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Effect of pulse shape and energy on the surface roughness and mass transfer in the electrospark coating process

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Abstract

The electrospark deposition process is used to improve wear performance and corrosion resistance of metal surfaces. In this study, a tungsten carbide (WC-92Co-8) coating deposited on a steel (St37) substrate using the ESD process has been carried out. Some technological parameters of coating, such as mass transfer, roughness, and diameter of droplets (splashes) that depend on pulse shapes (rectangular and triangular) and pulse energies were investigated. Amplitudes of current electrical pulse range changed from 50 to 250 A for both kinds of pulse shapes. It was found that conventional rectangular pulses were not very useful shapes for maximum mass transfer, whereas it was possible with triangular pulses to obtain maximum mass transfer results. On the other hand, the triangular pulses produced more rough surfaces than the rectangular pulses.

Key words: electrospark deposition (ESD), micro-arc welding, coating, pulse forms

1. Introduction

Electrospark deposition (ESD) is one of the most efficient coating methods of strengthening and repairing the operating surfaces of machinery parts and tools. ESD can be described as a pulsed micro welding process because it shows some of the same effects of welding parameters [1]. In the ESD process, high current-low voltage electrical pulse of short duration is used to alloy an electrode material (anode) with a substrate (cathode). During the process, the stored energy from high-voltage capacitors is discharged between the electrode and the substrate. In resulting electrospark, a small part of melted electrode material is removed from the electrode and deposited to the substrate [1, 2].

The ESD coating shows some unique advantages compared to the electrodeposition or other surface techniques. In a metallurgical way, the main advantage of this method is: the substrate and coating are bound with such a low total heat input that the bulk substrate material remains at near-ambient temperature. Therefore, the metallurgical structure of the bulk substrate is relatively unchanged, and thermal distortions and residual stresses are minimized as well. It has originally been used to generate wear – and/or corrosion resistant coatings [3, 4]. Other considerable advantage of the ESD method is the ability to use any electrical conductor as the electrode; thus a variety of surface types can be formed, and also the process equipments are relatively inexpensive and portable [1, 5].

Many applications of these coatings are now used in a wide range of industries; for instance, nuclear, fossil and geothermal energy, aerospace, machine manufacturing tools, petrochemical and pharmaceutical, modern sport equipment industries, waste reclamation and water treatment plants, agricultural and textile equipments, and medical equipments (in surgical instruments and tools) [6–11].

In modern ESD equipments, solid-state devices are used to produce more accuracy control over the ESD characteristics like spark energy (amplitude and duration time) and spark frequency [12, 13]. So a thicker deposition layer and less rough surface can be achieved. In the previous study [13], a new system was used and the setup system of the ESD coating process could have been set for various purposes according to technological requirements. The main objective of this study is to research an effect of the pulse shape

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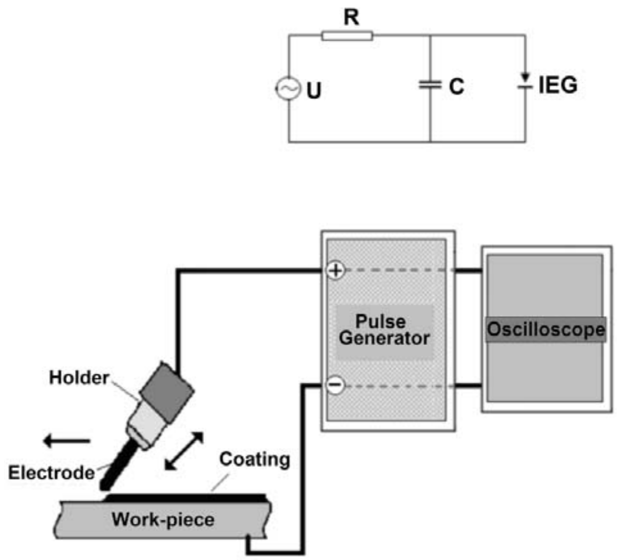

Fig. 1. The ESD coating system is a simple R-C circuit with IEG.

and energy on the deposit layer that is obtained using the ESD coating technique. With this aim, the ESD method has been successfully applied to deposit a tungsten carbide (WC-92Co-8) on a St37 steel substrate and the effect of the pulse shape and energy on the anodic erosion of treating electrode, mass transferring to the substrate and roughness of the coatings has been investigated during the ESD processing.

