Control of modified surface layer thickness in pulsed large-area EB irradiation

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In pulsed large-area EB irradiation method, wide area of metal surface can be instantly melted and the surface roughness can be decreased efficiently. This finishing method is already applied to metal molds. In addition, the surface modification effects were reported, since thin resolidified surface layer with microstructre is formed. For high performance of the layer, control of the layer thickness is important. In this study, the effects of EB conditions on the thickness are experimentally and analytically investigated.

Контрол на модифицираната дебелина на повърхността на слоя при импулсно електроннолъчево облъчване на голяма площ (Акира Окада, Того Шинонага, Мотохиро Иное). *При импулсно електроннолъчево облъчване на голяма площ, широка зона на металната повърхност може да бъде първоначално разтопена и неравностите на повърхността може да се намалят ефективно. Този довършителен метод вече се прилага към метални пресови форми. В допълнение са докладвани ефекти на модификация на повърхността, тъй като се образува тънък втвърден повърхностен слой с отново затвърдена структура. Контролът на дебелината на слоя е важен за високата производителност на слоя. В това проучване е изследвано експериментално и аналитично влиянието на условията на електроннолъчева обработката върху дебелината на този слой.*

Introduction

Metal molds is generally finished by hand lapping after shaping by milling and/or electrical discharge machining (EDM), in order to attain high shape accuracy and small surface roughness without cracks and heat affected layer. This process takes a lot of time and often needs special technical skills. Therefore, a high efficient finishing process is strongly required.

The authors [1 - 4] developed a new surface finishing method by pulsed large-area electron beam (EB) irradiation. In this method, EB with high energy density can be irradiated without focusing the beam. Therefore, large-area EB with an effective diameter of 60mm can be used for instant melting or evaporating metal surface. Then, wide area of metal surface can be instantly melted and the surface roughness can be decreased efficiently, as shown in Fig. 1 and Fig. 2. This finishing method is now practically applied to metal molds and the equipment is already introduced into the market. In addition, the surface modification effects are expected, since a thin resolidified surface layer with microstructure is formed on the surface. For long-term high performance of the layer, control of the thickness is also important, since the performance may last as long as the layer exists.

In this study, the structure of resolidified layer by large-area EB irradiation are firstly investigated. Then, the influences of large-area EB conditions on the resolidified layer thickness are experimentally discussed. Also, prediction of the thickness is tried with the temperature distributions near the metal surface obtained by a transient heat conduction model. Furthermore, the surface characteristics of the large-area EB irradiated surface, such as hydrophobicity and corrosion resistance are evaluated.

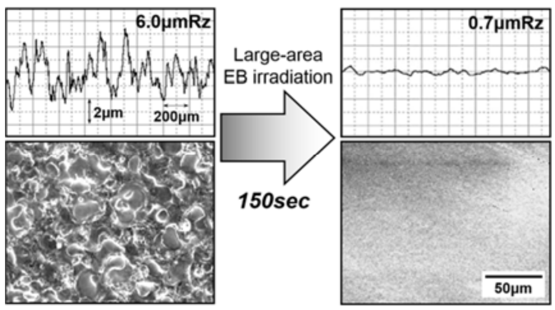

Fig.1. Surface roughness curves and SEM images of surface before and after EB irradiation.

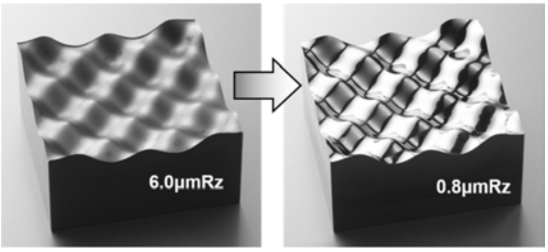

Fig.2. Large-area EB irradiated sample.

