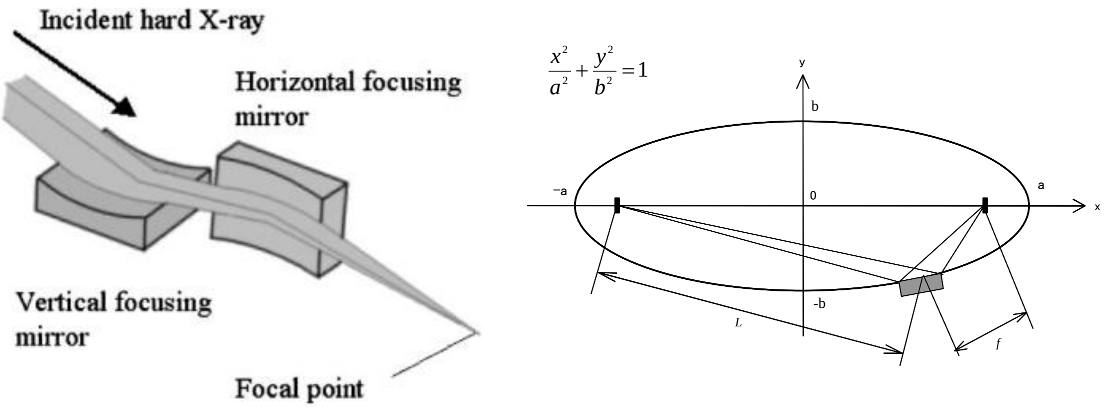

Figure 1 Kirkpatrick-Baez optics. It consists of two elliptical mirrors aligned perpendicularly to each other. X-rays from a light source placed at one focus are reflected on the mirror surface and always reach the second focus.

3. Fabrication process of X-ray mirrors

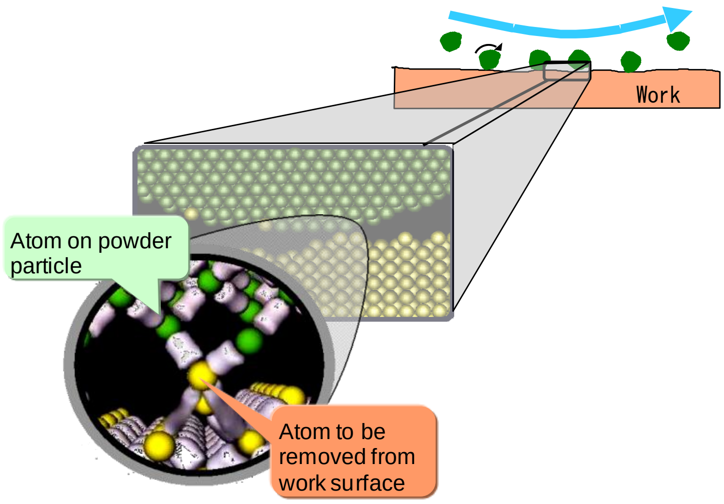

Figure 2 Elastic emission machining (EEM). EEM is an ultraprecise machining method that utilizes the chemical reaction between the surfaces of the workpiece and fine powder particles. Topmost atoms on the workpiece will preferentially adhere to and move onto the surface of the powder particle. Eventually, atomically smooth surfaces can be obtained.

Typical fabrication process (for Osaka Mirror) is described below (for more detail, see Ref. 1 and 2). First, a substrate (e.g. synthetic silica, silicon or BK7) are roughly figured with proper polishing methods (e.g. optical pitch polishing) until the obtained surface has figure errors of 1.0-0.5 μm. Then the mirror is figured by EEM process (Fig. 2) to have a figure error of 2 nm peak-to-valley and an RMS surface roughness of 0.2 nm over an area of 64 × 48 μm². For almost all mirrors, the figure accuracy is accurate enough. The figured mirror is coated with a thin chrome binder layer and a platinum (Rhodium or other heavy metals) layer using a coating system.

