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Development and Characterization of Electrical Discharge Coating Electrode Through Powder Metallurgy Process

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ABSTRACT

In this study, copper electrodes for electrical discharge coating (EDC) application were fabricated by using the powder metallurgy (PM) process. The effect of different compaction loads (ranging from 3 to 5 tons) and sintering temperatures (ranging from 450 to 650°C) on the mechanical properties of the PM electrodes, specifically on porosity, density, and microstructure were investigated. The copper powder was mixed with stearic acid by using a planetary ball mill, followed by compaction and sintering operations. The results showed that the PM copper electrodes exhibited higher density and less porosity with the increase in compaction load and sintering temperature. The PM copper electrode with the highest density and lowest porosity was obtained by using 5 tons of compaction load and 650 °C sintering temperature. Furthermore, the microstructures showed a dense network with minimal pores and smaller pore sizes, indicating excellent particle compaction and interconnectivity resulting from the combined effects of high compaction pressure and high sintering temperature.

1. Introduction

Surface coating techniques play a crucial role in enhancing the properties of engineering materials, particularly metals. Electro-less plating, plasma spraying, physical and chemical vapour deposition, and laser cladding are some of the surface modifications processes [1]. According to Chen *et al.,* [2], most of these techniques have the drawback of requiring specialised setup and arrangement, which raises the cost of production. Over the last few decades, researchers have experimented with a variety of low-cost surface modification methods, such as electrical discharge coating (EDC) [3].

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EDC is a revolutionary technology that can effectively deposit a coating material on the surface of a workpiece with the use of a high-current electrical pulse and a dielectric fluid [4,5]. Algodi *et al.*, [6] discovered that one of the benefits of the EDC method over other competing surface coating approaches is the ability to machine material and apply a coating with the same machine tool, without the necessity for post-processing. Tyagi *et al.*, [1] claimed that the EDC plasma enables the generation of extremely high temperatures that exceed the melting points of all materials. Consequently, EDC is able to produce coatings from high melting point and high hardness materials, such as difficult-to-process ceramics, and this technology has great promise for the formation of hard-wearing coatings to extend the lifespan of substrate material [6].

In the field of surface modification with EDC, one of the methods is using EDM die sinking with powder metallurgy (PM) electrodes. During the discharge process, intense sparks dislodge material from the tool electrode, which subsequently deposits onto the workpiece surface [7]. Harane *et al.,* [8] found that the tool electrode plays a crucial role in conducting electrical current to the workpiece. Hence, any material designated for use as a tool electrode must exhibit conductivity. Copper is frequently chosen as an electrode material because of its outstanding conductivity and cost-effectiveness in comparison to other materials [9].

However, pure copper has its drawbacks and limitations on the mechanical properties when it is being used as a PM electrode. For instance, Michailidis *et al.,* [10] claimed that PM copper electrode possesses porous structure. This can occur during the PM process due to different densities associated with powders and binders or non-uniform compaction loads during the compaction stage, which leads to inhomogeneity in the green part of the PM electrode.

From the previous research, there are extensive research has been done on the PM process. However, there remains a notable gap in comprehensive investigations on the development and characterization of copper electrodes via the PM process, particularly for EDC applications. Hence, in this paper, the copper electrodes were fabricated by varying the sintering temperature and compaction loads during the PM process, and the mechanical properties and microstructures of the PM copper electrode, including its porosity, density, and microstructure were analysed.

2. Methodology

2.1 Materials

In this experiment, the primary material used was high-purity copper obtained from Oerlikon Metro, United Kingdom, with a purity greater than 99.9%. The selection of copper as the base material was motivated by its superior electrical conductivity and thermal properties which are essential for efficient EDC processes. The copper powder used had a particle size greater than 25 µm with a cast spherical structure, as depicted in the field emission scanning electron microscope (FESEM) micrograph in Figure 1. Table 1 lists the specifications of the copper particles. To achieve the desired compaction attributes, stearic acid was employed as the binder, as it can significantly enhance the compressibility of powder [11].

