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Effect of Powder Metallurgy Copper Electrode on Surface Modification of Mild Steel

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ABSTRACT

Mild steel, widely used for its ductility, weldability, and cost-effectiveness, suffers from low corrosion and wear resistance. This study aims to enhance these properties by applying surface modification using electrical discharge coating (EDC) with powder metallurgy (PM) copper electrodes. The impact of varying compaction pressures and sintering temperatures on the microhardness and thickness of the deposited layer were examined. The results showed that maximum hardness can be obtained at 650°C and 3 tons, while maximum coating layer thickness was 12.5 µm at 550°C and 5 tons. Higher pressure generally reduces copper weight % and higher sintering temperature enhances the microhardness of the mild steel.

1. Introduction

Improving the surface characteristics of materials, particularly in metallurgy and manufacturing, is a critical concern in engineering. Among the emerging techniques, electrical discharge coating (EDC) stands out as a novel surface modification method for conductive materials. EDC is an adaptation of electrical discharge machining (EDM), traditionally used for material removal in creating parts, dies, and molds [1]. The EDC process utilizes an inverse polarity configuration where the tool electrode serves as the anode (+), and the substrate is the cathode (−), with a dielectric fluid facilitating the coating process. This enables materials released from the anode to form a strong coating on the substrate [2]. EDC can be executed using powder metallurgy (PM) electrodes [3] or through the dielectric powder mixing method [4].

A key advantage of EDC is its ability to create thick, well-adhered coatings, even from materials with varying melting points, which can enhance wear and corrosion resistance. Cogun *et al.*, [5] explored the use of a copper boron carbide (Cu/B_4C) powder metallurgy electrode to form hard layers on workpiece surfaces, establishing a correlation between deposited layer thickness and peak

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current for improved deposition and tool wear rates. Additionally, EDC is operationally simple, requiring minimal complex configurations and excels as a non-traditional coating technique. It produces robust coatings with elements like titanium (Ti), chromium (Cr), and tungsten (W), typically using tools made from materials such as tungsten carbide-cobalt (WC/Co) and cemented carbide (TiC/WC/Co) [6].

Unlike EDM, where carbon coating on the tool limits material removal, EDC utilizes a negatively charged compact tool to allow greater material transfer while bypassing carbon constraints [7]. EDC enhances the surface qualities of equipment such as molds, dies, and drills, minimizing imperfections, preventing damage, and improving resistance to wear and corrosion. These benefits contribute to longer product lifespans and improved functionality [7].

Recent studies highlight the flexibility of powder metallurgy (PM) electrodes, which can be made from materials like tungsten carbide, titanium, and copper (Cu), to achieve tailored surface modifications. For example, Elaiyarasan *et al.,* [8] demonstrated how using sintered PM electrodes could significantly enhance the microhardness and refine the microstructure of magnesium alloys. Their findings underscore the adaptability of Electrical Discharge Coating (EDC) for improving various substrate materials Similarly, Leszczy *et al.,* [9] worked with a Cu-ZrO_2 PM electrode to modify the surface of steel, achieving better mechanical properties through precise control over the deposition process

The success of EDC, however, largely depends on key process parameters like peak current and pulse duration. Norhazeratul *et al.,* [10] observed that these parameters directly influence the thickness of the coating layer, which plays a vital role in achieving the desired surface characteristics. Optimization techniques, such as the Taguchi method, have been employed to refine these settings. Mussada *et al.*, [11] for instance, demonstrated how this approach could improve the surface quality and performance of modified substrates, such as in applications involving wear-resistant aluminum alloys with Ti-B4C coatings [12].

Advancements in materials have also opened new possibilities for the EDC process. Composite coatings like those incorporating MoS_2 and Cu have shown potential for significantly enhancing surface properties while ensuring strong adhesion between the coating and substrate[13,14]. Research in this area reveals that EDC is not just about surface enhancement, it is also a gateway to creating multi-material coatings. These coatings can be customized for specific environments or mechanical stresses, broadening their applicability [15].

Although extensive research has been done using PM electrode, however, there is limited information specifically regarding the use of PM Cu electrode for the surface modification of mild steel. Clearly articulating this gap will provide a stronger rationale for the research and underscore its significance in advancing the field. The main target of this research is twofold. Firstly, the investigation seeks to understand the effect of compaction pressure and sintering temperature applied to Cu electrodes on the resulting deposition layer formed on mild steel. Secondly, the study aims to determine the micro-hardness and thickness of the deposited layer on mild steel after the EDC process.

