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Trajectory simulation of ion beams focused by magnetic lens for figuring small optics

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Abstract
Ion beam etching is effectively used for the fabrication of high-precision optics. Its main application is in figuring large optical surfaces to correct shape errors on polished surfaces. To figure small- or medium-sized optical surfaces, the generation of an ion beam with a small diameter and high ion current is required. In this study, we designed a magnetic lens with quadrupole magnets using permanent magnets to obtain an ion beam with a small diameter. Then, the trajectories of the ion beam when a doublet or a triplet magnetic lens is used were simulated. Ion beam distributions on a workpiece surface were also calculated for both magnetic lenses. As a result, the simulations demonstrated that the ion beam can be focused on a workpiece surface when a doublet or a triplet magnet lens is used: the distribution of an ion beam on a workpiece surface was calculated to be reduced from approximately 30 mm to 5-10 mm by using the triplet magnet lens.

Key Words: Optics, Fabrication, Figuring, Ion beam, Magnetic lens, Quadrupole lens, Ion gun, Ion source

1. Introduction

Ion beam etching is effectively used for the fabrication of high-precision optics to correct the shape errors remaining on the polished surfaces [1-5]. This procedure is called ion beam figuring (IBF). The main application of IBF is in figuring large optical surfaces. To figure small- or medium-sized optical surfaces, the generation of an ion beam with a small diameter and high ion current is required. In previous studies [1, 4], to obtain an ion beam with a small diameter, a diaphragm with an aperture was placed at the outlet of an ion gun. One disadvantage of such method is that the diaphragm reduces the ion current to decrease its removal rate.

In this study, we designed a magnetic lens with quadrupole magnets using permanent magnets to obtain an ion beam with a small diameter. Moreover, the trajectories of an ion beam when a doublet or a triplet magnetic lens is used were simulated to evaluate their convergence characteristics. A magnetic lens with quadrupole magnets is generally used in particle accelerators to converge electrically charged particles. Such a magnetic lens is large because its quadrupole magnets are electromagnets. On the other hand, our magnetic lens with permanent magnets is compact and simple, which is expected to be appropriate for industrial uses, such as optical fabrication.

2. Ion beam figuring device with magnetic lens

We designed an IBF device mainly consisting of an ion gun, a magnetic lens, a vacuum chamber, a multi-axis linear motion stage, and a controller. An ion beam extracted from the ion gun is irradiated on the workpiece surface placed on the motion stage. The magnetic lens is installed with the outlet of the ion gun. In this arrangement, the ion beam passing through the center of the magnetic lens is converged by the magnetic field.

3. Principle of focusing of ion beam using magnetic lens

We designed a magnetic lens with quadrupole magnets using permanent magnets to obtain an ion beam with a small

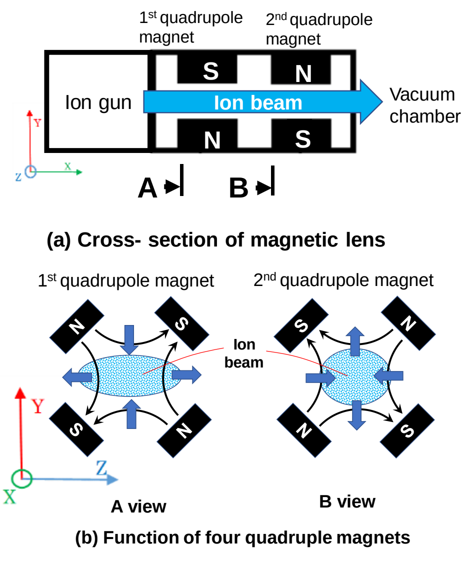

Figure 1. Schematic of magnetic lens with quadruple magnets.

diameter. Figure 1 shows the schematic of a doublet magnetic lens. As shown in Fig. 1(a), two quadrupole magnets are placed from upstream to downstream of the ion beam. As shown in Fig. 1(b), a single quadrupole magnet has four permanent magnets arranged with alternating S and N poles. The two quadrupole magnets are set such that the position of their magnetic poles are turned 90 degree to each other.

In the arrangement of the four permanent magnets shown in Fig. 1(b), magnetic flux density generated by the magnets varies in the radial direction from the center of the quadrupole magnet. The positively charged ion beam passing through the first quadrupole magnet shrinks in the y direction owing to the force toward the center of the quadrupole magnet, and it expands in the x direction because of the outward force to the magnet. Then, the ion beam passing through the second quadrupole magnet shrinks in the y direction and expands in the x direction. In this manner, theoretically, the magnetic lens converges and focuses the ion beam on a workpiece surface.

