A NEW POLISHING METHOD OF METAL MOLD WITH LARGE-AREA ELECTRON BEAM IRRADIATION

Y. Uno, A. Okada, K. Uemura [*], P. Raharjo [*], S. Sano [**], Z. Yu [**] and S. Mishima [†]

Graduate School of Natural Science and Technology, Okayama University,
3-1-1, Tsushimanaka, Okayama 700-8530, Japan

[*] Nagata Seiki Co., Ltd, 1451, Jizodo, Bunsui-cho, Niigata 959-0121, Japan

[**] Sodick Co., Ltd, 3-12-1, Nakamachidai, Tsuzuki-ku, Yokohama 224-8522, Japan

[†] ZenoTech Co., Ltd, 12-8, Toyohama-cho, Okayama 700-0853, Japan

Abstract

A new polishing method by large-area electron beam (EB) irradiation is proposed in this study. In the large-area EB irradiation equipment used here, an EB with high energy density is irradiated without focusing the beam. An EB irradiation in a few micro seconds with a maximum diameter of 60mm can be used for melting and evaporating metal surface instantly. The experimental results made it clear that the surface roughness decreases from 6μmRz to less than 1μmRz in a just few minutes under a proper machining condition. The corrosion resistance of metal mold surface also could be greatly improved by large-area EB irradiation. Furthermore it is clarified that even the surface roughness of tilting surface close to 90° could be well improved. Therefore, large-area EB irradiation method has a possibility to become a high-efficient polishing method of metal mold.

Keywords: electron beam; polishing; metal mold; corrosion resistance; EDM

1. Introduction

Metal molds are generally polished manually as the finishing process in order to improve the surface integrity such as surface roughness, micro crack and residual stress after milling and/or electrical discharge machining (EDM). This process takes the special technical skills and much time, which leads to higher cost of molds. Therefore it is strongly requested to perform this process more efficiently. Finishing robots with polishing tool are partly used for this process. However it is only applicable to the simple shape surface. Most of the molds have very complex shape, so it is difficult to replace the manual finishing with robot finishing.

In this study, a new polishing method by large-area electron beam irradiation 1) is proposed. The large-area irradiation equipment used here was recently developed using the phenomenon of explosive electron emission 2), and an EB with high energy density is irradiated without focusing the beam. An EB irradiation in a few micro seconds with a maximum diameter of 60mm can be used for melting metal instantly. Using this equipment, the possibility for high efficient finishing of metal molds is experimentally discussed.

2. Large-area EB irradiation equipment

Figure 1 schematically illustrates the EB irradiation equipment 2)-4). This equipment is developed recently using the phenomenon of explosive electron emission. Differently from general EB irradiation performed in a

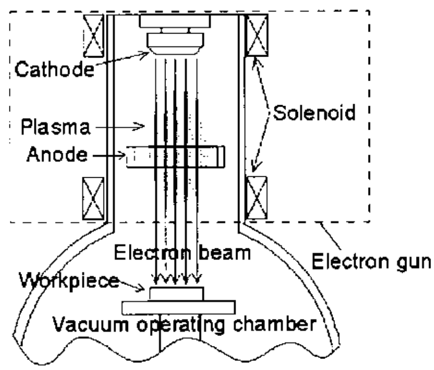


Fig.1 Large-area EB irradiation equipment

Table 1 Machining conditions

Energy density *Ed*	J/cm^2	1.4-10.7
Acceleration voltage *V*	kV	30
Number of irradiation *N*	shots	1-50
Pulse duration *tp*	μs	2-3
Pulse frequency *Fp*	Hz	0.2
Beam diameter *Db*	mm	60

