Study on Possibility of Micro-deburring by Large-area Electron Beam Irradiation

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Abstract

In a large-area electron beam (EB) irradiation method developed recently, high energy EB can be obtained without focusing the beam. Therefore, the large-area EB of 60mm in diameter with almost uniform energy distribution can be used for instant melting and evaporating of metal surface. The previous studies clarified that the surface smoothing of metal mold made of steel, cemented carbide and ceramics could be performed efficiently. Also this method can be applied to the surface finishing of biomaterials, such as stainless steel and titanium alloy. In this method, the sharp edge is possibly rounded to about half hundred microns in radius under relatively high energy density conditions, since the material removal remarkably progresses there due to the electron concentration and heat accumulation at the edge. In this study, the possibility of micro-deburring was investigated by using the preferential edge removal effect in the large-area EB irradiation. Experimental results showed that the micro-deburring was possible by large-area EB irradiation, and the burr height decreased with increasing energy density of EB and number of irradiation. The burr of about 50μm in height generated in EDM process could be removed completely. Furthermore, micro-burrs at the edge of several small holes within the wide area of 60mm in diameter could be removed simultaneously.

Key words: large-area EB irradiation, deburring, micro burr, alloy tool steels

1. INTRODUCTION

In the manufacturing of industrial products, burr often generates at the edge of parts by metal removal processes, such as cutting, milling, grinding, EDM, laser machining and others, as a results of plastic deformation or resolidification of material. The burr would lead to bad influence to the subsequent process, and the deterioration in product quality, function and appearance. In those cases, further extra finishing process is needed to remove burr. Then, some deburring methods [1] by using rotating brush, barrel finishing, dry blasting, water jet and electrochemical micro-deburring have been widely applied as a batch deburring method. However, these conventional deburring methods have 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. Also, the demand for machining of biomedical parts has increased. Thus, the complete removal of small burrs is often needed, and the deburring by hand work is necessitated if needed.

In a large-area electron beam (EB) irradiation method developed recently, high energy EB can be obtained without focusing the beam. Therefore, large-area EB of 60mm in diameter with almost uniform energy distribution can be used for melting or evaporating metal surface instantly. In the previous studies, it was clarified that the surface smoothing of metal mold made of steel, cemented carbide and ceramics could be performed efficiently [2]-[4]. Then, the machine for the surface smoothing of metal mold surface has been already introduced into the market and the method has been already applied practically. Also, a thin resolidified layer with the different structure from the base matrix is formed on the surface, which brings to increases in corrosion resistance, water repellency, releasability of molded resin products. Moreover, this method can be applied to the surface finishing and surface modification of biomaterials such as stainless steel and titanium alloy [5], [6].

In the large-area EB irradiation, the electrons emitted from the cathode tend to concentrate on the convex parts of micrometer-level height on the workpiece surface profile because of high intensity electric field generated at the convex part. Therefore, the sharp corner edge is rounded to about half hundred microns in radius by large-area EB irradiation with very high energy density conditions, since the material removal remarkably progresses due to the electron concentration and heat accumulation at the corner edge.

In this study, the micro deburring by the preferential edge removal effect in large-area EB irradiation was proposed, and the influences of EB irradiating conditions on the deburring characteristics were experimentally investigated. Also, batch removal of burrs generated at the edge of many small parts has been requested in a few decades, along with the miniaturization of industrial products. Also, the demand for machining of biomedical parts has increased. Thus, the complete removal of small burrs is often needed, and the deburring by hand work is necessitated if needed.

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electrical discharge machining (EDM) drilled holes was tried. Then the possibility of larger-area EB irradiation as a new efficient micro deburring process was experimentally discussed.

2. LARGE-AREA EB IRRADIATION METHOD

Fig.1 illustrates a large area EB irradiation equipment (Sodick PF00A), and the generation mechanism of large-area EB [7], [8]. First, an argon gas of about \( 10^{-2} \) Pa is beforehand introduced into the operating chamber. A magnetic field is generated by the solenoid coils mounted on the outer side of chamber. At the moment when the magnetic field takes a maximum intensity, a pulse voltage is loaded to a ring anode placed in the middle of chamber. In the chamber, the electrons move toward the anode. Simultaneously, Lorenz force acts the electrons to move spirally. Then, the argon gas atoms are ionized by the repetitious collision with electrons, which leads to plasma generation near the anode. When the plasma intensity takes a maximum, a pulse voltage is applied to the cathode at the top, and the electrons are explosively emitted from the cathode by very high electric field near the cathode. Then, the electrons with high energy are irradiated to the workpiece surface.