2. Description of the process

The ESD coating system is a simple resistance-capacitance circuit with inter electrode gap (IEG) (Fig. 1). The system equipment consists of a pulse generator and an electrode holder called electrode vibrator. The holder is mechanically vibrating to make and break the circuit due to generating sparks in the IEG. When the electrode (anode) comes to the contact with the substrate (cathode), a short circuit occurs between the anode and cathode. The electric pulsed current is carried through the anode and cathode in a very short time. This electric pulse has sufficiently high energy to melt and evaporate the parts of the anode and cathode. The interruption of short circuit, in other words, when the anode and cathode are discontacted, a spark (or arc) occurs for a short time in the IEG; this gives additional heat to the anode and cathode. When a spark discharge takes place, a plasma channel (plasma stream) forms between the anode and cathode. At both ends of plasma channel, the electrode (anode) and substrate (cathode) melt due to heat flow and form a molten volume at the tip of the electrode and a melting pool on the substrate. During the spark discharge, a series of forces (electromagnetic, electrostatic, shock wave, gravity and surface tension) operate on the molten part of the electrode. As a result of combined effect of these forces, a small molten part of the electrode (which is called a droplet or erosive part) detaches and deposits on the substrate [14].

This process is repeated 100 times per second, and in each second one-hundred electrode droplets are transferred and welded to the substrate [15]. The size and shape of the droplets depend on some factors: the kind of coating material (thermo-physical properties), the setting of the equipment (electrical parameters), and the kind of short circuit between the anode and the cathode; in other words, the kind of the pulse shape and energy [2, 13, 15].

Zolotykh [14] described that the plasma stream might have the greatest influence on the part of erosion in the ESD process. Moreover, Drabkina [16], who indicated that the diameter (d) of the plasma channel is the function of the energy generated in the channel, obtained results as follows:

$$d(t) = f(\text{energy, medium properties}).$$

In addition, Zingerman [17] showed that the shape of the pulse energy affected the diameter of the plasma channel as shown in Eq. (1):

$$d(t) = K_1^{n_1} K_2^{N} K_3 P_{\mathrm{M}}^{n_1} t^{n_2}, \tag{1}$$

where P_{M} is the maximum power of the pulse energy; t is the duration of pulse; K_1, K_2, K_3 are factors that depend only on the shape of the pulse energy; and n_1, n_2, N are factors of properties of the medium and the electrode materials. The electric pulse energy has the most important influence on the plasma channel, and hence on the droplet diameter. It is apparent that the employment conditions of pulse energy will have a significant effect on the anodic erosion and mass transfer process, and so they will cause different results on the thickness of coating and roughness.

3. Experimental procedure

3.1. Device

In the experiments, a special ESD machine was employed. Its power consumption was 180 W and the output of stabilized voltage was constant at 40 V. It has the capability to generate pulses with a given energy and shape form. The installation is run with a special computer program elaborated [13].

3.2. Materials

Generally, in the ESD process, a wide range of treating electrode materials can be used, but these materials must conduct electrical current. In this study, tungsten carbide (WC-92Co-8), which was selected as a treating electrode, was deposited on a steel (St37) workpiece as a substrate. The electrode has a cross-section of $3 \times 5\,\mathrm{mm}^2$ and the steel substrate samples are of $1\,\mathrm{cm}^3$ cubic shapes. Only five surfaces of these samples to each processing condition were coated, and one surface was marked with numbers.

