# Application of Large Area Electron Beam Irradiation for Surface Modification of Metal Dies

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**Abstract – Application of low energy high current pulsed electron beam for surface finishing of metal dies is described in this study. A large area electron beam with effective diameter of 60 mm is used for melting and/or evaporating surface of metal dies. The experimental results show that the surface roughness can be decreased from 6 μmRz to less than 1 μmRz with electron beam irradiation. Increase of corrosion resistance on the irradiated surface is observed on NAK80 die material. Observing the cross section of irradiated surface, it is confirmed that material removal is performed on the irradiated surface without any re-solidified layers. In this study, problem of craters on the NAK55 metal die materials is also evaluated by using scanning electron microscope (SEM) and electron probe micro analyzer (EPMA). From the results of surface evaluations, it can be shown that the craters are mostly related to additive elements included in the die material.**

## 1. Introduction

In traditional method, the surface of metal dies is usually finished by hand polishing after milling process and/or Electric Discharge Machining (EDM), in order to obtain small surface roughness without cracks and heat affected layer. This process takes a lot of time and requires special technical skills. A skillful technician for hand polishing needs several years of training to obtain good quality of polishing. Automation of this process meets difficulties, due to complicated shape of metal dies.

In this study, a new finishing process for metal dies with large-area pulsed electron beam system is introduced. The large-area EB irradiation system used in this study was recently developed for the purpose of surface treatment by Nagata Seiki Co., Ltd. (Japan), in collaboration with High Current Electronics Institute (Tomsk, Russia). The same EB system has been used in application for surface modification of dental materials [1, 2].

## 2. Experimental Procedures

To elaborate relationship between electron beam energy and surface roughness on die materials, samples of NAK80 (Daido Steel Co.,Ltd.) with dimension of 20×20×5 mm are prepared. The surface of each sample is EDMed using copper cylindrical electrode of 8 mm in diameter, and the surface roughness after EDM is about 6 μmRz. Chemical composition of NAK80 is shown in Table 1. The samples are irradiated with various beam energy density or different number of pulses. After the EB irradiation, surface roughness and glossiness of each sample is measured. The glossiness measurement is carried out in accordance with Japanese Industrial Standard (JIS) Z8741.

Table 1. Chemical composition of NAK80

| C | Si | Mn | Ni | Cu | Mo | Al | □ | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.15 | 0.3 | small qty. | 3.0 | 1.0 | 0.3 | 1.0 | □ | Balance |

To evaluate craters on the surface of die materials, NAK55 (Daido Steel Co.,Ltd.) die materials is also prepared. The chemical composition is shown in Table 2. SEM and EPMA are using for evaluation the surface on the position of crater. Comparing results of both analyses before and after electron beam irradiation, the elements inside the crater are identified.

Table 2. Chemical compositions of NAK55 die material for crater evaluation

| C | Si | Mn | Ni | Cu | Mo | Al | cutting element | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.15 | 0.3 | small qty. | 3.0 | 1.0 | 0.3 | 1.0 | S additive | Balance |

## 3. Results and Discussion

An optimum condition for surface smoothing is investigated with varying the energy density of the beam. Figure 1 shows SEM micrographs of the EB irradiated surfaces for various energy densities of electron beam. Under relatively small energy density of 1.4 J/cm$^2$, some melted parts can be observed on the surface. Increasing the energy up to 2.1 J/cm$^2$, the melting surfaces are confirmed obviously. Furthermore, under larger energy density condition, the morphology of the surface is completely differs from the initial (as-EDMed) surface.

Profiles of sample surfaces are shown in Fig. 2. In case of the EDMed surface before EB irradiation, the roughnes is about 6 μmRz. After EB irradiation, the roughness becomes smaller with increasing energy density, providing a minimum value of 0.7 μmRz at 6–7 J/cm$^2$, as shown in Fig. 3. However, excessive energy density makes the surface becomes worse.