2. Methodology

2.1 Material Preparation

For the process of preparing the workpiece fabrication, it starts with cutting the mild steel plate into square-shaped mild steel using a laser cutting machine. After finishing the cutting process according to the desired size, both sides of the surface need to be faced using a conventional milling machine before grinding so that the surface of the workpiece is rust-free and smoother to facilitate the coating layer to adhere to the surface using grinding polishing machine.

2.2 Workpiece Material

Mild steel has been selected as the workpiece for EDC experiment. This choice is rooted in several key considerations. Firstly, mild steel is a widely utilized material in various industrial applications, owing to its availability, affordability, and ease of manufacturing. However, mild steel has some limitations in terms of corrosion resistance and wear resistance. This limitation arises due to its exposure to varying chemical composition, temperature fluctuations, mechanical stress and friction conditions, which lead to accelerated deterioration and reduced longevity. Table 1 shows the mechanical properties of mild steel.

Table 1
Mechanical properties of mild steel [16]

Property	Value
Poisson's Ratio	0.3
Yield Stress	250 MPa
Ultimate Strength	360 MPa
Modulus of Elasticity	Around 210 GPa
Design Stress	176.25 (MPa)
Weldment Strength	200 MPa
Vickers Hardness	120- 210 HV

2.3 PM Copper Electrode

The selection of a PM Cu electrode for the EDC coating experiment on mild steel is based on its unique advantages. PM involves producing metal powders that are compacted and sintered into solid forms, offering a uniform and finely divided Cu structure. This allows precise control over deposition, ensuring uniform coverage and enhanced surface adhesion during the EDC process.

PM Cu's high purity and favorable properties, such as excellent electrical conductivity and corrosion resistance, make it ideal for coating applications. The sintering process further strengthens the cohesion and integrity of the Cu coating on the mild steel substrate, ensuring desirable performance characteristics.

2.4 Machine Tool

In this experiment, the machine that is involved is EDM die sinking Sodick AQ35L where electrical discharges occur between the electrode and workpiece. It facilitates controlled and precise deposition of Cu onto the mild steel workpiece. The Sodick AQ35L is known for its high precision and accuracy, ensuring that the EDC process is carried out with consistent and reliable results. Figure 1 shows the experimental setup.