3.3. Coating process

The efficiency of the ESD coating process depends on the amount of erosion of the treating electrode and the amount of mass transfer to the workpiece (substrate). Both of them are determined by the energy of the spark and this energy is directly proportional to the voltage drops at the IEG, the amount of current, and the duration of the pulse:

Energy of the spark $(E) \approx$ Voltage $(V) \times$ Current (I) $\times$ Time (t).

These electrical parameters of spark energy have the greatest influence on the quality of deposit and the rate of deposition. Thus, the control of these parameters has great importance for the ESD process. Improved ESD equipment with a transistorized pulse generator makes it possible to change the frequency and electrical parameters of spark discharge (discharge pulse) and it can provide different pulse forms [12, 13]. The system included a special oscilloscope (Tektronix TDS 220) to determine the energy of pulses.

The main control parameter of the ESD process is the working current that corresponds to the average current of the pulse generator. The average pulse energy is determined by using current-voltage diagrams (at the oscilloscope monitor). The results of numerical integration of the oscillograms of current-voltage could satisfy the pulse energy E_p [18]. It is defined in Eq. (2):

$$E_\mathrm{p} = \int_0^{t_\mathrm{p}} U_\mathrm{p}(t) I_\mathrm{p}(t) \mathrm{d}t, \qquad (2)$$

where U_p is the pulse voltage, I_p is the pulse current, and t_p is the pulse time.

To compare experimental results with each other in the system, the voltage drops at the interelectrode gap (17 V) and the amount of electricity (3 C) are kept constant. Two kinds of pulse forms were used: triangular and rectangular (Fig. 2). The ESD process was conducted in air with a series of pulses of certain duration of 12–70 μs, a repetition rate of 100 Hz, and amplitudes of current 50–250 A for two kinds of pulse forms (Table 1). One pass over the scanned area of $1\,\mathrm{cm}^2$ required approximately 0.5 min.

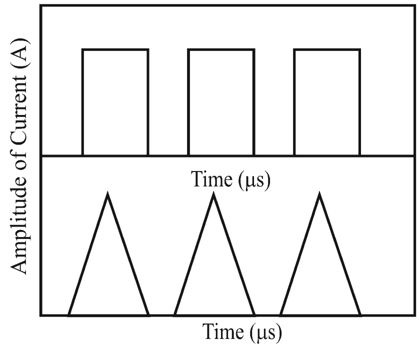

Fig. 2. Two kinds of used pulse forms (rectangular and triangular).

Table 1. Triangular (T) and rectangular (R) pulse forms

Amplitude of current (A)	Duration time (μs)	Energy of pulse (J)
50-T	12	0.005
100-T	21	0.018
150-T	16	0.040
200-T	42	0.071
250-T	50	0.105
100-R	20	0.018
100-R	25	0.071
100-R	70	0.110
150-R	44	0.069
150-R	58	0.112
200-R	52	0.110

3.4. Characterization

Investigation of the surface morphology on the coated samples was performed using a scanning electron microscope (SEM, Philips XL 30 SFEG). In these micrographs, the average diameters of splashes that have occurred during the mass transfer processing were measured. EDX spectrum analyses were performed using the embedded EDX digital controller (EDX detector operating 15 kV) and software (EDAX Digital Controller and Software 3.0) attached to the SEM. EDX analysis shown in Fig. 3 gives the surface composition of the substrate, a) before, and b) after the ESD process. For every process condition, the ESD process was conducted and then mass transfer of the treating electrode to the substrate samples was investigated. The mass changes in the treating electrode and the substrate samples (for five surfaces of samples to each processing condition) were measured with a balance (Metter Toledo 200) with a sensitivity of 0.1 mg.

