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Prediction of rounding phenomenon at corner tips in large-area electron beam irradiation

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ABSTRACT

In large-area electron beam (EB) irradiation method, corner tip of workpiece is generally rounded since removal of material at the tip is done preferentially. Investigation of the shape change is necessary to clarify rounding phenomenon with irradiation of EB. In this study, the shape changes of corner tips were experimentally investigated by Scanning Electron Microscope (SEM) observation of the cross sections. Then, electron track analysis in the EB irradiation was conducted to clarify an electron concentration at the tip. Unsteady heat conduction analysis at the tip was also done with considering the EB concentration at the tip and an electron penetration effect into the surface. The shape changes were estimated by simulation of temperature distribution at the tips. Experimental results show that the curvature radius increases with shot number of EB. The estimated shape changes show quantitatively good agreement with the experimental ones. These results indicate that the rounding phenomenon at the tips by large-area EB irradiation can be predicted by our electron track and unsteady heat conduction analysis model.

1. Introduction

Surface finishing of metal molds is generally done by hand lapping after milling and/or electrical discharge machining (EDM), in order to obtain small measure of surface roughness without micro cracks. However, this process needs special technical skills and takes a long time. Moreover, the automation of the polishing process might be difficult, since most of metal molds have very complicated shapes. On the other hand, laser polishing on metals has been demonstrated by CO_2 laser irradiation [1] and laser sintering [2,3], while these methods need adjustment of laser focusing point and heat effected zone is generally generated. Ultrasonic polishing has also been conducted for surface finishing [4]. However, this process requires abrasive fluids and there is limitation of the workpiece size. Therefore, a highly efficient surface finishing technique is required.

Recently, a large-area electron beam (EB) irradiation method has been developed. High energy density $E_d = 15\ \mathrm{J/cm^2}$ can be obtained without focusing the beam to small spot by using an Explosive Electron Emission phenomenon. The large-area EB with uniform energy distribution can melt or evaporate metal surface in large area about a diameter of 60 mm under 10 μs, since the large-area EB irradiation method is a pulsed process and the pulse width of the large-area EB is about 2 μs. [5–13]. In our previous study, highly efficient surface finishing with the large-area EB was possible for the various kinds of material, such as metal molds made of steel (SKD11 in JIS specifications) [6,7], ceramics (Aluminum oxide) [8], and cemented carbide [9]. The experimental results clarified that the surface roughness of metal mold steel on wide area uniformly decreased from 6 μmRz to less than 1 μmRz in a few minutes under appropriate conditions. Moreover, surface functions such as corrosion resistance and water repellency of the metal molds were improved by the large-area EB irradiation [10]. In the case of aluminum oxide and cemented carbide, the surface roughness also decreased after large-area EB irradiation. Then, the releasability of the molded resin could be improved, because the surface structure of cemented carbide was changed after EB irradiation. Tokunaga et al., also reported that large-area EB irradiation can be applied to the surface finishing and modification of biomaterials [11]. Surface roughness of pure titanium decreased from 2.3 μmRa to 0.1 μmRa and corrosion resistance was improved under appropriate conditions. Furthermore, A. Selada et al., showed that surface finishing at micro-injection molds surfaces was done by using the laser beam and large-are EB irradiation [12]. The large-area EB irradiation equipment has already been introduced into the market for practical use.

On the other hand, Murray et al., revealed that edge of microstructures on metal mold surface was slightly rounded after large-area EB irradiation [13]. It was also confirmed that corner tip on the metal mold steel (SKD11) was rounded due to preferential removal of material at the tip by large-area EB irradiation. Cross sectional Scanning Electron Microscope (SEM) images of the tips

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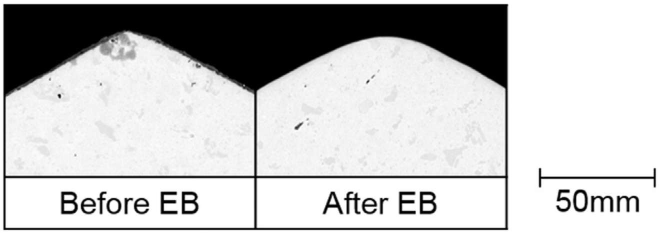

Fig. 1. SEM images of cross sectional corner tip before and after large-area EB irradiation.

before and after large-area EB irradiation are shown in Fig. 1. The tip is clearly rounded and curvature radius increases from 20 μm to 50 μm after EB irradiation for the energy density $E_d = 15$ J/cm^2 at shot number $N = 10$ shots. When metal mold with complicated shape is polished by large EB irradiation, excessive corner rounding of metal mold leads to deteriorate shape accuracy of the products. Therefore, precise prediction of the rounding phenomenon and discussion of the countermeasure are very important for higher performance and wide application of this method. The reason of the rounding phenomenon at the tip has not yet been clarified and it is probably because the EB easily concentrates on the tip because of high electric field intensity and the heat given from the EB is difficult to diffuse at the tip. It is expected that EB concentration phenomenon at the tip can be simulated by electron track analysis, since the electron behavior near the workpiece is simulated by electron track analysis with considering plasma generation, electric and magnetic fields. Moreover, temporal temperature distribution at the tips after EB irradiation is calculated by unsteady heat conduction analysis considering the electron concentration. Then, variation of curvature radius at the tips can be quantitatively compared with the temperature distribution of the analysis and experimental results. Therefore, prediction of rounding phenomenon at the tips is highly expected through this analysis.

