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Electrical Discharge Coating of Mild Steel with Fly Ash Suspension

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ABSTRACT

Mild steel is a soft substance that rusts easily. It is easy to wear and corrode when exposed to harsh circumstances, such as in manufacturing sector. As a result, the mild steel surface must be modified to boost its durability and wearability. There are various techniques for coating mild steel and one of them is electrical discharge coating (EDC). In this study, the surface of mild steel was modified using EDC with fly ash suspension. Prior to the experiment, the element content, particle size, and surface morphology of fly ash were investigated. The EDC process was carried out using a Sodick AQ35L die-sinker EDM machine. The effects of varied amounts of fly ash on the features of the coated surface were also investigated. The experimental results revealed that raising the fly ash content increases the micro-hardness of the coated surface. Furthermore, utilising 20 g/l of fly ash powder resulted in the best coated surface finish with the least surface roughness. The concentration of fly ash has a significant impact on the thickness of the coating layer. These findings substantiate the viability of recycling fly ash as an environmentally sustainable coating material for modifying mild steel surfaces through the EDC method.

1. Introduction

Surface modification of material by using hard coating is a process that can improve and modify the surface of the material in terms of its physical properties, mechanical properties, and biochemical properties [1]. There are many techniques for coating surfaces, such as electroplating and electrodeposition [2], hard anodizing [3], as well as chemical/physical vapour deposition technique [4]. The surface modification is very important because it can increase the workpiece surface's strength, corrosion resistance, and wear resistance, and it can also perform new surface functions such as biocompatibility [5].

Electrical discharge coating (EDC) is an alternative method to deposit a hard and wear-resistant surface onto the workpiece by a simple reverse polarity process [6-7]. When compared to other existing surface modification technologies, EDC is considered a new and advanced method of

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depositing a protective layer onto the workpiece [8]. According to Vijayakumar *et al.,* [9], the coating layer thickness is adjustable with the parameter setting on the electrical discharge machining (EDM).

As noted by Liew *et al.,* [10], there are several methods that can be used to coat the materials by using EDC process. One of them is through the powder suspension in the EDC process. In this process, a suitable amount of powder is mixed into the dielectric fluids, and electrode is normally connected to the anode (positive terminal), whilst the workpiece is connected to the cathode (negative terminal). Ionization is formed between the electrode and the workpiece, and the generation of electrical discharge sparks in the plasma channel melts the powder suspension in the dielectric fluid and deposits the material on the workpiece surface. During each electrical discharge spark, the deposited powder material on the workpiece surface is solidified via a rapid cooling process (quenching) and the deposited powder material bonds with the surface of the workpiece to create a layer of coating.

In previous studies, various types of powders have been employed as coating material in the EDC process, such as quarry dust [6], titanium (Ti) [11], molybdenum (Mo) [12], tungsten disulphide (WS_2) [13-14], hydroxyapatite (HA) [15], and etc. Although there has been substantial research conducted on surface modification through the EDC process using powder mixed dielectric fluid, a comprehensive investigation utilizing fly ash powder for enhancing the surface properties of mild steel via the EDC method is still lacking. Fly ash, a residual product resulting from coal combustion for electricity and heat generation [16], is rich in SiO_2 and Al_2O_3. This composition makes it a viable candidate for serving as a coating material in the surface modification of mild steel.

Therefore, in this study, the effect of fly ash suspension with different concentrations on the surface modification of mild steel was investigated by using EDC process. Coating layer thickness, surface roughness and Vickers micro-hardness of coated surface were carefully examined and analyzed.

