EFFECT OF POWDER METALLURGY COPPER ELECTRODE ON SURFACE MODIFICATION OF MILD STEEL

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This report is submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

by

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DECLARATION

I hereby, declared this report entitled "Effect of powder metallurgy copper electrode on surface modification of mild steel" is the result of my own research except as cited in references.

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Date : 11 July 2024

APPROVAL

This report is submitted to the Faculty of Industrial and Manufacturing Technology and Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

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Date : 11 July 2024

ABSTRAK

Keluli lembut, dikenali kerana kemuluran yang luar biasa, kebolehkimpalan, dan kos yang rendah, biasanya digunakan sebagai bahan asas dalam pelbagai industri. Gabungan kekuatan dan kebolehbentukan yang ideal dalam keluli lembut menjadikannya sesuai untuk fabrikasi komponen struktur, badan automotif, saluran paip, dan pelbagai jentera. Walau bagaimanapun, keluli lembut mempunyai rintangan kakisan yang rendah. Ini disebabkan oleh pendedahan kepada komposisi kimia yang berbeza-beza, turun naik suhu dan tekanan mekanikal. Selain itu, keluli lembut juga mempamerkan rintangan haus yang rendah, menjadikannya mudah haus dan lelasan dalam keadaan tertentu. Ciri ini disebabkan oleh sifat keluli lembut yang lebih lembut berbanding bahan lain yang direka khusus untuk rintangan haus yang tinggi. Oleh itu, apabila tertakluk kepada keadaan yang melibatkan geseran, lelasan atau haus mekanikal, keluli lembut mungkin mengalami kemerosotan yang dipercepatkan dan mengurangkan umur panjang. Oleh itu, dalam kajian ini, pengubahsuaian permukaan keluli lembut akan dilakukan menggunakan salutan nyahcas elektrik (EDC) dengan elektrod kuprum metalurgi serbuk (PM). Kesan elektrod kuprum PM dengan tekanan pemadatan yang berbeza-beza dan suhu pensinteran pada kekerasan mikro dan ketebalan lapisan termendap akan disiasat. Penguji kekerasan mikro Vickers akan digunakan untuk mengukur kekerasan mikro manakala ketebalan lapisan termendap akan ditentukan menggunakan mikroskop elektron pengimbasan (SEM) selepas proses penggilapan dan goresan. Daripada kajian ini, didapati kekerasan maksimum berlaku pada 650°C dan 3 tan, manakala ketebalan maksimum ialah 12.5 μm pada 550°C dan 5 tan. Tekanan yang lebih tinggi biasanya mengurangkan % berat tembaga dan suhu pensinteran yang lebih tinggi meningkatkan kekerasan mikro keluli lembut. Mengoptimumkan parameter ini adalah penting untuk sifat bahan yang dikehendaki dalam EDC.

ABSTRACT

Mild steel, recognized for its exceptional ductility, weldability, and cost-effectiveness, is commonly used as a basic material in various industries. The ideal combination of strength and formability in mild steel makes it suitable for the fabrication of structural components, automotive bodies, pipelines, and various machinery. However, mild steel has low corrosion resistance. This is due to exposure to varying chemical compositions, temperature fluctuations, and mechanical stresses. Besides, mild steel also exhibits low wear resistance, making it susceptible to wear and abrasion under certain conditions. This characteristic is due to the softer nature of mild steel compared to other materials designed specifically for high wear resistance. Therefore, when subjected to conditions involving friction, abrasion or mechanical wear, mild steel may experience accelerated deterioration and reduced longevity. Therefore, in this study, surface modification of mild steel was done by using electrical discharge coating (EDC) with powder metallurgy (PM) copper electrodes. The effect of PM copper electrodes with varying compaction pressure and sintering temperature on the microhardness and thickness of the deposited layer was investigated. Vickers microhardness tester was used to measure the microhardness whereas the thickness of the deposited layer was determined by using scanning electron microscopy (SEM) after the polishing and etching process. From this study, it is found that maximum hardness occurs at 650°C and 3 tons, while maximum thickness is 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. Optimizing these parameters is crucial for desired material properties in EDC.

DEDICATION

With heartfelt thanks to my family for their constant motivation and friends for their unwavering faith in my abilities. This project is dedicated to the supervisor who shaped me intellectually and spiritually. A humble salute to all who made this journey possible.

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First and foremost, I express my deepest gratitude to Allah S.W.T., the All-Powerful, for providing me with strength and guidance throughout my academic journey, enabling me to overcome challenges and successfully complete this study project.

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I am deeply thankful to my parents, and siblings, for their love, understanding, steadfast support, and confidence in my abilities. Their guidance and encouragement have been instrumental in my journey, inspiring me to reach for my aspirations.

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LIST OF ABBREVIATIONS

ANR	-	Air consumption 100 l / min
B4C	-	Boron carbide
Co-Cr	-	Cobalt-chromium
Cu-Mn	-	Copper-manganese
EDC	-	Electrical Discharge Coating
EDM	-	Electrical Discharge Machining
GPa	-	Giga Pascal
HA	-	Hydroxyapatite
kVA	-	kilo Volt Ampere
MC	-	Multi-Carbide
MoS2	-	Molybdenum disulfide
MPa	-	Mega Pascal
MTR	-	Material Removal Rate
NiTi	-	Nichrome Titanium
PM	-	Powder Metallurgy
SEM	-	Scanning Electron Microscope
UTeM	-	Universiti Teknikal Malaysia Melaka
W-Cu	-	Tungsten copper
WC	-	Tungsten carbide
WC-Co	-	Tungsten carbide-cobalt
XRD	-	x-Ray diffraction

CHAPTER 1

INTRODUCTION

1.1. Background of Study

One of the main concerns in engineering is the need to improve the surface characteristics of materials, especially in metallurgy and manufacturing. Electrical discharge coating (EDC) is a new surface modification method of conductive materials. It was developed using electrical discharge machine (EDM), which has been commonly used for many years as a removal method to create parts, dies, and molds.(Xie et al., 2016).

Furthermore, the EDC process offers recognized advantages, including good adhesion between the substrate and the coating, the capacity to produce thicker layers, and the ability to prepare the coating for the simultaneous deposition of several materials with varying melting points in wear and corrosion applications. Through an inverse polarity at EDC, i.e., the instrument electrode connected to the anode (+) and the substrate connected to the cathode (−) in the electrical discharge device as well as the existence of dielectric fluid, the working electrode (substrate) is then coated by materials releasing from the anode (Taheridoustabad et al., 2021). This process can be performed either by using powder metallurgy electrode (Tyagi et al., 2018) or by a dielectric powder mixing method (Venkata Rajesh and Abimannan, 2023). According to Cogun et al. (2015), a Copper Boron Carbide (Cu/B4C) electrode powder metallurgy tool were used to form a hard layer on the surface of the workpiece, then correlated the thickness of the deposited layer with the peak current function to increase the deposition and tool wear rate.

The main goal of this study is to examine how mild steel can be improved. A combination of powder metallurgy (PM) copper electrodes, and EDC was used to improve the steel surface. An investigation into whether this method can increase the steel's hardness and enhance the coating layer thickness was carried out. Finally, valuable insights and guidance for engineers and manufacturers who wish to improve the surface properties of mild steel was provided by this study.

1.2. Problem Statement

Mild steel, although widely used in industry due to its ductility, weldability and cost-effectiveness, faces significant 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.

To address this issue, surface modification techniques such as EDC using PM copper electrodes have been proposed. However, the influence of varying compaction pressure and sintering temperature of PM copper electrodes on the microhardness and thickness of the deposited layer on mild steel is not fully understood. This study aims to investigate this effect and optimize parameters to improve the properties of mild steel materials through EDC. Specifically, it aims to determine the optimal compaction pressure and sintering temperature to achieve the maximum microhardness and desired coating layer thickness.

1.3. Objectives

- To investigate the effect of compaction pressure and sintering temperature of copper electrode on the deposition layer of mild steel.
- To investigate the hardness and thickness of deposited layer on mild steel after EDC process.