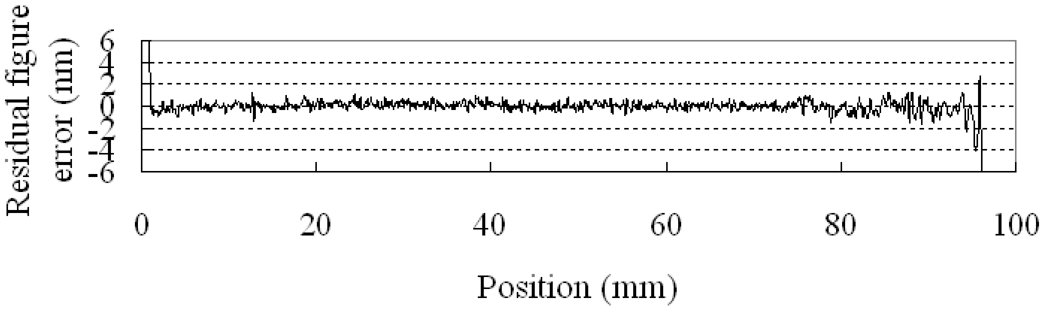

Figure 3 Typical figure error of an Osaka Mirror. Figure accuracy of 2 nm peak-to-valley can be easily obtained with our fabrication method.

4. Tolerance limits of mirror alignments

Tolerance limits of a typical KB optics (for more detail, see Ref. 3 and 4) are shown in Fig. 4. The most sensitive positioning is the alignment of the glancing angle. Fine tuning with an accuracy of 1 μrad level is required to obtain a sharp beam. On the other hand, in-plane rotation is not so sensitive. Adjustments for the in-plane rotation easily can proceed without special instruments.

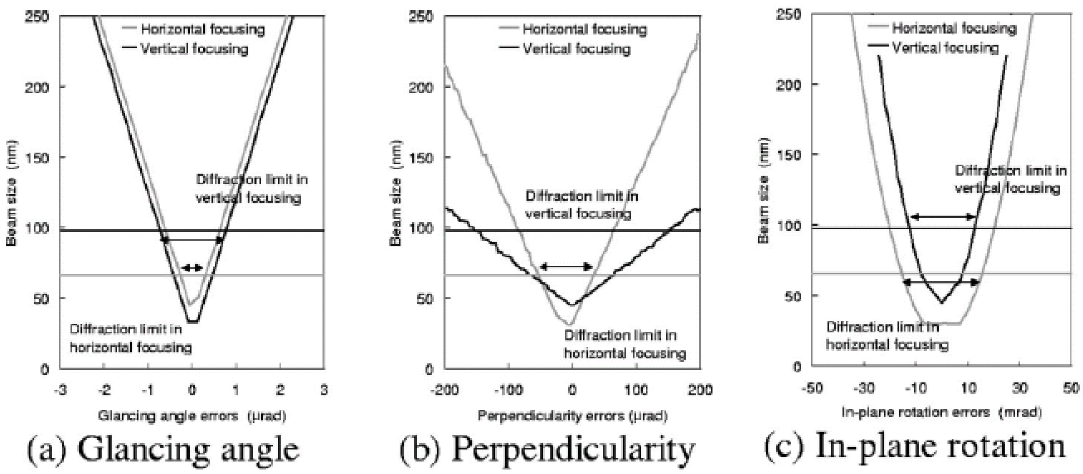

Figure 4 Tolerance limits of mirror alignments. The vertical axis means geometrical beam size calculated by ray-tracing simulator. The horizontal lines indicate the diffraction limits defined as the distance between the first minima.

5. Alignment procedure

To realize X-ray beams with an ideal focal size and high efficiency, it is important to align two mirrors properly. A typical alignment of KB optics proceeds in the following order (see the other sheet distributed in the BL practice). For the alignments, a mirror manipulator, which was specially developed, is used (Fig. 5). The most important points are the adjustments for perpendicularity and for glancing angles. The adjustment for the perpendicularity can easily proceed using two autocollimators and a pentaprism. The final fine adjustment proceeds repeating measurement of beam size with a wire scanning method and adjustments for the glancing angles and the focal lengths.