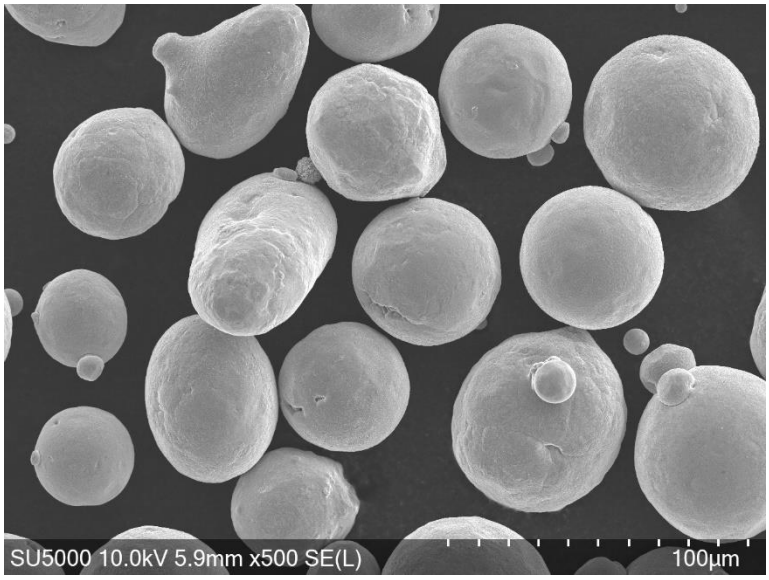


Fig. 1. FESEM micrograph of copper particles

Table 1
Specification of copper particles

Metal powder	Particle size (µm)	Particle shape	Producer/Supplier
Copper	> 25	Spherical	Oerlikon Metro, United Kingdom

2.2 PM Process

The PM process utilized in this study involved three fundamental phases: mechanical mixing, compaction, and sintering. Initially, copper powder and stearic acid were carefully measured and blended in a weight proportion of Cu 99% - stearic acid 1% using a RETSCH PM 100 model planetary ball mill at room temperature with a ball-to-powder ratio of 10:1. After meticulous mixing, the powders were subjected to the compaction phase. Uniaxial compaction was carried out using SPECAC manually hydraulic press, employing varying pressure levels (3 tons, 4 tons, and 5 tons) to create three sets of green samples with dimensions of 6 mm in diameter and lengths ranging from 10 to 12 mm. A slow compaction speed was applied during this process to prevent air entrapment and the formation of large pores. Subsequently, the green samples were subjected to the sintering operation. In a multi-position tube furnace, the electrodes were sintered under an argon gas atmosphere at a flow rate of 1.70 ℓ/min. The furnace was gradually heated to pre-set variable temperatures of 450°C, 550°C, or 650°C at a rate of 10°C/min. After reaching the target temperature, the semi-sintered electrodes were soaked for 30 minutes to facilitate essential atomic diffusion and consolidation processes. The semi-sintered copper electrodes were then allowed to cool in an inert environment within the furnace. In the sintering operation, the green samples were carefully enclosed within the crucible boat and layered with graphite powder. This deliberate arrangement served to achieve a uniform distribution of temperature throughout the samples during both the heating and cooling processes [12]. Figure 2 illustrates the schematic diagram of the fabrication process of PM copper electrode.