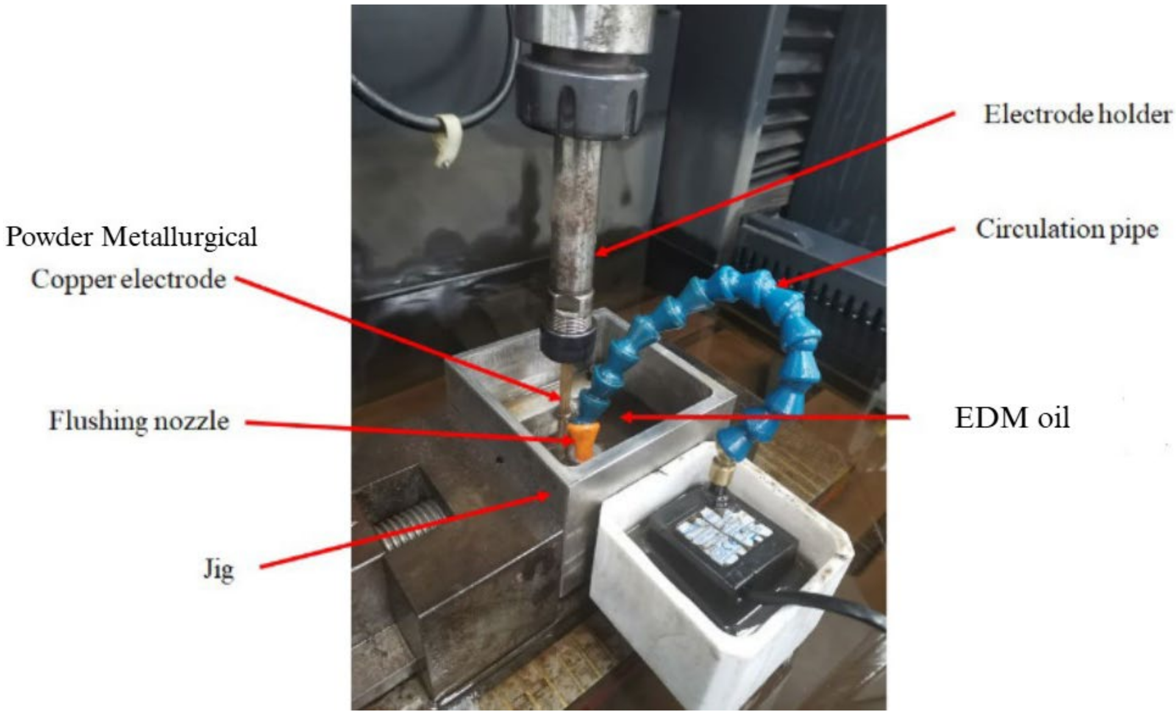

Fig. 1. Experimental setup

2.5 EDC Parameters

This study aims to investigate the impact of compaction pressure and sintering temperature of PM Cu electrode on the mild steel. Selected process parameters for the experimentation and their levels are given in Table 2.

Table 2
EDC parameters

Working Parameter	Description
Machining time	30 minutes
Peak current (Ip)	5 A
Voltage (V)	40V
Pulse on time (Ton)	250 µs
Pulse off time (Toff)	20 µs
Compaction pressure	3, 4, 5 tons
Sintering Temperature	450, 550, 650 ̊C

2.6 Measurement and Analysis

Using the Shimadzu Vickers Micro Hardness Tester for microhardness testing is justified due to its high precision and accuracy, essential for reliable measurements. The precise calibration ensures accurate force application and indentation measurements, crucial for consistent results. Measurements were taken with a pyramidal indenter at a 20N load and a 15s dwell period, repeated five times to ensure accuracy and reproducibility. For coating thickness measurement, the workpieces were cut using a Micracut 151, which provides precise and clean cuts, then ground and polished with a Buehler EcoMet 30 Grinder and Polisher. This machine ensures a smooth surface through sequential sanding with 120, 600, and 1200 grit papers at 150 rpm, essential for accurate thickness measurements. Etching with Nital 3% reveals the microstructure, allowing for detailed layer thickness analysis using a FESEM Hitachi SU 5000, which provides high-resolution imaging for precise and detailed examination of the microstructure. This combination of precise equipment and meticulous methodology ensures accurate and detailed examination of the microstructure and coating thickness

3. Results

3.1 Vickers Micro-Hardness

