FINISHING OF SYNCHROTRON BEAMLINE MIRRORS

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Abstract

Synchrotron radiation beamline is used for carrying out research on X-ray based techniques. A wide variety of beam lines are being developed for extending the applications in micro / nano domains of medical science, physics, semiconductor, optics, material science and many more. X-ray mirrors are essential component of any such beamline for guiding the X-ray beam and focusing it to a particular location. Different shapes of mirrors such as flat, cylindrical, elliptical and toroidal are generally used in the beamlines. Slope error in micro radian and surface roughness in a few Å (< 3) are the prime requirements for good focusing properties of synchrotron beam and good reflectivity of X-ray beam.

The above requirements and stringent control over the surface figures make the fabrication and finishing of these mirrors very challenging and extremely difficult. Fabrication and finishing of mirrors consist of loops of different process steps with intermediate metrology stages. The loops are continued until the surface attains the desired specification level. Due to very stringent requirements of surface roughness and figure accuracy, only few processes are used for fabrication of these mirrors. A brief overview of different finishing processes is given in this paper. A few processes are discussed in depth and a hybrid finishing process is proposed for finishing of mirrors.

Keywords: Synchrotron radiation, silicon mirrors, magnetorheological finishing, elastic emission machining, abrasive particles.

1 Introduction

The 2.5 GeV Indus-2 Synchrotron source which is commissioned at the Raja Ramanna Centre for Advanced Technology, Indore as a national facility for carrying out high quality research on X-ray based techniques. A wide variety of beam lines are being developed for research and characterization in micro / nano domain. The major applications of synchrotron radiation light source are in physics, materials science, biology and medicine. It is used for characterization, fabrication, visualization of the structure of matter from the sub-nanometer to millimeter scale.

Figure 1 shows a schematic diagram of synchrotron beamline. Synchrotron beam is channelized in different experimental hutches which is provided by bending magnets, wigglers or undulators. X-ray mirrors are essential component of any such beamline for guiding the X-ray beam and focusing it to a particular location.

X-ray mirror which is used for different purposes in different experiments viz., for vertical and horizontal focusing of the synchrotron beam, for rejection of higher harmonics from the synchrotron beam, for reducing the heat load on monochromators, etc. (Figure 2). When X-ray is incident on any material at a very small grazing angle of incidence less than its critical angle for that X-ray energy, major part of the X-ray would be reflected because of the "total external reflection" phenomenon. Hence,
these X-ray mirrors are used at a very small grazing angle of incidence with respect to the synchrotron beam.

![Figure 2 Types of mirrors (optics) in synchrotron beam line](image)

This paper reports basic requirements and properties of mirrors, fabrication and polishing processes of mirrors, some of the finishing processes are discussed in details which have been selected for development of new hybrid technique for finishing of mirrors.

2 Requirements and properties of mirror

These mirrors are made of Si, SiC (CVD), Zerodur, Fused silica, Cu with electroless Ni layer, Silicon Carbide (CVD), GlidCop (alumina dispersion strengthened copper alloys), Mo, etc. Generally, the length of these mirrors is approximately 1 m while the width is around 50 – 75 mm. Different shapes of mirror such as cylindrical, elliptical and toroidal are generally used in the beamlines. An important feature of toroidal mirror is the large difference in radius of curvature in different directions. It is in kilometre along the length (meridional) and few centimetres along the width (sagittal). One of such toroidal shape mirror is shown in Figure 3 (Barrett, 2011). Furthermore, slope error in micro radian and surface roughness in a few Å (< 3) are the prime requirements for good focusing and reflectivity properties of synchrotron X-ray beam. Other important requirements are as follows (Matsuhita, 2010):

- It can be polished to a smooth, accurate surface figure and can be bent.
- Material should be available in a large length (~1.4 m long).
- Mechanically hard, Radiation resistive.
- Good thermal conductivity
- No (low) gas emission under X-ray irradiation
- Reasonable cost of material as well as fabrication technique

The above requirements and stringent control over the surface figures make the fabrication and finishing of these mirrors challenging and extremely difficult.

These X-ray mirrors are available commercially from very few sources and are extremely cost intensive. These mirrors are exposed to very bright synchrotron radiation with high heat load and it sometimes damages the mirrors. Hence, they are consumable and required to be replaced periodically.

A comprehensive in-house facility for finishing of these X-ray mirrors with indigenous technologies is necessary to develop. It would provide long-term support to the synchrotron radiation based program which would also result in savings of a considerable amount of foreign exchange. The first major concern of these components is the selection of a manufacturing process and second is the finishing process to achieve the required surface roughness ($R_a$) on the final product. Surface quality is an important index for evaluating the part quality, and it has great influence on the properties, life and reliability of the part, especially on those parts working under high speed, high temperature and high pressure. Complex surfaces are very difficult to finish because of their irregular and non-rotational symmetry. It is also very difficult to generate tool path of such complex surfaces maintaining close dimensional tolerances.