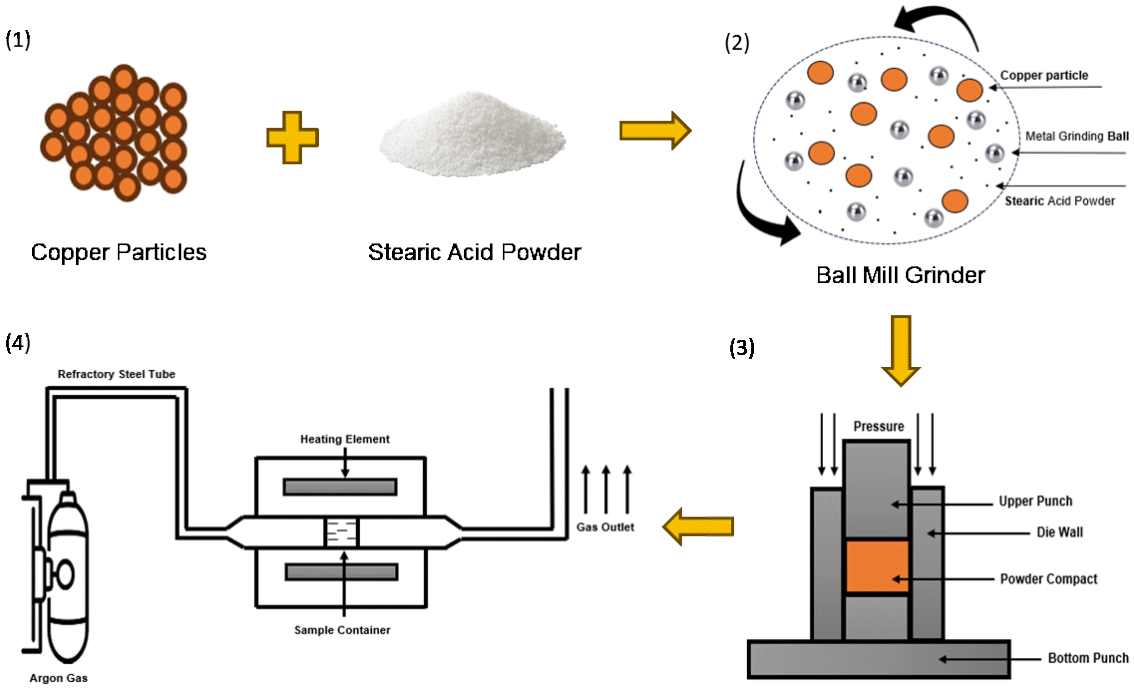


Fig. 2. Schematic diagram of copper electrode fabrication by PM process (1) raw materials; (2) mixing; (3) cold-compaction; and (4) sintering operation

2.3 Measurement and Analysis

The density of the semi-sintered copper electrodes was determined to account for their surface-connected porosity. A precision electronic densimeter with an accuracy of ±0.01g was used to measure the density of electrodes. Following the ASTM B962-15 standard, the Archimedes principle and mixing laws were utilized. Eq. (1) was employed to calculate the experimental densities of the copper electrodes [12]. Given that the electrode material was pure copper, its theoretical density is 8.96 g/cm³.

$$\text{Experimental density, } \rho_e = {}^{m_a\ \rho_w}/_{m_i - m_w} \quad (1)$$

Where ρ_e is experimental density (g/cm³), m_a is the mass of the electrode in air (g), ρ_w is the density of water which is 1 g/cm³, m_i is the mass of the oil-impregnated electrode (g) and m_w is the mass of the oil-impregnated electrode in water (g). Then, the comparison of porosity among electrodes was evaluated using Eq. (2) [12].

$$\text{Porosity: } \left({}^{\rho_{th} - \rho_e}/_{\rho_{th} - \rho_a}\right) \text{ x } 100\% \quad (2)$$

Where ρ_{th} is the theoretical density (g/cm³), ρ_e is the experimental density (g/cm³) and ρ_a is the density of air which is 0.001225 g/cm³. The microstructures of the copper electrodes were studied using FESEM. Prior to the measurements, a sequence of grinding operations was performed using 400, 600, 800, and 1200 grit sandpaper, followed by polishing with diamond suspensions and micro alumina suspensions. The FESEM allowed for magnifications of 200X, enabling a detailed examination of the electrode's morphology. Subsequently, the acquired FESEM images were subjected to pore size analysis using Image J, and at least four pores were analyzed per FESEM image to obtain an average pore size for each electrode.

3. Results

3.1 Density of PM Copper Electrode

The effect of sintering temperatures and compaction pressure on the density of copper electrodes is shown in Figure 3. It is observed that the density of the electrodes increases with the increase of compaction pressure, and this can be attributed to the progressive compression of the powder particles. As the applied pressure is incrementally raised, the interparticle voids within the powder material gradually diminish, leading to a denser packing of the powder particles. The increased pressure causes the particles to come into closer proximity and promotes better interparticle bonding, resulting in an increase in overall density [13].