1.4. Scope

This was conducted at the Laboratory of the Faculty of Industrial and Manufacturing Technology and Engineering to ensure the smooth operation of the EDC process. To maintain consistency, the key parameters of pulse duration (pulse-on time), pulse interval (pulse-off time), peak current, and peak voltage were kept constant throughout the experiments. The research will systematically vary compaction pressure and sintering temperature to investigate their influence on the quality and characteristics of the deposited layer. Advanced microscopy techniques, such as scanning electron microscopy, will be employed to closely examine the grain structure, surface uniformity, and any potential defects or irregularities in the deposited layer. Additionally, hardness tests will be conducted to assess material strength, and precise coating thickness measurements will be obtained through cross-sectional analysis using microscopes and measurement tools. Detailed results will be meticulously recorded for each combination of compaction pressure and sintering temperature.

1.5. Summary

In conclusion, this research study aims to investigate the surface hardness and thickness of deposited layer on mild steel after the EDC process using powder metallurgy copper electrodes, and electrical discharge coatings to improve the surface properties of mild steel. This study involves systematic experiments, microstructural analysis, and mechanical tests to understand the effect of compaction pressure and sintering temperature on the quality and characteristics of the deposition layer and the surface hardness and thickness of the deposition layer on mild steel after the EDC process. This research aims to provide recommendations to improve the utility and durability of mild steel in industrial applications.

CHAPTER 2

LITERATURE REVIEW

2.1 Electrical Discharge Coating (EDC)

EDC is widely used as a cost-effective method of applying coatings. This approach uses electric discharge method to apply substance for coating on the outer layer of a substrate. Using the negative polarity of EDM, a coated layer is efficiently kept on the workpiece, resulting in increased wear resistance and hardness qualities. Particularly, the thickness of the coating may be carefully monitored without the use of specialist equipment. Furthermore, EDC stands out for its operational simplicity, which eliminates the need for complex configurations and arrangements. This methodology may be described as a non-traditional coating process in which strong layers of coating comprising carbides of elements such as titanium (Ti), chromium (Cr), tungsten (W), and so on are created. This is performed by transmitting tool electrode substance using a compact electrode. Researchers are particularly drawn to this surface enhancement method, particularly for electric discharge purpose, using tools made from materials like tungsten carbide-cobalt (WC/Co) and cemented carbide (TiC/WC/Co) (Tyagi et al., 2022).

2.1.1 Working Principle of EDC

The EDC method involves a process of depositing a layer of coating onto a workpiece surface utilizing a PM electrode and a powder mixing method, which is accomplished via numerous electrical discharges involving the PM electrode and the workpiece. A binding substance is mixed alongside the required amount of coating material in the mixture of powders to assist in the formation of a high strength compact before starting the EDC process. Following complete mixing for an appropriate duration, the powder is compact using a mounting force.

Using the EDM die sinker, the PM electrode is attached to the positive power supply and the workpiece to the negative power supply. This reverse polarity, in conjunction with optimized process parameters, allows for optimal mixing of the PM electrode powder with the main material. As a result, when used with opposite polarity, EDC produces a thicker casting layer than EDM. Goto et al. (2003) discovered a thin EDC production method utilizing electrical discharge-induced heat generation, which results in a melt pool and hole on the substrate caused by loss of material and evaporation. Figure 2.1 shows the difference between the EDM and EDC mechanisms. Figure 2.1b depicts a succession of repeated sparks occurrences in EDC, which allows the continuous formation of a multi-carbide (MC) coating through the surface of the workpiece. The technique for modifying the surface of the workpiece by shifting metal from an electrode to the surface of workpiece in an EDM machine is known as EDC. This leads to the formation of a solid and thick carbide coating on the metal substrate (Figure 2.1b). Material removal in each cycle is limited in EDC due to carbon coating on the tool, necessitating the usage of a tool with positive charge in EDM. In EDC, the compact tool is utilized at negative charge to allow greater material removal without being constrained by carbon formation (Kumaran et al., 2023).

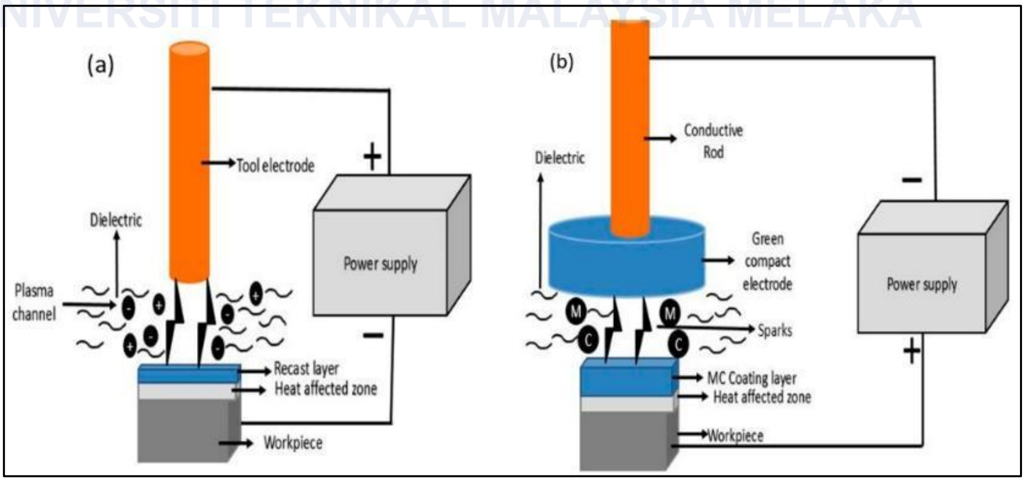


Figure 2. 1: (a) EDM mechanism and (b) EDC mechanism (Tyagi et al., 2022)

EDC offers a higher recast layer thickness than EDM because to reverse polarity and weakly bound grains in the PM electrode. As a result, EDC acts like an extension of EDM, with a PM electrode and powder mixed EDM including the required powder substance.

Proper selection of process parameters allows well-controlled surface quality of the layer and tribological properties. To summarize the differences between EDM and EDC methods, Liew et al. (2020) constructed a comparative table, which can be seen in Table 2.1.

Table 2. 1: Difference between machining and coating (Liew et al., 2020)

	EDM	EDC
Process	Material is removed from the workpiece in order to attain the desired appearance.	A material layering method that is carried out to produce a coating on the selected workpiece surface.
Tool electrode	Traditional solid tool	PM
Thickness of recast layer	Low	High
Polarity used	The tool can be attached both the positive or negative inputs.	The tool is attached to the positive input, while the workpiece is attached to the negative.
Roughness	Low	High
Quality of surface after process	Low	High
Workpiece weight	Reduces caused by elimination of material	Rises caused by the coating of the substance
Application	Conductive material machining	Conductive materials coating

According to current theory, the electric spark phenomenon causes the formation of small melt spots on the workpiece, which can be partly or completely melted. In the EDC process, these melt spots combine with dispersed material atoms from the PM electrode before swiftly cooling to form a coated layer. As shown in Figure 2.2, the conventional concept of electric spark discharge suggests that materials are discharged from melt spot on simultaneously the underlying material and the electrode after a discharge of electricity. The release of substance grains reduces the breakdown electricity, facilitating a spark in the region in which those particles merge with the melt spot of the subsequent spark. The mixing and hardening of different deposits contribute to create a continuous coating layer, illustrated in Figure 2.2. This sequence of sparking events can result in the creation of numerous overlying layers, ultimately resulting in a robust and wear-resistant layer of coating on the workpiece (Murray et al., 2017).