2. Methodology

2.1 Characterization of the Fly Ash Particles

The surface morphology of fly ash particles, particle size, and elemental composition were investigated before the EDC process. Figure 1(a) shows the morphology of fly ash which was taken by using FESEM model Hitachi SU8020 with 2.0kV and secondary electron emission. As can be seen in Figure 1(a), fly ash particles possess a unique spherical shape, not angular and uneven particle size distribution. Furthermore, a particle size analyser (PSA) model Mastersizer 2000 manufactured by Malvern Instruments Ltd. was used to determine the fly ash particle size. As shown in Figure 1(b), the particle size range was 4.083 µm to 106.485 µm, with an average particle size of 23.991 µm. Figure 1(c) shows the elemental composition of fly ash particles analysed by using the EDX model Oxford Instrument Energy-Dispersive Spectroscopy under 10kV. Based on Figure 1(c), the main elements of fly ash particle were O (37.9 wt%), Fe (26.8 wt%), Al (12.2 wt%), Ca (11.8 wt%), Mg (5.2 wt%), Si (2.9 wt%), S (1.9 wt%) and C (1.3 wt%) respectively. The result reveals that O has the highest weight percentage, followed by Fe, Al, Ca, Mg, Si, S and C, respectively. These results agree with the findings of Alehyen *et al.,* [17] where they reported that fly ash is a finely divided residue produced by the combustion of ground or powdered coal in power plants and made up of minerals like silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), and organic matter like carbon (C).

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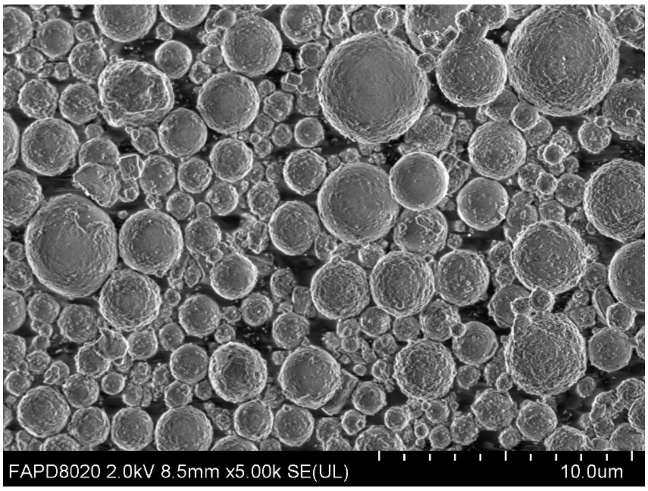
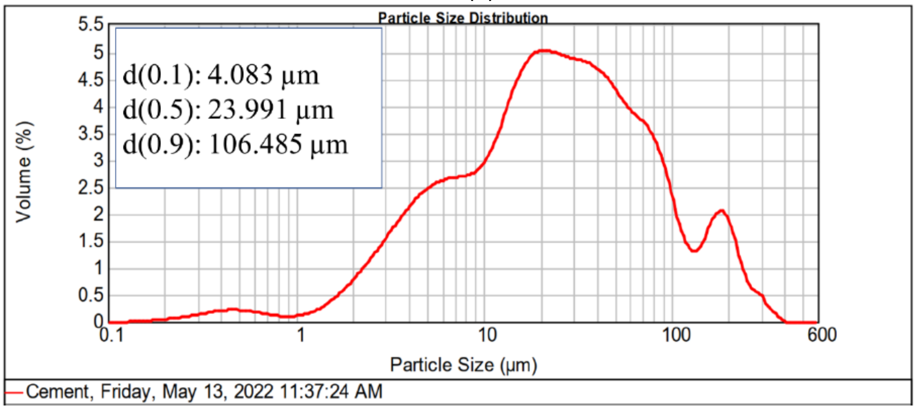


(a)



