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AFM surface imaging of AISI D2 tool steel machined by the EDM process

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Abstract

The surface morphology, surface roughness and micro-crack of AISI D2 tool steel machined by the electrical discharge machining (EDM) process were analyzed by means of the atomic force microscopy (AFM) technique. Experimental results indicate that the surface texture after EDM is determined by the discharge energy during processing. An excellent machined finish can be obtained by setting the machine parameters at a low pulse energy. The surface roughness and the depth of the micro-cracks were proportional to the power input. Furthermore, the AFM application yielded information about the depth of the micro-cracks is particularly important in the post treatment of AISI D2 tool steel machined by EDM.

Keywords: Atomic force microscopy (AFM); Electrical discharge machining (EDM); Surface morphology; Micro-crack; Surface roughness

1. Introduction

Surface morphology plays an important part in understanding the nature of machined surfaces. Before the 1990s, the surface textures of specimen were evaluated mainly with a contact stylus profiler. This instrument has various limitations including a large stylus radius, a large contact force and low magnification in the plane, which will result in surface damage of the sample and may misrepresent the real surface topography owing to the finite dimension of the stylus tip [1]. On the ultramicroscopic scale of surface measurements, atomic force microscopy (AFM) has been developed to obtain a three-dimensional image of a machined surface on a molecular scale. AFM overcomes almost all the above drawbacks of the stylus profiler. In recent years, AFM has been widely used for semiconductors to obtain the surface image in the nanometer scale [2–4]. With the progress of scientific technology, a product with advanced precision is, therefore, highly desirable; precision miniature parts can be formed using electrical discharge machining (EDM) [5,6]. The EDM process is used widely in machining hard metals and alloys in aerospace and die industries. Its main applications are in pressure casting dies, forging dies, powder metallurgy and injection mold. A major advantage

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of EDM is that the tool and the specimen do not come into contact with each other, thus eliminating chatter and vibration problems and allowing small or thin components to be machined without mechanical force. During machining, the discharge energy produces very high temperatures at the point of the spark on the surface of the workpiece removing the material by melting and vaporization. The top surface of the workpiece resolidifies and subsequently cools extremely quickly. This process causes a ridged surface and induces damage such as micro-cracks in the surface layer [7]. Lee and Tai [8] used the Digitizing Area-Line Meter to measure the total length of the cracks in the scanning electron microscopy (SEM) photograph and defined a surface crack density to evaluate the severity of cracking. Ramasawmy and Blunt [9,10] studied the 3D surface topography of the EDM specimen using 3D Talysurf with a 60° diamond conical stylus of 2 μm tip radius. Previous investigations [11,12] looked into the surface morphology and the crack depth of the cross-section profile in the EDM specimen using scanning electron microscopy. An understanding of the surface texture of the EDM specimens in the nanoscopic sense is required. In the present investigation, the three-dimensional images of AISI D2 tool steel machined by the EDM process were analyzed by means of the atomic force microscopy technique.

2. Experimental procedure

The specimen was made of the AISI D2 tool steel, which is widely used in the mold industry. The material was heated to 1030 °C at a heating rate of 20 °C/min. It was kept at 1030 °C for one hour and then quenched. After quenching, the specimens were tempered at 520 °C for two hours and then air cool. Table 1 lists the chemical composition (wt.%) of the material, while Table 2 lists the mechanical properties of the AISI D2 tool steel. The EDM specimens were performed on a die-sinking EDM machine model type Roboform 2000. The experimental set-up is shown in Fig. 1. The experiment was carried out in kerosene dielectric covering the workpiece by 10 mm. A cylindrical copper rod of 3 mm diameter was selected as the tool electrode for drilling the workpiece. The machining depth was 1 mm. The copper electrode was the negative polarity and the specimen was the positive polarity during the EDM process. During EDM, the primary parameters are pulsed current, pulsed voltage, pulse-on duration, and pulse-off duration. From the analysis carried out by Tung [13], Lee and Yur [14], in which the influence of these four parameters was investigated for AISI 1045 carbon steel and H13 die-steel using the Taguchi method, it is known that pulsed current and pulse-on duration are the principal factors which influence surface roughness, thickness of the recast layer, and induced stress. For this reason, this study establishes its full factorial design upon these same two parameters. Table 3 shows the electrical discharge machining conditions. During the EDM process, the pulse-off duration setting 20 μs could effectively control the flushing of the debris from the gap, giving machining stability. Hence, the

Table 1
Chemical composition of the AISI D2 tool steel (wt.%)