vacuum, an argon gas of about 10^{-2}Pa is beforehand mixed in the chamber. At first, a magnetic field is generated by the solenoid coil mounted on the outer side of the chamber. At the moment when the magnetic field takes a maximum intensity, a pulse voltage is loaded to a ring shape anode. In the chamber, the electrons start to move towards the anode. Simultaneously, the electrons move spirally due to the Lorentz forces. Next, argon atoms are ionized by the repetitious collision with electrons, which generates plasma near the anode. When the plasma intensity takes a maximum, pulse voltage is applied to the cathode. The electrons are accelerated by high electric field due to electric double layer formed near the cathode, and the explosive electron emission occurs. Then, EB with high energy density is irradiated to the workpiece surface. Moreover, the plasma is effective to make the life of EB long. That is, by passing through plasma region, the Coulomb's force among electrons is decreased and the straightness of EB can be improved. In this system, the EB irradiation is carried out in a series of pulses. By the above mentioned mechanism, high energy density EB can be produced without focusing the beam. Therefore, EB with a maximum diameter of about 60mm has a high energy density enough to melt or evaporate metal surface instantly.

Machining conditions are shown in **Table 1**. The EB irradiation time of one pulse is only 2-3μs, and the pulse frequency is set to 0.2Hz. The diameter of EB is about 60mm as shown above. Metal mold steel (NAK80, Daido Steel Co. Ltd.) is prepared as the workpiece material. Workpiece surface is beforehand EDMed using copper cylindrical electrode of 8mm in diameter. The surface roughness of the workpiece is arranged to about 6μmRz.

3. Results and discussion

3.1 Effects of EB condition

At first, an optimum EB condition for smoothing surface is investigated by changing the energy density of the beam. **Figure 2** shows SEM micrographs of the EB irradiated surface for various energy densities of EB. The number of irradiation is set to 30shots under every energy density condition. The EDMed surface before irradiation is also shown for comparison. Under the small energy density condition of 1.4J/cm^2, some melted parts can be observed on the surface. In the case of 2.1J/cm^2, more surface melting occurs and so the surface seems to become smoother. Furthermore, under larger energy density conditions, the state of surface completely differs from the EDMed surface before EB irradiation. Roughness curves are shown in **Figure 3**. In the case of EDMed surface before EB irradiation, the roughness is about 6μmRz. On the other hand, those after EB irradiation become smaller with increasing energy density. When the energy density is sufficiently large, high reduction in the surface roughness can be attained.

Figure 4 presents graphically the variations of surface roughness and the glossiness with the energy density. The measurement of glossiness was carried out in accordance with JIS Z8741. In this measurement, the glossiness of the perfect mirror surface is defined as just 1000, and the value over 300 means generally glossy surface. The surface roughness becomes smaller with increasing energy density, and takes a minimum value of

