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Surface smoothing technology using large current high enthalpy plasma beam

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Abstract: During the fabrication of high-precision parts and metal molds, manual polishing is used as the finishing process. However, this manual polishing process is time consuming, and it also requires special expertise from the operators. Thus, this manual finishing process greatly affects the productivity in total manufacturing system. In this paper, the large current high enthalpy plasma electron beam is proposed to smooth the work material surface. In the preliminary experimental study, high-density plasma electron beams with current density as high as 15J/cm^2 were irradiated onto the materials surface with a pulse duration of 2-4 μs. After irradiation within a short time, smooth surface finishing with a maximum diameter of 60mm was achieved. More martensite was observed on the machined surface. More importantly, the machined surface exhibits significant improvement of surface roughness and corrosion resistance.
Key works: electron beam, plasma, surface smoothing, corrosion resistance

1. INTRODUCTION

Nowadays, milling, electric discharge machining (EDM), and laser machining have been widely used for manufacturing dies and high precision parts in industries. However, it needs to polish the machined surface obtained with above machining methods in order to get better surface quality, such as good surface roughness, elimination of surface defect, and improvement of dimension accuracy. Normally, the polishing process not only needs special expertise from the operators, but also it is very time consuming, especially for dies with a complicated shape. Therefore, lower production rate and high production cost still remain a big problem for the abovementioned machining methods.

Recently, several non-conventional methods, such as focused electron beams, ion beams and laser beams, were tried for surface treatment of dies and precision parts [1], where the workpiece surface is melted during a very short time under the effect of high temperature heating. However, these high-energy beams have a small diameter of beam. Thus, with these beams, the total machining process for a practical surface cannot be finished without the movement of the beams or work materials. Therefore, when machining a large surface with these high-energy beams, longer processing time is needed. Moreover, cutting path left on the surface after machining cannot be removed, which affects the quality of surface roughness.

In this paper, surface treatment of dies and precision parts using high current high enthalpy plasma (HCHEP) is attempted, and the HCHEP method is capable of smoothing an area with a diameter of 60mm within 2-4μs. With this method, we investigate the possibility of a new process for surface finishing of dies and precision parts. In this study, the effects of energy distribution on the surface roughness, machined surface morphology and micro-structure, element distribution on the machined surface, crystalline structure, and corrosion resistance are observed.

2. EXPERIMENTAL METHOD

2.1 Structure of plasma generator

A schematic illustration of HCHEP machine used in this study is shown in Fig. 1 [2, 3, 4]. The work piece is mounted on a work table inside the vacuum chamber, which is evacuated to 0.03 Pa before argon gas is added into the chamber up to the pressure of 0.05 Pa. Then, a pulse current is supplied into the solenoid coil to generate magnetic field between the cathode and anode. In this method, there is no injection of electrons or photons from the outside of the chamber to generate the initial plasma. The plasma is initiated by existing cosmic electrons in the chamber. The solenoid magnetic field is important for the plasma preparation, because with this magnetic field the plasma can be kept at a low density, and the initial electron cannot be moved away. When the magnetic field produced by solenoid reaches to its highest strength, a pulse voltage is applied to the anode. Then, electrons are generated by the Penning effect and start to move towards the anode. Due to repetitious collisions between the electrons and argon gas atoms, argon atoms are ionized, and then the plasma is generated. The plasma diffuses in the space between cathode and work pieces. When the plasma intensity reaches a maximum value, a high pulse negative voltage is loaded to the cathode. Under the effect of the high voltage on the cathode, a plasma layer is produced near the cathode. Then the electrons are accelerated by the high-electric field due to electric double layer formed near the cathode. Finally, the accelerated electrons pass through the anode plasma and penetrate into the work piece surface. During their penetration inside the work material, the kinetic energy of high-speed electrons is converted into heat energy, so that the workpiece surface is heated. When the temperature reaches its melting point, the material at the workpiece surface is melted by a combination of electron pressure and surface tension. With the further increase of the temperature, the melted liquid is rapidly ejected and vaporized, thus causing the material removal. With the aforementioned method, a high-speed beam with an effective area of a maximum diameter of 60mm is generated, which has the maximum energy density of 15J/cm^2. The pulse duration of the beam is 2μs, and its peak beam current reach a maximum value of 40kA. In addition, in irradiation process, the depth of heat affected region is usually less than a few microns, or even less, which minimizes the effect of heat diffusion into the work material.