Table 3 shows the outcomes of an experiment that examined the impact of two variables, compaction pressure (t) and sintering temperature (°C) on the hardness (HV) of mild steel. The table contains 13 iterations, each featuring different values for the compaction pressure and sintered temperature, along with the corresponding microhardness data. The maximum measured microhardness value is 244.047 HV, observed in Run 4. The specified parameters for this run are a compaction pressure of 3 tons and a sintering temperature of 650°C. These findings indicate that the highest microhardness was achieved by using a lower compaction pressure and a higher sintering temperature. According to Wasim *et al.,* [17], at higher sintering temperatures, the material can relieve residual stresses more effectively, and controlled grain growth can occur. This leads to a more stable microstructure with improved hardness. Besides that, lower compaction pressures can prevent excessive deformation and damage to the particles. This helps maintain the integrity of the particles, allowing for better sintering and bonding at higher temperatures.

Table 3
Vickers micro-hardness results

Run	Compaction Pressure (kPa)	Sintering Temperature (°C)	Hardness (HV)
1	5	550	219.545
2	3	550	176.261
3	5	650	180.564
4	3	650	244.047
5	4	550	185.467
6	4	550	194.797
7	4	550	199.627
8	4	550	190.581
9	4	650	177.743
10	5	450	165.181
11	3	450	139.392
12	4	550	186.066
13	4	450	163.632

3.2 Coating Layer Thickness

3.2.1 Compaction pressure

The effect of compaction pressure on the coating layer thickness and FESEM image of coating layer thickness are shown in Figure 2 and 3, respectively. It was discovered that as the compaction pressure increased from 3 tons to 5 tons, the average coating layer thickness also increased. The average coating layer thickness was 8.2 µm (3 tons), 11.85 µm (4tons), and 12.5 µm (5 tons) respectively. According to Ahmed *et al*., [18], with an increase in the compaction pressure, the surface morphology becomes more irregular/non uniform and material deposition occurs in the form of globules. This morphological change can contribute to an overall increase in coating thickness as material is deposited more densely and extensively.

