

Accelerated Electrospark Deposition and the Wear Behavior of Coatings

P.-Z. Wang, G.-S. Pan, Y. Zhou, J.-X. Qu, and H.-S. Shao*

Electrospark deposition (ESD) is a coating process that is featured by low heat input to the substrate. Low coating efficiency and other limitations influence its wider application. The present paper introduces newly designed ESD equipment, by which a higher coating rate can be reached. The relationship among coating thickness, surface roughness, and process parameters such as pulse energy, pulse frequency, and deposition time are presented. Electrospark deposition coating by the new equipment on AISI 1045 steel (with WC-8%Co as electrode) increases the wear resistance by 5 to 8 times. The micromechanism is investigated by scanning electron microscopy observation.

Keywords coating, electrospark deposition, equipment, wear behavior

1. Introduction

Electrospark deposition (ESD) is a coating process in which short-duration, high-current electrical pulses are supplied between the electrode (anode) and the workpiece (cathode). A coating is deposited onto the surface of workpiece by pulse-arc microwelding. Since its invention, ESD has been used mainly in two kinds of applications. One is to enhance the performance of electrical contact points such as those used in relays (Ref 1), while the more common application is to increase service life of many parts subjected to wear, such as lathe tools, drills, milling cutters, hacksaw blades, camshafts, turbine blades, and so forth (Ref 2-6).

Electrospark deposition coating possesses some unique advantages. The principal one is that the coatings are metallurgically bonded to their substrate with such low total heat input that the bulk substrate material remains at or near ambient temperature (Ref 2). The short duration of the electrical pulse results in an extremely rapid solidification of the deposited material and produces an exceptionally fine-grained coating that approaches an amorphous structure. In most cases the ESD equipment is simple, cheap, portable, and easy to operate for any surface, especially those that are irregular and complex.

There are also some limitations, such as the low coating efficiency, stress relief cracking in coating, both workpiece and electrode must be electrically conductive, and so forth. Several factors influence the coating efficiency, such as the properties of the electrode (melting points, heat capacities), environment (gas, oil), and materials transfer mode (molten globular mass transfer or spray transfer) (Ref 7). However, the charge-discharge frequency is the most important factor. The two typical kinds of conventional ESD equipment are shown in Fig. 1. For the vibrating electrode, Fig. 1(a), the mechanical restrictions on solenoid design (limit 100 Hz) bring about a rather low coating efficiency. Spark frequency is increased by an axially rotating electrode, as shown in Fig. 1(b), but the irregular contact between the electrode and the workpiece surface makes the charged voltage of the capacitor highly variable. Also, the fact that the electrode contacts the workpiece more or less continuously makes the capacitor voltage quite low on the average, which results in a slow and unstable coating process. The discharge voltage can be increased by incorporating a silicon-controlled rectifier (SCR) into the discharge circuit. However, the inductor used to prevent short circuit currents prolongs the discharge period and again influences spark frequency (Ref 2). This paper introduces a new type of ESD equipment by which the coating efficiency can be increased with satisfactory surface finish and stability.

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2. Principle of the Accelerated ESD Equipment

Isolated gate bipolar transistor (IGBT) switches that have high maximum holding currents were used, and the incorporating controlling and driving circuits were applied, as shown in

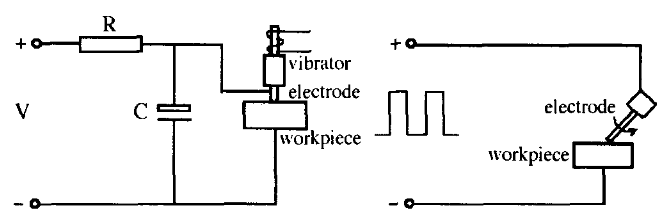


Fig. 1 Schematic of two kinds of conventional ESD equipment

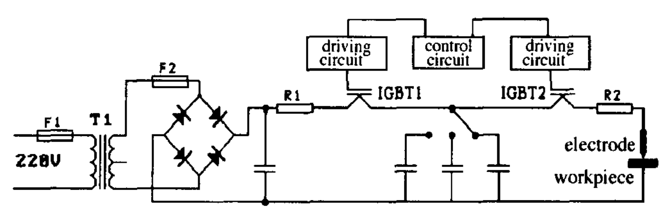


Fig. 2 Principle of newly designed accelerated ESD equipment

Fig. 2. Isolated gate bipolar transistor switch components are easy to control, and their adjustable voltage and current ranges are wider. This allows higher charging voltage in order to reduce the pulse period and increase the spark frequency.