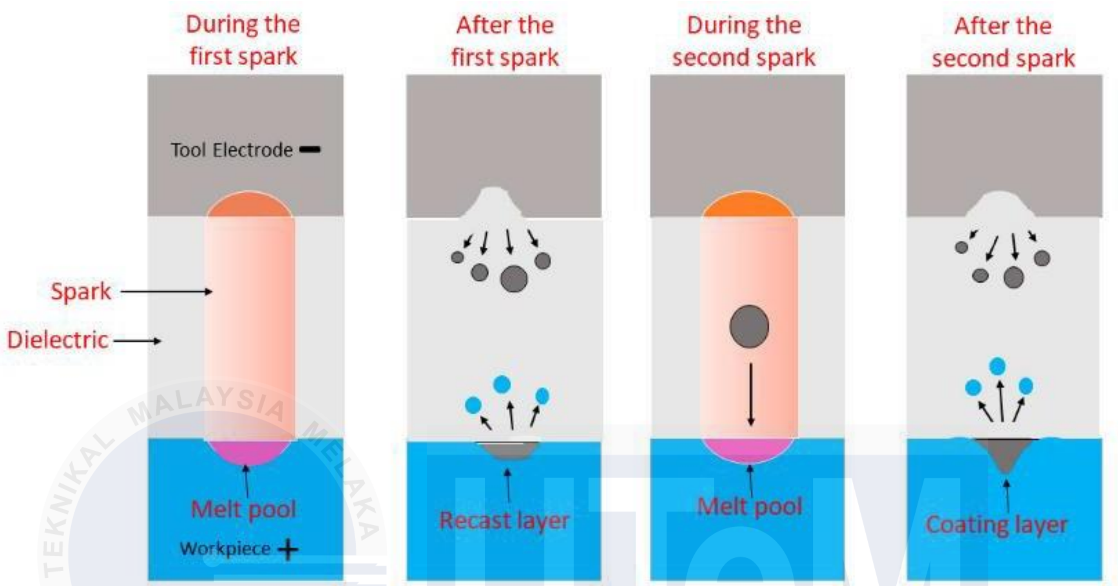


Figure 2. 2: Mechanism of material transfer (Murray et al., 2017)

2.1.2 Application of EDC

EDC processed equipment, such as molds, dies, and drills, has improved surface qualities while reducing imperfections. This process aids in preventing damage, improves attributes including resilience to corrosion and wear performance, and increases overall product longevity. In summary, the EDC process not only improves the functional ability of equipment but also contributes to surface enhancements (Kumaran et al., 2023).

Based on Prakash C et al. (2021) research, ball burnishing electric discharge cladding was used on biological implants to offer a HA coating for medical and commercial uses. They investigated the outermost microstructure of Ti alloy with a combination of ultrasonic waves, abrasive water jet, and EDM method. Agrawal et al. (2021) highlighted the combination of the EDM process with various approaches to enhance the ability to be machine including the investigation of the EDM process with laser and ultrasonic machining. Nguyen et al. (2019) used micro EDM to enhance the surface durability of steel with titanium powder combination, leading to higher micro hardness under various ideal circumstances. Korada et al. (2019) enhanced the surface characteristics of D3 steel by adding tiny powder particles combined with a dielectric fluid, leading to improved ability to be machined.

Figure 2.3 illustrates diverse applications of the EDC process. Improved surface quality is essential for materials utilized in the biomedical industry, particularly in applications such as bone replacement of broken bones, and various surgical tools. Bio-implants and surgical instruments commonly use materials such as Ti alloy, Co-Cr alloys, stainless steel, and magnesium (Mg) alloy. However, these materials often exhibit suboptimal surface properties, particularly in terms of biocompatibility, with Co-Cr alloy, stainless steel, and Mg alloy being notable examples (Kumaran et al., 2023).

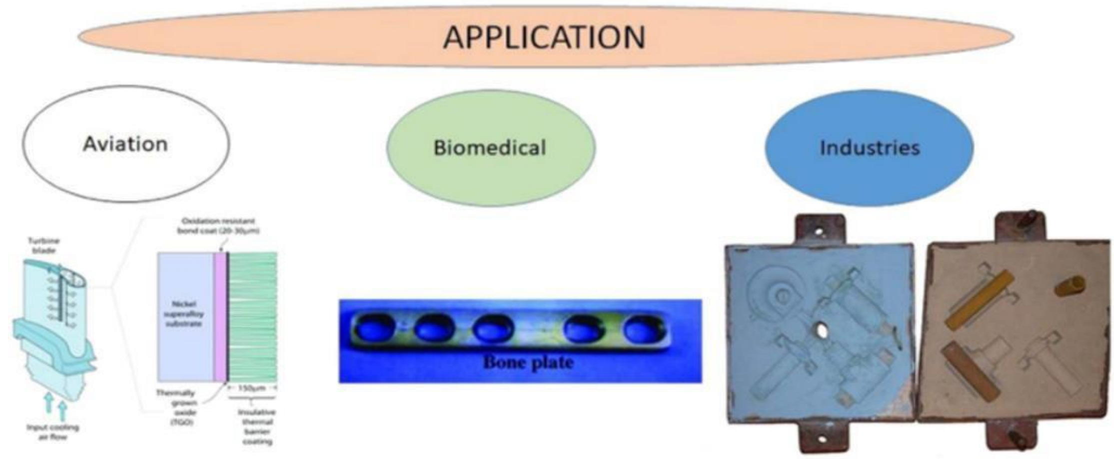


Figure 2. 3: Application of EDC process (Kumaran et al., 2023).

2.1.3 Dielectric Fluid

The dielectric fluid employed in EDC should not only offer a machining environment devoid of oxygen but also possess dielectric resistance. It must strike a balance by not undergoing electrical breakdown too quickly while allowing for the formation of a plasma channel. Commonly used dielectric fluid mediums in EDC include inert gases, EDM oil, kerosene, and deionized water. Furutani et al. (2009) explored the use of powder combined with EDM oil, resulting in a uniform coating with minimal cracking in the coated area.

In another study, Sadagopan et al. (2017) examined the impact of utilizing biodiesel for a dielectric medium. The low-density characteristics of biodiesel were found to enhance process productivity. Kolli et al. (2015) demonstrated the influence of graphite powder on the dielectric fluid of a Ti alloy. Huang et al. (2015) enhanced the surface of nichrome titanium alloy with acetylene and nitrogen gas as a dielectric fluid to improve wear performances. Yu et al. (2020) investigated the existence of Ca and P on titanium implants using a gas-assist dielectric fluid.

2.2 Parameters of EDC

2.2.1 Gap Voltage

A discharge voltage is the voltage at which sparks of electricity happen over the electrode and the material, and its magnitude depends on the spark gap. Once electrodes reach an open gap voltage, it generates an ionization transmit across the medium, leading to an increase in current flow. As the current progresses, the voltage decreases and eventually stabilizes at the working gap level. This voltage corresponds to the width of the spark gap between the workpiece and the tool electrode. An elevation in this voltage enhances flushing and promotes a stable discharge process (Tyagi et al., 2022). Table 2.2 shows overview of previous literature research on the influence of voltage during EDC.

Table 2. 2: Overview of previous literature research on the influence of voltage during EDC.

Author	Workpiece	Tool	Gap Voltage (V)	Discovery
V. Prakash et al., (2018)	Ti6Al4	Nickel tool	20, 30, 40, 50, 60	The thickness of the coating layer is influenced by the voltage.
Liew et al., (2018)	Aluminum	Tungsten powder suspension	20, 25, 30, 35, 40	With an increase in voltage to 40 V, there was a corresponding increase in the quantities of tungsten and carbon. This is attributed to the influence of voltage on the spark gap
Mansor et al., (2019)	Nitinol	Nickel–titanium shape memory alloy	70–160	In the EDC process, a low gap voltage was favoured to achieve optimal surface roughness and greater uniformity in material deposition.

2.2.2 Peak Current

Peak current refers to the maximum current delivered by the energy supply in a single cycle. This peak current plays a role in the EDC process because it produces the electric spark and enables it to attain the necessary spark temperature before transferring the coat material onto the workpiece. As a result, establishing the ideal current value is critical for facilitating maximal material transfer, resulting in a firmer and more consistent coating (Khan et al., 2021). Table 2.3 shows an overview of previous literature research on the influence of peak current during EDC.

Table 2. 3: Overview of previous literature research on the influence of peak current during EDC.

Author	Workpiece	Powder	Peak Current (A)	Discovery
Tyagi et al., (2019)	Mild steel	MoS2 + Cu	4, 7, 10	Lower thickness was obtained at the lowest peak current, while a higher thickness was obtained at the highest peak current.
Algodi et al., (2016)	SS 304	TiC-Fe	2, 6, 10, 14, 19	A current ranging from 2 to 10 A contributes to achieving favorable hardness and surface finish, accompanied by a reduced presence of cracks and voids.
Prakash et al., (2017)	Titanium	HA powder.	15	Applying a high peak current and a low pulse duration led to the formation of a uniform. hydroxyapatite (HA) layer

2.2.3 Pulse Duration

To attain a consistent tool wear rate and ensure a uniform coating, the duration and interval of pulses are crucial factors. The electrode material experiences wear and deposits onto the substrate during the pulse-on time. In contrast, the deposited material undergoes cooling and solidification on the substrate surface during the pulse-off time. The energy applied during the pulse-on duration is directly linked to the material removal rate. Prolonged pulse durations, causing excess melting, can lead to the removal of more substrate material, resulting in a rough surface finish. Pulse cycles represent repetitive processes, and an increased number of cycles contribute to achieving a smoother surface finish (Kumaran et al., 2023). Table 2.4 shows an overview of previous literature research on the influence of pulse on-time during EDC.