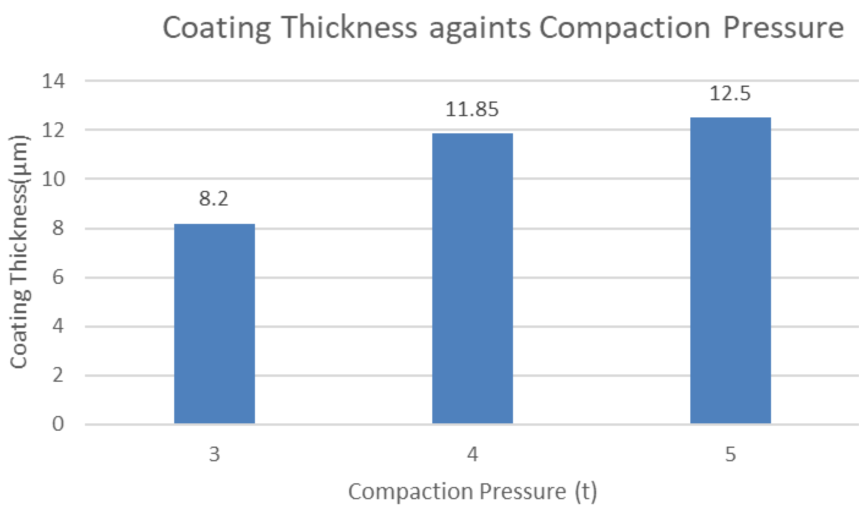

Fig. 2. Effects of compaction pressure on coating layer thickness

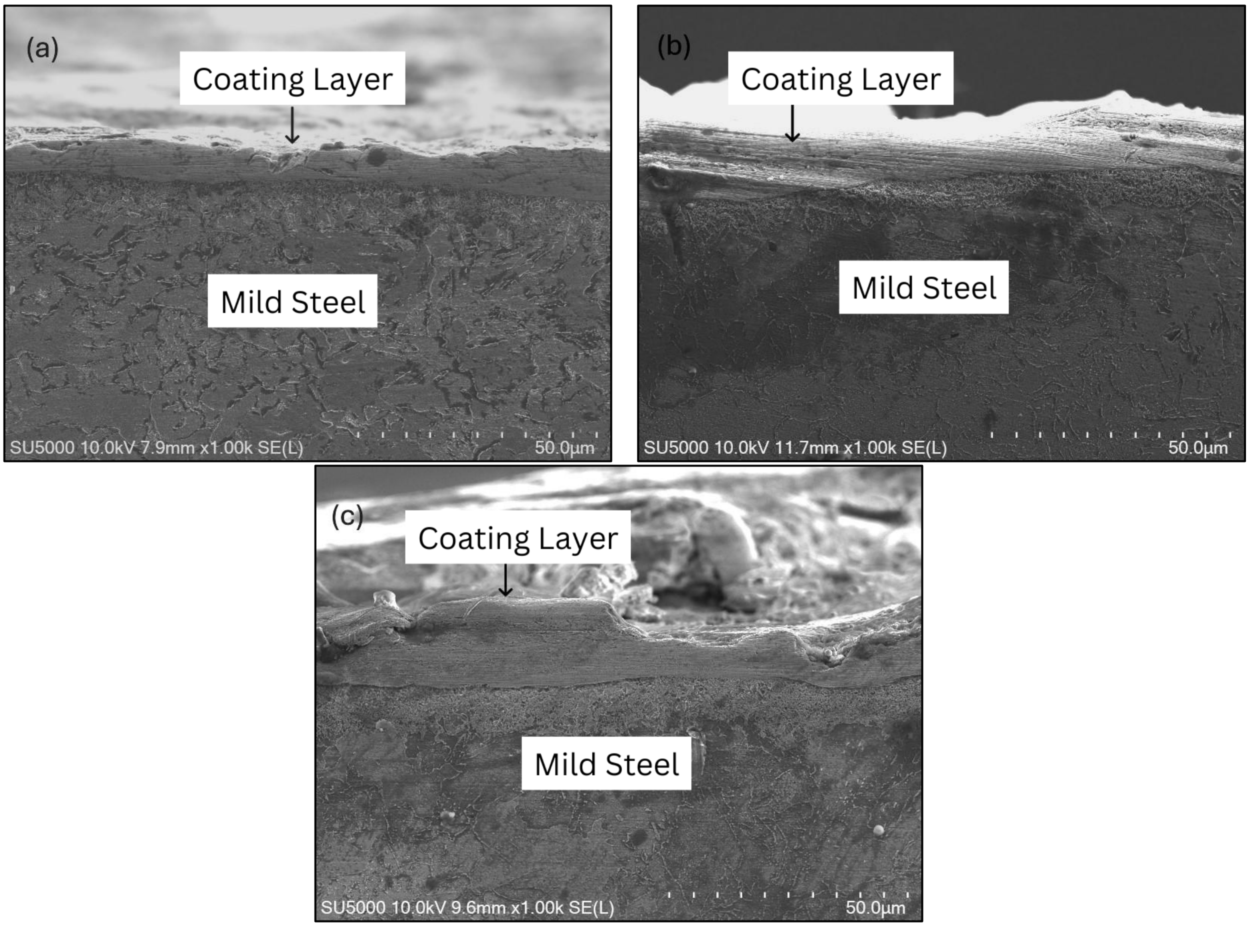

Fig. 3. FESEM images of coating layer thickness under different compaction pressure (a) 3 tons, (b) 4 tons, and (c) 5 tons

3.2.2 Sintering temperature

Figure 4 shows the effect of sintering temperatures on the coating layer thickness and Figure 5 shows the coating layer thickness under FESEM. It is clearly seen that lower (450°C) and higher (650°C) temperatures resulted in thinner coatings layer thickness of 3.48 µm and 3.75 µm, respectively. This indicates that intermediate sintering temperatures are more effective in forming a uniform and robust coating layer. Referring to Huang *et al*., [19], the trend appears due to the optimal balance between particle diffusion and densification processes. At intermediate temperature, the energy provided is sufficient to enhance particle mobility and bonding without causing excessive grain growth or defects.

