Study on Variation of Burr Height in Micro-deburring with Large-area Electron Beam

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Abstract

In a large-area electron beam (EB) method developed recently, the EB of 60mm in a diameter can be used for melting or evaporating of metal surface instantly. Thus, smoothing of metal surface could be performed efficiently by preferential melting of convex parts with the surface roughness of several μmRz. It was also confirmed that edge of convex parts was rounded by the EB irradiation, since the material removal remarkably progressed due to the electron concentration and heat accumulation at the edge. It is highly expected that micro burrs can be instantly and preferentially removed by the EB irradiation. In this study, micro-deburring of rollover burr is experimentally investigated by using the preferential edge removal effect in the large-area EB irradiation. In addition, variations of burr height for each number of shot are analyzed and predicted by unsteady heat conduction analysis.

Key words: large-area electron beam, micro-deburring, rollover burr, unsteady heat conduction analysis

1. INTRODUCTION

In the manufacturing site of industrial products, high-efficiency and high-accuracy processing has been required. In the processing, micro burr often generates at the edge of parts by metal removal processes, such as cutting, milling, grinding, electrical discharge machining (EDM) and laser machining, as a result of plastic deformation or resolidification of material. The burr would lead to unsafe operation of a machine, deterioration in product quality, function and appearance, or generation of friction and wear in the moving parts. Therefore, precise micro-deburring method is required in the manufacturing process. Some deburring methods by using rotating brush, barrel finishing, dry blasting, water jet and electrochemical micro-deburring have been widely applied as a batch deburring methods1)-3). However, these conventional deburring methods have still some problems of its low efficiency, treatment of the waste working fluid, the limitation of removable burr size and so on. Furthermore, more precise machining technology has been requested in a few decades, along with the miniaturization of industrial products. Thus, the complete and precise removal technique of micro burrs is needed, and the deburring by a hand work is necessitated if needed4). However, the deburring method by hand work takes a lot of time and needs special technical skills.

Recently, a large-area electron beam (EB) irradiation method has been developed5). In this method, high energy density of EB can be obtained without focusing the beam, and the large-area EB of 60mm in diameter with a uniform energy distribution can lead to melting or evaporating of metal surface instantly5)-9). Our previous study showed that highly efficient surface finishing with the large-area EB was possible to the various materials, such as steel5), titanium alloy6), and cemented carbide7). The experimental results clarified that the surface roughness of metal molds decreased from several μmRz to less than 1.0μmRz in a few minutes under appropriate EB conditions. In addition, when the large-area EB was irradiated to edge of convex shape, the material removal remarkably progressed due to the electron concentration and heat accumulation at the edge. Therefore, the sharp edge with 20μm in radius was easily rounded to about half hundred microns in radius after the EB irradiation5). It is expected that the burrs with the size of a few dozen micro meter will be instantly and preferentially removed by the large-area EB irradiation.

In this study, micro-deburring of rollover burr generated in milling process is experimentally investigated by using the preferential edge removal effect in the large-area EB irradiation. Then, shape variation of burr is examined for each number of shot in order to discuss the variation of the burr height after the EB irradiation. In addition, prediction on variation of burr height with number of shot is conducted by an unsteady heat conduction analysis.

2. EXPERIMENTAL PROCEDURE

2.1 Large-Area EB Irradiation Method

Figure 1 schematically illustrates large-area EB irradiation equipment. In this method, ambience inside the chamber is argon gas of about 10⁻²Pa. At
first, a magnetic field is generated by the solenoid coils set on the outer side of the chamber. When the magnetic field takes a maximum intensity, pulse voltage is loaded to the anode. Then, argon plasma is generated in the operating chamber by rapid changes in magnetic and electric fields. Next, a pulse voltage is applied to the cathode, and the electrons are explosively emitted from the cathode by high electric field near the cathode. Therefore, a large-area EB with uniformly high energy density on the workpiece can be obtained. Table 1 shows large-area EB irradiation conditions. Energy density $E_d$ was varied from 2.0 to 15J/cm$^2$, and number of shot $N$ was varied up to 50 shots.

