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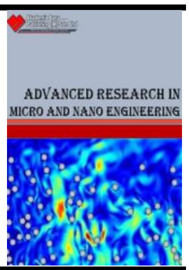

Enhancing Mild Steel Surface Characteristics through Electrical Discharge Coating with Titanium Dioxide Suspension

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ABSTRACT

In this research, surface modification of mild steel was carried out by using electric discharge coating (EDC) with titanium dioxide (TiO_2) powder suspension. The concentrations of TiO_2 powder were varied and their effect on the surface roughness and deposited element were investigated. The results showed that elements such as titanium, carbon, copper, oxygen, zinc and iron were successfully coated on the mild steel surface. Aside from that, the weight % of the titanium element increased with an increase of TiO_2 powder concentration. The surface roughness was also reduced 62.9% by using 5 g/l TiO_2 powder when compared to the pure kerosene oil.

1. Introduction

Mild steel is considered as low carbon steel because it contains low carbon (0.15 to 0.20%) in its composition. Due to its superior mechanical properties and inexpensive cost, mild steel is frequently used as a construction material in most industries, such as food, power generation, petroleum, chemical and electrochemical sectors [1]. However, fatigue and rusting are the most common causes of structural steel damage over time. Besides that, mild steel corrosion is the biggest challenge because corrosion damage results in high maintenance and protection costs for the materials used [1,2].

Surface coating is a common technique for modifying surface characteristics including hardness, resistance to corrosion, heat and wear without changing the original properties of the base material [3]. Based on the previous research, there are several methods that have been used for coating, for example, sol gel [4], electrophoretic deposition [5], thermal flame spray [6], chemical vapour deposition [7], physical vapour deposition [8] and hard anodizing [9]. However, there are some shortcomings of these coating processes, including expensive capital costs, vacuum requirements

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and complicated operational procedures [10,11]. Alternatively, electrical discharge coating (EDC) has emerged as an economical technique for forming a coating layer on the surface of a workpiece [12]. Moro *et al*., [13] stated that the EDC process, which is an alteration of the electrical discharge machining (EDM), uses the sparking principle to deposit a specified quantity of material on the substrate.

In conventional EDM, material is removed while a dielectric fluid is present through a sequence of electrical discharges in a sparking gap. The discharging process is done under the positive polarity [14]. Nonetheless, during the EDC, negative polarity is frequently used, where the anode is typically connected to the electrode and the cathode is connected to the workpiece [15]. To improve the chemical and physical properties of the surface material, EDC can be performed by suspending powder in dielectric fluid. When a proper quantity of powder is mixed in the dielectric fluid, the powder attempts to construct a conductive bridge in the spark gap when an electric field is present. The sparks' heat energy then melts the material of the workpiece and the suspended powder, causing part of the molten elements to be expelled from the powder and workpiece. Unremoved molten materials will migrate and solidify on the workpiece surface as a result of a quick cooling process, and forming a coating layer [16,17].

Numerous researchers have examined the modification of the workpiece surface utilising powder suspension in the EDC process. For example, Tijo and Masanta [18] successfully deposited TiC-TiB_2 on the Ti-6AL-4V surface by utilizing Ti and B_4C powder and appropriate processing conditions. Their results indicated that the coated surface's microhardness and wear resistance improved up to 3 times and 7 times, respectively compared to the uncoated substrate. This result is in agreement with the one obtained by Sharma *et al.,* [17], who found that by inclusion of hBN powder into deionized water, the microhardness of Ti-6AL-4V significantly improved because of the presence of BN, TiN and TiAlN. Very recently, Kiran *et al.,* [19] mixed the MoS_2 powder in Jatropha and Neem oil to modify the surface of Ti-alloy. The results revealed that the microhardness and surface finish of the coating was further improved compared to the pure Jatropha and Neem oil without MoS_2 powder.

From the literature review, even though a lot of studies have been carried out on the surface modification by EDC with powder suspension, however, very few studies have been reported on the use of EDC with titanium dioxide (TiO_2) for surface modification of mild steel. TiO_2 is a desirable ceramic material because of its good chemical, mechanical, thermal stability as well as its non-toxicity [20].