	Element								
	C	Si	Mn	Mo	Cr	Ni	V	Co	Fe
wt.%	1.5	0.3	0.3	1.0	12.0	0.3	0.8	1.0	Balance

Table 2
Mechanical properties at room temperature of the AISI D2 tool steel

0.2% offset yield strength	1532 MPa
Tensile strength	1736 MPa
Hardness (HRC)	57

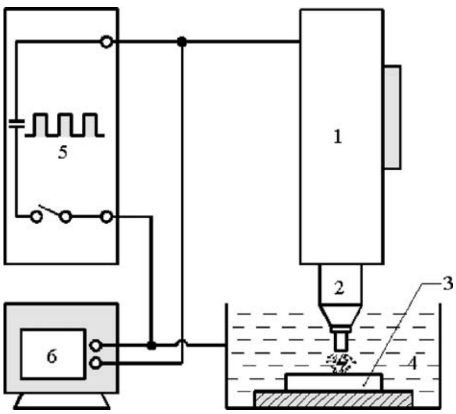

Fig. 1. Schematic diagram of the EDM process (1: servo-control; 2: electrode; 3: specimen; 4: dielectric fluid; 5: pulsed generator; 6: oscilloscope).

Table 3
Experimental conditions for EDM

Dielectric	Kerosene
Work material	AISI D2 tool steel
Electrode material	Copper
Pulsed current	0.5, 1.0, 1.5 A
Pulse-on duration	3.2, 6.4 μs
Pulse-off duration	20 μs

effect of the pulse-off duration on the machined characteristics was not considered in the present work. After each experiment, the machined surface of the EDM specimen was studied by means of an atomic force microscope. The AFM, produced by NT-MDT, included the Solver P47H main units, the SMENA measuring head and the vibration isolation system for measurement of the sample properties with nanometer-scale resolution. The measurements were performed with the contact model in air using a Si probe. The radius of the tip was approximately 10 nm. All samples were examined in scanning areas of 40 μm × 40 μm. Selected samples were also analyzed by using the scanning electron microscopy method.

3. Results and discussion

3.1. Surface morphology

During the EDM process, the primary parameters were pulsed current and pulse-on duration, both of which are settings of the power supply. In order to assess the surface measurement results, an AFM study of the surface nanomorphology of the EDM machined surface was conducted. Fig. 2 shows the three-dimensional AFM images of the machined surface obtained from the EDM specimens, where I_p is the pulsed current, and τ_{on} denotes the pulse-on duration. The darker contrast corresponds to the lower areas of the surface, and the brighter corresponds to the higher. It is clear that the surface microgeometry characteristics include machining damages such as ridge-rich surfaces, micro-voids, and micro-cracks. The ridge-rich surface was formed by material melted during EDM, and blasted out of the surface by the discharge pressure. However, the surface immediately reached the solidification temperature being cooled by the surrounding working fluid. The micro-voids can be attributed to the gas bubbles expelled from the molten material during solidification. The micro-cracks were the result of the thermal stresses. The primary causes of the residual stress in the machined surface were the drastic heating and cooling rate and the non-uniform temperature distribution. In addition, the morphology of the EDM surface was dependent on the applied discharge energy. When applying the smaller pulsed current, 0.5 A, and the pulse-on duration, 3.2 μs (Fig. 2a), the surface characteristics have minor hillocks and valleys. When the pulsed current and pulse-on duration increased (Fig. 2b), the machined surface exhibited a deeper crack or void and more pronounced defects. The EDM specimens were also analyzed by means of SEM technique. Selected images are shown in Fig. 3. Compared with the AFM method, the SEM technique allows a rapid survey of large sample areas, but it does not reveal the depth of the micro-cracks and the 3D surface textures of the EDM specimen. In the