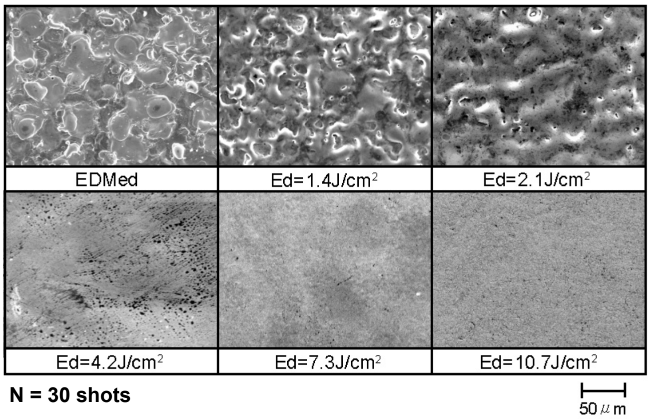


Fig. 1. Electron beam irradiated surfaces for various energy densities

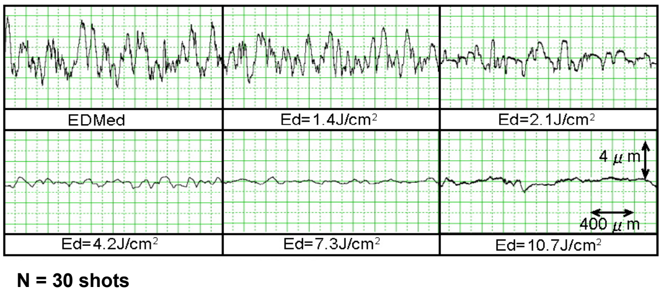


Fig. 2. Profiles of irradiated surfaces for various electron beam densities

From the measurement of glossiness, it can be shown that the glossiness increases with increase of electron beam energy, and decreases again if energy density is too high. The change of glossiness relatively corresponds to the change of surface roughness.

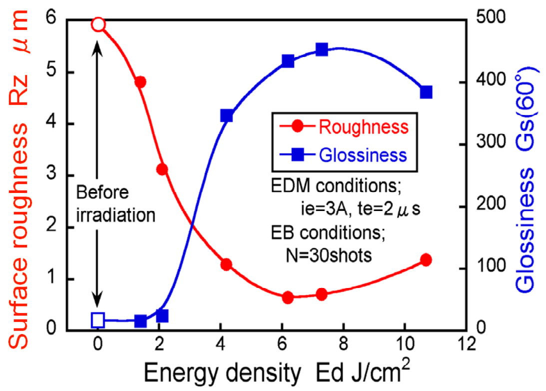


Fig. 3. Dependence of surface roughness on electron beam energy density

Figure 4 shows EB irradiated surfaces when the number of pulses is varied under a constant energy density (4.2 J/cm$^2$ per pulse). By a single shot, the surface melting is occurred as observed apparently from the SEM micrograph, and the surface smoothing has started. When the pulse number of irradiation is more than 10 times, no significant change of surface morphology is detected.

Correlating these results with the effect of energy density shown above, it can be considered that the sufficient surface smoothing might be possible by relatively high energy density of EB or large number of EB irradiation pulses. In other words, it may be presumed that the roughness depends on the total energy density (number of pulses×x energy density per each pulse). Variation of surface roughness with different total energy is shown in Fig. 5, in the cases of energy densities per pulse are 4.2 J/cm$^2$ and 7.3 J/cm$^2$, respectively. Surface roughness decreases with increasing of total energy, and takes a minimum at 200–300 J/cm$^2$ for both energy densities. However, the minimum value of surface roughness in the case of 4.2 J/cm$^2$ is smaller than that of 7.3 J/cm$^2$. As a conclusion, the sufficient smoothing can be attained under condition of small energy density and large number of irradiation.

Figure 6 shows SEM micrographs of the cross sections of as-EDMed, EDMed and EB irradiated, and EB irradiated surface after grinding, respectively. In the case of EDMed surface, the re-solidified layer (white layer), which is a melted part by high tempera ture during electrical discharge machining is re-solidified, can be observed clearly, and undulation of surface is large. However, the thickness of white layer decreases, the undulation becomes smaller after electron beam irradiation. Moreover, no white layer is observed on the EB irradiated surface, which is previously ground without EDM process. Therefore, EB irradiation on NAK80 does not perform any white layer as formed in the EDMed surface, and conversely it can be used for removing the white layer formed after EDM process on die materials.