Based on Figure 3, the effect of sintering temperature on the density of the electrodes is significant. Comparing the densities achieved under the same applied pressure but different sintering temperatures, it was observed that the higher the sintering temperature, the higher the density of the electrodes. For example, at 450 °C, the density was 6.7857 g/cm^3 for 3 tons, while at 550 °C, the density increased to 7.03571 g/cm^3 under the same applied pressure. This trend persisted at 650 °C, resulting in a density of 7.4231g/cm^3 under 3 tons of pressure.

This phenomenon is supported by Latief *et al.,* [14], as it was suggested that the diffusion of atoms readily occurred which motivates the formation of a new chemical bonding among the available particles inside the structure. Thus, the increase in density with higher sintering temperatures can be attributed to enhanced atomic diffusion and interparticle bonding. As the temperature rises, the diffusion of atoms within the powder material becomes more active due to the particle energies, facilitating the formation of stronger bonds between the powder particles. This leads to a denser packing of the particles and a reduction in interparticle voids, resulting in an overall increase in density.

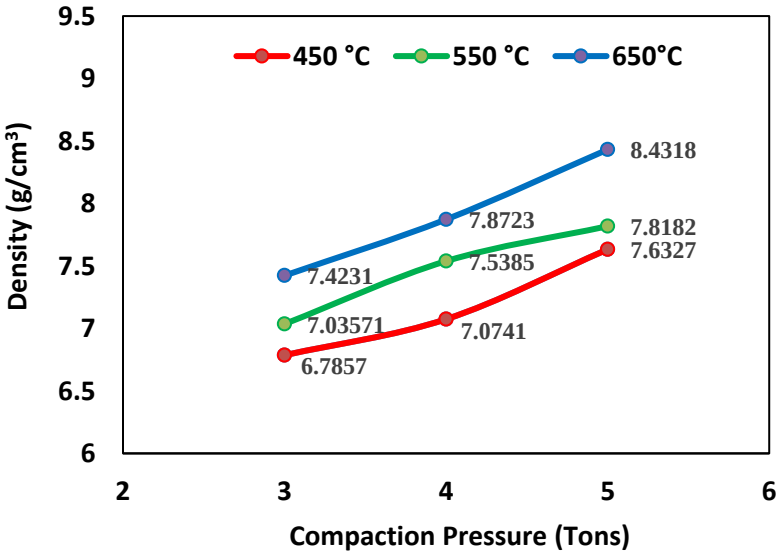


Fig. 3. Effect of compaction pressure and sintering temperatures on the density of PM copper electrode

3.2 Porosity of PM Copper Electrode

The percentage of the porosity level of each sample electrode is presented in Figure 4. According to the figure, the porosity percentages were determined to be 24.27% for 3 tons of applied pressure, 21.05% for 4 tons, and 14.82% for 5 tons. When the sintering temperature increased to 550 °C, the

porosity percentages decreased to 21.48% for 3 tons, 15.87% for 4 tons, and 12.75% for 5 tons. Besides, further increasing the sintering temperature to 650°C resulted in porosity percentages of 17.16% for 3 tons, 12.14% for 4 tons, and 5.90% for 5 tons. These results clearly demonstrate the inverse relationship between sintering temperature and porosity. This phenomenon can be explained by the more prominent increased diffusion of copper atoms, allowing for a more extensive rearrangement of the powder particles. This rearrangement helps to fill the gaps and voids between the particles, resulting in a decrease in porosity.

Besides, the influence of applied compaction pressure on porosity was also examined. Increasing the applied pressure from 3 tons to 5 tons resulted in a consistent decrease in porosity. At a sintering temperature of 450 °C, the porosity percentages decreased from 24.27% to 21.05% and to 14.82% as the applied pressure increased from 3 tons to 4 tons and 5 tons, respectively. Similarly, at 550°C, the porosity percentages decreased from 21.48% to 15.87% and 12.75%, and at 650°C, they decreased from 17.16% to 12.14% and 5.90%. According to Dixit and Srivastava [13], the progressive compression of the powder particles leads to a denser packing arrangement and improved interparticle bonding, resulting in decreased porosity percentages. The results emphasize the importance of carefully controlling the applied pressure to achieve copper electrodes with minimal porosity and superior material properties.