By this mechanism, EB with high energy density can be produced without focusing the beam, and large-area EB with a maximum diameter of 60mm can be used for melting or evaporating the workpiece surface.

Large-area EB irradiating conditions are shown in Table 1. Pulse duration \( D_p \) and pulse frequency \( f_p \) are constantly 2\( \mu \)s and 0.125Hz respectively. The energy density of the beam \( E_d \) and the number of irradiation \( N \) are varied in order to investigate the effects of them on deburring characteristics.

3. RESULTS AND DISCUSSION

3.1. Removal of rollover burr

At first, the removal of rollover burr, which generates in cutting process, was investigated [1]. The size of the burr can be roughly controlled with the depth of cut. As shown in Fig.2, face milled surface of alloy tool steel SKD11 was made using a square endmill of 3mm in diameter by constant offsets of the one directional tool pass. The milling conditions are as follows; depth of cut \( d \) is 1mm, spindle speed \( N \) is 2400rpm, and feed rate is fixed to 100mm/min.

Standard experimental setup for deburring by large-area EB irradiation is shown in Fig.3 (A). Workpiece was fixed with chucks and placed in the center of the large-area EB. In this method, the rollover burr turns upward and the burr height direction is parallel to the EB irradiation direction.

Firstly, the EB was irradiated to the rollover burr by varying the energy density \( E_d \) of EB in order to investigate the effect of the energy density on the decrease in burr height. Fig.3 (B) shows a tilting method discussed later, in which the burr tilts to the EB direction and the edge position becomes higher than the surroundings (\( \theta = 45^\circ \)).

Fig.4 shows scanning electron microscope (SEM) images of the burr before and after EB irradiation with various energy density of EB. The number of irradiation \( N \) is fixed to 30shots. Before EB irradiation, it can be confirmed that the burr continuously generates along the workpiece edge like a ribbon, and the height is not uniform. The average burr height is approximately 60\( \mu \)m. After the EB...
irradiation, the height becomes uniform under each energy density condition. Also, the burr average height decreases as the energy density increases.

The variation of burr height measured from the SEM images is shown in Fig.5. The average burr height and its scatter become smaller with an increase of energy density of EB. The average burr height and the scatter before EB irradiation are about 60μm and 90μm respectively. When the energy density $Ed$ is 10.0J/cm$^2$, those after EB irradiation are about 20μm and 10μm. However, the burr height could not be decreased any more when the energy density is higher than 10 J/cm$^2$. Therefore, it can be concluded that the height of rollover burr decreases to some extent by large-area EB irradiation and the reduction of the burr height is limited.

Next, the effect of EB irradiation number was investigated as the energy density $Ed$ was fixed to 10.0J/cm$^2$. In this experiment, two EB irradiating methods shown in Fig.3 were compared. (A) is a normal fixing method, in which the burr of edge turns to the EB irradiating direction ($\theta_t=90^\circ$). (B) is a tilting method, in which the burr tilts to the EB direction and the edge position becomes higher than the surroundings ($\theta_t=45^\circ$). In the previous studies, it was made clear that the EB was easy to concentrate and the heat is easy to accumulate to the convex part under this situation.

Fig.6 shows the variations of burr height with number of EB irradiation for two different workpiece fixing methods. In both fixing methods, when the number of irradiation is small, burr height greatly decreases with an increase of EB irradiation number. Then, it gently decreases. Furthermore it becomes almost constant when the number of irradiation is more than 20shots. In addition, the burr height when the workpiece tilts is always smaller than those in the case of normal fixing method. In the case of tilting method, the average burr height takes a minimum of 15μm only at 10shots. This result indicates that workpiece tilting is effective in decreasing the burr height efficiently.

In order to discuss the change in burr shape with number of EB irradiation, the cross-sectional shapes of burrs were observed. Fig.7 shows the SEM images of the cross-sections of burr for various number of irradiation. It can be confirmed again that the burr
height decreases with increasing the number of EB irradiation but the burr width increases. Also in the case of large number of irradiation, resolidified layer can be observed on the surface. At the number of irradiation of 30shots, the resolidified layers on the left-side wall and on the right-side flat surface of burr are much thicker than other parts. This indicates that the burr reduction was done not only by the boiling and melting of burr part with high temperature given by EB but also the moving of molten parts with surface tension. It is also considered that the electrons easily concentrate to the convex corner and the burr due to high electric field there. Therefore, for further detailed discussion of the deburring characteristics in this method, the temperature distribution of the burr part and the time variations with considering the electron concentration phenomenon should be investigated and the deburring mechanism should be clarified on the base of the investigations of temperature distribution.