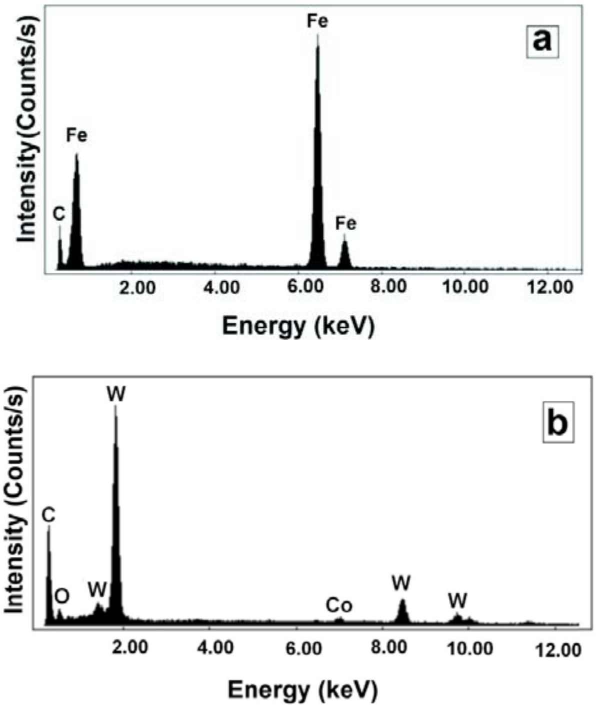

Fig. 3. EDX analysis of a) substrate and b) coating layer.

Roughness measurements were conducted by using a profilometer device (SJ-400 Mitutoyo) with a precision of 0.01 μm. The average roughness values (*Ra*) of five measurements were reported for every surface of samples for each processing condition (total of 25 measurements for each condition).

4. Results and discussion

Properties of electrode materials (composition, microstructure, porosity, thermal and electrical conductivity, etc.), environmental conditions (in air, gas or vacuum), and electrical parameters (pulse discharge energy and frequency) of processes are determined according to the mass transfer conditions (mass gain of substrate and mass loss of treating electrode) [13, 15]. In this study, the focus of interest is mainly on the electrical parameters of the process. These parameters are pulse energy and frequency, which depend on the pulse shape, amplitude of current, and duration.

It is known [1, 2] that, during the development of the ESD coating process, a droplet mass transfer mechanism takes place. A molten droplet forms at the treating electrode tip and this droplet moves and then collides on the surface of the substrate. This causes a splash appearance on the surface. Because of droplet mass transfer from the treating electrode to the substrate surface during the coating process, all sample surfaces are non-uniform. This coating topography, which has been performed by the ESD process, is characteristic for samples.