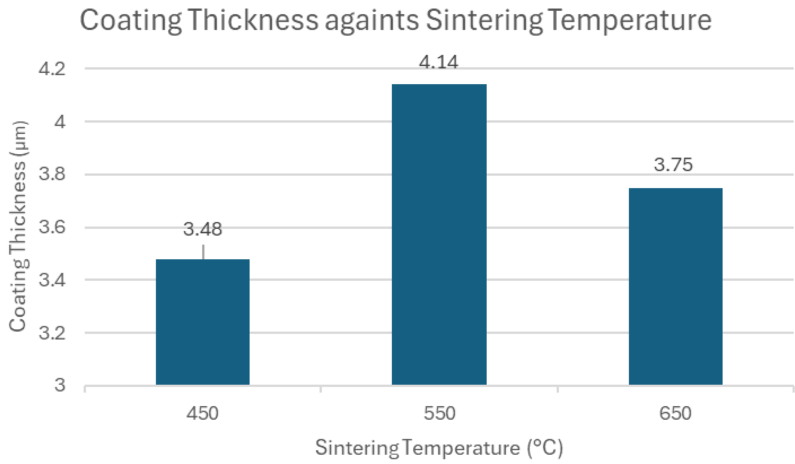

Fig. 4. Effect of sintering temperature on the coating layer thickness

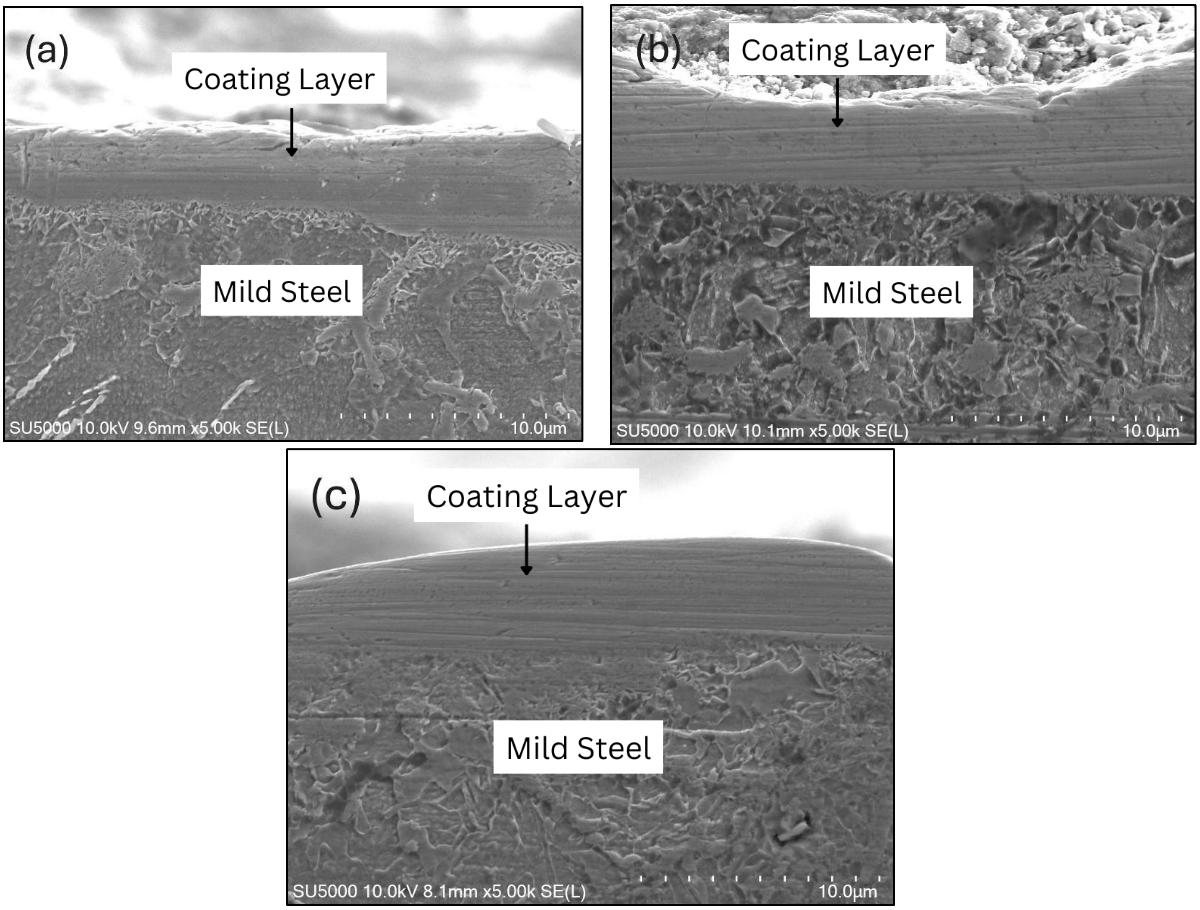

Fig. 5. FESEM of coating layer thickness under different sintering temperatures (a) 450 °C, (b) 550 °C, and (c) 650 °C

3.3 Element Composition of Cu Coating Layer
3.3.1 Compaction pressure

Table 4 shows the result of Cu coating layer weight % under different compaction pressure and Figure 6 shows the selected area for EDX. As the compaction pressure increases from 3 tons to 4 tons, the Cu weight percentage decreases slightly from 73.6% to 72.1%. A further increase in compaction pressure to 5 tons results in a more significant decrease in the Cu weight percentage to 65.1%. This trend confirms that higher compaction pressures reduce the Cu weight percentage in the material, as Cu particles more easily adhere to the mild steel surface under higher pressure. This trend is consistent with the findings of Ahmed *et al*., [18]. When the compaction pressure is increased, the powder particles become tightly bound together during the PM process. During erosion, these particles erode as a cohesive mass and are deposited onto the workpiece.

Table 1
Result of Cu weight % under different compaction pressure

Compaction Pressure	3 tons	4 tons	5 tons
Element	Weight %		
Cu	73.6	72.1	65.1
Carbon (C)	16.3	20.0	20.8
Iron (Fe)	10.0	7.2	14.1