Therefore, the aim of the present study is to examine the influence of different concentrations of TiO_2 powder on the surface modification of mild steel. The values of surface roughness and weight percentage of the elements that were deposited on the workpiece surface were determined and analyzed.

2. Methodology

2.1 Equipment and Materials

A die-sinking EDM machine (Sodick AQ35L) was used to perform the EDC experiment. The workpiece material was a mild steel plate with dimensions of 25x25x6 mm. As an electrode, a copper rod of 78 mm in length and 6 mm in diameter was selected. In this experiment, TiO_2 was used as the coating agent and mixed into the kerosene oil. Prior to the experiment, the mild steel surface and the end of the copper electrode were ground to remove rust, burr and to achieve the flat surface. Tables 1 and 2 outline some typical properties of mild steel workpieces and copper electrodes, respectively.

Table 1
Properties of the mild steel [21]

Properties	Value
Density (kg/m^3)	7.8e3-7.9e3
Melting point (°C)	1.48e3-1.53e3
Resistivity (μΩ.cm)	15-20
Hardness Vickers (HV)	108-153

Table 2
Properties of the copper electrode [22]

Properties	Value
Density (kg/m3)	8.93e3-8.94e3
Melting point (°C)	982-1.08e3
Resistivity (μΩ.cm)	1.74-5.01
Hardness Vickers (HV)	44-180

2.2 Preparation of TiO_2 Suspension

Before the EDC experiment, the TiO_2 suspensions were prepared by dispersing different concentrations (0 to 20 g/l) of TiO_2 in kerosene oil. The mixture was stirred for 30 minutes with a Sartorius Labsonic P ultrasonic homogenizer set to 50% amplitude and 0.5 interval time. During the mixing process, cetyltrimethyl ammonium bromide (CTAB) surfactant was added to avoid the agglomeration of TiO_2 powder during the EDC process. The ratio for TiO_2 powder and CTAB is 1:1. The formula for calculating the concentration of TiO_2 powder is shown in Eq. (1).

$$\text{Concentration (g/l)} = \frac{\text{Mass of the powder (g)}}{\text{Volume of kerosene oil (l)}} \quad (1)$$

2.3 EDC Conditions

In this experiment, reversed polarity was used as the positive terminal that connected to the copper electrode while the negative terminal linked to the mild steel workpiece. Figure 1 shows the experimental setup. The machining time for each test was 30 min, and to confirm the correctness of the results, each parameter setting was repeated three times. Following the experiment, deposited elements and surface roughness were examined. Table 3 shows the machining parameters and the experimental conditions for this research.

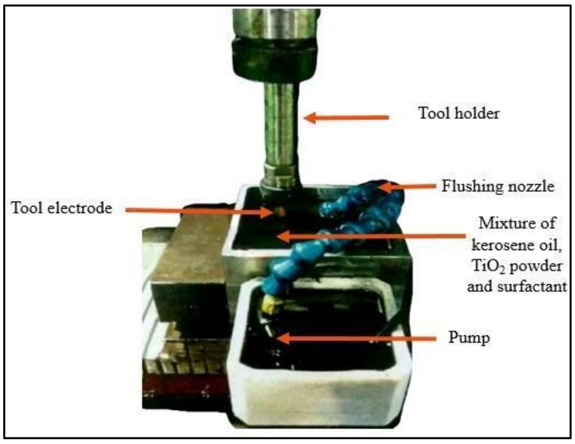


Fig. 1. Experimental setup

Table 3
Experimental conditions

Parameters	Conditions
Workpiece	Mild steel
Electrode	Copper
Dielectric fluid	EDM LS (low smell) kerosene oil
Polarity (Reverse polarity)	Mild steel workpiece- negative Copper electrode-positive
Powder	TiO_2
Surfactant	CTAB
Machining time	30 minutes per cycle
Concentration	0, 5, 10, 15 and 20 g/l
Peak current (I_p)	3 A
Pulse on time (T_{on})	100 µs
Pulse off time (T_{off})	300 µs
Discharge voltage (V_d)	30

2.4 Measurement and Analysis

After the EDC process, a surface roughness tester model Mitutoyo SJ-301 was used to measure the surface roughness (Ra) of the coated surface. To obtain an average value, three readings were taken on the coating layer's surface. The weight percentage of deposited elements on the coating layer was then determined using Energy Dispersive X-ray (EDX).