![Figure 3 A typical toroidal mirror from SESO, France (Material-coating: Silicon-Pt, Roughness ≤ 2Å rms, Radii of curvature:Sagittal: 71.60 mm and Meridional: 25 km, Slope error (RMS): 0.7 µrad over 450 mm and 1.0 µrad over 900 mm)](image)

3 Fabrication and finishing of mirrors

Fabrication of mirrors generally includes the following steps (Standa, 2013; Zeiss)

- **Grinding** the pre-manufacturing substrates and optical surface geometry.
- **Etching** to reduce stress and sub-surface damages.
- **Lapping** to set a good thermal contact at the side faces and to optimize the optical surface for next steps.
• Several levels of polishing for removing subsurface damage, correcting residual surface errors, and achieving the required micro-roughness.

![Mirror Figure](image)

Figure 4 (a) Static and (b) dynamic figuring. (Barrett, 2011)

Fabrication of flat mirrors is easy compared to that of curved or toroidal mirrors. Therefore, curved mirrors are also fabricated by bending a flat mirror when the radius of curvature is very high (called dynamic figuring, Figure 4 (b)) and it results in less fabrication time as well as cost. However, this technique is not applicable when the radius of curvature is small because mirror will break while bending. In such case, static figuring (Figure 4 (a)) is used where computer controlled polishing or lapping tool having an inverse replica of the mirror is used for removal of material from the mirror blank. However, it is a lengthy and expensive process.

Bending of flat mirror may be performed by many methods as shown in Figure 5.

In case of curved or toroidal mirror, initial shaping from the ingot/blank is generally performed by diamond turning (fly cutting) (Higashi et al., 1989). However, alternate processes are under investigation which would take less time and leave fewer defects. The entire process consists of loops of the individual manufacturing steps with intermediate metrology stages. The loops are continued until the surface attains the desired specification level. Due to very stringent requirements of surface roughness and figure accuracy, only a few processes are used for fabrication of these mirrors. However, extensive research and development are required for fine tuning of these processes for finishing of X-ray mirrors. A comparison of different fabrication processes in terms of figure accuracy and final surface finish is given in Figure 6 (Mori et al., 2005).

![Figure 6](image)

Figure 6 Comparison of the various machining methods with reference to (a) figure accuracy and (b) surface roughness. (EEM: Elastic Emission Machining, PCVM: Plasma Chemical Vaporization Machining, IBF: Ion Beam Figuring, CCP: Computer Controlled Polishing, RIBE: Reactive Ion Beam Etching, PACE: Plasma Assisted Chemical Etching, PJCE: Plasma Jet Chemical Etching, MRF: Magnetorheological Finishing, FJP: Fluid Jet Polishing)

4 Finishing or figuring processes

It is observed from Figure 6 that Computer Controlled Polishing (CCP) covers a large area as compared to other processes. CCP works on the theory of Preston where a small tool such as the small pitch polisher is employed to realize the desired removal depth profile with respect to the pre-machined surface. Tool velocity, dwelling time, and pressure can be employed as the parameters to be controlled in figuring. However, figure accuracy of 10 nm (p-v) seems to be the achievable limit, because of the difficulty in controlling process parameters, such as slurry concentration, temperature, and conditions of the tool surface (Mori et al., 2005).
On the other hand, ion beam figuring (IBF), which is a dry process, has been developed as a method of computer-controlled figuring. The process parameters, such as gas pressure and ion current, can be more easily kept constant than those in the CCP method. As a result, the expected figuring accuracy is considered to be higher compared to that of the CCP method. Currently, the achievable p–v figure error is as small as a few nanometers (Mori et al., 2005).

However, CCP and IBF utilize the mechanical effects in material removal, whereby a crystallographically damaged layer and plastically deformed or amorphous layers will be introduced. As a result, they cannot be applied in fields such as Bragg diffraction optics in which the crystallographic nature of the polished surfaces is utilized (Mori et al., 2005).

It is observed from the earlier discussion that many processes and steps are required to fabricate a beamline mirror complete in all aspects. Initial stage of fabrication (electric discharge machining, grinding or diamond turning) should not create any defect (subsurface damage, cracks, scratches, deep indentation, etc.). Application of subsequent process step (finishing) may not be able to remove these defects and the finishing may not be very effective. As a result, optimum setting of process parameters of each process is utmost important.

Plasma Chemical Vaporization Machining (PCVM) utilizes highly reactive neutral radicals such as halogen atoms (Mori et al., 1993). The radicals generated in high-pressure very high frequency plasma, react with the atoms of surface to be finished and they transform them into volatile molecules. However, some problems associated with PCVM are low machining efficiency and uncontrolled material removal due to low-pressure (1-10³ Torr) plasma. Chemical etching / machining also requires stringent control over temperature and time.

