

MATERIAL DEPOSITION PROCESSES THROUGH ELECTRIC DISCHARGES - A REVIEW

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ABSTRACT: The application of hard coatings is widely used in industry as a method of preventing mechanical parts from corrosion, temperature extremes, stress, and other hostile environments. An innovative method of surface modification, electrical discharge deposition (EDD) involves coating a layer of material on a part to improve its surface properties or develop new functions. Electrical Discharge Deposition (EDD) is a hybrid coating technique that has the advantage of being less expensive than other similar techniques. The technology is different from electrical discharge machining (EDM), this process deposits metal by exploiting the electrode's high wear rate. It provided a comprehensive review of the EDD process for a variety of materials, as well as details of the types and main parameters of the process, as well as a description of the characteristics of the coatings obtained.
KEYWORDS: electrical discharges, hybrid coating technique, parameters

1. INTRODUCTION

Companies can only gain competitive advantages over their competitors by using green production methods. New trends are emerging in the production of metal parts, including environmentally friendly manufacturing [1]. Recently, researchers have been investigating more on electrical discharge deposition (EDD) or electrical discharge coating (EDC) due to better environmental conditions and process improvements [2]. Electrical discharge deposition (EDD) is an advanced method for coating conductive materials, valued for its strong adhesion, ability to produce thick layers, and flexibility in adjusting the coating composition using different electrode materials and dielectric fluids [3]. Similar to electrical discharge machining (EDM), EDD uses electric sparks given by EDM generator between the tool-electrode and workpiece-electrode to convert electrical energy into thermal energy [4].
In this process, electric sparks produces by pulsed voltage between the tool and the workpiece transform electrical energy into a plasma channel, facilitating the deposition process. During EDD, the electrode enables the transfer of coating material to conductive substrates, allowing for precise application. High temperatures lead to electrochemical reactions between the electrode materials and hydrocarbons, resulting in a robust coating layer on the substrate. Recent research has demonstrated the effectiveness of this technique in achieving targeted coatings through the continuous generation of electrical sparks during the machining process, highlighting its potential for advancing surface engineering and enhancing material properties in various applications [5-6].
Using electrical discharge coating (EDC) or electrical discharge deposition (EDD) technology, illustrated in Fig. 1, the electrodes can consist of metallic materials (1.a), or which can be obtained from powder metallurgy (1.b) or produce the latest 3D printing techniques (1.c). Deposition occurs by sparks generated in the gap between the tool and the substrate, which can be filled with either dielectric fluid (1.d) or air (1.e). The deposited material (2) consists of impulse voltages acting on a particles (2.a) from dielectric liquid in the gap. Moreover, metal carbides can be created by combining the metal deposited from the tool electrode with the carbon resulting from cracking of dielectric fluid molecules (2.b) [7].

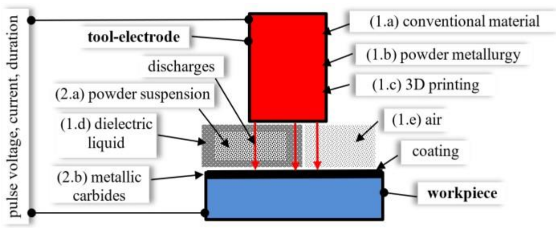

Figure 1. Technology system of EDD [7]

2. PHENOMENOLOGY

In electrical discharge deposition (EDD), the tool is linked to the positive connection, while the workpiece is attached to the negatively charged connection, as illustrated in Fig. 2. [8]. Normally, in electrical discharge machining, the used dielectric helps in generating plasma where the spark happens between the electrodes, and on the collapsing of the plasma/end of discharge, the dielectric helps in flushing away the melted material that falls off the workpiece. In EDD the dielectric used helps in only creating discharges. Because there is no need to remove material from the workpiece, air is always preferred as a dielectric for EDD. A tool is connected to the positive terminal, releasing heavier ions from the surface and workpiece, emitting electrons that are lighter but more numerous than the ions. Because the ions have a greater mass, they deposit the electrode onto the surface part. [9].

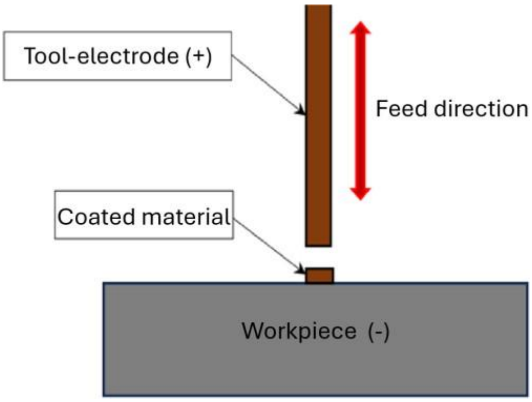

Figure 2. Diagram of electrical discharge coating

The discharge process consists of applying a voltage across two electrodes: tool-electrode and tool-workpiece. When the electrodes are nearby (with a gap distance measured in micrometers), Joule heating and electrons will accumulate on machined surface as a result of the electric field.