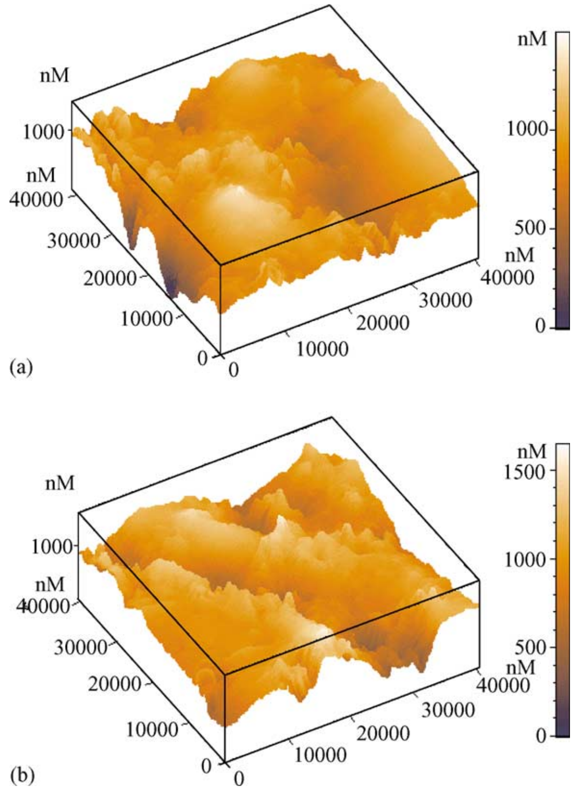

Fig. 2. The three-dimensional AFM images of the AISI D2 tool steel after EDM at (a) I_p = 0.5 A, τ_{on} = 3.2 μs; (b) I_p =1.5 A, τ_{on} = 6.4 μs.

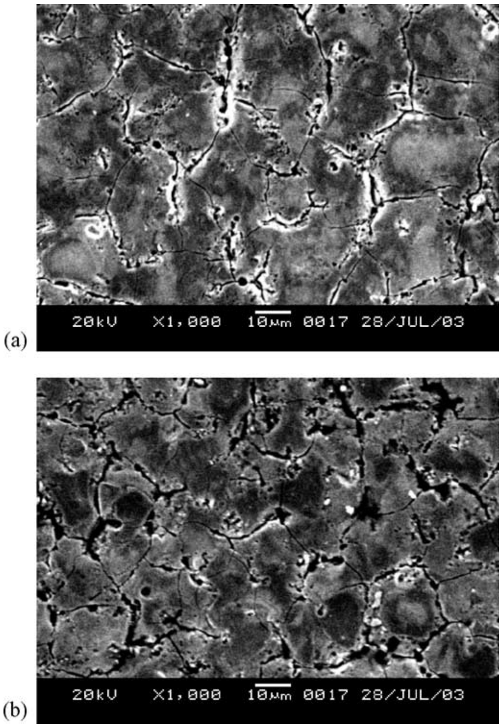

Fig. 3. The SEM images of the AISI D2 tool steel after EDM at (a) I_p = 0.5 A, τ_{on} = 3.2 μs; (b) I_p = 1.5 A, τ_{on} = 6.4 μs.

AFM image, it can be seen that the pits have a dark contrast, an observation in accordance with that found in the SEM image.

3.2. Surface roughness

EDM erodes surfaces randomly. To determine the effect of the EDM process on the surface roughness of the tool steel, the surface profiles of the EDM specimens were measured by AFM. The average surface roughness, R_a, of the machined specimen was calculated from the AFM surface topographic data in a scanning area of 40 μm×40 μm by the equation

$$R_a = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} |Z(x_i, y_j)| \quad (1)$$

where $Z(x_i, y_j)$ denotes the height of a surface point (x_i, y_j) relative to the mean plane; MN is the number of points in an analyzed area. Fig. 4 shows the measurement results. The surface roughness on the machined surface varied from 103 to 172 nm. From these results

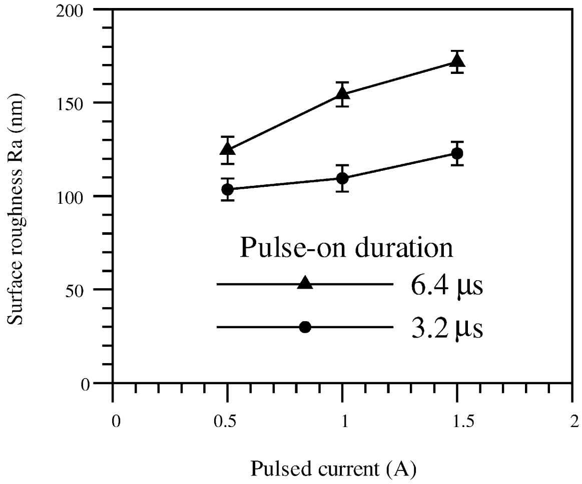

Fig. 4. The average surface roughness at various machining conditions.

it is clear that a higher pulsed current and a longer pulse-on duration cause a poorer surface finish. This can be attributed to the fact that a higher pulsed current and a longer pulse-on duration may cause more frequent cracking of the dielectric fluid, there is also more frequent melt expulsion leading to the formation of deeper and larger craters on the surface of the workpiece. Comparing with the results of Figs. 2 and 4, we find that an excellent machined finish can be obtained by setting the machine parameters at a low pulsed current and a small pulse-on duration. The trends agree with the results reported by previous investigators (Lee et al. [7]).