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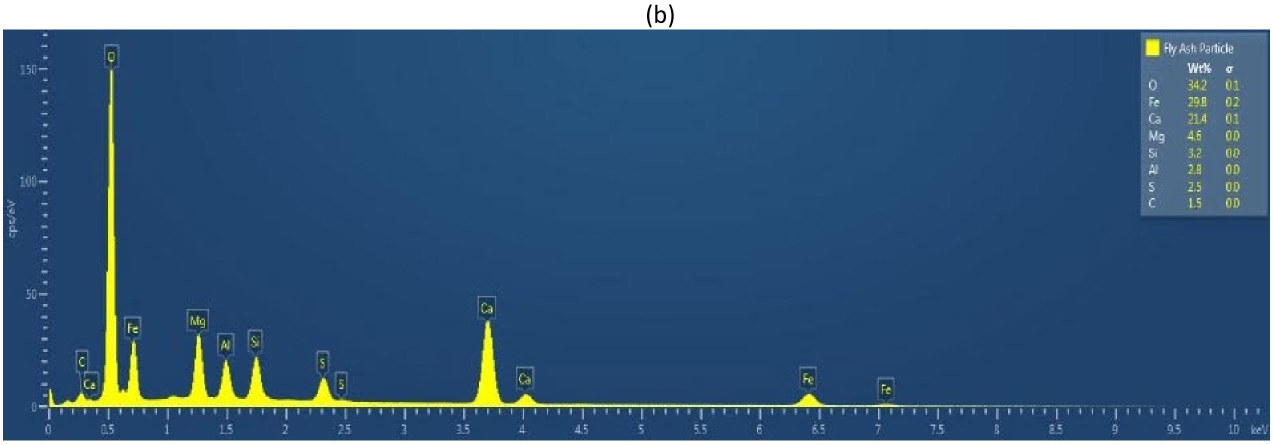


(c)

Fig. 1. Fly ash particle (a) Surface morphology (b) particle size (c) EDX result

2.2 Preparation of Fly Ash Suspension

In this study, the dielectric mixture with different concentrations ranging from 0 to 40 g/l was mixed well by using ultrasonic homogenizer type P series. First, fly ash and surfactant Span 85 with ratio 1:1 were mixed with the 500 ml of kerosene oil. The amount of fly ash powder and Span 85 was measured using the weighing scale to make sure the composition is accurate. The formula for calculating concentration of fly ash and Span 85 is shown in Eq. (1).

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

2.3 Equipment and Materials

The EDC process was carried out by using Sodick AQ35L die-sinker EDM machine. Mild steel 25 mm x 25 mm x 5 mm and copper (Cu) rod 6 mm diameter were chosen as the workpiece material and electrode respectively. To achieve a smooth electrode surface, the Cu electrode was polished after each EDC cycle with a grinding machine with a continuous speed of 300 rpm and 320-grit sandpaper with an 8-inch diameter.

2.4 EDC Conditions

The experimental setup is depicted in Figure 2. The Cu electrode was set to anode (+ve) and the mild steel workpiece was connected to cathode (-ve), resulting in a reverse polarity. For comparison, kerosene oil was used as the dielectric fluid, and different amounts of fly ash were mixed into the kerosene oil. A flushing system was also installed to circulate the fly ash suspension. The machining time for each test was 30 minutes, and three repetitions for each parameter setting were performed to confirm the accuracy of the results. Table 1 displays the experimental conditions.