### Table 1 Large-area EB irradiating conditions.

| Parameter                  | Value          |
|----------------------------|----------------|
| Pulse duration $T_\text{d}$| 2 µs           |
| Pulse frequency $F_\text{p}$| 0.125 Hz       |
| Energy density $E_d$       | 2.0-15 J/cm$^2$|
| Number of shot $N$         | 1-50           |

### 3. RESULTS AND DISCUSSION

#### 3.1 Removal of Rollover Burr

In the first experiments, the removal of rollover burr generated in cutting process was tried. As shown in Fig.2, a face milled surface of alloy tool steel SKD11 was made using a square endmill of 3mm in diameter by constant offset of the one directional tool pass. The milling conditions are as follows: depth of cut is 1mm, spindle speed is 2400rpm, and feed rate is fixed to 100mm/min.

Experimental setup for deburring by large-area EB irradiation is shown in Fig.3. Workpiece is fixed with chucks and placed in the center of the large-area EB. In the experiment, two EB irradiating methods shown in the figures were compared. Figure 3(a) is a normal workpiece fixing method, in which the burr of edge turns to the EB irradiating direction ($\theta_t=90^\circ$). In contrast, Fig.3 (b) is a tilting fixing method, in which the burr tilts to the EB direction and the edge position becomes higher than the surroundings ($\theta_t=45^\circ$). EB
irradiations to the rollover burr were performed with varying the energy density $E_d$ and number of shot $N$ in order to investigate the effect of them on the decrease in burr height.

Figure 4 shows scanning electron microscope (SEM) images of the burr before and after EB irradiation for various energy densities at same number of shot $N=30$ shots. Before EB irradiation, it can be confirmed that the burr continuously generates along the workpiece edge, although the height is not uniform. The average rollover burr height is approximately 60µm. After the EB irradiation, the burr height becomes uniform under each energy density condition. Also, the average burr height decreases from 60µm to 20µm as the energy density increases to 15J/cm$^2$. However, the burr height cannot be decreased any more when the energy density is higher than 10J/cm$^2$. Therefore, the height of rollover burr can be decreased to some extent by large-area EB irradiation.

Figure 5 shows SEM images of the burr for two different fixing methods at same EB conditions of $E_d=10$J/cm$^2$ and $N=20$ shots. The initial burr height is about 60µm as described before. The burr height is reduced to about 25µm in the case of normal fixing method at $\theta_t=90^\circ$, while it becomes less than 20µm in the case of tilting fixing method at $\theta_t=45^\circ$. These results suggest that EB more concentrates on the burr by tilting fixing method compared with the normal fixing method.

Figure 6 shows the variations of burr height with number of shot for two different fixing methods. In both fixing methods, burr height decreases with increasing number of shot. However it becomes almost constant when the number of irradiation is more than 20 shots. Moreover, the average burr height takes a minimum of 15µm only at 10 shots in the case of tilting fixing method, and the burr height is always smaller than that in the case of normal fixing method. Therefore, tilting the workpiece is effective for decreasing the burr height of rollover burr efficiently.

### 3.2 Shape Change of Rollover Burr

In order to discuss the variations of the burr height, the shape changes of burr for each number of shot after large-area EB irradiation at normal fixing method were investigated in detail by the cross-sectional observation with a SEM. Figure 7 shows cross-sectional SEM images of burr shape in each number of shot. Before EB irradiation, rollover burr is generated at the workpiece tip and the burr height is approximately 60µm. In the cases of $N=1$ to 5 shots, it is found that the burr height is reduced to about 40µm, and the burr shape is drastically changed. Furthermore, in the cases of...
$N=15$ and 30 shots, burr height becomes constant at about $20\mu$m, and the shape change of burr becomes small. Moreover, width of burr increases with increasing number of shot. These results suggest that heat accumulation and/or EB concentration effect at the burr are reduced with increasing the number of shot, since the aspect ratio of the burr becomes smaller with the number of shot. Therefore, reduction effect of burr height decreases at large number of shot.

In the cross-sectional SEM images, re-solidified layer is also obviously confirmed on the EB irradiated material surface. Figure 8 shows variations of the re-solidified layer thickness on burr tip for each number of shot. As shown in the figures, the re-solidified layer thickness drastically increases from 1 to 2 shots, while it decreases from 2 to 4 shots and becomes almost constant when the number of shot is more than 5 shots. These results suggest that the melted part at the burr tip slightly increases at number of shot less than 2 shots. At number of shot more than 2 shots, the melted part tends to be moved from burr tip to side or flat area of the burr due to surface tension of the melted part. Moreover, the removal of the re-solidified layer at the burr tip is preferentially caused at number of shot from 3 to 5 shots, since the aspect ratio of burr shape is relatively large after the EB irradiation and the EB can concentrate on the burr tip. Then, the re-solidified layer thickness decreases at the number of shot. On the other hand, when the number of shot becomes more than 5 shots, the EB cannot easily concentrate on the burr tip, since the aspect ratio of burr shape becomes small. Therefore, the valance of movement and removal of the melted part at the burr tip becomes equivalent at large number of shot. In other words, the movement of melted part is remarkably confirmed on the burr tip at small number of shot.

