Flat mirrors are widely used in miscellaneous optical systems. The current technology for precise flat mirror fabrication is continuous polishing (CP) \cite{1,2}, also called annular polishing \cite{3,4}. The CP uses a large annular pitch polishing pad that is at least three times the size of the flat mirror being polished and turns continuously, so the flat mirror held on the annulus is polished continuously. There are some advantages of CP technology: 1) it can produce multiple flat mirrors at the same time, 2) it can get a certain figure accuracy of the flat mirror rapidly by increasing loads on the mirror, and 3) it can polish smoothly out to the flat mirror edges because of the uniform contact between the mirror and polishing pad. However, the disadvantage is that CP technology is excessive dependent on technician’s experience, so it is not a deterministic polishing process. When the figure of the flat mirror converges to certain accuracy, it is difficult to improve it further with CP technology.

Ion beam figuring (IBF) is an advanced technology for ultra-precise optics polishing \cite{5,6}. Material of the optics being polished is removed by physical sputtering effect, where energy is transferred from the energetic ions to the optical surface during the bombarding process \cite{7}. IBF is highly deterministic polishing process. Edge effect and tool wear are avoided in IBF. Depending on these advantages, IBF becomes the final procedure for high-quality optics polishing. However, due to atomic or molecular form material removal, the polishing efficiency of IBF is low, and pre-polishing is required.

Optical fabrication is a very complicated process. It is difficult for a single method to complete the whole fabrication process. For the sake of polishing optical components reasonably, some combined polishing technologies are presented \cite{8,9}. In order to polish high-quality flat mirror efficiently, combined CP with IBF, a serial mode combined polishing technology is presented. The function of CP technology is to get a certain figure accuracy of the flat mirror from initial figure rapidly. IBF technology is used for the final high precise polishing of the flat mirror.

The CP machine basically consists of a large annular pitch lap and a circular glass conditioner. A top view diagram of a CP machine is shown in Fig. 1.

During polishing process, the annular pitch polishing pad, which is driven by electric motor turns steadily and continuously. The flat mirror to be polished is placed front surface down on the annular lap in the holder. The holder and conditioner are also driven by driver system. They rotate at a certain speed. Because the flat mirror is in synchronous motion with the polishing pad,
In the vacuum chamber, ions generated by ion gun hit the surface of the optical element to make its material removed. The ion gun is fixed on the stage, which consists of a high accurate mechanical translation system with three linear axes and one angular axis. All axes are controlled by CNC controller so as to figure optical components precisely.

To accomplish a deterministic polishing process, the accurate and stable material removal function of this polishing method must be acquired. The material removal function of IBF is acquired by etching experiments, and the etching experiments are implemented on IBF-1500 facility which is shown in Fig. 2.

In order to test the stability of IBF removal function (footprint), on a $\Phi 100$ mm fused silica flat mirror 10 footprints are etched over a period of 8 h. The etching time of each footprint is 100 s, and the two adjacent etching time interval is approximately an hour. Process parameters are as follows:

- Argon: 4 sccm,
- RF power: 50 W,
- Beam: 1000 V, 1.5 mA,
- Acceleration: 100 V, 0.25 mA,
- Neutralization: 50 mA, and
- Etched time: 100 s.

Later these footprints are measured on ZYGO interferometer. The test results are shown in Fig. 3. According to analysis of the test results of footprints, some conclusions are drawn as follows: the mean value of maximum etching (removal) rate is 3.643 nm/s, the mean value of volume etching rate is 0.0093 mm³/min, and the mean value of full wave at half maximum is 5.701 mm. The instability of the footprint is less than 3%. All these data build up a good basis for the application of IBF.

IBF is a highly stable, highly deterministic, and non-contact technology for ultra-precise optical elements polishing. It utilizes the physical phenomenon of atom sputtering to remove a defined amount of material from the optical component being polished. In high-vacuum conditions, a broad beam ion source generates a defined flux profile of ions with energy in the order of about 1000 eV. Each ion that hits the surface of the optical component generates a collision cascade within the component. With a certain probability surface atoms at the end of the cascade may overcome the surface binding energy and get removed from the surface of optical element, which leads to a macroscopic removal of material. Compared with conventional polishing methods, the removal rate is lower but stability and predictability are superior, hence IBF is extremely suitable for ultra-precise optics final polishing.

Fig. 2. IBF-1500 facility.

Fig. 3. The test results of footprints.

Fig. 4. The surface error of the flat mirror after pre-polishing.
the surface error of the flat mirror was 21.3 nm RMS as shown in Fig. 5.

The final polishing step was IBF. Process parameters were as the same as those of footprint experiments. Through one figuring process of 2.45 h, the surface error was reduced from 21.3 to 2.06 nm RMS as shown in Fig. 6.

The surface roughness of the flat mirror was measured using the ZYGO New View 7200 Microscope, and the test result was 0.42 nm RMS as shown in Fig. 7.

In conclusion, we present a serial mode combined polishing technology consisting of CP and IBF. The CP technology is used for polishing the flat mirror with large surface error and IBF technology is used for final ultra-precise polishing of the flat mirror. A Φ 160 mm fused silica flat mirror is polished by the serial mode combined polishing technology. After polishing, the surface error and roughness of the flat mirror are 2.06 and 0.42 nm RMS, respectively. The experiment results confirm that serial mode combined polishing technology is effective for polishing high-quality flat mirror.

**References**