In this study, the rounding phenomenon at corner tip of metal mold steel in large-area EB irradiation was analyzed by electron track analysis and unsteady heat conduction analysis, and these phenomena were experimentally examined by SEM observation of cross sections. At first, distribution of magnetic field in the working chamber was analyzed by the electron track analysis to clarify the concentration of the EB on the tip. Distribution of electric field was also analyzed to investigate the electron velocity and estimate the relative energy density of EB on the tip. Secondly, unsteady heat conduction analysis was carried out with considering the EB energy distribution at the tip obtained by electron track analysis and the electron penetration effect into the surface. Then, shape changes at the tip after EB irradiation were simulated by the temperature distribution from the model. Finally, experimental and simulated results of shape changes were quantitatively compared, and prediction of rounding phenomenon at the tips was discussed.

2. Investigation of electron behavior during large-area EB irradiation by electron track analysis

2.1. Equipment of large-area EB irradiation

Schematic illustration of large-area EB irradiation equipment is shown in Fig. 2. In this method, ambience inside the chamber is argon (Ar) gas of about 10^{-2} Pa. At first, a magnetic field is generated by the solenoid coil set on the outer side of the chamber. At the moment when the magnetic field takes a maximum intensity, pulse voltage is loaded to the anode ring. In the chamber, the electrons are generated by the Penning effect and start to move towards the anode. At the same instant, the electrons spirally move due to the Lorentz forces. Next, Ar gas atoms are then ionized by the repetitious collision with electrons, which generates plasma near the anode. When the plasma intensity reaches a maximum, pulse voltage is applied to the cathode and the electrons are accelerated by high-electric field due to electric double layer formed near the cathode. Then, large-area EB with high-energy density is irradiated to the workpiece surface. The detailed mechanism for large-area EB irradiation is shown in Ref. [5,6,14]. In the experiments, −32 kV was applied to the cathode, which corresponds to the energy density of the EB, $E_d = 15$ J/cm^2. Shot number was varied from $N = 1$–10 shots to investigate shape change on each EB shots.

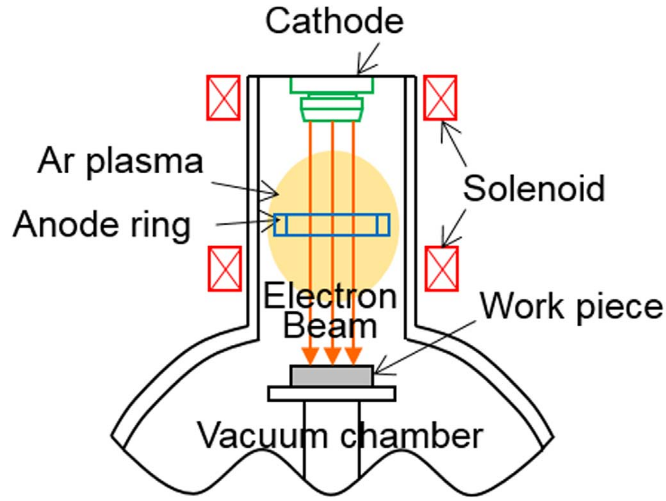

Fig. 2. Schematic diagram of Large-are EB irradiation equipment.

2.2. Modeling of electron track analysis

Schematic illustration of workpiece model shape with corner tip is shown in Fig. 3. Metal molds of steel of SKD11 were assumed as a workpiece material. Relative permeability of workpiece $\mu_w = 5000$ was assigned to the workpiece in this model, since magnetic property affects calculation of the electron track. As shown in the Figure, width and height of the workpiece are 10 mm and 15 mm, respectively. The angles of the tip were set to $\theta = 60°$, 90° and 120°. Flat surface ($\theta = 180°$) was also used for comparison.

Fig. 4 schematically illustrates the electron track analysis model in this study. The analysis model is made, based on the cross-sections of the workpiece and working chamber of large-area EB irradiation equipment. The rectangular part is the working chamber, in which the large-area EB is irradiated to the workpiece. The size of the chamber is 250 mm length and 180 mm width. At the upper end of the chamber, a circular area of 70 mm in diameter is set as an electron gun, and electrons emit from it. The inside of the chamber is vacuum ambience, and Ar plasma region with 0.03% in ionization degree is arranged in the middle of the chamber, which is shown with orange hatching, since Ar plasma is observed in the middle of the chamber during EB irradiation as described above. The workpiece is placed at 50 mm above the bottom surface of chamber. Upper and lower solenoids are placed both on side of the chamber, and an anode ring is also placed in the middle of the chamber. In this analysis, the wavelength of Ar plasma is required in order to calculate the plasma affecting region. The wavelength of Ar plasma generating around the middle of chamber during large-area EB irradiation was measured using a spectrometer (Hamamatsu Photonics, PMA-10). The peak