The electric field force accelerates the emitting electrons, causing them to run toward the anode. In the presence of dielectric medium particles, high-speed electrons will collide with many electropositive particles. When it comes to the discharge process, this collision of electric particles occurs continuously, resulting in a plasma channel forming [10].

There are three main characteristics of plasma channels, namely the heat transfer, magnetic properties, and exerted pressure, as illustrated in Fig. 3a.

In the channel, high-temperature heat is produced instantaneously due to plasma jet action. Convection, radiation, and conduction are the three mechanisms by which heat fluxes from plasma channels are transmitted to their surroundings (cathode, anode, and dielectric).

When a discharge current is initiated, a magnetic field surrounds the plasma channel. As the plasma channels transfer energy, the magnetic field exerts a Lorentz force on the moving charges.

Because of this magnetic force, centripetal magnetic compression occurs on the plasma channels. (see Fig. 3b). Furthermore, the Lorentz force affects the movement of molten materials in a molten pool.

Expansion of plasma channels causes pressure to be exerted on the surrounding area, removing discharge debris and modifying the shape of discharge craters at the interface of the molten pool. [11].

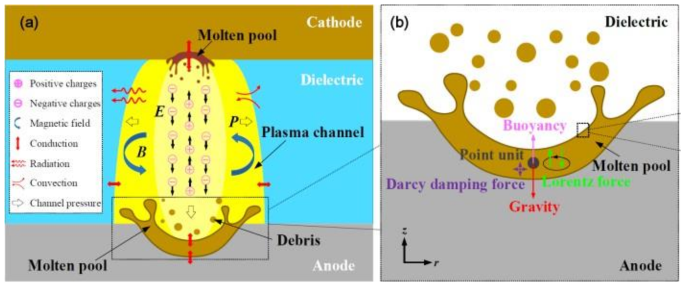

Figure 3. Models of plasma channels and discharge craters: (a) Channel characteristics of plasma; (b) Analysis of forces in the molten pool [11]

Several recent studies have shown that electrical discharge plasma at atmospheric pressure exhibits characteristics similar to a type of vacuum discharge called a hot anode vacuum arc (HAVA).

It has been reported that HAVA produces high electron energies and positive potential near its anode. This phenomenon appears when the discharge is focused on a high-temperature anode target. Located near the electrode surface, the anode site can be characterized by high temperatures and high electron concentrations.

EDD in liquid results in non-equilibrium plasma regions forming in front of the electrodes; these regions are referred to as sheaths. This area has a thickness on the nanometer scale compared to the gap width. As a result of its high electron concentration, the anode sheath can cause voltage drops [12].

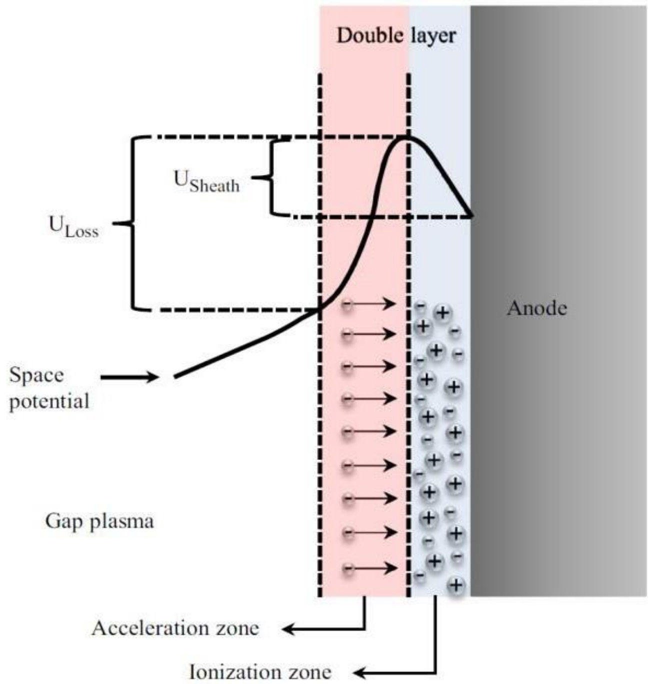

Figure 4. Anodic double layer and space potential [13]

The anode sheath ionizes nearly all the atoms, while the electric field accelerates electrons toward the anode. It is possible to form a two-layered anode that consists of a charging region and an ionization region. Therefore, there are positive and negative curvatures in the potential profile near the anode, as shown in Figure 4 [12].
According to high-speed images, discharges conducted in oil are enveloped by a gas bubble, while discharges that occur in air only produce plasma plumes (Fig.5-7) [14].