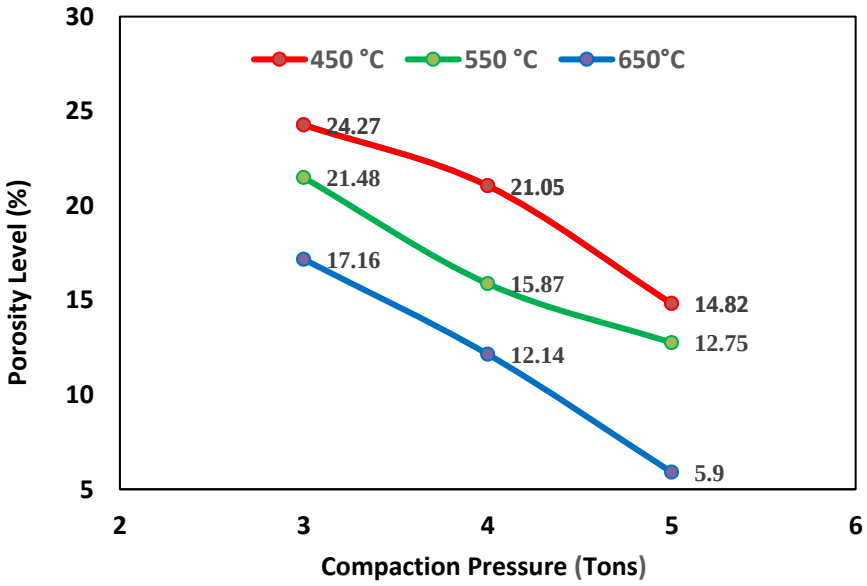


Fig. 4. Effect of compaction pressure and sintering temperatures on the porosity of PM copper electrodes

3.3. Pore Size Analysis

The pore size area (μm^2) for each of the electrodes was examined and is depicted in Figure 5. At a sintering temperature of 450°C, the pore size area exhibited a consistent trend of reduction as the compression pressure increased. When the sintering temperature was increased to 550°C and 650°C, similar trends in pore size area were observed. Besides that, the smaller pore size area also can be attained when higher compaction pressure is used. The elevated sintering temperature and compaction pressure enhance particle diffusion and bonding, resulting in denser structures and reduced pore formation. Consequently, the compression forces become even more effective in reducing the pore size area.

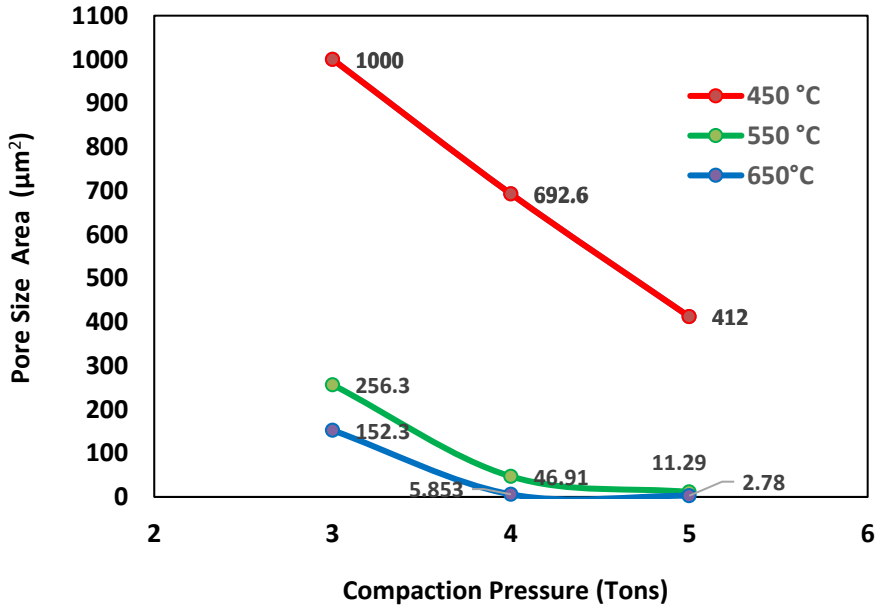


Fig. 5. Effect of compaction pressure and sintering temperatures on the pore size area of PM copper electrodes