3. Results

3.1 EDX Analysis

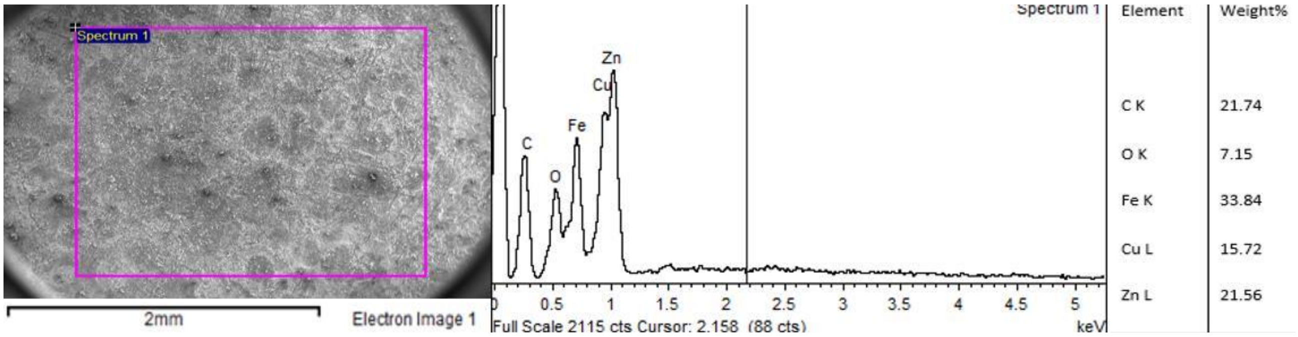
Figure 2 shows the EDX spectrum analysis of the coating layer for various TiO_2 powder concentrations starting at 0 (without TiO_2), 5, 10, 15 and 20 g/l. As can be seen in Figure 2(b)-2(d), six elements were detected on the mild steel coating surface, which were carbon (C), oxygen (O), titanium (Ti), iron (Fe), copper (Cu) and zinc (Zn). However, Ti was not found on the coated surface when 0 g/l was used (Figure 2(a)). This indicates that Ti from TiO_2 powder was successfully coated on the mild steel surface through the EDC process.

The C element that coated on the workpiece surface was decomposed from the kerosene oil due to the extraordinary high temperature. According to Collins [23], the kerosene oil that was used in the EDC process, contained a long hydrocarbon chain with a boiling point between 150 and 300 °C. Due to the spark that was generated at a temperature between 8000 and 12000 °C during the EDC process, the hydrocarbon chains in kerosene oil will break down, causing the C element to be deposited on the mild steel workpiece. This result is supported by Liew *et al.*, [12] and Yap *et at.,* [16].

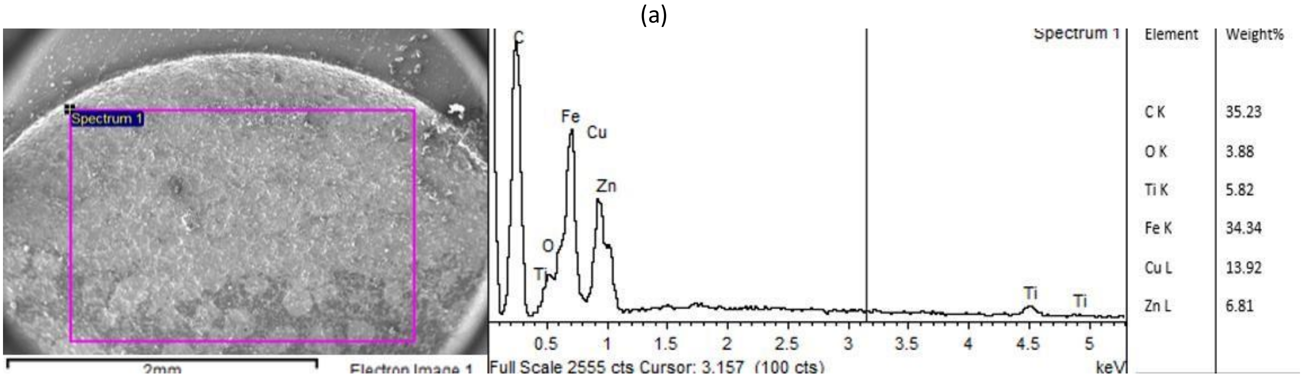
Moreover, Fe, Zn and Cu were also found in the EDX spectrum. These elements were originally from the mild steel workpiece material and copper electrode material. Based on Yap *et al.,* [16], during the EDC process, the heat from the sparks melts the workpiece and electrode material, causing part of the molten materials to be expelled from the mild steel workpiece (Zn and Fe) and electrode (Cu). The flushing pressure provided by the burst of vapour bubbles, however, is insufficient to evacuate all of the molten elements [24]. Thus, these molten materials migrated and solidified on the mild steel surface.