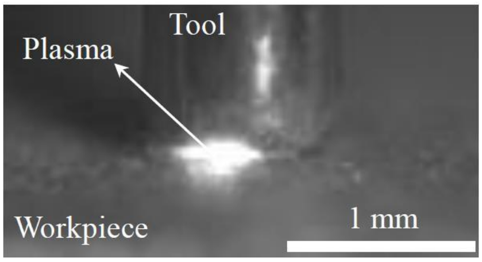

Figure 5. Discharge plasma expansion in air [14]

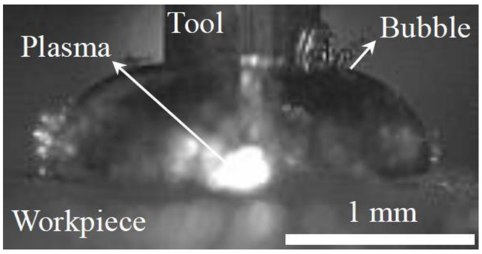

Figure 6. Discharge plasma expansion and gas bubble in oil [14]

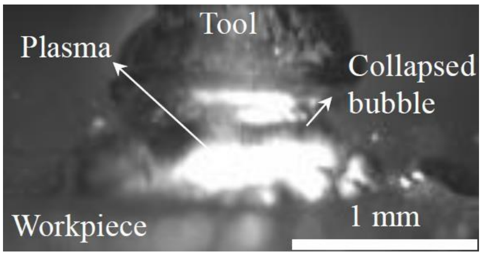

Figure 7. Discharge plasma expansion and collapsed gas bubble in oil [14]

The results of high-speed imaging experiments indicate that oil discharge particles are notably bigger at the beginning of the event. During the initial phase of these discharges, substantial light is emitted due to electrical breakdown. In liquid EDD plasmas, the thickness experiences only minor variations throughout the pulse duration. Consequently, the plasma thickness in oil discharges remains relatively stable over time, averaging around 500 µm [14].

3. PROCESS PARAMETERS OF ELECTRICAL DISCHARGE COATING

It is important to list the technological parameters that directly influence the quality of the deposited layer. These parameters include the electrical current, the discharge voltage, the pulse time, and the electrode polarity.

3.1. Discharge voltage

The breakdown voltage is described as the voltage across the distance between two electrodes. An electrical spark occurs between an anode and the cathode when a discharge voltage is reached. Its value is influenced by the discharge gap and electrode breakdown strength. Current flow is increased as a result of an open cutoff voltage, which causes an ionization channel in the dielectric. A voltage drop appears after the current passes through the device and becomes stable once it reaches the operating range. Voltage determines the gap width between the anode and the cathode. By increasing this voltage, the flushing process and discharge stability will improve. Due to increasing discharge voltages, surface roughness, tool wear rates (TWR), material removal rates (MRR), and microhardness will increase. In this way, by increasing the open-circuit voltage, a stronger electric field is generated, which results in higher machining, tool wear, and roughness rates. In the opposite direction, a low voltage will produce a low discharge energy in the coating region. In addition, sintered electrodes improve material movement across the electrode to the product and enhance the weight of the part when the voltage is properly selected [15].

3.2. Peak current

Peak current refers to the highest level of current that can be generated by a power generator per pulse. During a cycle, the average current is determined by the average amperage across the void between the electrodes during the pulse period. During EDC, a peak current is needed to generate the electrical spark, which reaches the spark temperature necessary for depositing the tool material onto the substrate. Therefore, the current must be optimized to transfer the maximum amount of material for a uniform and dense coating. Surface roughness is worsened by a large peak current value. A higher peak current causes increased discharge energy, which increases surface roughness. The increased peak currents cause more melted materials to come out of the crater, which results in rough surfaces [15].

3.3. Pulse on time

To ensure uniformity in the product and tool wear, it is necessary to consider the pulse time and period. Due to the pulse-on-time, the electrode material erodes and solidifies on the workpiece. A pulse-off period facilitates the deposited material to cool and solidify on the part. There is a direct relationship between the energy generated during the pulse on time and the rate of material expulsion. In the circumstance of excessive melting during a long pulse, more substrate material will be expelled from the tool-electrode, resulting in a rough surface finish. An increased number of impulse cycles results in a more satisfactory surface finish since impulse cycles are repetitive processes [16].