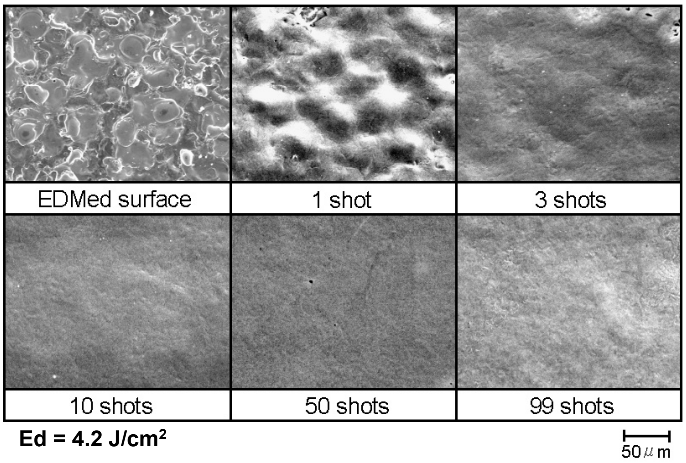


Fig. 4. Electron beam irradiated surfaces for various number of pulses

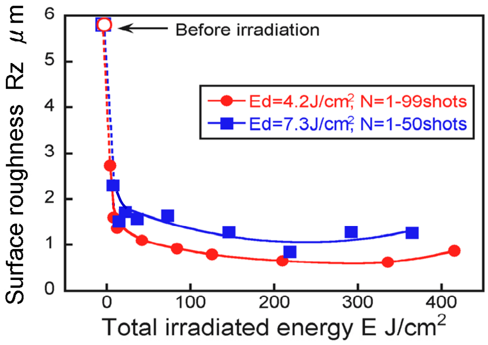


Fig. 5. Dependence of surface roughness on total irradiated energy

Corrosion resistance is also increase after EB irradiation as shown in Fig. 7.

Since metal die usually has many inclined curved surfaces, the effect of curve on surface smoothing should be investigated. Assuming that the beam modifies surface samples only in perpendicular direction, then an inclined surface will be irradiated by perpendicular energy of $E_d = E_{do}\cos\theta$ as illustrated in Fig. 8. Where $E_{do}$ is energy density of incident beam and θ is incline angle.

Using data of energy density vs. surface roughness shown in Fig. 8, we can expect surface roughness from energy density of $E_{do}\cos\theta$. Comparison between the expected and experimental roughness is shown in Fig. 3 for different degrees of incline angle.

The graph shows that for small incline angle, the surface roughness decreases to 0.7 μmRz and it is almost the same as the expected value. However, for large incline angle, the experimental surface roughness is much lower than the expected one. The result suggests that in the case of a simple shaped small die consisting of relatively small angle inclined surface (less than 45°), the smoothing of whole surface is possible without tilting the die. Even for surface with incline angle close to 90°, the surface roughness can be improved.

Main problem in application of intense charged particle beam for metal surface irradiation is formation of craters[3].

Figure 9 shows photo of craters observed on different die materials. Compared to NAK80, NAK55 has additive element sulphur (S) as indicated in composition written in Table 2. Significant difference of crater amount is obviously detected in between two materials.