Table 2. 4: Overview of previous literature research on the influence of pulse on-time during EDC.

Author	Workpiece	Powder	Pulse on Time	Discovery
Yap et al., (2021)	WC-Co	Quarry dust	100–300 µs	The results indicate that as Ton increases, there is a simultaneous increase in hardness and layer thickness, accompanied by a decrease in surface finish.
Leszczy et al., (2021)	60CrMoV18-5 Steel	Cu-Zr2	12.8, 25. 50	A higher material removal rate (MTR) is attained when Ton (pulse duration) is set at 25 µs.
Mussada et al., (2017)	Aluminum 6351	W-Cu	25, 106, 463, 1010	As the pulse duration increases, there is a gradual decrease in microhardness. This is attributed to the reduction in carbon particles on the workpiece, as longer pulse durations result in the flushing away of particles from the work surface.

2.3 Type of EDC method

2.3.1 Powder Mixed EDC

Powder mixed EDC is the condition when metal powders are combined into the dielectric fluid. This addition aimed to enhance the surface characteristics of the workpiece, including wear resistance, microhardness, and corrosion resistance. The incorporation of conductive powders led to an increased spark gap distance, contributing to improved surface quality by reducing spark impulse and promoting a better distribution of discharges across the entire outmost layer (Tyagi et al., 2022). In this method, the surface of the workpiece undergoes fine formation, and both its composition and topography are altered through the incorporation of alloying oxides, bioactive compounds, and carbides. Additionally, a rapid drop in voltage induces a magnetic field that charges the powder particles, forming a bridge between them in the discharge gap. The electrical sparks generate an extremely high temperature in the gap, ranging from 8000°C to 15000°C, surpassing the melting point of all metallic biomaterials and additive powders. Consequently, the powders melt, and materials dislodge from both the work-material and electrode surfaces.

Due to the small gap distance and the ion and electron storage on the surfaces of powder particles, molten powders easily adhere to the electrode surface due to electromagnetic forces and the negative pressure of electrophoresis. Simultaneously, the dielectric liquid decomposes, supplying carbon, hydrogen, and oxygen. The ions react, forming compounds that melt due to the high-temperature environment. The dielectric fluid, acting as insulation, coolant, and flushing system, causes a rapid temperature to drop in the gap, leading to the solidification of molten metals, which are the compounds generated by melting and chemical reactions with the powders, electrode, and workpiece materials.

The solidified compounds adhere to the workpiece, forming a hemisphere shape after resolidification, marking the initiation of the recast layer or coating process. Moreover, particles and compounds with certain charges remain fully or partially molten, perpetuating the cycle and contributing to a modified surface. During the re-solidification process, a considerable amount of absorbed gas is expelled from the substrate, resulting in a foamy and porous surface. (Al-Amin et al., 2020). Figure 2.4 shows the formation of a plasma channel that occurs within the powder-mixed dielectric. The suspended particles play a role in enlarging and broadening the plasma channel, attracting electric trees in various directions. Previous research has demonstrated that the use of a powder-mixed dielectric not only imparts the desired surface properties to the workpiece but also significantly diminishes micro-cracks while enhancing the uniformity of coating thickness (Xie et al., 2016).

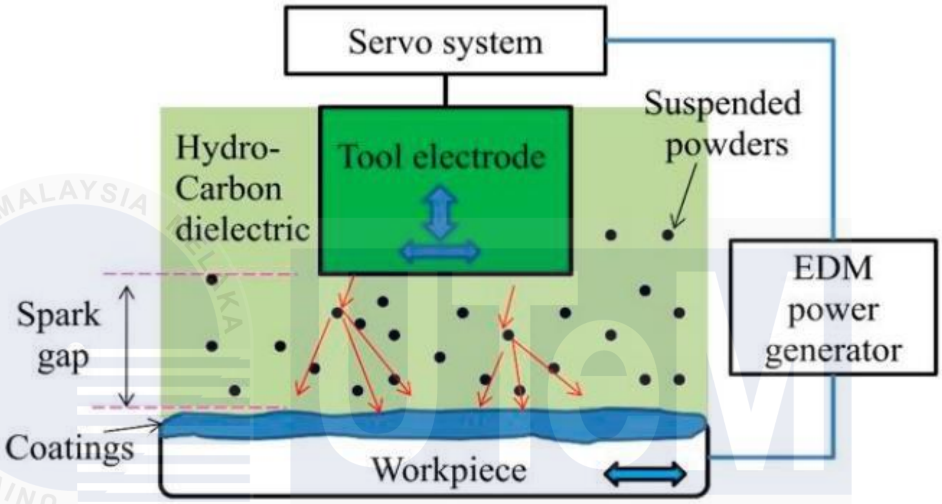


Figure 2. 4: Schematic of powder mixed EDC (Xie et al., 2016).

2.3.2 Powder Metallurgy (PM) Electrode

PM plays a crucial role in the preparation of electrodes for the EDC process. The bonding strength of electrodes produced through PM is notably lower than that of traditional metal electrodes. This characteristic facilitates the easy breaking of bonds, allowing effective coating over the substrate.

Control over the material properties of PM electrodes is achieved by adjusting factors such as constituents, mixing ratio, compaction pressure, and sintering temperature. In the PM tool, the melt combines with the breakdown components of the dielectric medium, leading to deposition on the workpiece. Utilizing powder metallurgical tools in the EDC process offers advantages in selecting the type and composition of the powder material for coating. Metal powders like Ti, Cr, molybdenum (Mo), and W can form carbide structures, enhancing wear resistance properties. Hard-phase additive powders such as iron (Fe), cobalt (Co), and molybdenum (Mo) serve as PM tools for developing coatings suitable for solid lubrication. In applications requiring high-temperature wear and corrosion resistance, powders like Inconel and stellite can be employed.

The deposition height and the occurrence of defects can be managed by adjusting input process parameters. It is noteworthy that even less electrically conductive materials can be effectively used as electrodes when produced through PM processes (Kumaran et al., 2023).

2.3.3 PM Copper Electrode

Copper, possessing the second-highest electrical conductivity after silver, proves to be a suitable alternative in EDC, especially when silver is considered cost-prohibitive. In EDC applications, copper is commonly employed in the form of a PM electrode. It serves as an effective binding material when depositing coatings with semiconducting or non-conductive powders. The inclusion of copper powder enhances the overall conductivity of the green compact (Tyagi et al., 2018).

Furthermore, raising the quantity of primary powder in the mixing rate reduces the rigidity of the electrode. This allows more substance to be effectively layered onto the workpiece. Cu relatively low melting temperature allows for quicker melting, which contributes to the efficient coating of the PM material. Copper and its associated alloys are suitable coating materials due to their great anti-corrosion properties and low rate of friction. (Tyagi et al., 2022).

2.3.3.1 Parameters for the Preparation of PM Copper Electrode

2.3.3.1.1 Compaction Pressure

The wear of the electrode used in EDC is determined by this parameter, which is defined as the amount of force supplied per unit area to powder materials during the making of PM copper electrode. Achieving the appropriate compaction pressure is crucial in this process to attain the necessary strength for the electrode.

For instance, to facilitate easy material removal from the compact electrode, it is essential that the particles are loosely compacted, enabling their effective transfer onto the workpiece. Conversely, if the compact strength is increased significantly beyond the required threshold, it leads to a reduction in tool wear, but simultaneously causes a decrease in the deposition rate. Therefore, maintaining an optimum level of pressure becomes imperative, ensuring that the tool attains sufficient strength while allowing for perfect material removal from the tool electrode in the EDC process (Tyagi et al., 2022).