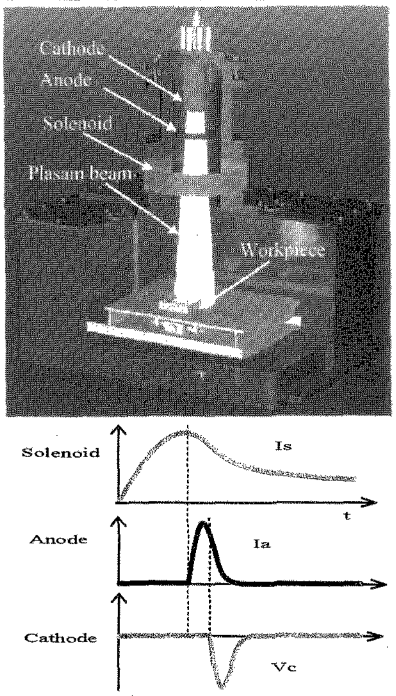


Fig. 1 A schematic illustration of high current high enthalpy plasma machine

2.2 Experimental conditions

Heat-treated die steel SKD11 is selected as the workpiece in this study, and its chemical composition is shown in Table 1. The work material surfaces were pre-machined with EDM, and their surface roughness (R_y) is 5μm. During the experiments, the EDM-ed surfaces are machined by E-Beam with pulse duration of 2-4μs and a pulse frequency of 0.2 Hz under different pulse energy densities, which is generated with the method as given in Section 2.1. The experimental conditions are given in Table 2.

Table 1 Chemical composition of SKD11

C	Si	Mn	P	S	Cr	Mo	V
1.50	0.25	0.45	0.025	0.010	12.00	1.00	0.35

Table 2 Machining conditions

Acceleration voltage (kV)	10, 15, 20, 25
Number of pulse	1-100
Discharge duration (μs)	2-4
Discharge frequency (Hz)	0.2
Plasma diameter (mm)	60

3. RESULTS AND DISCUSSION

3.1 Measurement of energy density per single pulse

Measurement of energy density with a common faraday cup is rather difficult because pulse duration of the HCHEP is very short. Therefore, in this study, a calorimeter with thermal resistors is used to measure the energy densities. The calorimeter has a diameter of 120 mm, and there are nine thermal resistor placed on it, as shown in Fig. 2. The nine resistors locate at nine different positions so as to measure the radial distribution of beam energy densities. Based on the increase of temperature measured by the thermal resistors, the beam energy density can be calculated.

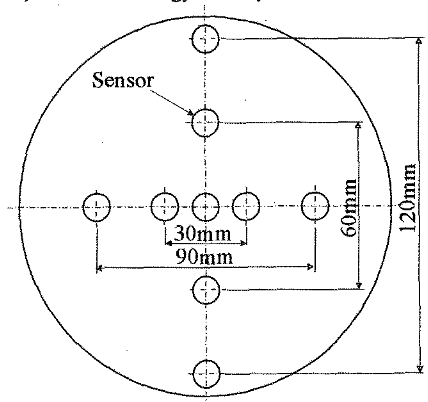


Fig. 2 The structure of calorimeter of measuring energy density of electron beams

Figure 3 shows the measurement result of energy density of each irradiation using a calorimeter under the cathode voltage of 20kV. From Fig. 3, it can be seen that the reduction of beam energy is less than 20% within a diameter of 60mm. Therefore, it can be assumed that the effective energy density for the beam is distributed uniformly in an area with a diameter of about 60 mm. Similarly, under other three acceleration voltages, the measured beams energy densities are 4.64, 6.06, 10.31 J/cm^2, respectively.