### 3.3 Analysis on Variation of Burr Height

In order to predict the variation of burr height for each number of shot, FEM program (ANSYS ver.15) was used for unsteady heat conduction analysis. Figure 9 shows the analysis model of workpiece with burr for prediction on variation of burr height. In consideration of the symmetry of workpiece and workpiece chuck shapes, one half of the cross section of them is modeled. From the cross sectional SEM images of burr shape (shown in Fig. 7), the burr with trapezoidal shape is placed on the upper end of the workpiece. The upper base length, lower base one and burr height of the trapezoidal burr in the model were $20\mu$m, $60\mu$m and $60\mu$m, respectively.

Heat flux distribution in the analysis model is shown in Fig. 10. Heat energy input of $E_d=10J/cm^2$ was given on the upper part of burr and the flat surface of workpiece, since the EB was vertically irradiated to the burr in the experiments. In addition, it is considered that the heat energy input on the slope surface of burr becomes small, since slope surface inclines with the respect to the EB irradiating direction. Thus, the heat energy input of $E_d=5.5J/cm^2$ was given on the slope surface of burr.
with considering ratio of the actual length and width of the slope surface. Moreover, the EB was also irradiated to the side wall. Assuming that half energy density was irradiated to the side wall, the heat energy input of $E_d = 5.0 J/cm^2$ was given on the side wall.

In this analysis model, the burr shape is reconstructed from the temperature distribution of analytical result in each number of shot. Since the movement of melted part was confirmed remarkably at small number of shot in the experiments (shown in Fig. 8), the movement of melted part at small number of shot was considered in the analysis model. From these boundary conditions of heat input, prediction on variation of burr height in large-area EB irradiation is performed for each number of shot.

Figure 11 shows temperature distributions on cross section of burr shape after large-area EB irradiation for each number of shot. The temperature distributions are obtained at the time of about 10μs after large-area EB irradiation, since the burr shape in the temperature distributions at 10μs is simillar to one in the experiment as shown in Fig.7. The area above the boiling point is assumed that the material is removed from workpiece due to the evaporation of the material. Also, the area above the melting point is assumed as re-solidified part of the workpiece. Then, the burr height is measured from the melted area at the burr tip to the area at the flat part as shown in the figures. Moreover, in the cases of number of shot $N=2$ and 3shots, the burr height of melted area at burr tip is defined to be a half as shown in the figures, since the movement of melted part was remarkably...
caused at the number of shots. The temperature distributions show that shape variations of burr for each number of shot can be simulated in the analysis. Moreover, the height decreases with increasing number of shot.

Variations of the burr height with number of shot are shown in Fig. 12. Initial burr height is fixed at 60µm as described above. The experimental results show that the burr height linearly decreases from 60µm to 29µm with increasing number of shot. These results indicate that the burr height of rollover burr can be controlled by changing the number of shot in the large-area EB irradiation. Moreover, the analytical results show quantitatively agreement with the experimental ones. Therefore, the variations of the burr height on rollover burr can be predicted by using our unsteady heat conduction analysis model with considering the movement of melted part at small number of shot.

4. CONCLUSIONS

In this study, micro-deburring of rollover burr was experimentally investigated by using the preferential edge removal effect in the large-area EB irradiation. Then, shape variation of burr was examined for each number of shot in order to discuss the variation of the burr height with number of shot. In addition, variation of burr height for each number of shot was analyzed and predicted by unsteady heat conduction analysis. Main conclusions obtained in this study are as follows;

1) Burr height of rollover burr decreases with increasing energy density of EB and the number of shot, while it becomes constant when the energy density and number of shot increase to some extent.

2) Micro-deburring effect is improved by tilting fixing method of workpiece.

3) In micro-deburring of rollover burr with large-area EB irradiation, reduction effect of burr height decreases at large number of shot, since the aspect ratio of the burr becomes smaller with increasing the number of shot.

4) Variations of burr height can be predicted for each number of shot by unsteady heat conduction analysis model with considering the movement of melted part at small number of shot.

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![Fig.12](image-url) Comparison of experiment and analysis results for variations of burr height with number of shot.