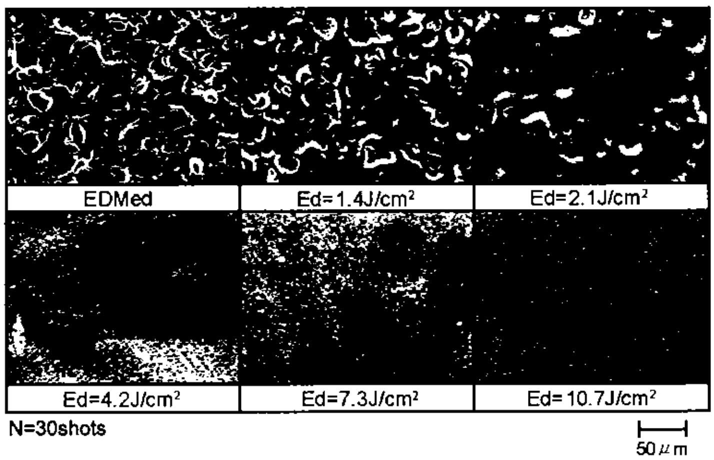


Fig.2 Large-area EB irradiated surfaces for various energy densities

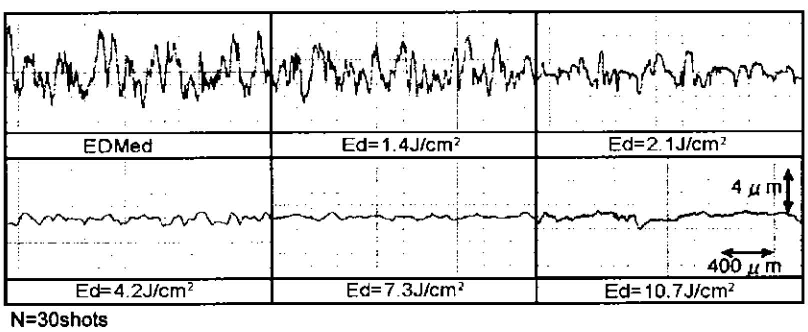


Fig.3 Profiles of EB irradiated surface for various energy densities

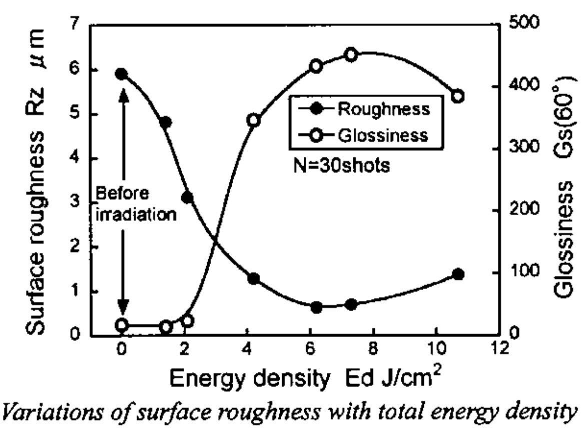


Fig.4 Variations of surface roughness with total energy density

0.7μmRz at 6-7J/cm^2. At that time, the glossiness becomes higher with increasing energy density, which corresponds well to the change in the surface roughness. However, excessive energy density makes the surface roughness and the glossiness a little worse.

In the same way, the variation of surface roughness was discussed when the number of irradiation was changed from 1 to 99shots. As a result, the surface roughness decreased with the number of irradiation. And, when the number of irradiation is more than 30shots, the surface roughness did not change so much. From the abovementioned results, high efficient surface polishing of metal mold could be attained by large-area EB irradiation, since the process takes only 150sec under a proper condition of 30shots and 6-7J/cm^2.

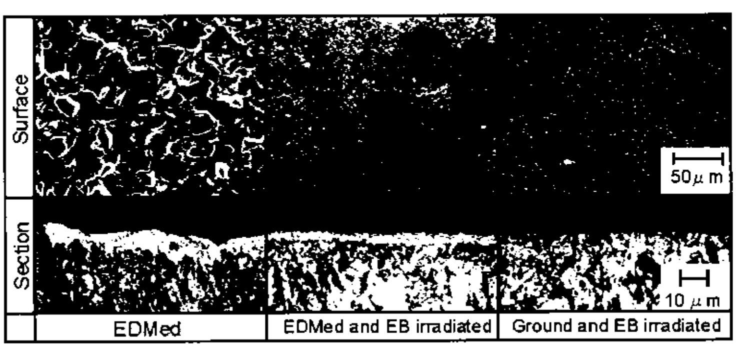
3.2 Surface smoothing mechanism

SEM micrographs in **Figure 5** are the cross sections of EDMed surface, EB irradiated one after EDMing, and EB irradiated one after grinding. In the case of EDMed surface, a resolidified layer (white layer), where the material is melt with high temperature due to electrical discharge and then solidified again back, can be observed clearly. Besides, the undulation of surface is large. On the other hand, the thickness of white layer decreases, and the undulation becomes smaller, in the case of EB irradiated surface after EDMing. Moreover, there seems to be no or little white layer on the EB irradiated surface after grinding. Therefore, the white layer observed on EB irradiated surface after EDMing is formed by not EB irradiation but by EDMing. It is guessed that the effect of heat conduction on the surface is very small, since EB irradiation time of one pulse is so short as 2-3μs. Consequently, the material removal by melting and evaporation occurs just near the surface.

Next, the material removal thickness by EB irradiation was examined. In **Figure 6**, the left side of the EDMed surface was covered with a thin stainless plate before EB irradiation. That is, only the right side of the EDMed surface was irradiated with EB. The comparison of both profiles makes it clear that the material removal occurs just near the surface and the thickness of removed material in this method is uniformly as small as 1μm for 30 EB shots. In conventional finishing of metal mold surface by hand polishing, it is difficult to keep material removal quantity constant on the whole surface, which leads to the deterioration in the shape accuracy in some cases. This new polishing method does not deteriorate the shape accuracy, since material removal quantity is very small and almost constant.