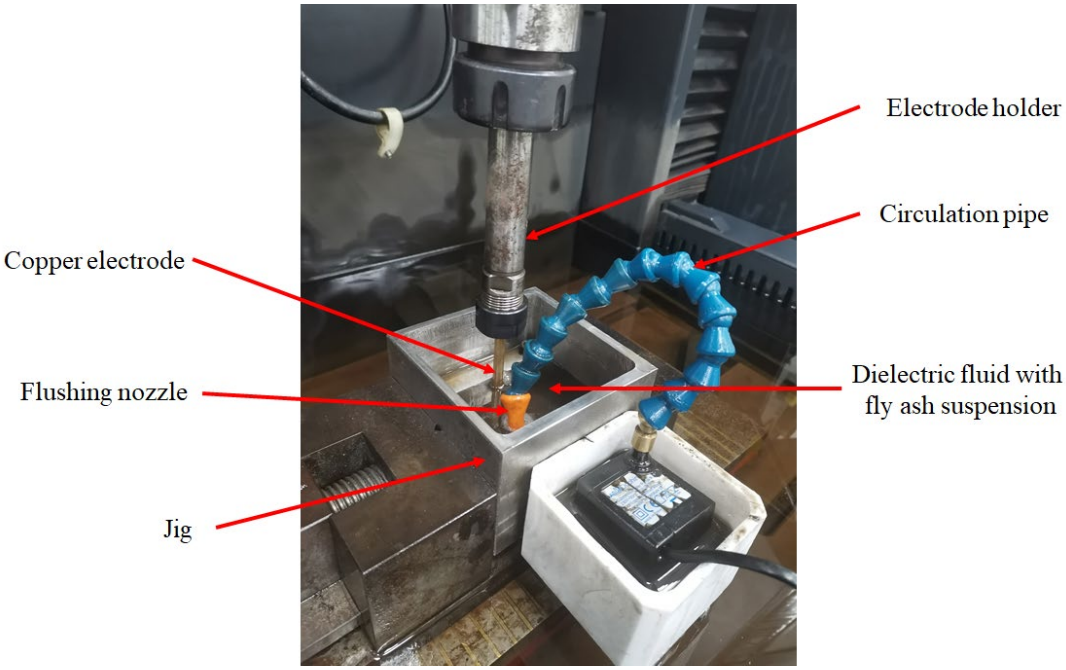


Fig. 2. Experimental setup

Table 1
Experimental conditions

Parameters	Conditions
Workpiece	Mild steel
Electrode	Copper
Dielectric fluid	EDM LS (low smell) kerosene oil
Polarity (Reverse polarity)	Mild steel workpiece- negative; Cu electrode-positive
Machining time	30 minutes per cycle
Additive	Fly ash
Concentration	0, 10, 20, 30 and 40 g/l
Peak current (I_p)	4 A
Pulse on time (T_{on})	100 µs
Pulse off time (T_{off})	300 µs
Discharge voltage (V_d)	30

2.5 Measurement and Analysis

After the EDC process, the micro-hardness of the coated surfaces was determined using a micro-hardness tester (Mitutoyo HM-200 Series 810) machine. Measurement was repeated 15 times at different spots of the coating layer to ensure data accuracy. A PLu neox SENSOFAR 3D Optical Profiler machine was employed to measure the surface roughness of the coated surface. Furthermore, optical microscope was used to determine and measure the coating layer thickness.

3. Results and Discussion

3.1 Coating Layer Thickness

Figure 3 and Figure 4 depict the effect of fly ash concentration on coating layer thickness. According to Figure 3, the average coating layer thickness increases as the fly ash concentration increases from 0 g/l to 40 g/l. The average coating layer thickness was 5.344 µm (0 g/l), 9.952 µm (10g/l), 10.692 µm (20 g/l), 11.488 µm (30 g/l) and 14.674µm (40 g/l), respectively. This result is consistent with the findings of Sharma *et al.,* [18]. When the concentration of fly ash rises, the number of particles per unit area also increases, leading to a faster deposition rate. Furthermore, as particle density increases, more particles are entrapped in the molten area, increasing the coating layer thickness.