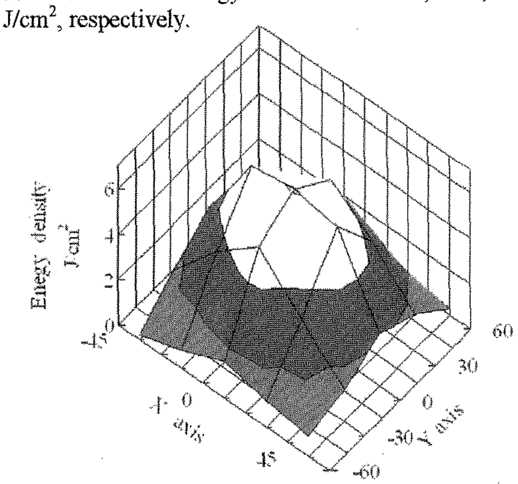


Fig. 3 Energy density distribution of one irradiation shot

3.2 Analysis of machined surface roughness

Figure 4 shows the surface roughness at different energy densities after ten irradiation shots on the SKD11 surface. It can be seen from Fig. 4 that the surface roughness of the machined surface is improved with the increase of electron beam's energy density. Therefore, it can be concluded that if the amount of energy applied on the workpiece surface reaches the required melting energy of the work material, it is possible to smooth the surface. In addition, in comparison to that at low energy density, irradiation under high energy density can provide better smoothing abilities.

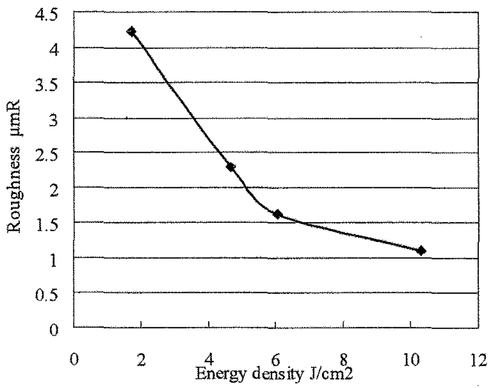


Fig. 4 Surface roughness vs. energy density of E-beams

The surface roughness under different number of irradiation shots is shown in Fig. 5. The minimum surface roughness can be attained after 40 shots of irradiation except that at the energy density of 1.72 J/cm^2. Moreover, there is no improvement in surface roughness when the number of irradiation shots is greater than 40. The optimal number of irradiation shots appears to be independent of the applied energy density.

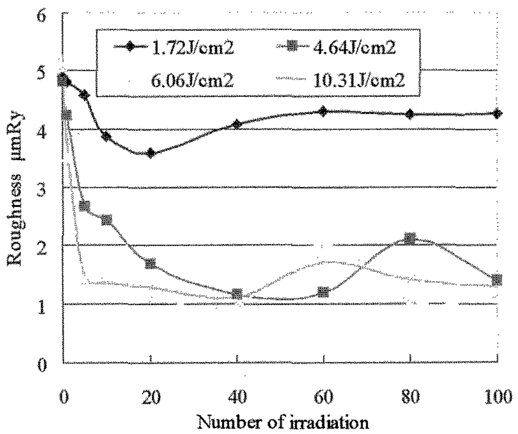


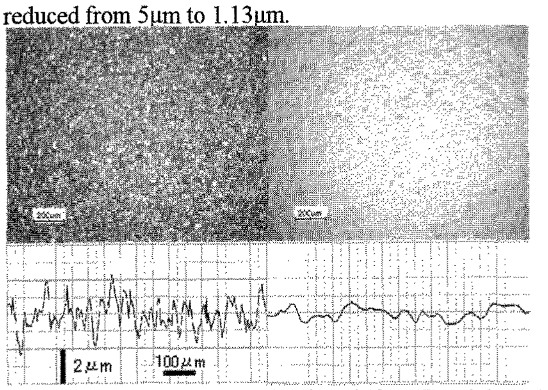
Fig. 5 Surface roughness at different number of irradiation shots

In case of irradiation happened at low energy density of 1.72J/cm^2, the change rate of surface roughness is smaller than the other three cases. The possible reason could be that the energy is not high enough to melt the work material at the surface within one irradiation shot. While for other three cases, the best surface roughness is attained after 40 irradiation shots. With the further increase of irradiation shots, the surface roughness shows a trend to increase with the irradiation shots. It can be assumed that there is an optimal number of irradiation to achieve good quality surface.