3.2. Removal of EDM burr

From the experiment results on the deburring of rollover burr discussed above, deburring by large-area EB irradiation can be expected when the initial burr height is about 30μm or less. Then, the deburring of smaller burr generated in EDM was investigated.

The set-up of EDM for the burr generation is shown in Fig.8. The burrs were made by EDM of shallow cavity of 0.3mm in depth using a copper cylindrical electrode of 40mm in diameter. The burrs are generated at the edge of the cavity as shown in the figure. EDMs were carried out under four different discharge conditions in order to make different burr heights. Condition A is the lowest discharge energy condition with small discharge current, and the burr generated under this condition is the shortest. Condition D is the highest energy condition. The energy density $E_d$ of EB was fixed to 15.0J/cm$^2$, and the number of EB irradiation $N$ was changed.

Fig.9 shows SEM images of the burr generated in EDM under condition C, and those after EB irradiation with various number of irradiation. The burrs discontinuously generated, differently from the rollover burr shown above, and the burr height before EB irradiation was about 52μm. Then, the burr height decreases with an increase of EB number. The burr could be removed completely after 50shots or fewer. In particular, the smallest burr obtained by EDM conditions A is completely removed by only 5shots. From these results, it is clear that highly efficient micro deburring is possible for EDM burr of a few dozen micrometers in height.

3.3. Batch deburring of small holes

Since the beam is as wide as 60mm in diameter in the large-area EB irradiation method, simultaneous removal of many micro burrs within the beam area, namely batch micro-deburring is highly expected. Thus, the removal of several micro burrs generated at
the edges of many small holes machined by EDM drilling was investigated. The diameter of EDM drilled holes is 1.0mm, and 5x5 holes at a constant interval of 1.5mm are arranged on SKD11 plate of 1.0mm in thickness. In the large area EB irradiation, all holes are within the EB irradiation area and deburring are processed simultaneously without scanning the EB.

Fig.11 shows the optical and SEM images of workpiece surface before and after large-area EB irradiation. Before EB irradiation, the generation of micro burr at the hole edge and remarkable adhesion of debris to the surface can be noticed. The surface also might be oxidized and rusted since these holes were fabricated by EDM drilling in water based working fluid. By large-area EB irradiation under appropriate EB conditions of 15.0J/cm² and 30shots, the burrs, the adhered debris and the rust were completely removed, and the surface got glossy.

Fig.12 shows SEM images of burr and the profiles of the hole edge. The energy density was fixed to 15.0J/cm² and the number of irradiation was varied. The burr height was about 40μm in highest before EB irradiation, but it decreases with the number of irradiation as shown in the figure. In the cases of 5 and 10shots, the burr becomes very small but the surface around machining holes became a little rough, because of the EDM debris adhesion on the surrounding. On the other hand, the deburring was completely performed and the surrounding surface was very smooth in the case of 30shots. From these results, it was made clear that large-area EB irradiation had high possibility as an efficient micro deburring method.

Application of this method to other material was investigated. Fig.13 shows the deburring results of EDM holes on titanium alloy (Ti-6Al-4V). The dimensions and the arrangement of holes are the same as SKD11 shown above. The burr shape is spherical in some cases as shown in upper side images and it is different from that in the case of SKD11. This may be because the thermal properties such as heat conductivity and the melting point of the titanium alloy are different from those of SKD11. While the initial burr height is about 50μm, it becomes zero and the surface becomes very smooth at 50shots, due to sufficient surface melting. However, the edge shape remarkably rounds at this time, which might deteriorate the hole shape accuracy. Further discussion should be needed for better deburring performance of titanium alloy. Also the applicability of this method to other materials should be investigated.
4. CONCLUSIONS

In this study, the possibility of micro-deburring by using large-area EB irradiation was investigated. Main conclusions obtained are as follows;

1. The burr height decreases with increasing of the energy density of EB and the number of irradiation.
2. By tilting the workpiece so that the position of edge with burrs is higher than the surroundings, the burr reduction effect becomes high due to the enhancement of electron beam concentration.
3. The rollover burr of about 60μm in height generated in cutting can be decreased to about 15μm by large-area EB irradiation.
4. The discontinuous burr of a few dozen micrometer height generated in EDM can be removed completely, and highly efficient batch micro-deburring of many small holes within wide area of 60mm in diameter is possible.
5. Large-area EB irradiation has high possibility as an efficient micro deburring method.

REFERENCES


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