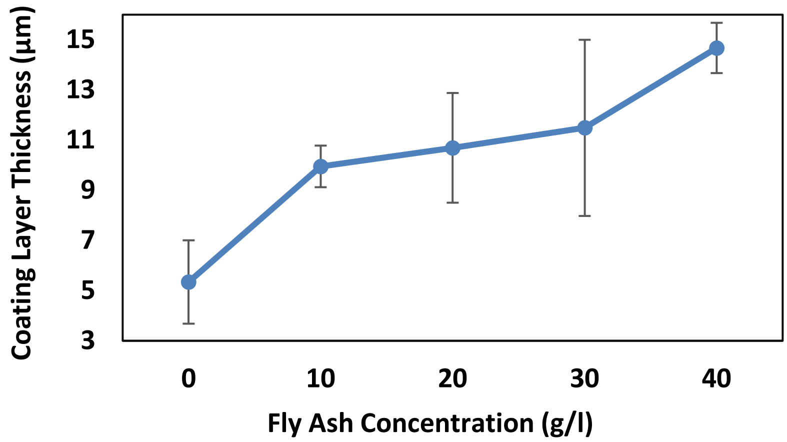
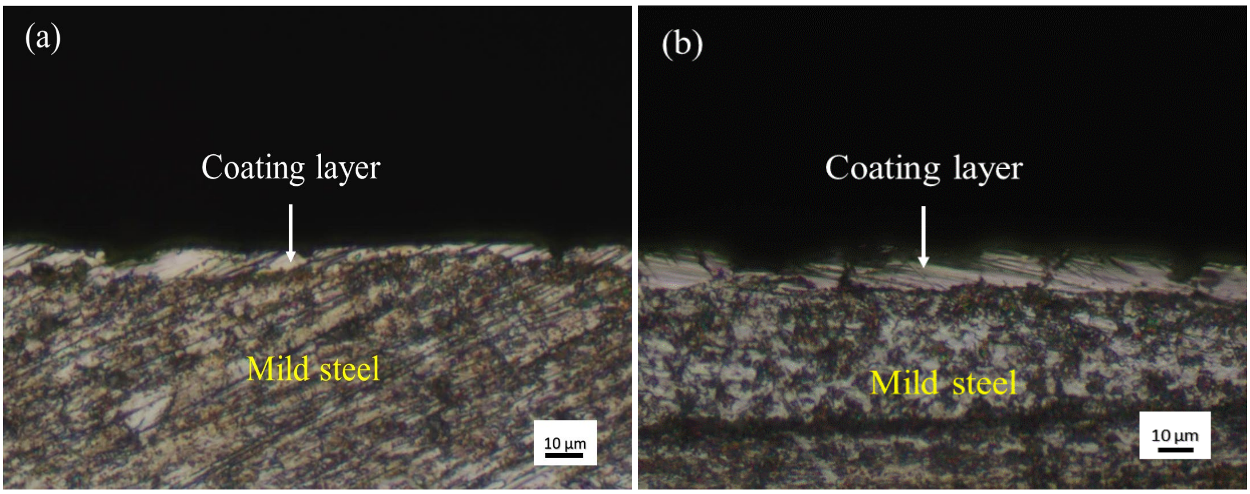