3.3 Analysis of surface morphology

Characteristics of irradiated surface, such as surface morphology, microstructure and element distribution, crystalline structure, and corrosion resistance are investigated.

The work material surface, which was pre-machined with EDM, is treated with EB irradiation; and the pre-machined surface and that after 20 irradiation shots are shown in Fig. 6. During irradiation shots, materials at the surface were melted and consolidated in a very thin zone, so that most craters produced by EDM can be removed. After machining, the surface roughness (Ry) is reduced from 5μm to 1.13μm.



(a) EDM (Ry =5μm) (b) EB irradiation (Ry =1.13μm)

Fig. 6 Morphology of workpiece surfaces before and after EB irradiation shots

After etching with the picric acid, the microstructure of cross section is also observed by light microscopy, as shown in Fig. 7. There is a bright layer at the work material surface. This layer was formed after melting and consolidation of the work material at the top surface during the EB irradiation process, and it is difficult to be etched.

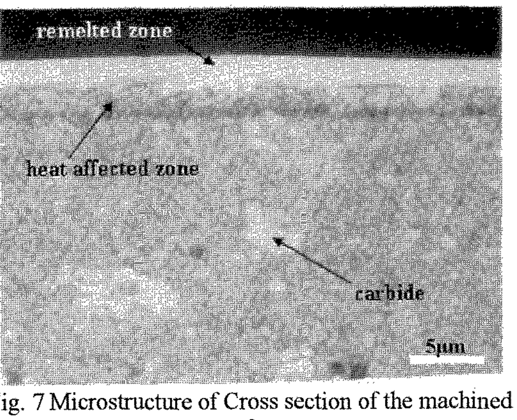


Fig. 7 Microstructure of Cross section of the machined surface

In order to detect the element distribution on the machined surface, an electron probe micro analyzer (EPMA) was used, and the measured result is shown in Fig. 8. Fig. 8 (a) presents the profile of section surface, and small areas in Figs. 8 (b), (c) and (d) indicate the presence of C, Cr and V, respectively. It was found that large carbides only exist in the substrate, and the surface layer becomes more homogenous. This is due to overheating of the melted layer at the machined surface during EB irradiation. When reaching a critical temperature, the melted metal at the surface layer is fully austenized, which then causes the carbides to dissolve in it. In addition, at high temperature, the alloying elements, such as Cr, V, are also dissolved in austenite.

Figure 9 shows X-ray diffraction profiles of the irradiated surface, and the profile of substrate steel is also given for comparison. Both austenite and martensite are detected on the machined surface, but the carbide which exists in the substrate steel cannot be observed. In addition, more martensite was observed on the machined surface. It is also found that the grain size becomes smaller and the crystalline structure becomes uniform. This may result from rapid consolidation and quench of the melted material at the machined surface under the short heating of high-speed irradiated electrons.

The corrosion resistance of machined surface was also evaluated with the salt spray. During the test, two test samples were kept in the sink at 35°C, where the two circular areas on the samples in Fig. 10 were machined with EDM and EMD + EBM, respectively. In the salt spray test, 5% salt fog was sprayed to the two circular areas continuously for 30 minutes. The EDM-ed circular area becomes rusty, while for the EB irradiated surface, no rust was observed, so the corrosion resistance has been greatly improved by EB irradiation. This may be attributed to the uniform material structure and no carbide on the machined surface, as shown in Fig. 8. Moreover, the higher percentage of martensite on the irradiated surface also improves the corrosion resistance.