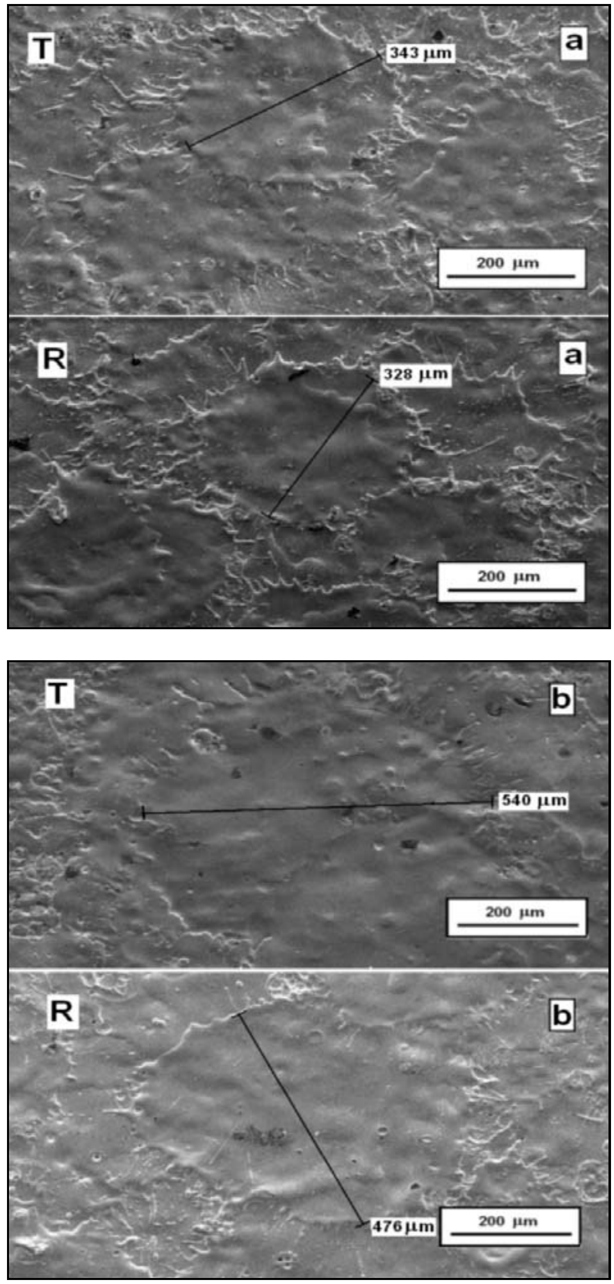

Fig. 4. SEM micrographs of the morphology of some coated surfaces at triangular (T) and rectangular (R) pulse forms, for pulse energies of a) 0.018 J and b) 0.071 J.

Figure 4 shows SEM micrographs of the morphology of some coated surfaces of two kinds of pulse forms with different pulse energies. Although their pulse energies used in experiments are the same, it is seen that splashes gained in using triangle pulses have bigger diameters than those gained by using rectangular splashes. Furthermore, this is especially clearer when using pulses with high energy (Fig. 4 a,b). It can

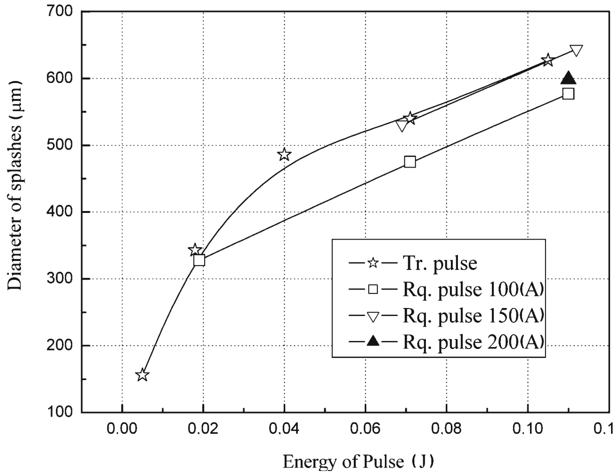

Fig. 5. This plot demonstrates the change in average diameters of splashes as a function of pulse energy under the condition given in Table 1.

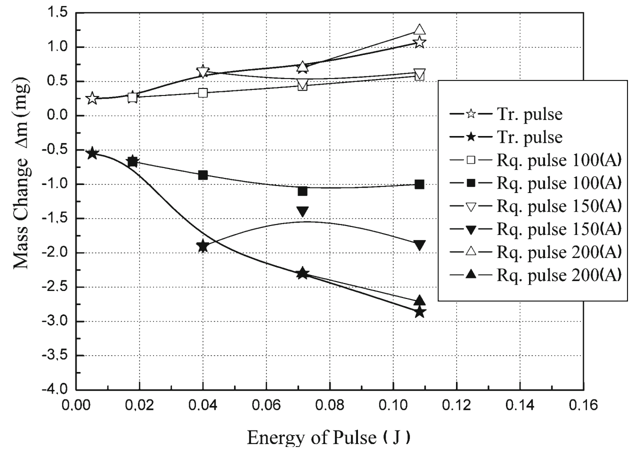

Fig. 7. Plots of change in the treating electrode (solid dots) and substrate sample mass increment (Δm) as a function of the pulse energy after 30 s of processing for different pulse forms in the ESD process.