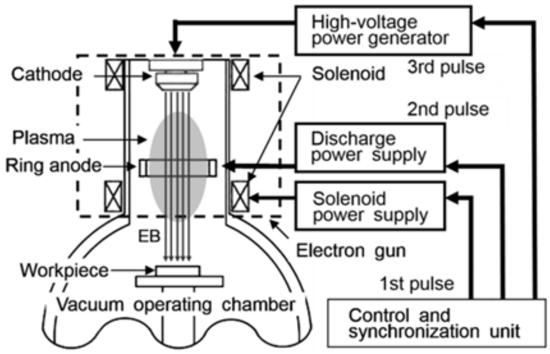

Fig.3. Large-area EB irradiation equipment

Experimental Procedure

Fig. 3 schematically shows the large-area EB irradiation equipment (Sodick PF-00A) used in this study and the generation mechanism of large-area EB [5]. The operating chamber is filled with an argon gas of about 10^{-2} Pa. At first, a magnetic field is generated by the solenoid coil mounted on the outer side of the chamber. A pulse voltage is applied to the ring anode placed in the middle of chamber. In the chamber, electrons are generated by the Penning effect, and move towards the anode. Simultaneously, a Lorentz force is applied to the electrons, which causes the electrons to move spirally, and so plasma generates near the ring anode. When the plasma intensity reaches maximum, a pulse voltage is applied to the cathode set on the top. The electrons are accelerated by high electric field due to electric double layer formed near the cathode, and an explosive electron emission [6] occurs.

By this mechanism, high energy density EB can be generated without focusing the beam. Then, large-area EB of 60mm in diameter can be used for instant melting and evaporation of work-piece surface. In this system, the EB irradiation is carried out in a series of pulses.

The EB irradiation time of one pulse is only 2 μs, and the pulse frequency is set to 0.2 Hz. Alloy tool steel SKD11 in JIS specifications is prepared as the work-piece material. The chemical composition is shown in Table 1. The surface is beforehand ground, and the surface roughness is arranged to about 3 μmRz. In the following experiment, the energy density of electron beam *E*d and the number of irradiation *N* are varied to discuss the effect of these conditions on the surface structure and surface characteristics.

Structure and Thickness of Resolidified Layer

Fig. 4 shows the energy distribution type X-ray spectroscopy (EDX) of the surface before and after large-area EB irradiation. It is noticed that chromium peaks become higher than those before EB irradiation. It means that content of chromium increase on EB irradiated surface. SKD11 generally includes large size chromium carbide and/or chromium oxide in the matrix. It is guessed that the chromium carbide or oxide might have been uniformly rearranged and resolidified on the surface by EB irradiation.

Then, the cross-section of resolidified layer was observed by SEM. The SEM images after EB irradiation with different number of EB irradiation are shown in Fig. 5. A resolidified layer can be noticed on the EB irradiated surface in any EB irradiation numbers. In the resolidified layer, chromium carbide grains cannot be clearly observed, and fine structure is formed, which indicates that the surface material was once melted by high temperature due to EB irradiation, and rapidly solidified. Therefore, the resolidified layer has a different microstructure from that of the matrix. Furthermore, the thickness slightly increases with an increase of EB irradiation number.

Table 1

Chemical compositions of SKD11

C	Si	Mn	P	S
1.40 - 1.60	≦ 0.40	≦ 0.60	≦ 0.030	≦ 0.030
Cr	Mo	V	Fe	
11.0 - 13.0	0.80 - 1.20	0.20 - 0.50	Bal.	

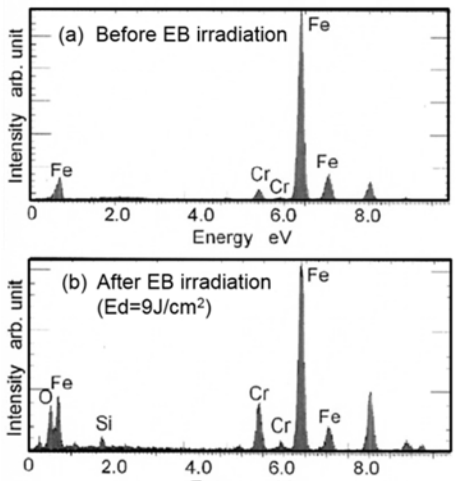

Fig.4. EDX spectra of surface

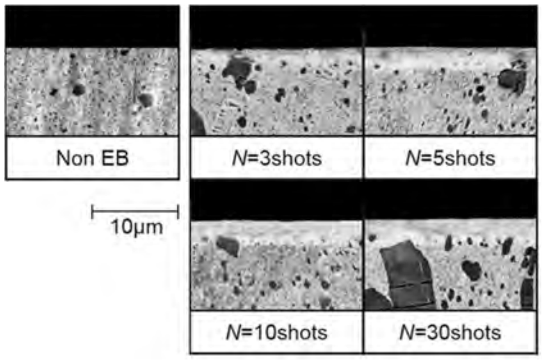

Fig.5. Cross-sectional SEM images of resolidified layer with different EB irradiation number