The capacitor is discharged by the workpiece surface. A regular pulse is obtained by incorporating one switch, IGBT1, into the charge circuit and the other, IGBT2, into the discharge circuit. A controlling circuit and two driving circuits let the two switches turn on and off. The charge-discharge cycle starts with IGBT1 on and IGBT2 off, the capacitor being charged. When the voltage reaches a reference value, the controlling circuit turns IGBT1 off and IGBT2 on, then the capacitor discharges. When the voltage of the capacitor drops to a low value, IGBT1 is turned on and IGBT2 off, and then the next charge-discharge cycle begins.

The regular switching by the new circuits can produce a higher discharge voltage when the spark frequency is equal to others, while for the same discharge voltage a higher spark frequency is available. Another advantage of the equipment is the high stability (Ref 8).

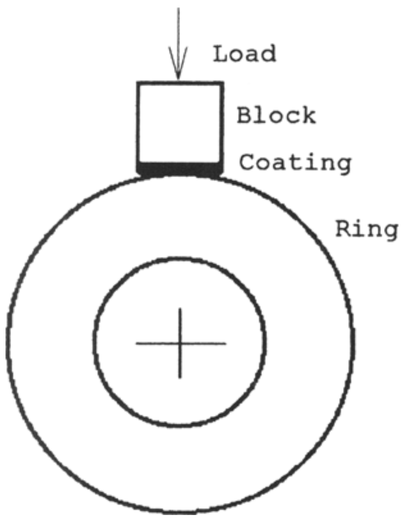


Fig. 3 The principle of wear test

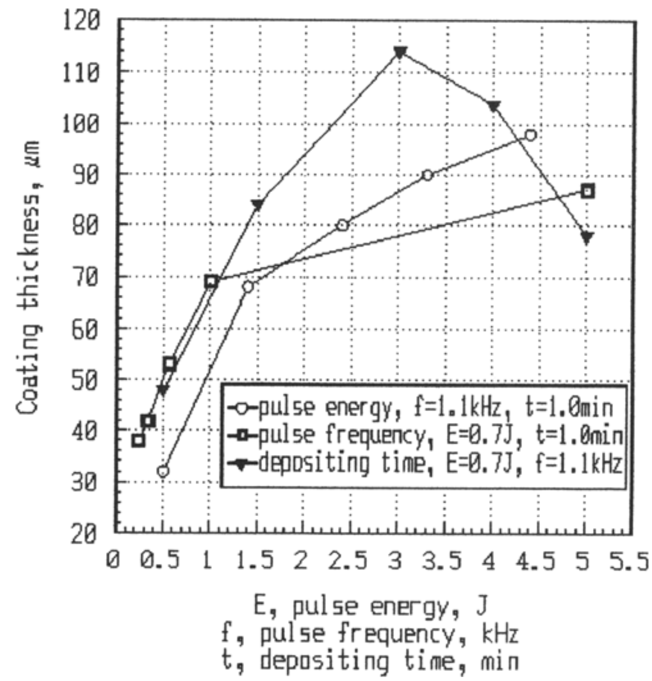


Fig. 4 The relationship between coating thickness and process parameters

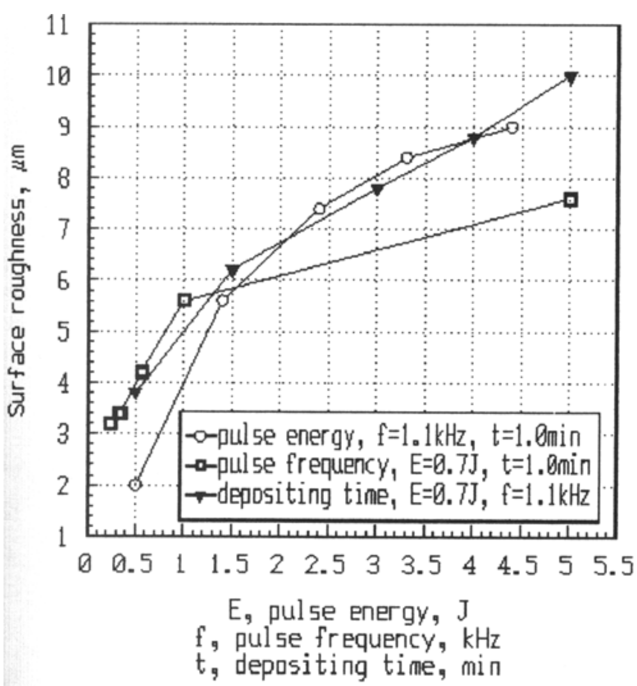


Fig. 5 The relationship between surface roughness and process parameters

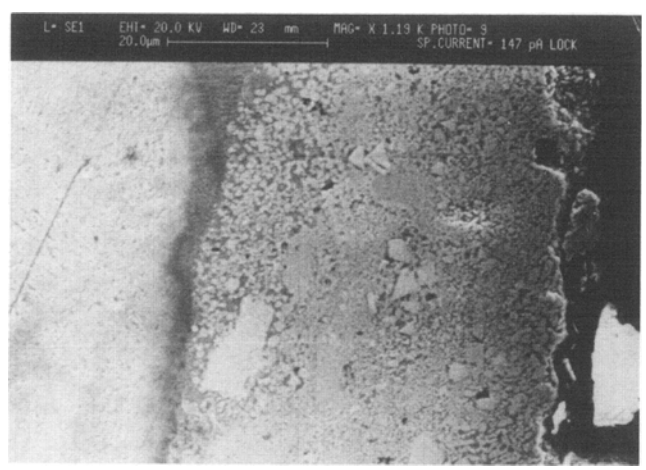


Fig. 6 The microstructure of ESD coating (spark energy 0.7 J, spark frequency 1.1 kHz, depositing time 1.0 min), cross section, SEM

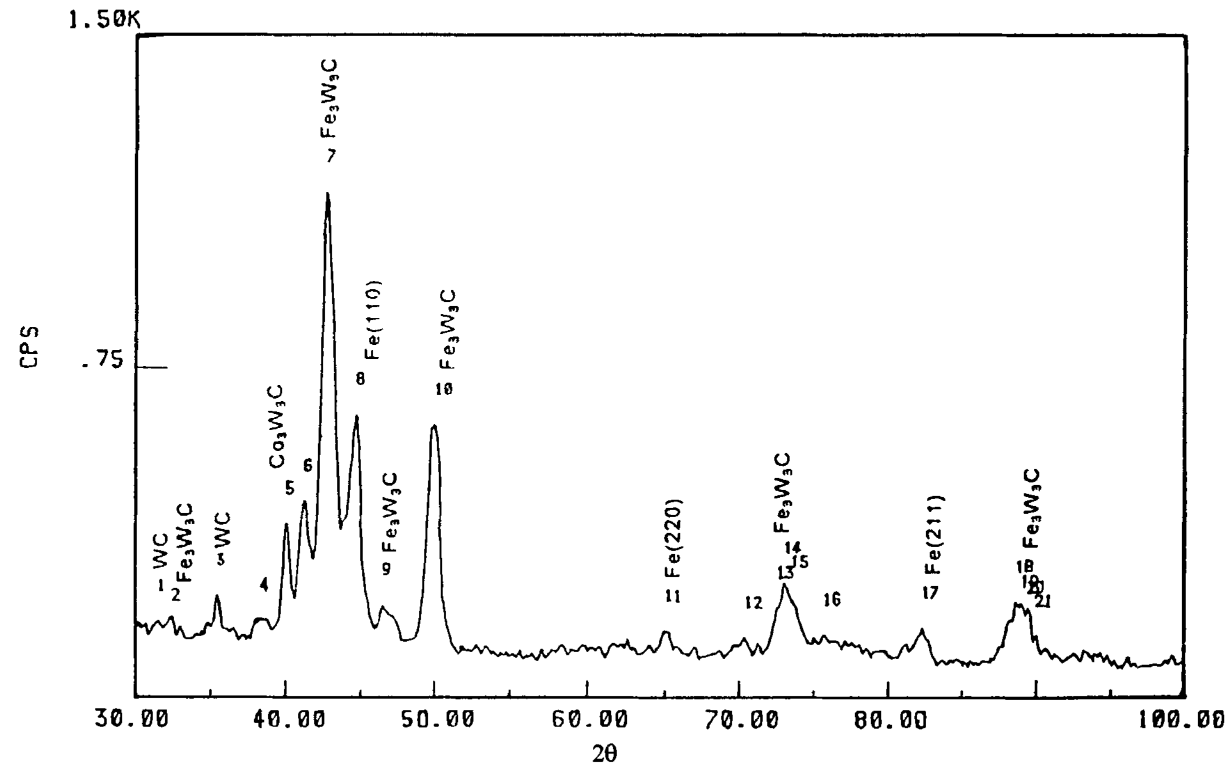


Fig. 7 X-ray diffraction results of electrospark deposition coating (spark energy 0.7 J, spark frequency 1.1 kHz, depositing time 1.0 min)