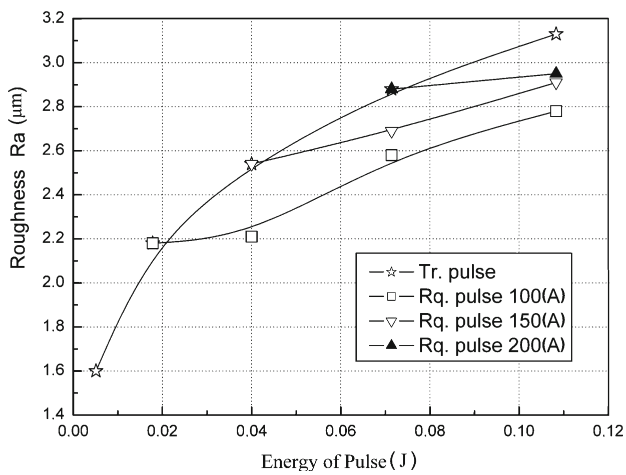

Fig. 6. Plots of change in the surface roughness (Ra) of coating as a function of the pulse energy after 30 s of processing for different pulse forms in the ESD process.

be deduced that the diameter of these splashes varies with pulse forms since the diameter of the splash is dependent on the pulse characteristics (energy of pulse) as shown in Fig. 5. In addition to this, it can be said that the droplet mass transfer mechanism, which occurs and leads to the appearance of the splash on the substrate surface, determines the structure and the dimension of these splashes. The average roughness values, Ra, and amount of the mass transfer depend on these properties of splashes.

In this study, two kinds of pulse forms (triangular and rectangular) were used for certain process times in the ESD process. These different types of pulses were applied for 30 s. The mass loss of the treating electrode (Δma), the mass gain of substrate (Δmc), and the roughness values (Ra) of the surface of the substrate were measured every 30 s. The mass transfer and roughness values for the two groups (triangular and rectangular) at equivalent pulse energies were compared with each other.

Plots of the change in the treating electrode and the substrate sample mass increments (Δm) and roughness values (Ra) as a function of the pulse energy after 30 s of processing for different pulse forms are shown in Figs. 6 and 7.

As the current value increases, both anodic erosion and mass transfer increase as well. Triangular pulse causes more anodic erosion compared with rectangular pulse, thereby more mass transfer occurs. For rectangular pulses with shorter pulse duration and bigger current amplitude, these pulses have more contribution to the mass transfer and anodic erosion mechanism since density of energy is higher. When using triangular and rectangular pulses with the same energies, especially for triangular pulses with bigger current intensity, anodic erosion and thereby mass transfer are dominant.

Although the amount of energy was the same for both kinds of pulse forms, experimental results (mass transfer and roughness) were different. The reason is that the diameter of the splash depends not only on the increasing pulse energy but also on the rate of energy transfer. It is understood that both initial slope and amplitude of current have great importance for both triangular and rectangular pulses.

5. Conclusions

In the present study, tungsten carbide (WC-92Co-8) material was deposited on a steel (St37) substrate by using the ESD process and it is seen that the mass transfer mechanism occurs in the shape of a droplet.

The results of the study have indicated that the changes in the pulse forms (pulse shape, amplitude of current, and duration time) provide a significant influence on the plasma channel and therefore on the size of the splashes, amount of mass transfer, and the values of roughness. As the pulse energy raises, the amount of the anodic erosion and mass transfer, the diameter of splashes, and the roughness of surface increase.

The conventional rectangular pulse has been applied for decades since it is the easiest one to produce, but it is shown that conventional rectangular pulses are not optimum pulse forms for maximum anodic erosion and mass transfer in ESD process. It was deduced that using triangular pulse shapes in the ESD process allowed more mass transfer and larger splashes than rectangular pulse shapes. On the other hand, rectangular pulses produce less rough surfaces than the triangular ones. It is expected that these results will help us in properly selecting the kind of pulse shape in the ESD process.

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