3.4. Microstructure of PM Copper Electrode

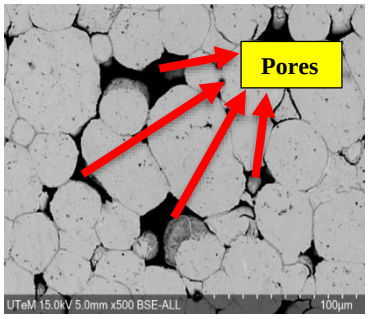
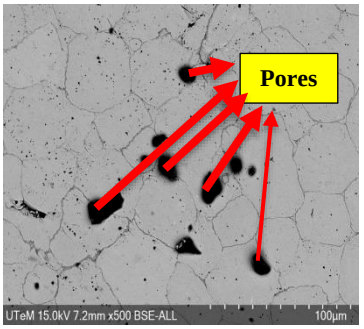
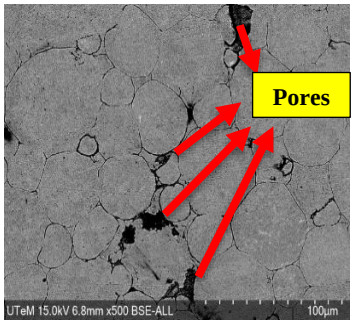
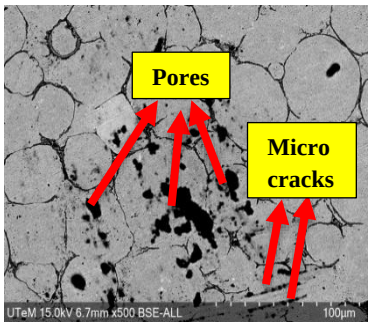
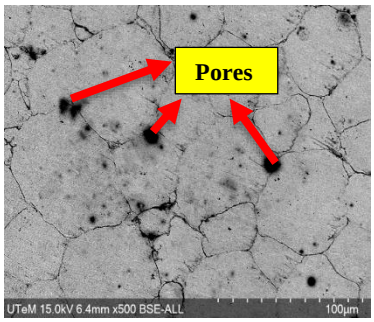
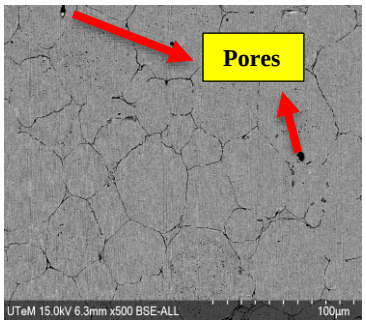
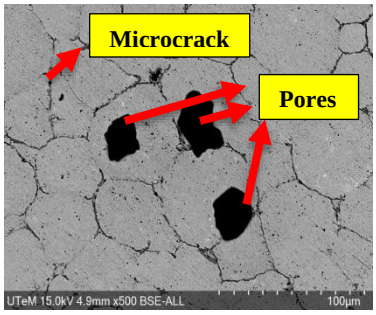
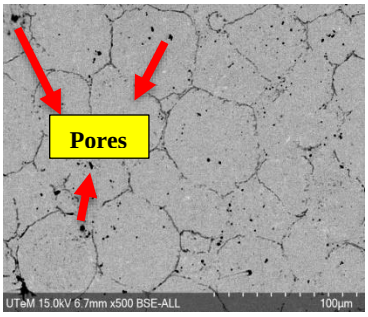
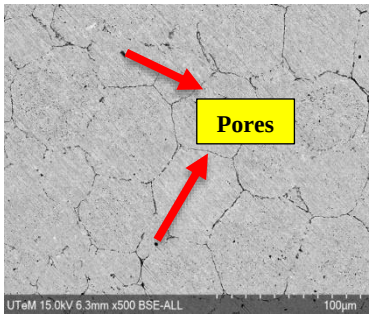
The surface morphology of PM copper electrodes was examined using FESEM under varying sintering temperatures and compaction loads, as detailed in Table 2. It is clearly seen that a significant number of pores and voids are present within the microstructure under a compaction pressure of 3 tons and a sintering temperature of 450°C. This observation suggests that the compaction pressure of 3 tons resulted in inadequate particle compaction and the occurrence of compaction-related defects. As depicted in Table 2, micrographs corresponding to compaction pressures of 4 tons and 5 tons, while maintaining the same sintering temperature of 450°C, exhibit a noticeable reduction in the presence of pores and voids. This reduction can be attributed to the increased compaction pressure employed in these instances. However, it is noteworthy that microcracks are visible in the samples that compacted under 4 tons and 5 tons of pressure and a sintering temperature of 450°C. This finding indicates that an improper application of higher compaction pressure may induce localized stresses during the compaction process, leading to the formation of microcracks. These findings are supported by Kumar and Pandey [15], who noted that when the particles are unable to uniformly withstand the applied stress, localized areas of high stress may arise, ultimately resulting in the formation of microcracks.