2.3.3.1.2 Sintering Temperature

Sintering temperature also plays a crucial step in the preparation of a PM copper electrode. In certain conditions, the bonding among the particles of copper powder may be imperfect, resulting in suboptimal binding. Therefore, after compaction, sintering is employed to enhance compact durability. At certain sintering temperature has remained constant (Tyagi et al., 2021).

To prevent abrupt changes in copper powder properties, it is essential to ensure that the sintering temperature remains below the powder's melting point. Higher sintering temperatures contribute to increase strength in the compact, but a fully densified electrode may lead to high electrical conductivity, resulting in continuous sparking. However, this can limit the release of material, leading to reduced surface alloying.

Hence, maintaining an optimal sintering temperature is critical to prevent copper powder melting while ensuring strong bonding among powder particles (Tyagi et al., 2022).

2.4 Characteristic of EDC Coating

2.4.1 Micro-hardness

The EDC process is anticipated to result in forming a solid coating layer on the workpiece. Arulkumar et al. (2019) demonstrated improvements in substrate micro-hardness by up to 233% and an 80% reduction in wear loss by incorporating TiO_2 powder into the EDC process. The application of electric spark deposition, as highlighted by Vasylyev et al. (2020), contributed to heightened surface hardness and corrosion resistance. Whether employing a PM electrode or a powder mixed EDC process, the microhardness of the material can be improved. Additionally, the EDC process is utilized for coating solid lubricant materials, resulting in a 50% reduction in substrate microhardness.

2.4.2 Surface Roughness

Surface roughness is a critical indicator of a surface's texture, with higher roughness levels being associated with increased susceptibility to corrosive effects and adverse effects. The material's erosion ability and friction coefficient are proportional to surface roughness, underscoring its significance as a fundamental surface property. Kar et al. (2017) used Taguchi approach to optimize the surface roughness variable of an aluminum alloy. Their results showed that peak current, and pulse duration, are the most important factors influencing surface roughness. In a study by Gill et al. (2016), the surface roughness and microhardness of Cu-Mn PM tool electrodes on die steel were evaluated. Interestingly, the research found that the duty factor did not have a significant impact on surface roughness. Wandra et al. (2021) experimentally explored the surface roughness and hardness of materials during electric discharge cladding on bio implants. Additionally, Rahang et al. (2016) modified the surface enhancement parameters and evaluated the influence of substances layering on surface roughness. It is worth noting that the particle size of the powder was identified as a factor influencing surface roughness in these studies.

2.4.3 Wear Resistance

EDC coatings often improve wear resistance, crucial for components subjected to friction and abrasion. The assessment of wear performance is a crucial aspect when analyzing coated surfaces for critical applications. In this study, the coated samples were affixed as pins in a pin-on-disc wear test instrument was used, and the material breakdown during the test was determined. This was then compared to material loss from uncoated samples to determine that samples with coatings had significant durability against wear. Tyagi et al. (2021) investigated the wear durability of an EDC specimen made with a PM electrode using a sliding corrosion test. The findings showed a particularly low specific wear ratio. In a separate study, Sugumaran et al. (2021) conducted dry sliding wear tests on a Co-Cr plasma-coated Ti alloy implant. The nitride coating substrate exhibited remarkable wear resistance, with the reported lowest wear coefficient being $1.11\times10^{-15} m^3/Nm$, observed over a sliding distance of 2 kilometres.

2.4.4 Layer Thickness

The thickness of a coating, often referred to as layer thickness, indicates the height of material deposition from the base metal. The coating thickness is commonly assessed through the cross-sectional structure of coating specimens. Mussada et al. (2015) performed a thorough examination of the layer of coating characterization utilizing methods such as SEM, EDS, and XRD. Their research revealed insights into surface flaws, the presence of components, phase verification, and the surface thickness of the coated surface. In a separate study, Rajeshshyam et al. (2022) used powder mixed EDC to produce a solid oil coating for Al alloy. The study found that the thickness of the coating layers varied between 35 μm and 55 μm based on powder concentration.

2.5 Summary

EDC is a widely adopted and economically viable method for coating applications, utilizing electrical discharge process to layer material onto a metal surface. This technique enhances wear resistance and hardness properties, particularly with robust layers containing carbides like Ti, Cr, and W. EDC stands out for its operational simplicity, precise coating thickness control, and the ability to produce coatings with distinct advantages over conventional methods. The process involves depositing a coating layer using a PM electrode and a powder mixed method, with multiple spark energy between the PM electrode and the workpiece. The application of EDC extends to various industries, such as industrial and medical. Dielectric fluids and process parameter act as crucial part in EDC, significantly influence the coating outcomes.

From the previous study, the existing body of research lacks comprehensive studies on the utilization of PM copper electrodes to modify the surface of mild steel through the EDC method. This gap highlights the need for a deeper understanding of the interactions and outcomes associated with using PM copper electrodes in the EDC process for mild steel surface modification. The main target of this research is twofold. Firstly, the investigation seeks to understand the effect of compaction pressure and sintering temperature applied to

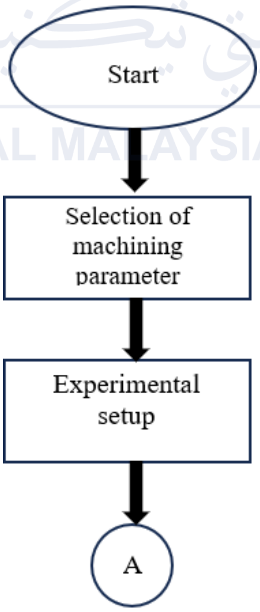
Cu electrodes on the resulting deposition layer formed on mild steel. This aspect addresses the key parameters in the EDC process involving copper electrodes and their impact on modifying the mild steel surface. Secondly, the study aims to determine the surface hardness and thickness of the deposited layer on mild steel after the EDC process. This objective focuses on evaluating the mechanical properties of the modified surface, specifically the hardness, and understanding the thickness of the deposited layer. By achieving these objectives, this study expects to contribute valuable ideas into improvement of EDC process for enhancing the surface characteristics of mild steel using PM copper electrodes.

CHAPTER 3

METHODOLOGY

3.1. Introduction

Figure 3.1 shows the overview of this project. This flow chart was started by selecting suitable parameters for the EDC process, like peak current, gap voltage, and pulse duration. Then, the experiment was conducted by preparing the sample of mild steel to be coated and the experiment was set up. Next, microhardness and layer thickness of the sample were tested, and the results obtained from the experiment were analyzed.



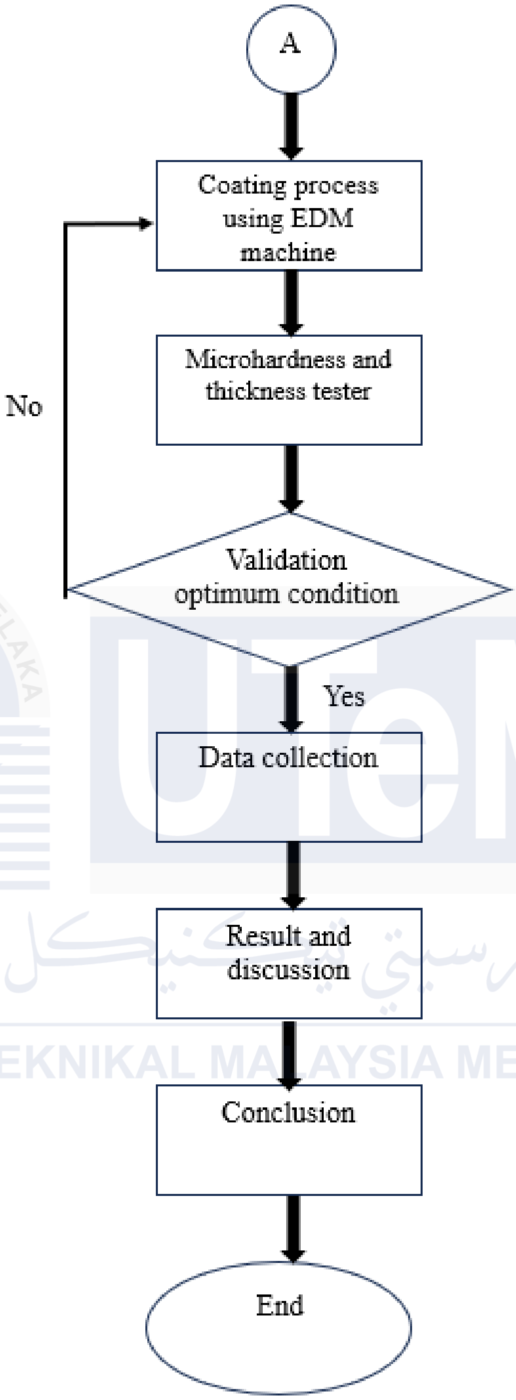


Figure 3. 1: Process flow chart

3.2. 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 as shown in Figure 3.2. After finishing the cutting process according to the desired size, both sides of the surface need to be faced using a conventional milling machine as shown in Figure 3.3 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 shown in Figure 3.4.