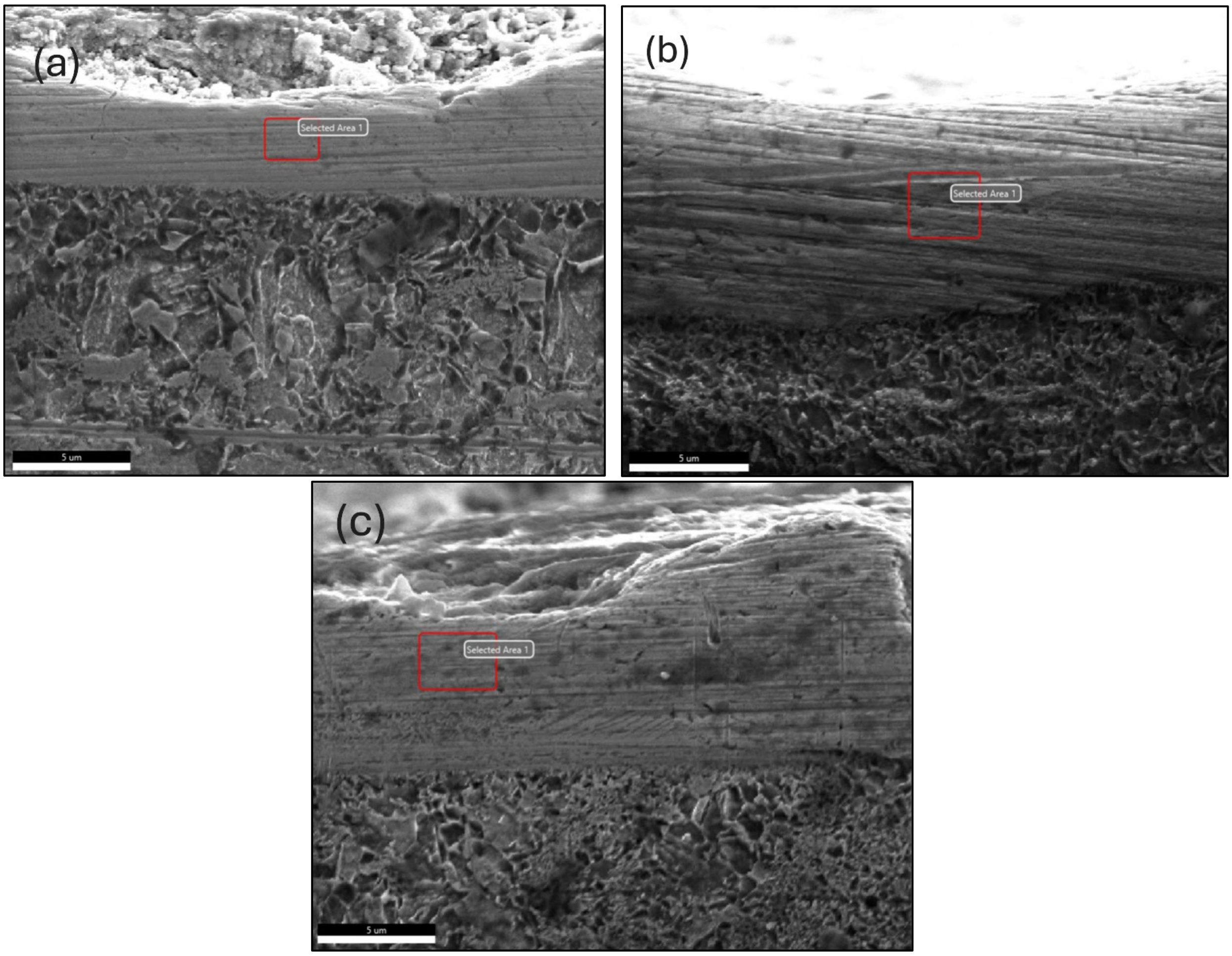

Fig. 6. Selected Area for EDX analysis under different compaction pressure (a) 3 tons, (b) 4 tons, (c) 5 tons

3.3.2 Sintering temperature

Table 5 shows the result of Cu weight percentage under different sintering temperatures. Figure 7 shows the selected area for EDX. At 450°C, the Cu content is 56.1%, which increases to 73.6% at 550°C due to enhanced diffusion and particle bonding at this intermediate temperature [20]. However, at 650°C, the Cu content drastically decreases to 6.2%, likely because higher temperatures promote the formation of other phases, such as C and Fe, which dominate the composition [21]. Additionally, the coating thickness data shows that the optimal sintering temperature for maximum thickness is 550°C, further supporting the idea that intermediate temperatures favor better diffusion and bonding of Cu particles [22].

Table 2
Result of Cu weight % under different sintering temperature

Sintering Temperature	450°C	550°C	650°C
Element	Weight %		
Cu	56.1	73.6	6.2
C	16.5	16.3	57.3
Fe	25.8	10.0	36.4