3.3 Corrosion resistance of EB irradiated surface

Figure 7 shows the large-area EB irradiated and non-irradiated samples left for 1 year in the atmosphere. The center circular part of the workpiece is the EDMed surface and the surrounding part is the ground one. In the case of non-EB irradiated workpiece, the ground surface has extensively been rusty. Moreover, the EDMed



Ed = 7.3 J/cm^2, N = 30 shots

Fig.5 Cross sections of EDMed surface and electron beam irradiated surfaces

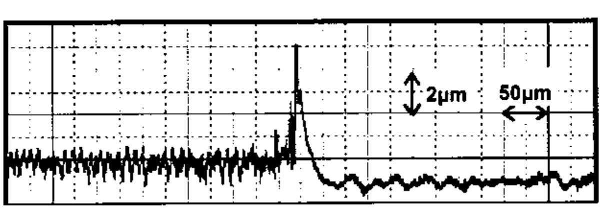


Fig.6 Thickness of removed material with large-area EB irradiation


(a)Non-EB irradiated (b)EB irradiated

Fig.7 Workpieces left for 1 year in atmosphere surface has been somewhat rusty, although the EDMed surface generally has high corrosion resistance. On the other hand, in the case for EB irradiated sample, there is no rust at all, and very glossy surface could be kept.

In order to evaluate accurately the corrosion resistance of EB irradiated surface, the anodic polarization curves are measured by an electrochemical analysis system. **Figure 8** shows the result with 1N-HCl solution. The equilibrium potential for EB irradiated surface is smaller than that for EDMed one and ground one. Also the current density for EB irradiated surface is much smaller than that for EDMed one and ground one at any potential, which agrees well with the results shown in the Figure 7. Therefore, it was made clear that the corrosion resistance of metal mold surface could be greatly improved by large-area EB irradiation.

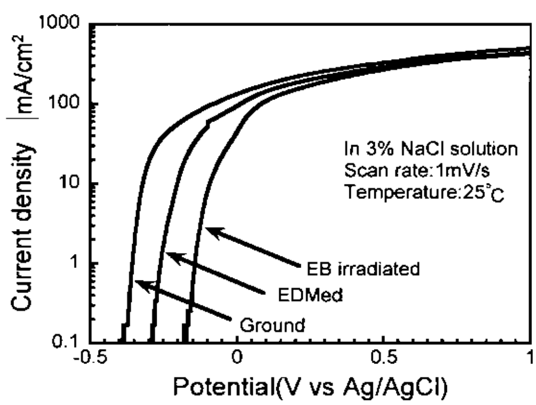


Fig.8 Anodic polarization current curves

3.4 Smoothing of tilting surface

In this section, the smoothing of tilting surfaces is tried for practical use, since metal mold usually has many tilting surfaces. As shown in **Figure 9**, the surface roughness is measured when the surface tilting angle θ with respect to EB irradiation direction varies. At this time, EB irradiating conditions are set to energy density Ed_o=7.3J/cm^2 and number of irradiation N=30shots. If the surface roughness after EB irradiation is decided by only the total energy density Ed, the surface roughness will become the same for energy density of $Ed_o*\cos\theta$.

Experimental results are shown in **Figure 10**. The dotted line in the graph is the expected surface roughness corresponding to $Ed_o*\cos\theta$. In the case of small tilting angle, the surface roughness decreases to 0.7μmRz and it is almost the same as expected. On the other hand, the experimental surface roughness is much smaller than the expected one for larger tilting angles. For example, when the tilting angle is 60°, the surface roughness is about