Figure 3. 2: Laser Cutting Machine

Figure 3. 3: Conventional Milling Machine

Figure 3. 4: Double Disc Grinding Polishing Machine

3.2.1. Workpiece Material

Mild steel has been selected as the workpiece for EDC experiment as shown in Figure 3.5. 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. Its common usage makes it a practical choice for experimental studies. Moreover, mild steel's versatility, characterized by its ease of machining, welding, and forming, adds to its suitability for the study. Table 3.1 shows the chemical composition of mild steel and Table 3.2 shows the mechanical properties of mild steel respectively.

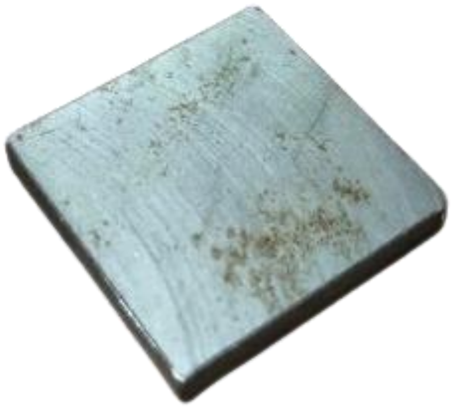


Figure 3. 5: Mild steel workpiece

Table 3. 1: Chemical composition of mild steel

Element	**Wt%**
Carbon, C	0.05-0.25
Manganese, Mn	0.3-0.6
Silicon, Si	0.1-0.4
Sulphur, S	0.05
Phosphorus, P	0.05

Table 3. 2: Mechanical properties of mild steel.

Property	Value
Tensile Strength	400 - 550 MPa
Yield Strength	250 - 450 MPa
Elongation	20% - 25%
Modulus of Elasticity	Around 210 GPa
Brinell Hardness	120 - 200 HZ
Rockwell Hardness (B Scale)	60 - 80 HRB
Rockwell Hardness (C Scale)	70 - 90 HRC
Vickers Hardness	120- 210 HV

3.2.2. PM copper electrode

The choice of a PM copper electrode for the coating experiment involving EDC with mild steel as the workpiece is rooted in several strategic considerations. PM is a manufacturing process that involves the production of metal powders, which are then compacted and sintered to form solid metal objects. In the context of this experiment, PM copper electrode provides a finely divided and highly uniform form of copper, allowing for controlled deposition during the EDC process.

The use of PM copper as the electrode material offers distinct advantages. Firstly, the powder form enables precise control over the deposition process, facilitating uniform coverage on the mild steel surface. This is critical for achieving consistent and reproducible results in the study. Additionally, the fine particles allow for enhanced surface contact and adhesion during the EDC process.

Moreover, PM copper exhibits favorable characteristics for coating applications. It often possesses high purity, which is beneficial for obtaining a coating with desirable properties. The sintering process further enhances the cohesion and integrity of the copper coating on the mild steel substrate. The inherent properties of copper, such as its electrical conductivity and corrosion resistance, make it a suitable choice for applications where these attributes are desirable.

In this study, the PM copper electrodes with different compaction pressure and sintering temperature were used as a tool for EDC process. Figure 3.6 shows the example of PM copper electrode.

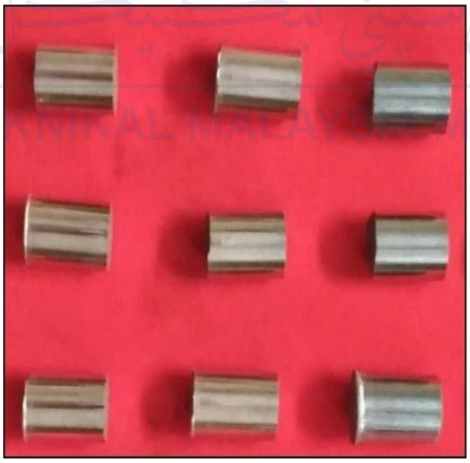


Figure 3. 6: PM copper electrode.

3.3. Experiment setup

3.3.1. 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 copper 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 3.7 shows the EDM Die Sinking Sodick AQ35L and Table 3.3 shows capabilities and specification of EDM Die Sinking Sodick AQ35L.

Figure 3. 7: EDM Die Sinking Sodick AQ35L (FTKIP Laboratory)

Table 3. 3: Capabilities and specification of EDM Die Sinking Sodick AQ35L

Machine Capabilities	Specification
Table size	600 x 400 mm
Internal dimensions of the treatment tank	750 x 550 x 320 mm
Fluid dielectric level range	60-270 mm
Treatment tank capacity	112 l
X axis travel	350 mm
Y axis travel	250 mm
Z axis travel	250 mm
Maximum electrode weight	50 kg
Maximum workpiece weight	550 kg
Electric power	8 kVA
Distance from the table to the grip surface	212-462 mm
Table height from the floor	850 mm
Transformer power supply	3 x 400 VAC, 10 kVA, 50 Hz / 60 Hz
Required pressure, manual chuck	0.44 MPa (4.5 kgf / cm2)
Required pressure, automatic chuck	0.64 MPa (6.5 kgf / cm2)
Air consumption	100 l / min (ANR)

3.3.2. EDC Parameters

This study aims to investigate the impact of compaction pressure and sintering temperature of PM copper on mild steel. In the present work, experiments were conducted on mild steel using copper tool electrodes manufactured by PM process. The properties of the workpiece are enlisted in Table 3.2. Selected process parameters for the experimentation and their levels are given in Table 3.4.

Table 3. 4: EDC parameters

Working Parameter	**Description**
Workpiece material	Mild steel (25 mm × 25 mm × 5 mm)
Electrode material	Copper electrode (6 mm of diameter)
Dielectric fluid	Kerosene oil (500 ml)
The polarity (Reverse polarity)	Mild steel – negative Copper electrode – positive
Machining time	30 minutes
Peak current (I_p)	5 A
Voltage (V)	40V
Pulse on time (T_{on})	250 µs
Pulse off time (T_{off})	20 µs
Compaction pressure	3, 4, 5 tons
Sintering Temperature	450, 550, 650℃

3.3.3. Measurement and analysis

3.3.3.1. Micro-hardness

Micro hardness testing was performed using a Shimadzu Vickers Micro Hardness Tester. It is important to carry out a careful calibration of the machine to ensure accurate and reliable results. This calibration process involves the precise adjustment and verification of equipment settings, such as load and deflection measurement parameters, to meet the required test standards. Attention to detail during the calibration process is important to maintain instrument accuracy and obtain consistent and valid microhardness measurements in subsequent testing procedures. During the micro-hardness testing, the measurements were conducted using a pyramidal indenter weighing 20 N and a dwell duration of 15 s. The measurement was repeated five times to ensure the accuracy of the acquired data. Figure 3.8 shows the Shimadzu Vickers Microhardness Tester.

Figure 3. 8: Shimadzu Vickers Microhardness Tester (FTKIP Laboratory)

3.3.3.2. Layer Thickness

To get the coating layer thickness, the EDC workpieces were sliced in half using a Micracut 151 Low Speed Precision Cut Off Machine with a diamond cutter disc, as shown in Figure 3.9. After that, the samples were ground with a Buehler EcoMet 30 Semiautomatic, Manual Grinder and Polisher, as illustrated in Figure 3.10. To get a smooth surface, the sample was first ground with 120 grit sandpaper, then followed by 600 grit sandpaper, and finally with 1200 grit sandpaper. To avoid excessive grinding and distorted angles, the turning speed was adjusted to 150 rpm. Before measuring the coating layer thickness, the cross-section surface was etched using Nital 3% etchant as shown in Figure 3.11 to disclose the sample's microstructure. To acquire a clear microstructure, the cross-section sample was submerged in Nital 3% etchant for 5 seconds. Then, the layer thickness test was carried out using a FESEM Hitachi SU 5000. This high-resolution imaging tool enables accurate inspection and measurement of layer thickness. FESEM capabilities facilitate detailed analysis and characterization of deposited layers, providing valuable insight into the structure andmorphology of materials. The deposited element composition also was analysed using Energy Dispersive X-ray (EDX) Figure 3.12 shows the FESEM Hitachi SU 5000.