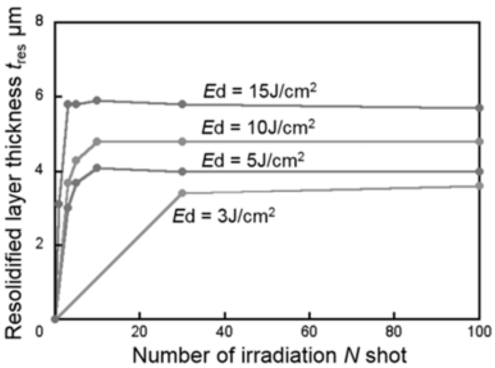

Fig.6. Variations of resolidified layer thickness

Fig. 6 shows the variations of resolidified layer thickness with number of EB irradiation for different energy density of EB. The resolidified layer thickness increases with an increase of EB irradiation number until 30 shots. When the EB irradiation number is over 30 shots, the thickness does not change. Therefore, critical thickness exists and it becomes thick with the energy density of EB. When the energy density is 15 J/cm^2, the thickness is as thick as 6 μm.

Heat Conduction Analysis

In order to simulate resolidified layer thickness, the change of temperature distribution in the work-piece surface during the large-area EB irradiation was calculated by heat conduction analysis. Fig. 7 shows the analysis model. Finite element method (FEM) program (ANSYS ver. 13) was used for unsteady heat conduction analysis. Since the large-area experiments were carried out using the SKD11 work-piece plate of 25 mm * 30 mm * 5 mm clamped with stainless steel chucks, the model was build based on the experimental set-up shown in the figure. Considering their symmetric shape properties, rectangular FEM model of one cross-sectional shape of work-piece and chuck was built. In the model, horizontally long rectangular part is SKD11 work-piece. The physical and thermal properties of the work-piece and chucks are listed in Table 2.

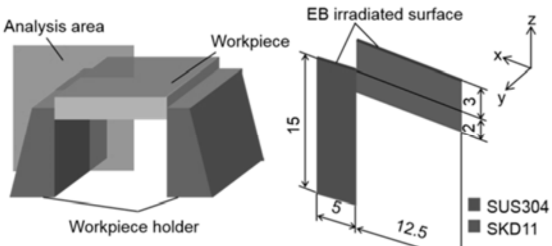

Fig.7. Heat conduction analysis model

Table 2

Physical and thermal properties of work-piece and work-piece holder

Properties	Parts	Work-piece	Work-piece holder
Material		SKD11	SUS304
Specific heat	c [J/(kg·K)]	457	502
Thermal conductivity	λ [W/(m·K)]	22.2	16.3
Density	ρ [kg/m^3)]	7.700	8.027

The boundary conditions of the model were set in the followings. The ambient temperature in the model is kept constant at 300 K, since the temperature in the chamber during the process didn't change at all when it was measured with a thermocouple set 200 mm far from the work-piece. As for heat transfer between the work-piece and the chuck, only heat conduction can be considered. Large-area EB is performed in a vacuum of about 10^{-2} Pa. It was reported that the heat transfer by convection of the gas under the pressure less than 10^{-2} Pa can be neglected (h = 0 W/m^2) [7]. Furthermore, the measurement results of emissivity of work-piece surface just after EB irradiation using an infrared thermos- viewer (NEC TH7102WX) indicated that the emissivity was about 0.2 (ε = 0.2).

In order to consider latent heat during melting and vaporization of work-piece material, enthalpy-temperature curve of SKD11 is used in this simulation. In the simulation software, latent heats cannot be given at particular melting and boiling points, and so they are gradually given at some temperature ranges, as shown in the graph.

In large-area EB irradiation, the effective beam diameter is 60mm and the large-area EB is irradiated to the top surfaces of the work-piece and holder. Then heat energy inputs are given to the top surfaces. However all heat energy due to EB irradiation is absorbed not only from the surface. The electrons penetrate to a certain depth, and the kinetic energy of electron changes to heat energy by losing its velocity.