3.3. Micro-cracks

In order to measure the maximum depth of the micro-cracks of the EDM specimen, the AFM was used to measure the object generating the surface topography (Fig. 5a) and the cross-section profile (Fig. 5b). A dotted line in the surface topography shows the position of the cross-section profile. The maximum depth of the micro-cracks can be determined from the distance between the highest peak and the lowest valley. The maximum depth of the micro-cracks is defined as

$$D_{max} = h_{max}/h_{min} \quad (2)$$

where D_{max} denotes the maximum depth, h_{max} and h_{min} represent the maximum height and the minimum

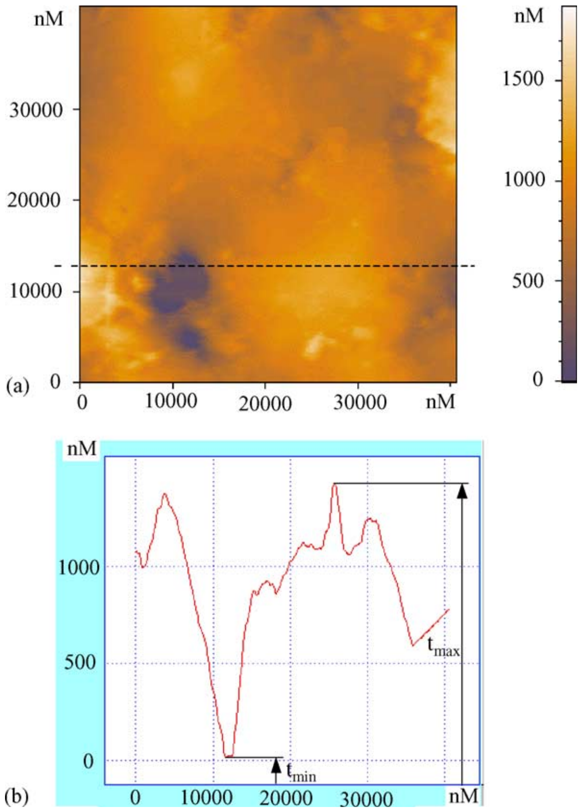

Fig. 5. Observation on an EDM surface by AFM (a) topography with 1.5 A pulsed current and pulse-on duration 6.4 μs; (b) cross-section profile on the morphology signal along the dotted line in image (a).

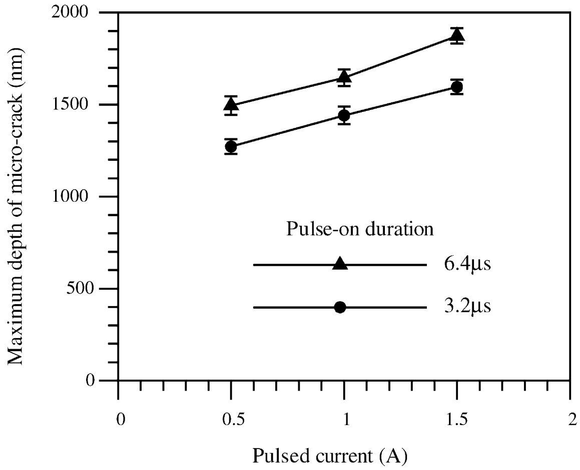

Fig. 6. The maximum depth of the micro-cracks on the EDM specimen at various machining conditions.

height of the section profile respectively. Fig. 6 shows the dependence of the maximum depth of the micro-cracks on the EDM parameters. The figure shows that the depth of the micro-cracks on the EDM specimen ranges from 1272 to 1873 nm increasing significantly with the pulsed current and pulse-on duration. This effect can be explained by the fact that high energy causes a steep thermal gradient beneath the melting zone. Previous investigators [15–17] have reported that the depth of the surface cracks increases with increasing discharge energy, and the depth of the cracks correlates well with the thickness of machined damage. The machined damages layer generated by the EDM process produces a harmful influence decreasing the service strength and life of the virgin material. This damage layer should be removed before being put to use. It is therefore recommended that the EDM specimen should be polished down to at least the maximum depth of the micro-cracks in order to improve its service life.

4. Conclusions

EDM is a thermal removal process. The AFM study of the surface morphology of the EDM specimen has revealed that a higher discharge energy results in a poorer surface structure. To avoid excessive machined damage, low discharge energy should be used. The AFM technique can be successfully applied to obtain a three-dimensional image with a nanometer scale and to evaluate the depth of the micro-cracks formed on the EDM surface. It is suggested that the EDM components be polished down to at least the maximum depth of the micro-cracks prior to use.

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