Figure 3. 9: MICRACUT Precision Cutting Machine

Figure 3. 10: Double Disc Grinding Polishing Machine

Figure 3. 11: Nital 3% etchant

Figure 3. 12: FESEM Hitachi SU 5000

3.3.3.3 Design of Experiment (DOE)

Design of Experiment (DOE) is a systematic method used to plan, conduct, analyze, and interpret controlled tests to evaluate the factors that may influence a particular outcome or response. It helps in understanding the relationship between input variables (factors) and output variables (responses). DOE is widely used in various fields, including engineering, manufacturing, pharmaceuticals, and social sciences, to optimize processes, products, and systems. In this case, the main objective of the DOE is to examine the impact of compaction pressure and sintering temperature on the material's hardness. Through systematic control of these variables and then measuring of the resulting hardness, it can identify the main effect of each variable on hardness, identify any potential interactions between the variables, and develop a prediction model to enhance the process for achieving the required hardness characteristics. The DOE offers a systematic method for investigating the relationship between compaction pressure, sintering temperature, and hardness. Through data analysis, important information on how to effectively control and improve manufacturing methods can be obtained in order to achieve the required material properties.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Microhardness of deposited coating layer

4.1.1 Design of Experiment (DOE)

Table 4.1 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 when the workpiece was tested, the highest microhardness was achieved by using a lower compaction pressure and a higher sintering temperature.

In contrast, the lowest recorded hardness value is 139.392 HV, specifically seen in Run 11. The specified parameters for this run consist of a compaction pressure of 3 tons and a sintering temperature of 450°C. These findings suggest that reducing the compaction pressure and sintering temperature leads to the material having the least hardness.

In summary, the data indicates that the sintering temperature has significant effects on the microhardness of the mild steel, with higher temperatures generally resulting in increased hardness values. The compaction pressure also impacts the microhardness, however its impact seems to be less significant in comparison to the sintering temperature. From the table, it is clearly seen the highest micro hardness obtained was 244.047 HV.

Table 4. 1: Micro-hardness result

Run	Compaction Pressure (kPa)	Sintering Temperature (°C)	Micro-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

4.1.2 ANOVA for 2FI model analysis

Table 4.2 represents a summary of the results from the research of the two-factor interaction model (2FI), focusing on the impact of compaction pressure (A) and sintering temperature (B) on the response variables. The table provides important statistical measurements, including the sum of squares, degrees of freedom (df), mean square, F value, and P value for various sources of variation. The "Model" row summarizes the combined impact of the factors and their interactions, showing a significant p value (0.0280), which indicates that the model is statistically significant. The p-values for the individual components, A-Compaction Pressure and B-Sintering Temperature, are 0.9045 and 0.0159, respectively. This suggests that the sintering temperature has significant effects on the response, but the compaction pressure does not. The interaction term (AB) is statistically significant with a P value of 0.0390, suggesting that the combined effect of compaction pressure and sintering temperature has a significant effect.

The "Residual" row displays the factor of the model's variation that cannot be explained, with a sum of squares of 3078.96 and a mean square of 342.11. The row labeled "Poor Fit" has a p-value of 0.0091, which is statistically significant. This suggests that the model does not accurately represent the data, indicating the presence of unidentified factors or higher order interactions. The "Pure Error" line, which indicates the changes in duplicated observations, has a sum of squares equal to 143.50. The "Total Cor" row displays the total amount of variation in the data, represented by a sum of squares equal to 8075.87. In summary, the ANOVA table shows that although the model and factors are statistically significant, the presence of a significant lack of fit suggests that the model may require improvement in order to enhance its predictive accuracy.

Table 4. 2: ANOVA Analysis

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4996.91	3	1665.64	4.87	0.028	significant
A-Compaction Pressure	5.21	1	5.21	0.0152	0.9045	
B-Sintering Temperature	2999.33	1	2999.33	8.77	0.0159	
AB	1992.37	1	1992.37	5.82	0.039	
Residual	3078.96	9	342.11			
Lack of Fit	2935.46	5	587.09	16.36	0.0091	significant
Pure Error	143.5	4	35.88			
Cor Total	8075.87	12				

4.1.3 Predicted vs Actual Graph

Figure 4.1 shows a scatter plot named "Predicted vs. Actual," which illustrates the comparison between predicted values and actual values. The x-axis indicates the actual values, which range from around 120 to 260, while the y-axis displays the expected values within the same range. The data points are represented by orange squares on a plot, while a diagonal line extends from the bottom-left to the top-right, symbolizing the optimal situation where the expected values perfectly align with the actual values.

The scatter plot provides a way to visually assess the performance of the prediction model. Data points that fall on or near the diagonal line represent precise predictions, whereas ones that are distant from the line indicate differences between the predicted and actual values. The graph shows a moderate distribution of data points around the diagonal line, indicating that while some predictions closely match with the actual values, there are also multiple data where the predictions diverge considerably. This spread indicates that the model shows various levels of precision over different ranges of actual values. There are many data where the predicted values greatly exceed the actual values, especially in the upper range of actual values (about 240-260). This graph allows identifying the presence of spots where the model can be overestimating or underestimating the true values, hence guiding subsequent improvements and optimization of the prediction model.

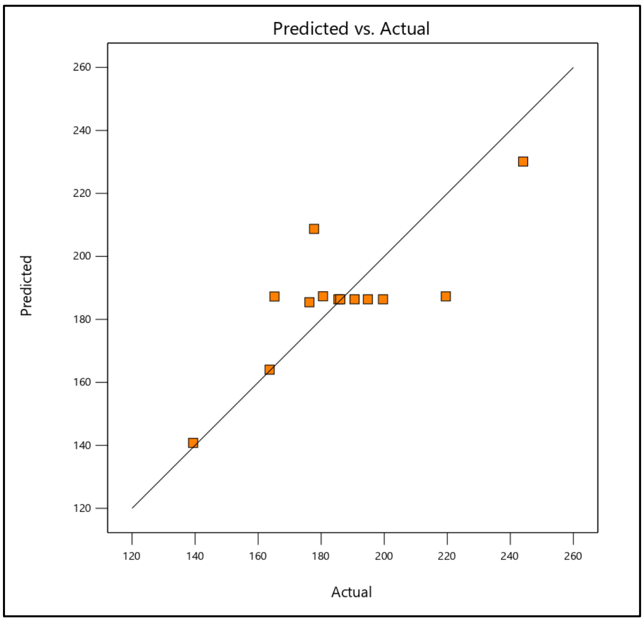


Figure 4. 1: Predicted vs Actual Graph.

4.1.4 3D Surface Graph

Figure 4.2 shows a 3D surface plot that displays the correlation between compaction pressure (A) and sintering temperature (B) on the micro-hardness (HV) of deposited layer.a material. The x-axis refers to the compaction pressure measured in tons, while the y-axis refers to the sintering temperature measured in degrees Celsius. The z-axis represents the numerical number that indicates the level of micro-hardness. The surface plots are color-coded, with blue representing lower hardness values and red representing higher hardness values. This gradient facilitates quickly recognizing regions within the plot where materials display a variety of hardness. In addition, the plot includes design points that are separated by red and white markings. The red points represent specific data points above the surface, while the white points represent specific data points below the surface.

From Figure 4.2, it is clearly seen that higher sintering temperatures and lower compaction pressures are observed resulting in increased micro-hardness. The region with high hardness (244.047 HV) is observed at high sintering temperatures (650°C) and low compaction pressure (3 tons). The region with poor lower hardness (139.392 HV) is located at lower levels of both sintering temperature (450°C) and compaction pressure (3 tons). The result agrees with the findings of Lee et al. (2015) where they reported that the hardness of the material increases at higher sintering temperatures due to the rise in bonding energy between the powder particles.