Consequently, not only the surfaces but also materials to a certain depth are heated up in a moment. The electron penetration depth is calculated according to the equation proposed by Kanaya et al. [8].

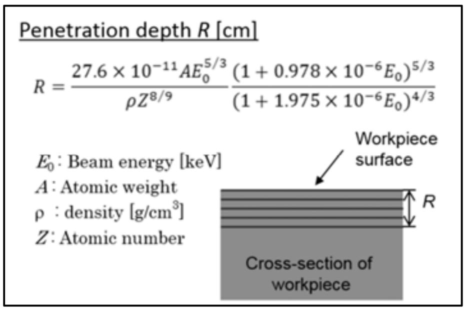

Fig.8. Consideration of electron penetration effect

According this phenomenon, a uniform energy distribution to the depth is defined as a heat input in this analysis model, as shown in Fig. 8. Thus, the surface layer is divided into some layers and uniform energy inputs are given to the surfaces of these layers. For example, when the energy density of EB is 2 J/cm^2, 0.4 J/cm^2 is given uniformly to the surfaces of 5 surface layers.

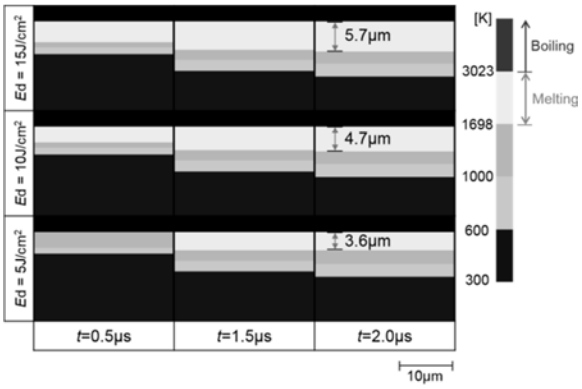

Fig.9. Simulated temperature distributions at workpiece surface

Fig. 9 shows simulated temperature distributions at material surface for various energy densities at 0.5 μs, 1.5 μs and 2.0 μs after EB irradiation start. The EB irradiation duration for one pulse is 2.0 μs. As shown in the figure, the melting region increases with energy density E_d. It also rapidly increases with time t until 1.5 μs but it does not increase afterward. In principle, it is guessed that the melting region becomes resolidified layer. The thickness at 2.0 μs are 3.6, 4.7 and 5.7 μm for 5, 10 and 15 J/cm^2, respectively.

The resolidified layer thickness values were compared with experimental ones obtained by the above-mentioned experiments in order to verify the accuracy of simulation. Fig. 10 shows the variations of resolidified layer thickness calculated by the simulation and experimental ones. The simulated thickness values are almost same as the experimental ones, which indicates its high accuracy of the simulation model. Therefore, the simulation model with electron penetration effect on the surface and latent heat of work-piece material well represent the actual temperature distribution of work-piece surface and the surface material condition during the large-area EB irradiation.

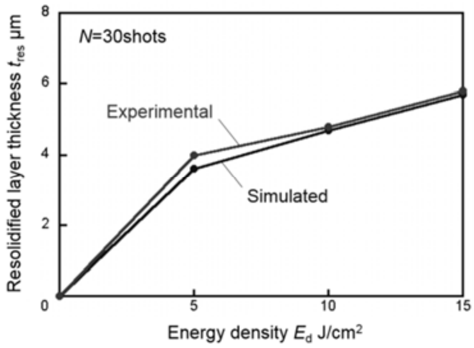

Fig.10. Comparison of simulated resolidified layerwith experimental one

Hydrophobicity and Corrosion Resistance

The contact angle of water droplets over large-area EB irradiated surface was tested in order to evaluate hydrophobicity. A water-drop of 2 mm in diameter is put on the work-piece surface using a syringe, and the height and radius of the drop were measured through a microscope to calculate the contact angle.