4. Design of magnetic lenses and simulation of ion beam trajectories

4.1 Method

We designed the magnetic lens as follows. The magnetic field around four permanent magnets functioning as quadrupole magnets was calculated. The permanent magnets are made of neodymium. By referring to a material table of neodymium, we set the residual magnetic flux density and coercive force to 12,000 gauss and 10,900 Oe, respectively. By using the resulting magnetic field, we modeled a magnetic lens. Then, the trajectories of an ion beam were calculated using a commercially available ion optics simulation software (SIMION™). The ion particle distributions irradiated on a workpiece surface were also calculated. These calculations were conducted for different emittances ε_{rms} of an ion beam entering to a magnetic lens from an ion gun. The emittance ε_{rms} corresponds to the distribution of the incidence angle of ion particles to the magnetic lens. For instance, the emittances ε_{rms} is large when the distribution of the incidence angle of ion particles is broad, and it is small when the distribution is narrow. In this paper, the simulation results for emittance ε_{rms} = 17.2 πmm·mrad are shown as an example. The diameter of the ion beam at the outlet of the ion gun was set to 6 mm.

4.2 Results and discussion

Figures 2(a) and 2(b) show the simulation results of the trajectory of the ion beam and the ion particle distribution on the workpiece surface, respectively, when no magnetic lens was used. As shown in Fig. 2(b), the ion beam was expanded to an area of 30 mm × 30 mm from a diameter of 6 mm at the outlet of the ion gun.

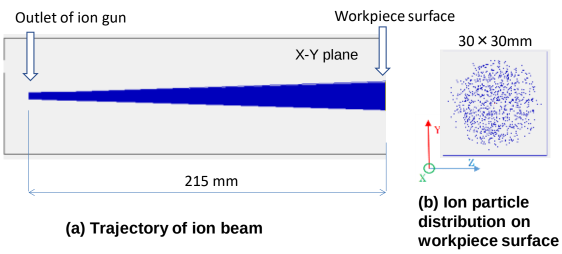

Figure 2. Simulation results without magnetic lens.

Figures 3(a) and 3(b) show the trajectory of the ion beam and the ion particle distribution, respectively, when a magnetic lens was used. As shown in Fig. 3(b), the ion beam is focused to 5 mm in the y direction, but it is negligibly focused in the z direction. The length of the area in the z direction is almost the same as that without the magnet lens. Such expansion in the z direction is found to have originated from the outlet of the second quadrupole magnet.

Next, we designed a triplet magnetic lens to further focus the ion beam in the z direction and performed the simulation again. Figures 4(a) and 4(b) show the trajectory of the ion beam and the ion particle distribution for a triplet magnetic lens, respectively. As shown in Fig. 4(b), the ion beam is focused to 10.0 mm and 5.2 mm in the y and z directions, respectively.

We simulated the trajectories of the ion beam for various conditions, such as magnetic flux densities and arrangements of the magnets. As a result, the ion beam was converged to the spot with the smallest diameter on the workpiece surface in the conditions shown in Fig. 3 or 4.

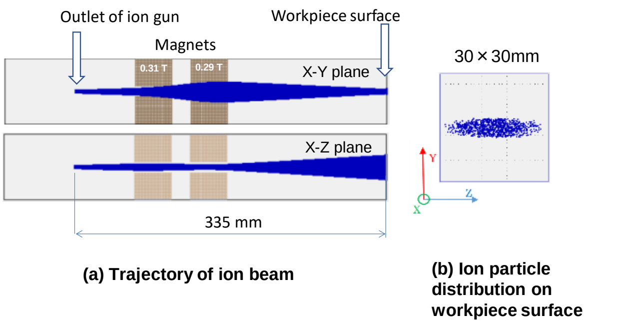

Figure 3. Simulation results with double magnetic lens.

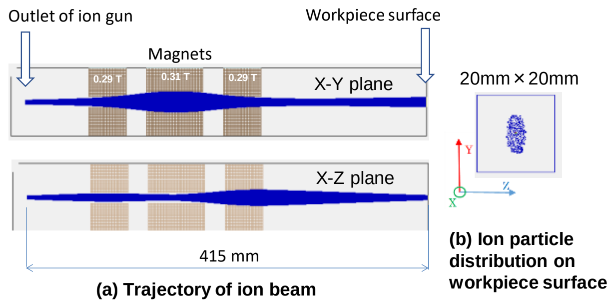

Figure 4. Simulation results with triplet magnetic lens.

5. Conclusions

To figure small- or medium-sized optical surfaces by IBF, the generation of an ion beam with a small diameter is required. Thus, we designed magnetic lenses with quadrupole magnets using neodymium magnets to focus the ion beams. The magnetic lens was installed with the outlet of the ion gun, which enabled the changing of the trajectory of the ion beam in the chamber. We investigated the characteristics of the magnet lenses by numerical simulation of the trajectories of ion beams. The simulation results demonstrated that the magnet lenses we designed enables the focusing of the ion beams. The size of the ion beam irradiated on the workpiece surface using the triplet magnetic lens was found to be reduced to 10 mm from that of 30 mm without the magnetic lens.

We are planning to manufacture the magnetic lenses to install them in an IBF device to evaluate their convergence characteristics in our next study.

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