Furthermore, as can be seen in Table 2, the samples that compacted under 3 tons, 4 tons, and 5 tons while maintaining a constant sintering temperature of 550°C demonstrate a more uniform distribution of particles compared to the samples under the sintering temperature of 450°C. This suggests that the higher sintering temperature promotes particle rearrangement and interparticle bonding, leading to improved densification and a reduction in porosity. The enhanced interconnectivity between particles contributes to a more uniform microstructure with improved material integrity, which aligns with the findings of Manohar *et al.,* [16].

Moreover, at a constant sintering temperature of 650°C and 5 tons compaction pressure, significant microstructural improvements are observed, attributable to the combined effects of higher compaction pressure and increased sintering temperature. The microstructures show a dense network with minimal pore, indicating excellent particle compaction and interconnectivity. The size

of the grain boundaries decreases as the particle contact area decreases, suggesting enhanced interparticle bonding and improved mechanical properties. These microstructures demonstrate the potential for achieving high-density electrodes with enhanced material integrity through the appropriate combination of compaction pressure and sintering temperature. These findings were further supported by Biswal *et al.,* [17], which emphasised the importance of optimizing compaction pressure and sintering temperature to achieve improved material properties.

Table 2
FESEM micrographs of copper electrodes under different sintering temperatures and compaction load

Compaction load	Sintering temperature		
	450 °C	550 °C	650 °C
3 tons			
4 tons			
5 tons			

4. Conclusions

The main objective of this study was to fabricate the semi-sintered copper electrodes using PM techniques by varying the sintering temperature and compaction loads. Through comprehensive analysis, the mechanical properties and microstructures of the PM copper electrodes, including porosity, density, and microstructural study of the surface of electrodes were investigated. The main conclusions that can be drawn are as follows:

- The semi-sintered copper electrodes using PM techniques were successfully fabricated by varying the sintering temperature and compaction loads.
- The density and porosity measurements revealed a clear correlation with the level of compaction and sintering temperature, demonstrating that higher compression pressures and sintering temperatures led to increased density and decreased porosity. The PM copper electrode with the highest density and lowest porosity can be obtained using 5 tons of compaction load and 650 °C of sintering temperature.
- A homogeneous distribution of particles and an optimized grain boundary size can be observed in the microstructure of the copper sample at a high compaction load and high sintering temperature.
- The reduction in pore size was observed alongside the density increase, indicating the efficacy of the manipulation parameters in minimizing porosity and enhancing material quality.

In the future study, these PM copper electrodes will be used as the tools for surface modification in the EDC process. The selection of the optimal electrode will be determined based on the performance metrics of the EDC process.

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