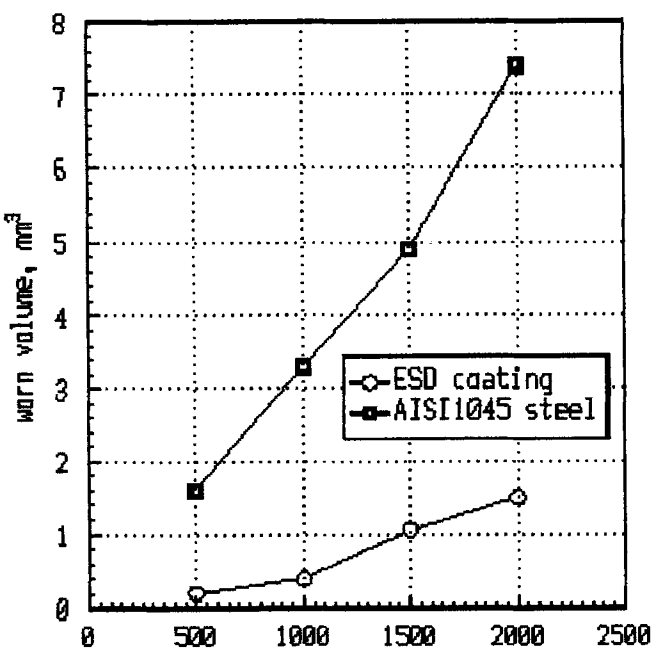


Fig. 8 Wear experimental results: worn volume versus sliding distance

3. Experimental Conditions

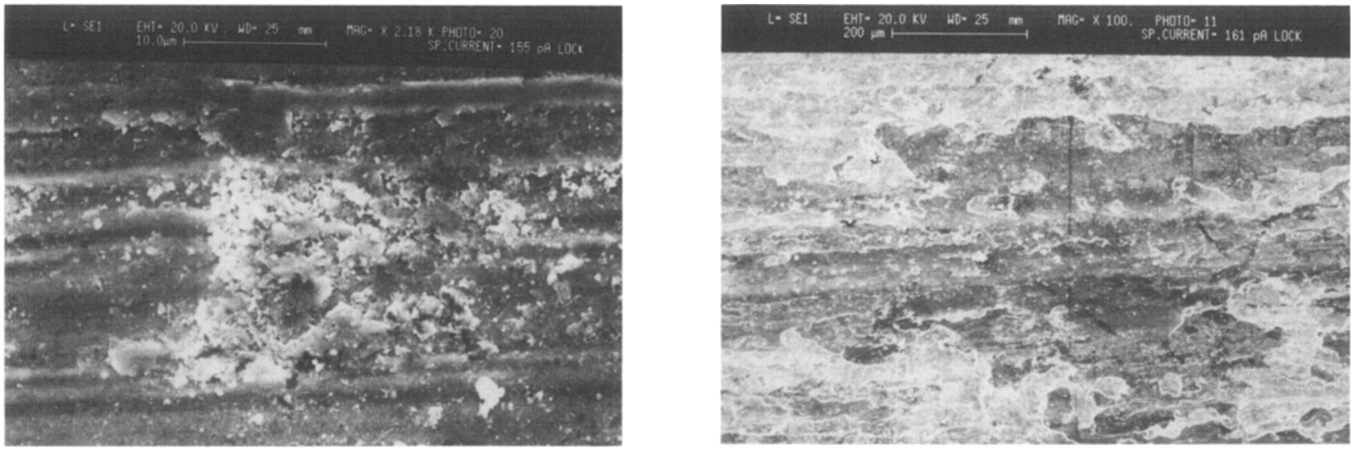
Commercial WC-8%Co is used as the electrode (8 mm diam) material. Substrate specimens are prepared with AISI 1045 steel, size 20 by 20 by 10 mm. Before depositing, specimens were quenched and tempered, hardness was 500 $HV_{0.05}$. All depositions were performed in air.