The presence of O element that detected by the EDX spectrum was most likely originated from the atmosphere during the cooling phase. This result is corroborated by the findings of Wang *et al.,*

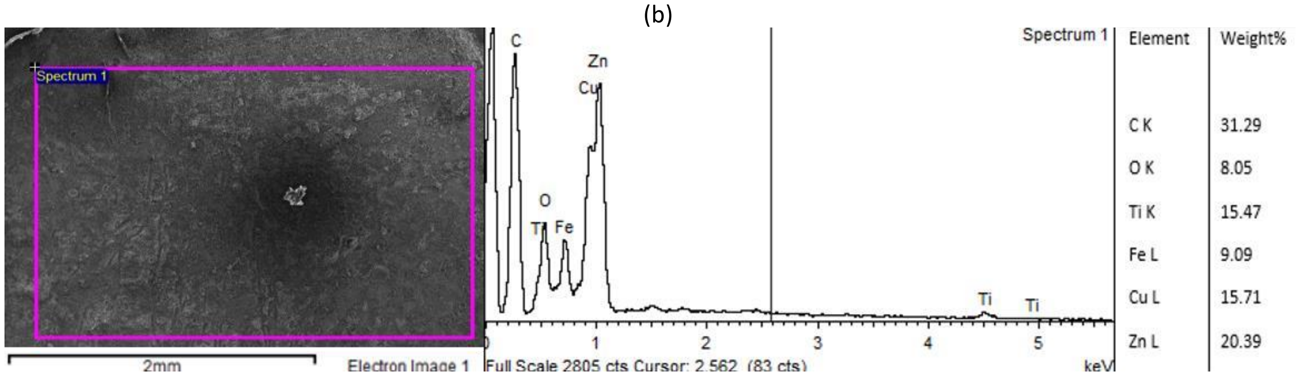
[25]. The O element might also has decomposed from the suspended TiO_2 powder when struck by the spark at a high temperature.



(a)



(b)