Fig. 3. Effect of fly ash concentration on the coating layer thickness



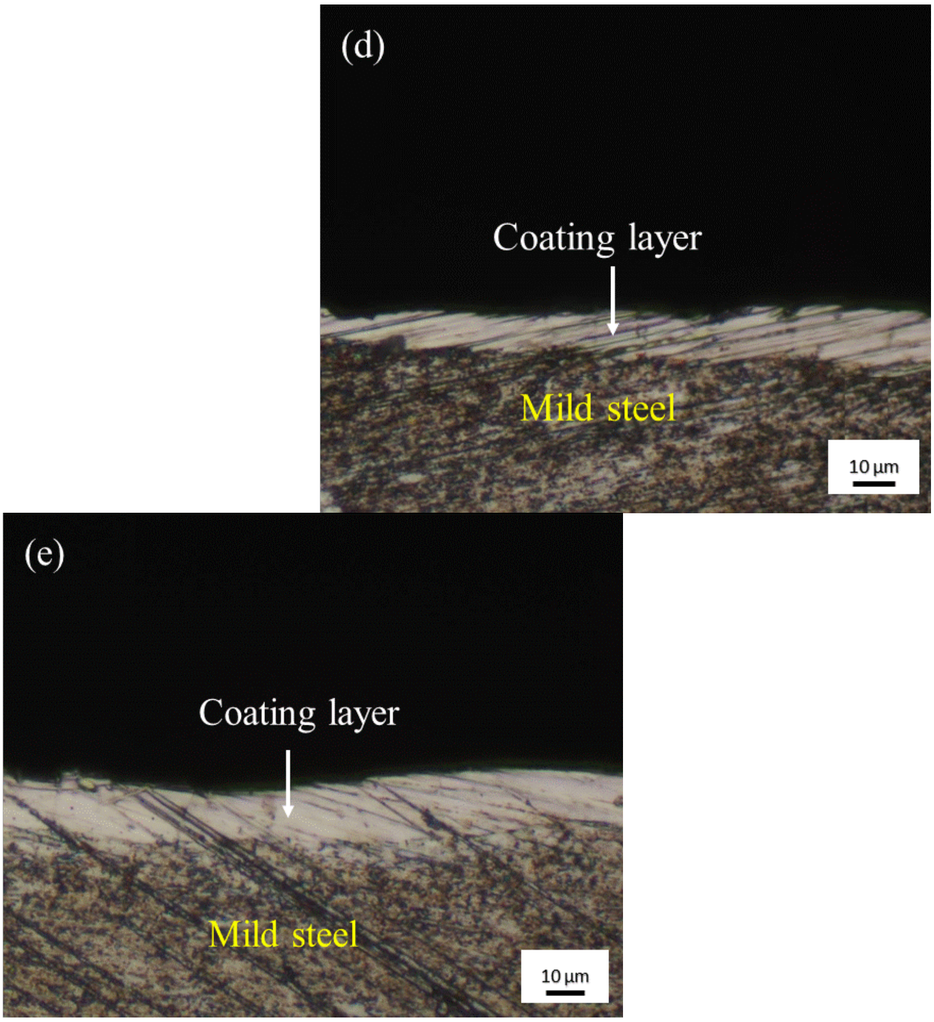


Fig. 4. Coating layer thickness under different fly ash concentration (a) 0 g/l, (b) 10 g/l, (c) 20 g/l (d) 30 g/l and (e) 40 g/l

3.2 Surface Roughness

Figure 5 shows the effect of fly ash concentration on the surface roughness of the coated surface. As indicated in Figure 5, the utilization of pure dielectric fluid without the presence of fly ash particles resulted in the highest surface roughness, measuring approximately 8.3085 µm. When 10 g/l fly ash concentration was used, the surface roughness exhibited a reduction to 7.23927 µm, and this trend continued with a further decline to 6.05303 µm when employing a 20 g/l fly ash concentration. However, when the fly ash concentration increases further (30g/l and 40 g/l), the surface roughness also tends to increase.

As noted by Peças & Henriques [19], when a minimal amount of powder was introduced, the electrical sparks led to the melting and uniform deposition of suspended powder onto the workpiece's surface, yielding a favourable surface finish. Nevertheless, when the powder concentration was increased, an excess of particles within the sparking gap caused a bridging effect and subsequent short circuit. This phenomenon resulted in irregular discharges, ultimately leading to the formation of profound valleys and craters. Consequently, this escalation in surface irregularities contributed to an increase in surface roughness.