The electrical discharges from the point-type cathode tool correspond to the characteristics of HAVA. Cathodes provide electrons in HAVAs, but anodes and working gap plasma provide most of the discharge energy. HAVAs provide electrons from cathodes, but most of the discharge power is supplied from anodes and inter-electrode plasmas. Cathode activity is limited, and it is considered a passive electrode. As a result of the low energy of ions coming from the anode, there is very limited cathode material sputtering. Also, the cathode receives material from the anode, resulting in negative cathode erosion. According to Figure 8, the electrodes have been discharged 30 times under different polarities. This picture shows the electrodes from the top of their conical extremities. A clear difference between the anode tool and the cathode tool is that the anode contains craters, but the cathode is covered by aluminum from the workpiece, with no visible craters [2].

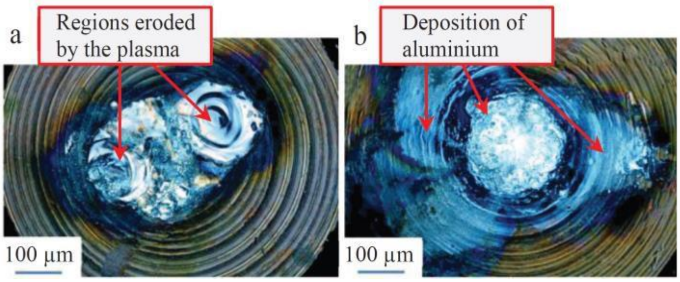

Figure 8. (a) Anode electrode; (b) Cathode electrode [2]

4. ELECTRICAL DISCHARGE COATING CHARACTERISTICS

It is important to take into account three major characteristics: roughness, thickness, and micro-hardness.

4.1. Roughness

Measurement of surface roughness is a crucial aspect of evaluating the structural condition of deposited materials. As a result, the machined surface can be viewed with greater clarity, providing valuable insights into its quality and integrity. As a result, parts can be assessed for their overall performance and functionality. There are a variety of factors involved in the machining process that influence surface roughness. A key factor to consider is particle size, as smaller particles tend to contribute to a smoother surface, while larger particles tend to be rougher. Furthermore, the concentration of materials in dielectric fluid is a crucial factor in surface roughness. By increasing the concentration, the material can be removed more efficiently, thereby improving the final finish. During the electrical discharge deposition (EDD) process, the maximum current setting also determines surface roughness. The surface roughness tends to increase with an increase in current. Achieving the desired surface quality requires optimizing and carefully controlling machining parameters [17].

4.2. Thickness

In terms of thickness, a layer is the height above the base metal at which material is deposited. Technology parameters have a direct influence on the thickness of the coated layer, namely, the thickness grows proportionally by rising current and pulse rate. In table 1, data from the specialized literature are presented regarding the thicknesses of material deposited based on electrode-tool materials.

Table 1. Coating thickness after EDC [17]

Workpiece material	Electrode material	Work environment	Thickness [µm]
β-Ti alloy	Ti	Dielectric liquid	18–20
Al	TiC–Cu	Dielectric liquid	30,11 – 60,34
Al	Ti–B4C–Al	Dielectric liquid	22,4
WC-Co	Cu	Dielectric liquid	5
C45	Ti	Dielectric liquid	25
Aluminium	SiC–Cu	Dielectric liquid	44,01 – 83,644
Aluminium	Ti	Air	20
Ti30Ta	Ti	Dielectric liquid	9
Ti–6Al–4V	Cu	Dielectric liquid	12–18
70Ti–Ta30	Ti	Dielectric liquid	7

4.3. Micro-hardness

The deposition of layers on the surface of a material by electrical discharges creates layers with higher micro-hardness compared to the base material. A certain element, especially C (carbon) and cementite particles, in the deposited layer, causes this phenomenon. It is also important to mention that the coating or deposition procedure is associated with an extremely rapid cooling process. It is generally accepted that materials that are subjected to rapid cooling tend to form structures with greater hardness.

Certain manufacturing processes are characterized by rapid cooling, which prevents the formation of larger crystal structures and results in finer and harder microstructures. Based on the combination of specific elements in the deposited layer, and with rapid cooling, the coating achieves a higher micro-hardness in comparison with the original workpiece.

Coated materials may benefit from this process in terms of their mechanical properties and wear resistance [17].

5. CONCLUSION

The electrical discharge coating technique uses an electrode tool to modify the surface of a product. The properties of the material can be obtained at an affordable cost.

The coated layer is well-suited for numerous industrial applications because of its wear resistance, surface roughness, microhardness, adhesion to the substrate, biocompatibility, and thickness. It is crucial to recognize that the properties of the electrodes and input parameters (such as intensity, voltage, and pulse duration) significantly influence the coating process. Electrode materials produced through powder metallurgy perform better than usual ones in respect of transfer / deposition rate, micro-hardness, and layer quality. The development of mathematical models, analysis, and optimization of specific process parameters allows more possibilities for developing EDD technology that is more competitive than traditional coating processes. Further investigation is needed on the effect of variables in this process on the deposition rate and microstructure of the deposited coatings.

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