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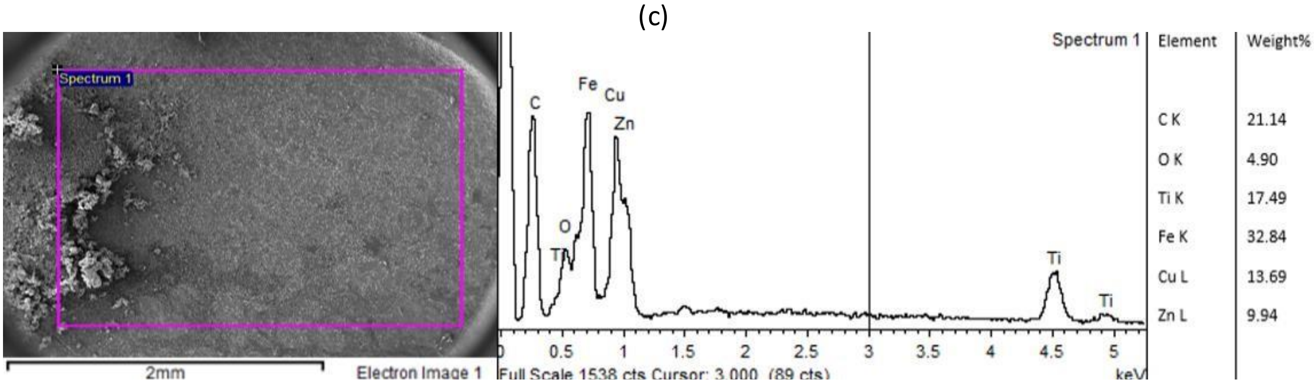
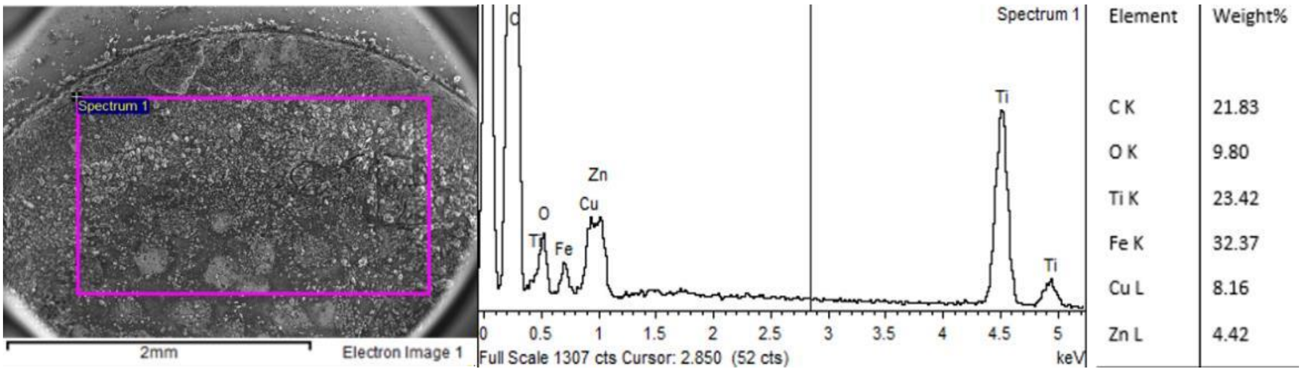


(d)



(e)

Fig. 2. Scanning area and EDX spectrum result for a) 0 g/l, b) 5 g/l, c) 10 g/l, d) 15 g/l, e) 20 g/l concentration of TiO_2 powder

3.2 Deposited Ti Element

As shown in Figure 2, the Ti element, which originated from the suspended TiO_2 powder, was deposited and coated on the mild steel surface. Therefore, in this subsection, the effect of TiO_2 powder concentration on the deposited Ti element was analysed. Figure 3 shows the relationship between powder concentration and deposited Ti element. As can be seen in Figure 3, the value of the weight percentage of the Ti element was significantly increased when the powder concentration increased. Nevertheless, the coating layer that is formed by the 0 g/l TiO_2 concentration as illustrated in Figure 2(a) does not contain any Ti elements. This result reveals that when a greater amount of TiO_2 is added, a higher number of Ti elements will be deposited on the surface of mild steel. This result is consistent with the one obtained by Yap *et al.,* [16], who found that an increase in quarry dust powder concentration will increase the percentage of Si element, which is one of the elements found in quarry dust powder.

During the EDC process, a plasma channel was generated in the gap between the workpiece and the electrode. The discharge spark that formed in the plasma channel caused the suspension powder to melt and deposit on the workpiece surface. The higher the concentration of powder suspension employed, the greater the amount of powder will be coated on the mild steel surface due to the eroded debris and powder particles that are difficult to flush away. The molten element from the powder material was solidified during the cooling process, and the coating layer was formed [16].