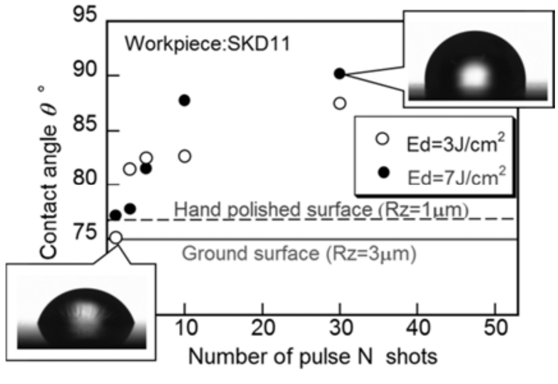

Fig.11. Variations of contact angle

Fig. 11 shows the variations of contact angle with number of EB irradiation when the energy densities are 3 and 7 J/cm^2. The contact angles of ground surface before EB irradiation and hand polished surface with the surface roughness of about 1 μmRz are also shown for comparison. Under any EB irradiating conditions, the contact angle of EB irradiated surface is higher than that of the initial ground surfaces. It is also larger than that for the hand polished one. In EB irradiated surfaces, the angle becomes larger with increasing the number of EB pulses. Furthermore, the contact angle becomes higher with high energy of EB under large number of EB irradiation. The maximum contact angle exceeds 90 deg. From these results, the hydrophobicity of metal mold surface can be improved by large-area EB irradiation, and it can be controlled mainly by the number of EB irradiation. This result also indicates that the surface free energy of SKD11 surface can be decreases by large-area EB irradiation. The hydrophobicity of pure chromium surface is very high. Therefore, it is considered that the improvement of hydrophobicity by large-area EB irradiation with large number of EB irradiation is caused by the uniform Cr component distribution on the surface as shown in Fig. 4.

Finally, the anodic polarization current density curves are measured by using an electrochemical analysis system in order to evaluate the corrosion resistance of EB irradiated surface. The system consists of a potentiostat with linear sweep voltammetry (LSV), an electrochemical reaction cell, a reference electrode cell, and a salt bridge. Anodic polarization current is measured when the potential difference between counter electrode and work one increases at a constant potential scan rate using LSV. 3% NaCl solution was used as an electrolyte.

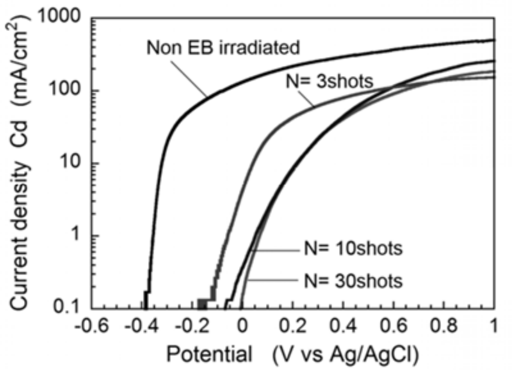

Fig.12. Anodic polarization current density of large-area EB irradiated surfaces.

Fig. 12 shows the anodic polarization current density curves of large-area EB irradiated surfaces with the energy density 7 J/cm^2 and the surface before EB irradiation. The current density increases with the potential in any surfaces. The equilibrium potentials for EB irradiated surfaces are larger than that for non-EB irradiated surface. In addition, the current densities are smaller than those for the non-EB irradiated surface at all potentials. Furthermore, the equilibrium potential increases and the current density becomes smaller with an increase of number of EB irradiation. This is because the resolidified layer thickness tends to increase and Cr content on the surface increases with them as shown above. Therefore, corrosion resistance can be improved by large-area EB irradiation, and it varies with the number of EB irradiation.

Conclusions

In this study, the structure of resolidified layer by large-area EB irradiation were investigated. Then, the influences of large-area EB conditions on the layer thickness were investigated. Also, prediction of the thickness was tried by a transient heat conduction model. Furthermore, the hydrophobicity and corrosion resistance of large-area EB irradiated surface were evaluated. Main conclusions obtained are as follows:

1) In thin resolidified layer formed on metal mold steel by large-area EB irradiation, chromium carbide is uniformly rearranged;
2) The resolidified layer thickness increases with energy density of EB and irradiation number, and the critical thickness becomes thick with the energy density of EB;
3) The heat conduction analysis model with considering electron penetration effect and latent heat of workpiece material has sufficiently high accuracy;
4) The hydrophobicity and corrosion resistance of metal mold surface can be improved due to the change in the surface structure, and it varies with the EB irradiating conditions.

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