Table 1 Comparison between newly designed ESD equipment and the conventional D9130 type

	D9130	New
Power supply, V	220, single phase	220, single phase
Highest output voltage, V	40, 50	30-75
Operating current, A	1-3	<10
Maximum coating thickness, μm	50-60	100
Roughness, μm	1.6-6.3	2.6-6.3
Coating rate(a), mm^2/s	0.5-0.8	1.6-3.2

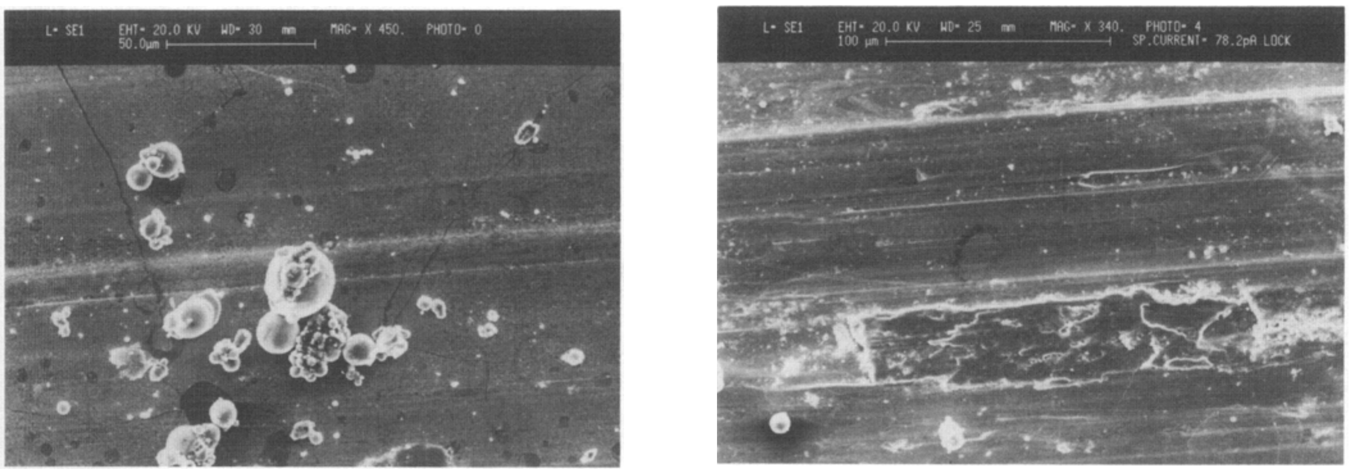
(a) For highest coating thickness

Microstructures and thickness of the coating were observed with scanning electron microscopy (SEM), while x-ray diffraction was carried out to reveal the phase components. Surface roughness was measured by a three-dimensional surface analyzer, and values were calculated by R_a (centerline average). Wear tests were performed on an MM-200 wear tester at the Xuanhua Materials Testing Equipment Factory in China (Fig. 3). Block specimens with ESD coatings were fixed against a rotating ring, which was also made of AISI 1045 steel and quenched and tempered to 500 $HV_{0.05}$. The load was 250 N; sliding speed was 0.84 m/s. For comparison, block specimens of the same material without ESD coatings were tested under the same conditions. Worn volume of block specimens was calculated by measuring the width of the wear scar on the coating, using roughly the same curvature for each specimen. Four groups of specimens were run for 500, 1000, 1500, and 2000 m individually. At least five tests were conducted for each condition, and the results showed good reproducibility with deviations in the range of 10 to 15%. The difference in worn volumes of specimens with and without ESD coatings at the same sliding distance reflects the difference in wear resistance.