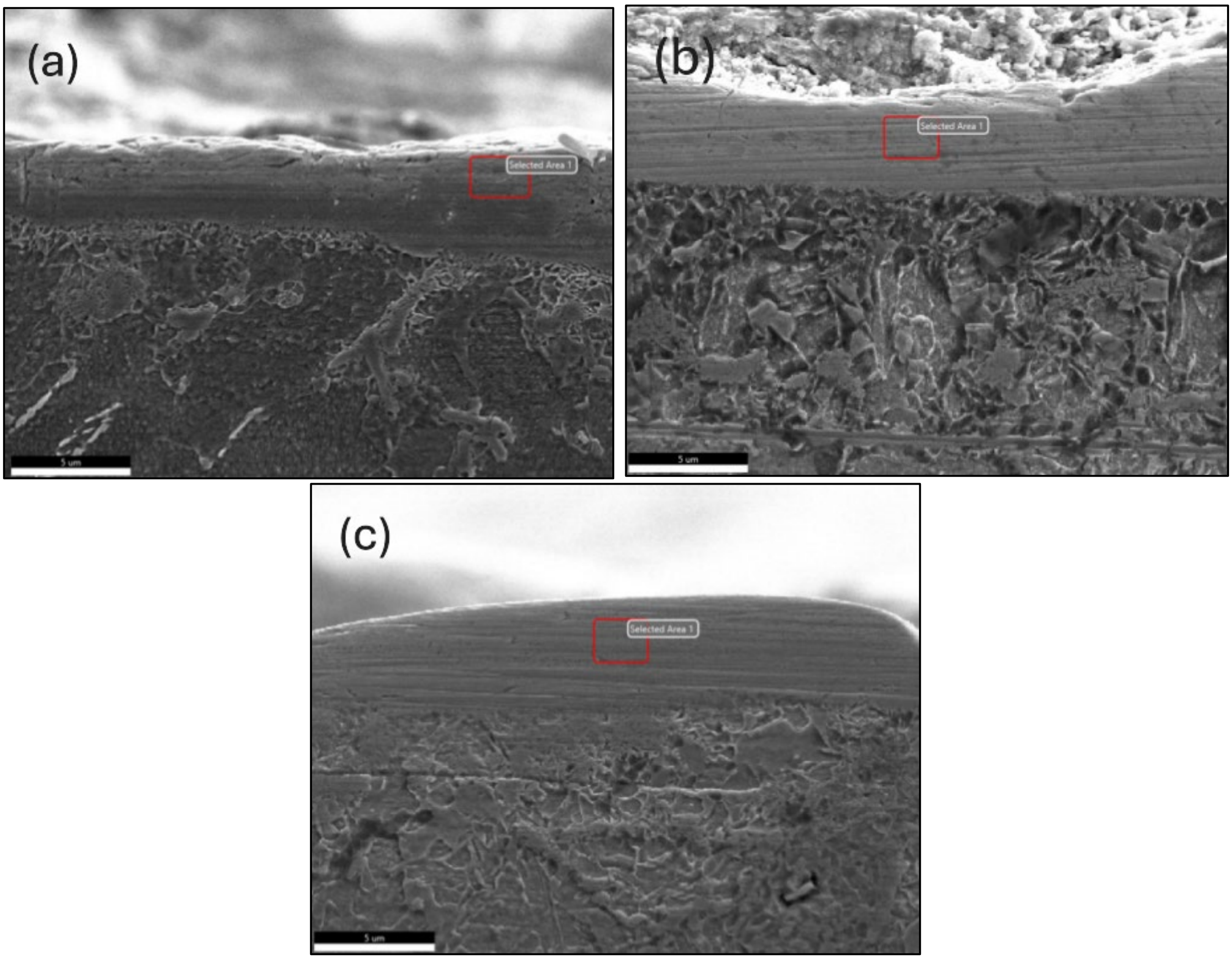

Fig. 7. Selected Area for EDX analysis under different sintering temperature (a) 450 °C, (b) 550 °C, and (c) 650 °C

4. Conclusions

The main objective of this study is to examine the effect of compaction pressure and sintering temperature of PM Cu electrode on the coating layer thickness and micro-hardness of mild steel after EDC process. The results obtained offer useful insight into the correlation between these parameters to micro-hardness, Cu weight % and the thickness of the deposited layer.

i. The highest microhardness can be obtained at 650°C and 3 tons, while the lowest is at 450°C with 3 tons. Higher sintering temperatures enhance hardness, though compaction pressure also plays a crucial role.
ii. Maximum thickness (12.5 µm) is achieved at 5 tons and 550°C, and the minimum (8.2 µm) at 3 tons and 550°C. Uneven coatings at higher pressures yield unexpected trends.
iii. The highest Cu content (73.6%) occurs at 550°C and 3 tons, while the lowest (65.1%) is at 550°C with 5 tons. Increased pressure tends to reduce Cu content.

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