4.1 Elastic emission machining (EEM)

Elastic emission machining (EEM) works on the principle that when two solid phase materials composed of different chemical elements make contact with each other, a binding force between two contacting surfaces appears as a result of the release of the surface energy before contact. Therefore, when these solids are separated by some mechanical means, it happens, with some probability, that the atoms of one surface move onto the other surface. This fact is applied to machining, and the machining using this kind of phenomenon is called EEM (Mori et al., 1987).

In EEM, ultra-fine abrasive particles having diameters much smaller than 1 µm are uniformly mixed with water (Figure 7). The choice of the abrasive particles is very important for effective machining. Utilizing the flow of this mixture, abrasive particles are accelerated and transported to the work surface with little normal load to the surface. When they contact the work surface, removal of the surface atoms takes place. The working area is limited within the contacting area to be smaller than 10 nm². Even in this area, removal becomes possible only where mutual surface atoms are ideally binding (Yamauchi et al., 1999). From these points of view, both the machined area and the depth become approximately of atomic order so that a geometrically perfect surface can be obtained.

4.2 Magnetorheological finishing (MRF)

Magnetorheological finishing (MRF) is a deterministic process for figure correction of optical components and a few metals also. MRF is successfully used for figuring / final polishing of spherical / aspherical lenses, mirrors, etc. (Jones et al., 2006). MRF is also getting attention for finishing of synchrotron X-ray mirrors (Takacs, 2006). MRF process uses magnetorheological (MR) fluid which consists of nonmagnetic polishing abrasives, magnetic carbonyl iron particles (CIPs), carrier liquid and some additives. Figure 8 shows a schematic diagram of MRF process for finishing of small optical components (Kordonski and Jacobs, 1996). A meter sized components can be also finished by other configuration of MRF machine where workpiece is fixed on a bed and carrier wheel is located over it (Messner et al., 2007). Apart from finishing of optical
MR fluid ribbon is deposited on the rotating carrier wheel rim by a MR fluid circulatory system. When MR fluid is exposed to magnetic field in the working gap, it gets stiffened and forms a transient work zone or finishing spot. Surface smoothing, removal of sub-surface damage, and figure correction are accomplished by rotating the lens on a spindle at a constant speed while sweeping the lens about its radius of curvature through the stiffened finishing zone. Material removal takes place through the shear stress created as the magnetorheological polishing ribbon is dragged into the converging gap between the part and carrier surface. The zone of contact is restricted to a spot, which conforms to the local topography of the part. Deterministic finishing of variety of shapes, including flats, spheres, aspheres, and prisms, with a variety of aperture shapes can be accomplished by mounting the part on the rotating spindle and sweeping it through the spot under computer control, such that dwell time determines the amount of material removal.

5 Development of hybrid finishing process

It is observed in Figure. 6 that volumetric removal rate in EEM is the lowest among all the selected processes. Therefore, EEM is very time consuming if it is used without pre-polishing of mirrors by other process. If EEM is combined with other similar finishing process, finishing time can be reduced without sacrificing the advantages of EEM as well as other selected process. MRF process has many similarities with EEM as shown in Figure 9. Both processes use abrasive particles, carrier liquid and process principle is also matching considerably. Furthermore, MR fluid in MRF process easily conforms the shape of the workpiece which provides more flexibility in finishing complex surfaces.

A hybrid finishing process of EEM and MRF will provide reasonable high volumetric removal rate with atomic scale finishing. It is planned to integrate both processes in a single setup in such a way that processing of component from one step to another does not require any modification in the setup or transfer of component to other setup. Furthermore, these processes also have many similarities. Both of these processes use abrasive particles for material removal by mechanical action, deionized water as a carrier fluid, abrasive slurry which is chemically active with workpiece material, and material removal due to normal force and shear force. By this hybrid process time as well as errors (placement, alignment, handling, etc.) can be reduced to a great extent.
Mid and High as shown in Fig. 10 (Harvey et al., 1995). However, complete information of these frequencies on the finished component is very difficult to get from only one instrument. Generally interferometry based profilometer is used for measurement of low spatial frequency roughness (Figure) while Atomic Force Microscope (AFM) is used for High spatial frequency roughness (Finish).

![Figure 10 Spatial frequency relationships of figure and roughness](image)

**Remarks**

Development of indigenous technology for fabrication of synchrotron beamline mirror needs immediate attention to save considerable foreign exchange and also to provide alternate finishing solutions to many other components (optical lenses, silicon wafer, etc.) which demand similar accuracy. The hybrid process under development will be able to remove wide range of spatial frequency roughness as compared to individual process. As a result, pre-finishing and final finishing steps can be performed on a single setup.

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