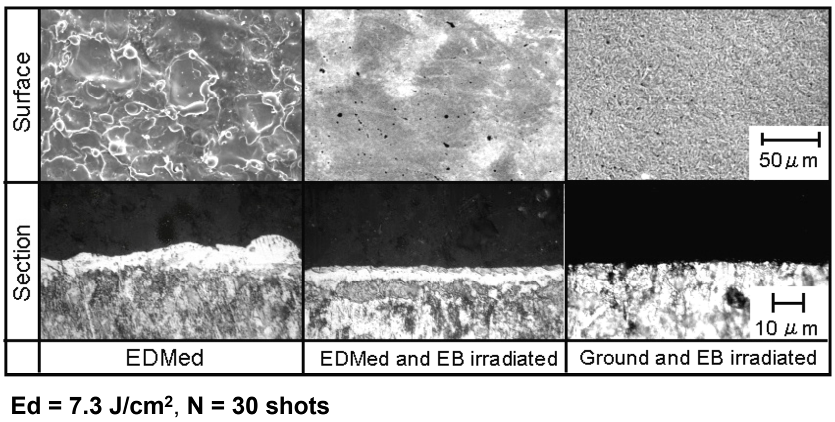


Fig. 6. Cross-sections of EDMed surface and EB irradiated surface

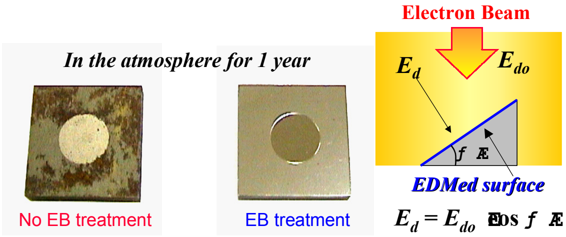


Fig. 7. Comparison of corrosion in the atmosphere for 1 year

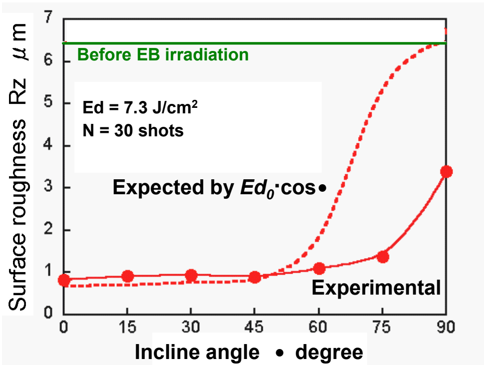


Fig. 8 Roughness of EB irradiated surfaces with different incline angle, compared to the expected roughness

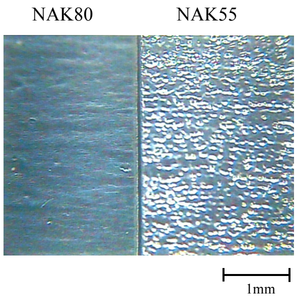


Fig. 9 Difference of crater amount on NAK80 and NAK55 after EB irradiation

Applying low energy of irradiation as 1.5 J/cm$^2$, the surface is evaluated as shown in Fig. 10. EPMA of the surface after EB irradiation indicates sulphur (S) inside the craters. Sulphur is slightly detected before irradiation, however, after EB irradiation, the content becomes obvious. Mn is also observed in the craters where S appears. It suggests that crater formation may be related to the S and Mn contents in the NAK55.

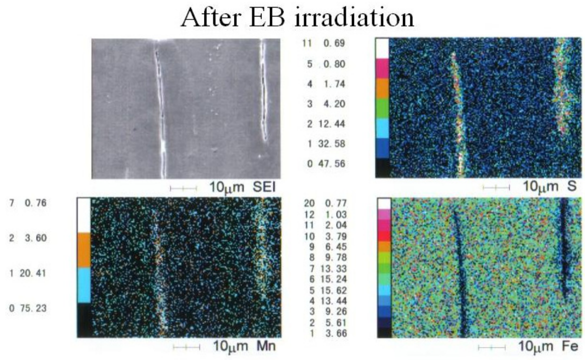


Fig. 10. Surface evaluation by SEM and EPMA on the surface before and after EB irradiation of NAK55

## 4. Conclusions

1. Roughness of EB irradiated NAK80 die material decreases as increasing energy density. At optimum energy of 6–7 J/cm$^2$, it can provide minimum roughness as about 0.7 μmRz.

2. Material removal by melting and evaporation occurs near the surface and no re-solidified layer is formed. Increasing of corrosion resistance can be obtained.

3. Even for inclined surface with angle close to 90°, the surface can be modified.

4. After EB irradiation, sulphur in NAK55 dies is detected in the crater as the same location as Mn. It suggests that the crater formation may be related to additive elements included in the die.

## References

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