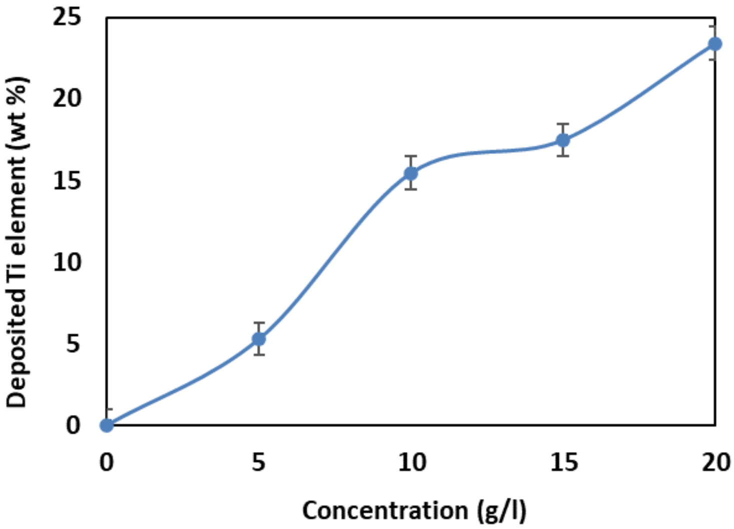


Fig. 3. Effect of TiO_2 concentration on the deposited Ti element

3.3 Surface Roughness

Figure 4 illustrates the relationship between TiO_2 powder concentration and surface roughness (Ra). It is seen that without the inclusion of TiO_2, the surface value was the highest. The high value of surface roughness could be because of craters on the coating surface. According to Singh *et al.,* [26], the spark was discharged at the gap between the electrode and the workpiece throughout the EDC process. The explosion caused by the discharge spark will then result in the formation of a deep crater and leading to a high surface roughness value.

Nevertheless, when 5 g/l of powder was added, the surface roughness value significantly dropped to 0.56 µm. This result clearly shows that when a lower quantity of powder is mixed in the dielectric fluid, the surface roughness value will be reduced. This happened because the heat from the electric spark melted the powder particle, which was then uniformly deposited over the surface of the workpiece. This finding is supported by Mughal *et al.,* [27], who stated that the addition of powder will improve the surface finish as a result of the enhanced interspace between the workpiece and tool and the balanced distribution of discharge.

When a high concentration of powder was added (10 to 20 g/l), the surface roughness was increased gradually. This happened because the powder particles accumulated in the plasma channel, causing contamination and unstable machine performance. Excess particles present in the spark gap also resulted in a short circuit as a consequence of the abnormal discharge, leading to the formation of deep craters and valleys, as a result, made the surface rougher [28,29].

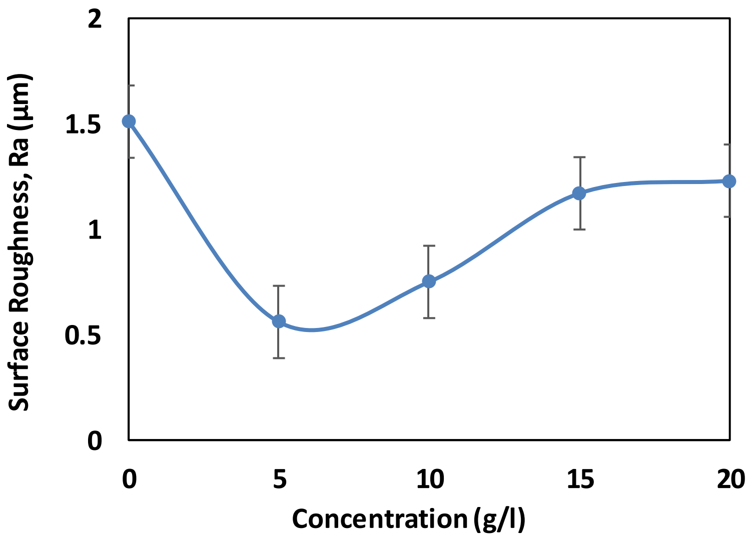


Fig. 4. Effect of TiO_2 concentration on the surface roughness

4. Conclusions

In the present study, the surface modification of mild steel workpieces was examined experimentally by using the EDC method. The primary purpose was to analyse the influence of various TiO_2 concentrations (0 to 20 g/l) on the coating elements and surface roughness of the coating surface. The important outputs of this study were as follows:

- With the TiO_2 powder addition, six elements such as Ti, O, C, Cu, Fe and Zn were coated on the mild steel surface after the EDC process.

- The Ti element that originated from the TiO_2 powder was successfully deposited on the mild steel surface and the weight percentage of Ti element was directly proportional to the powder concentration value.
- Without the addition of TiO_2 powder, the machined surface was the roughest, and the best surface finish can be obtained by using 5 g/l TiO_2 powder concentration.
- At a higher concentration of TiO_2 powder, the surface roughness value also increased.

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