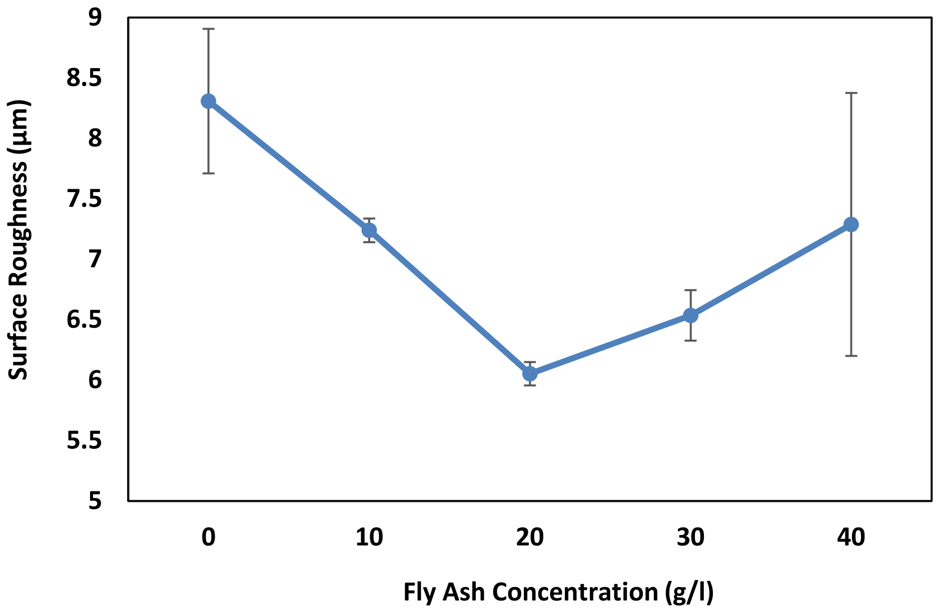


Fig. 5. Effect of fly ash concentration on the surface roughness

3.3 Vickers Micro-Hardness

Figure 6 depicts the effect of different fly ash concentrations on the Vickers micro-hardness of coated surface. It is clear that the Vickers micro-hardness increases as the concentration of fly ash increased. The lowest micro-hardness is 179.268 HV for original mild steel, which is raw mild steel without any coating layers placed on it. The low value of micro-hardness can be attributed to the mild steel's low carbon content, which makes it ductile and low hardness. When pure dielectric fluid was used, the hardness value is increases to 311.713 HV, which is slightly higher than the pure mild steel. A substantial increase in micro-hardness is observed with the incorporation of fly ash powders. The micro-hardness values for fly ash concentrations of 10 g/l, 20 g/l, 30 g/l, and 40 g/l are approximately 486.571 HV, 536.459 HV, 844.933 HV, and 1266.470 HV, respectively. The rise in Vickers micro-hardness can potentially be attributed to the formation of silicon carbide (SiC). This phenomenon could occur due to the ejection of silicon (Si) from the fly ash particles, coupled with the decomposition of carbon (C) from the kerosene oil. As outlined by Ding *et al.*, [20], these carbides are interconnected through robust covalent bonds within a sturdy lattice structure that resists fracture even when subjected to external forces. This particular characteristic is likely to contribute to the observed enhancement in micro-hardness.

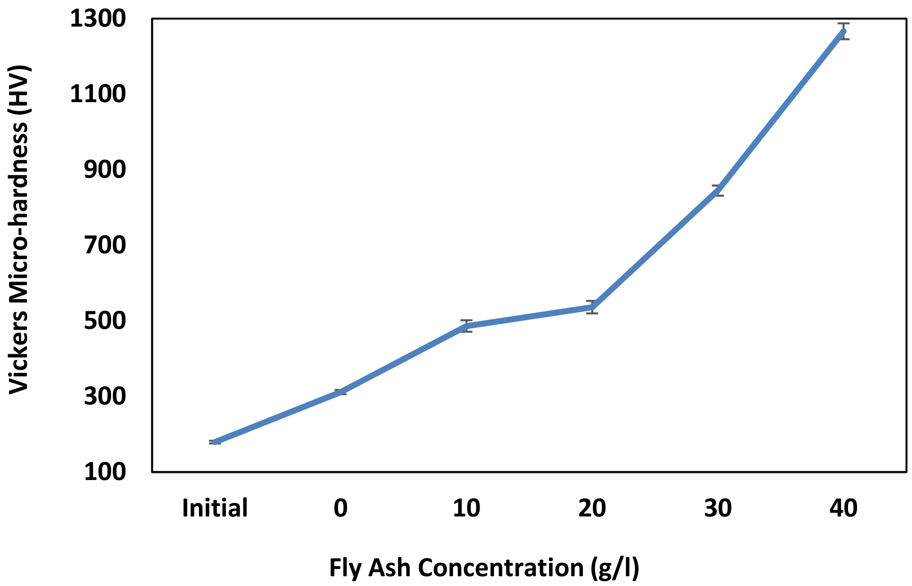


Fig. 6. Effect of quarry dust concentration on the Vickers micro-hardness

4. Conclusions

The feasibility of using fly ash to improve the properties of mild steel was investigated in this study using the EDC process. Fly ash morphology, elemental composition, and particle size were investigated and analyzed. The effect of fly ash concentration on coating properties (coating layer thickness, surface roughness and Vickers micro-hardness) was investigated. As a result, the following conclusions can be drawn:

i. The main elements of fly ash were O and Fe, and followed by Al, Ca, Mg, Si, S and C. It has a spherical shape with an uneven particle size distribution. The average particle size of fly ash was 23.991 µm.
ii. During the EDC process, fly ash particles were deposited on the mild steel surface, and formed a coating layer on the mild steel workpiece.
iii. The thickness of the coating layer and the Vickers micro-hardness of the coated surface showed a pronounced increase with higher fly ash concentrations.
iv. The optimal coated surface finish was achieved using a fly ash concentration of 20 g/l, resulting in an Ra value of 6.05303 µm.

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