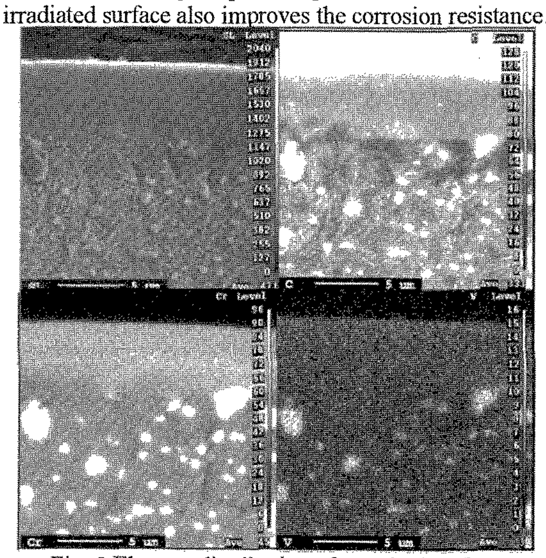


Fig. 8 Element distribution of remelted surface

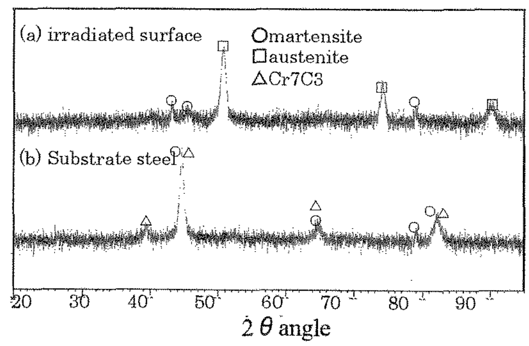
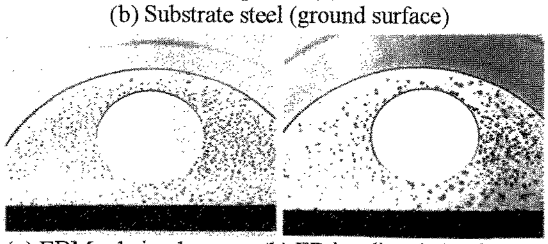


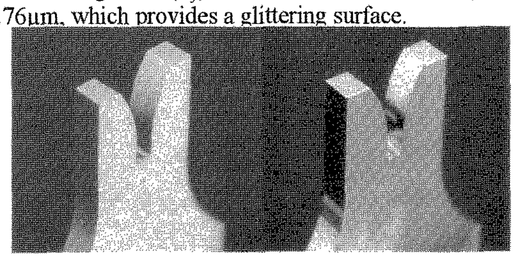
Fig. 9 X-ray diffraction profile (a) EB irradiated surface (b) Substrate steel (ground surface)



(a) EDM-ed circular area; (b) EB irradiated circular area
Fig. 10 Surface profiles of EDM-machined and EB irradiated surface after the salty spray corrosion test

4. CASE STUDY

Figure 11 shows an example of surface treatment on a crimper for wire terminal pressing. In the test, the beams with a low energy density at 4.64 J/cm^2 were used, and totally 20 irradiation shots were applied on the test sample. With conventional method, the sample is manufactured with wire-EDM together with the hand polishing, and it takes around 3 hours. However, with the method proposed in this study, the process can be finished within 15 minutes. At the same time, the surface roughness (R_y) can be reduced from 1.16μm to 0.76μm, which provides a glittering surface.



(a) Wire-EDM (b) EBM
Fig. 11 Test sample before and after EBM

5. CONCLUSIONS

In this study, a new method, the high current high enthalpy plasma method, is proposed to manufacture dies and precision parts. From the experimental results, the following conclusion can be made:

1. The surface smoothing process is possible to be conducted in a short time on an area with the maximum diameter of 60 mm.
2. To obtain the good surface finish with EB irradiation, a minimum amount of the energy density is required. When the applied energy density is higher than the minimum required one, the machined surface can be improved with certain number of irradiation shots. The surface roughness of electric discharge machined surface can be greatly improved through EB irradiation shots.
3. The size of large carbide particle existing in SKD11 was decreased on the machined surface, and the homogenous distribution of the carbide is achieved. Therefore, the grain size at the EDM-ed surface can be decreased by this method.
4. From the experimental results, it was found that the remelted layer on the work material surface consists of more martensite, which can improve corrosion resistance of the machined surface.
5. Using the present method, there is a possibility to perform a finishing process for EDM-ed surfaces of dies and precision parts with high efficiency.

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