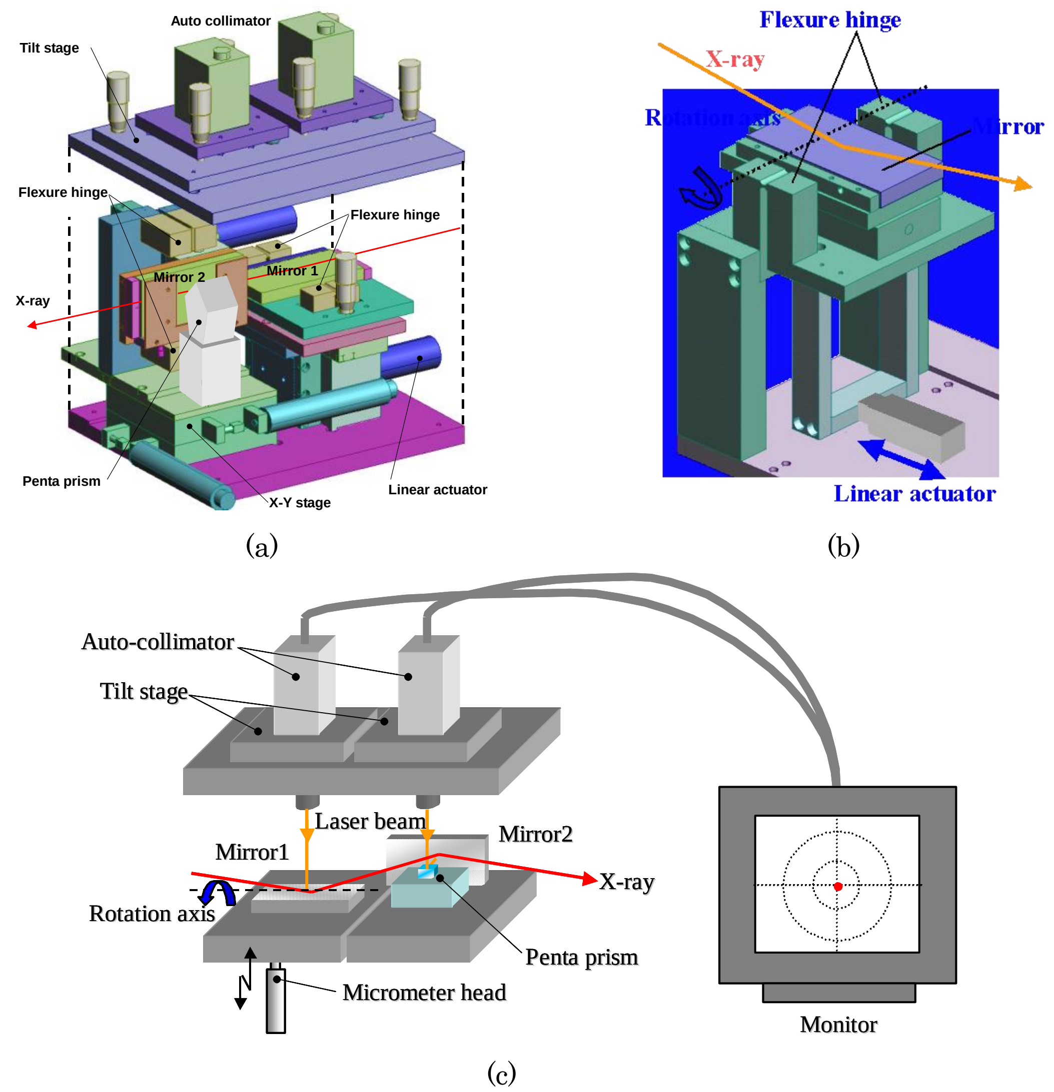

Figure 5 (a) Mirror manipulator equipped with (b) glancing angle adjustment systems and (c) a perpendicularity adjustment system

References

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