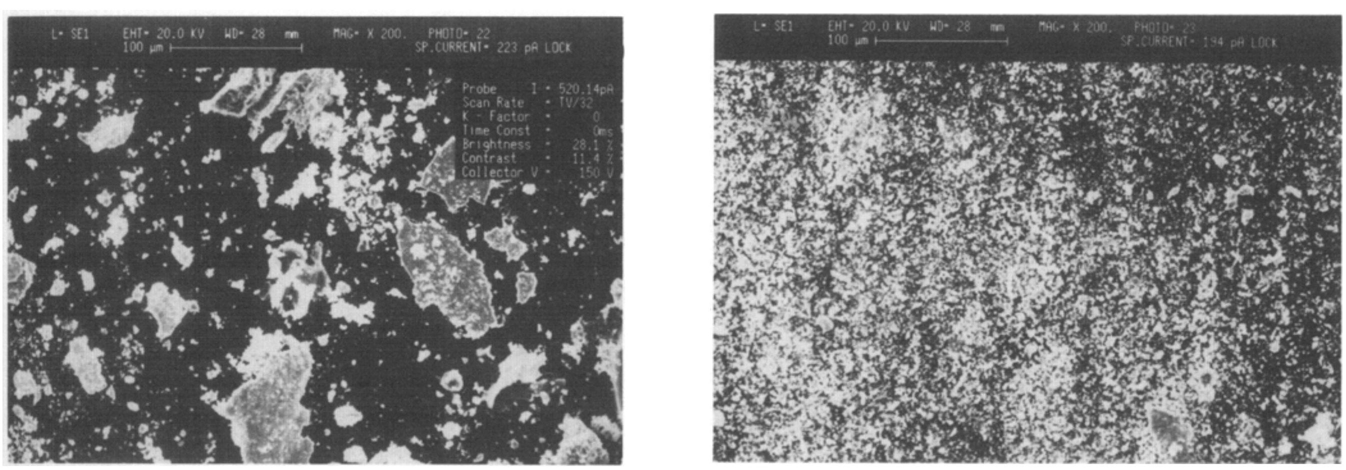
(a) (b)

Fig. 9 Worn surfaces of (a) 1045 steel block without coating and (b) ring as its counter surface to the 1045 steel block



(a) (b)

Fig. 10 Worn surfaces of (a) ESD coating on block and (b) ring as its counterpart



(a) (b)

Fig. 11 Wear debris of (a) 1045 steel block/1045 steel ring pair and (b) ESD coating block/1045 steel ring pair

4. Comparative Experiments for the Accelerated ESD Equipment

Comparison between the newly designed accelerated ESD equipment and a conventional D9130 type is shown in Table 1; it can be seen that coating rate has been increased three to four times, while the lowest value of surface roughness increases a little.

The influence of process parameters on coating thickness and surface roughness are shown in Fig. 4 and 5. The important fact revealed in Fig. 4 is that the coating thickness has a highest value at a special depositing time, about 3 min, in the experiments of this paper. This resulted from the thermal residual stress generated in the coating, which induces microcracking and then deterioration; thus excessive depositing time is useless or even harmful. In Fig. 5, it seems a little difficult to explain that surface roughness increases with the increase of pulse frequency. Further research will be carried out.

5. Microstructures and Phase Components

Figure 6 shows the microstructure of a coating. X-ray diffraction reveals that the main phases are M_6C-type carbides such as Fe_3W_3C, Co_3W_3C, while W_2C, WC were also present (Fig. 7). Underneath the coating is the thermally affected substrate. The hardness of the ESD coating is 1400 to 1600 $HV_{0.5}$.

6. Wear Behaviors

Comparative wear experimental results between quenched and tempered AISI 1045 steel, with and without ESD coatings, are shown in Fig. 8. It can be seen that wear resistance is increased by 5 to 8 times.

Scanning electron microscopy observation on the worn surfaces of the two groups of specimens revealed the wear mechanisms: For steel-block/steel-ring pair, severe adhesive wear is the dominating mechanism, as shown in Fig. 9. For coating-block/steel-ring pair just mild wear occurred, including oxidization and melting (Fig. 10), molten spheres on worn surface of ESD coating have been observed (Fig. 10a). Analyses using energy dispersive x-ray spectroscopy indicated that their main element is iron; that is, they come from the surface of the ring, as 1045 steel has a much lower liquefaction point (1500 °C) than carbides (for WC + W_2C, 2715 °C). Wear debris also reflects the different wear characteristics, as shown in Fig. 11; those collected from steel-block/steel-ring pair are larger size flakes (Fig. 11a), while those of coating-block/steel-ring are small size powders, which are typical debris of mild wear. So, it is the difference in composition, microstructure, and hardness brought about by ESD coating that reduces adhesion and wear and increases the wear resistance.

7. Conclusions

- By use of new switch components IGBT, and new electric circuits, accelerated ESD equipment has been produced. The coating rate has been increased by 3 to 4 times.
- Coating thickness and surface roughness increase with higher pulse power and frequency. There exists an optimized depositing time at which the thickest coating can be obtained.
- ESD coating on AISI 1045 steel with WC-8%Co as the electrode increases the wear resistance by 5 to 8 times.

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