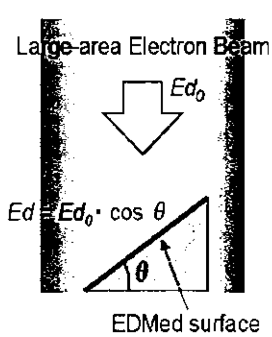


Fig.9 Large-area EB irradiation to tilting surface

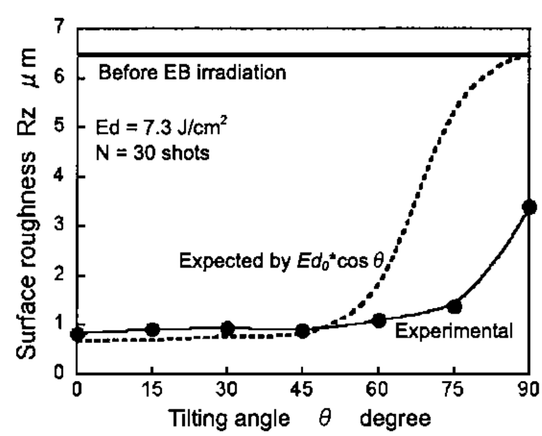
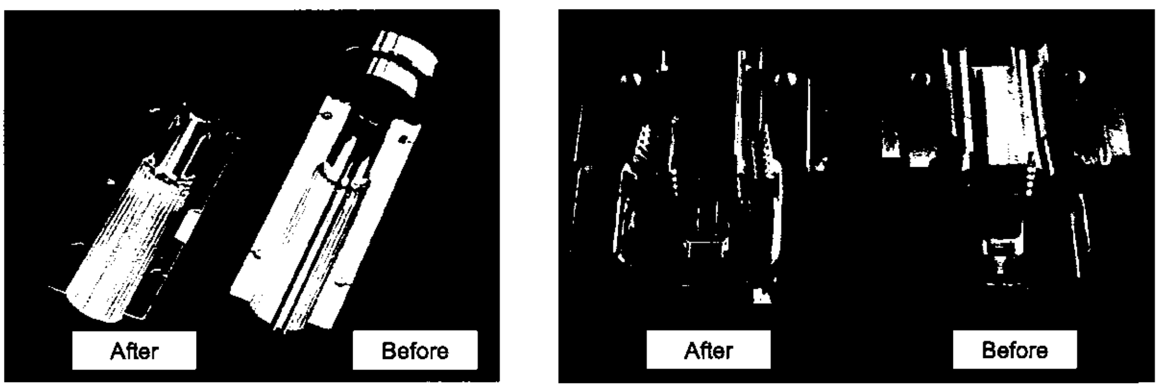


Fig.10 Variations of surface roughness with surface tilting angle

1μmRz, while the expected one is about 2μmRz. Furthermore, even if the tilting angle is close to 90°, the surface roughness can be improved. The results indicated that in the case of small simple shaped mold consisting of relatively small tilting angle surfaces, the smoothing of the whole surface is possible in a few minutes without moving and tilting the metal mold.

3.5 Large-area EB irradiation to practical metal molds

Figure 11 shows large-area EB irradiated practical metal mold samples (NAK80 and SKD61 in JIS specification). As can be seen from the photos, both samples have very complicated shape. However, the surface becomes very glossy after large-area EB irradiation, compared with those before irradiation. The process takes only 150sec, and EB irradiation was carried out without moving and tilting the metal molds. Therefore, this finishing technique by large-area EB irradiation is applicable to high efficient finishing process for metal molds.



(a) NAK80 (b) SKD61

Fig. 11 Large-area EB irradiated practical metal mold samples

4. Conclusions

(1) The roughness of large-area EB irradiated surface becomes smaller with increasing energy density of beam and number of irradiation. Under proper conditions, the surface roughness decreases to about 0.7μmRz in just a few minutes.
(2) In the smoothing process by large-area EB irradiation, the material removal by melting and evaporation occurs near the surface and resolidified layer is not formed. The thickness of removed material is uniformly as small as 1μm for 30 EB shots.
(3) The corrosion resistance of metal mold surface could be improved greatly by large-area EB irradiation.
(4) Even if the tilting angle of surface is close to 90°, the surface roughness could be well improved.
(5) Large-area EB irradiation has a possibility to become a high efficient polishing process for metal molds.

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