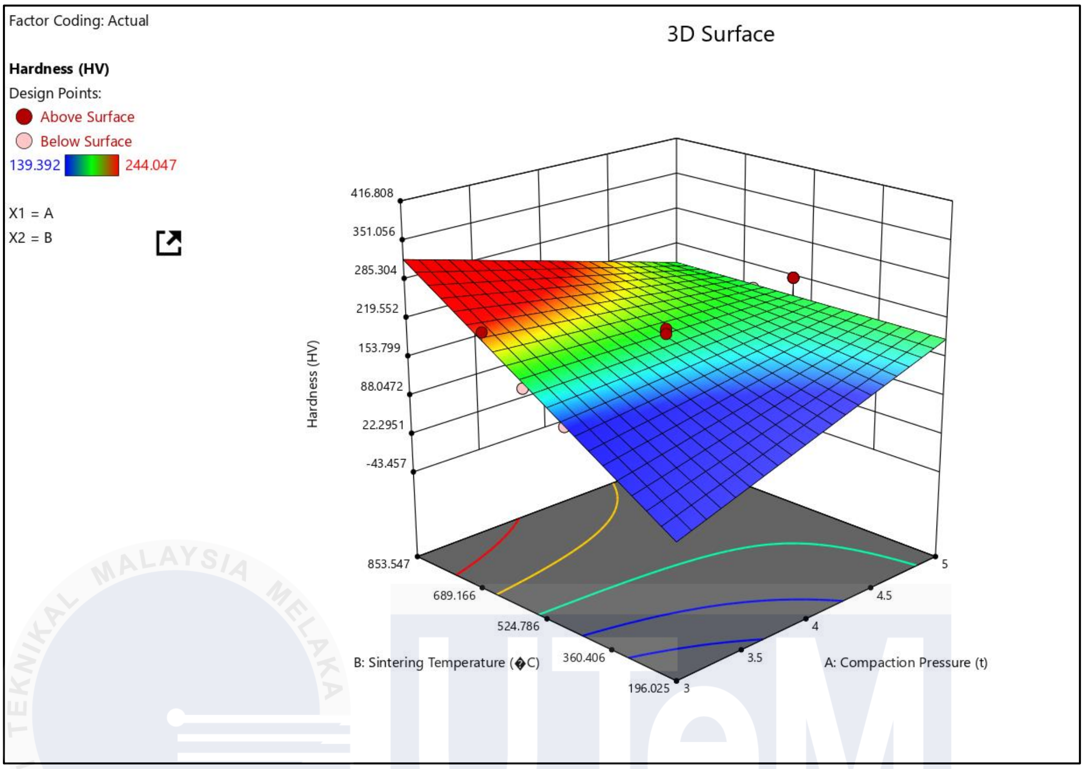


Figure 4. 2: 3D Surface Graph

4.2 Coating Layer Thickness

The experimental results for coating layer thickness and the effect of compaction pressure on coating layer thickness are shown in Table 4.3 and Figure 4.3, respectively. Figure 4.4 shows a visual of the coating layer thickness that was obtained from FESEM with different compaction pressure. It was discovered that as the compaction pressure increased from 3 tons to 5 tons, the average coating layer thickness increased. The average coating layer thickness was 8.2 µm (3 tons), 11.85 µm (4tons), and 12.5 µm (5 tons) respectively. This trend shows that when the compaction pressure increases, so does the coating layer thickness, resulting in a thick coating layer. According to Ahmed et al. (2016), 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.

Table 4. 3: Results for Coating Layer Thickness

Compaction Pressure(t)	Coating Thickness(μm)
3	8.2
4	11.85
5	12.5

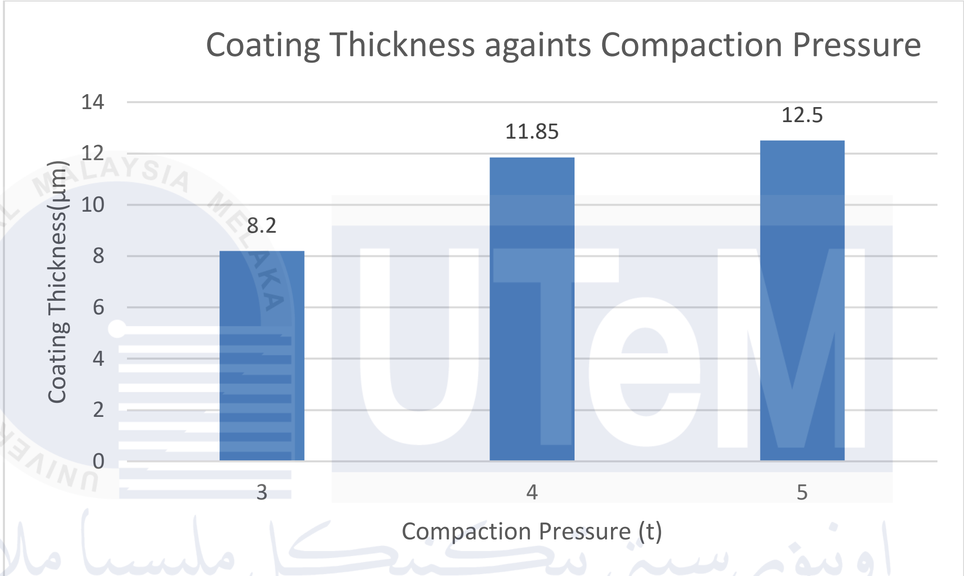


Figure 4. 3: Results for Coating Layer Thickness

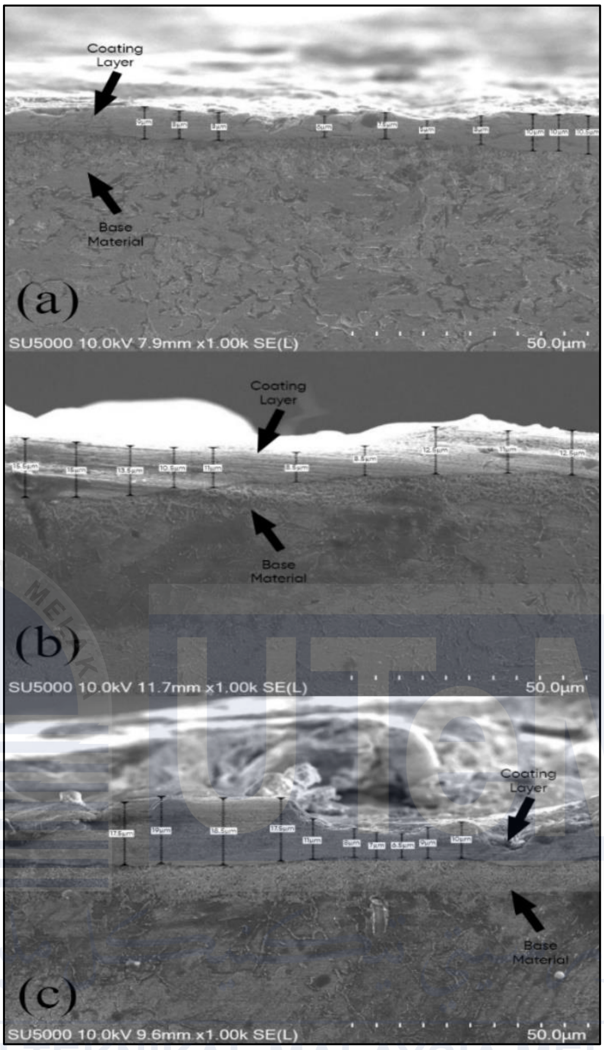


Figure 4. 4: Visual coating layer thickness (a) 3 tons (b) 4 tons (c) 5 tons.

4.2.1 Element Composition of Copper Coating Layer.

4.2.1.1 Compaction Pressure (3 tons)

Figure 4.5 shows an SEM image that displays a microscopic cross-section of 3 tons sample. A scale bar is displayed to indicate a length of 5 micrometers (µm), emphasize the utilization of high magnification to capture fine characteristics of the material structure. The image shows an intricate and layered composition, with different regions showing different textures and shapes. The outermost layer is very uniform and consistent, indicating the presence of a coating on this material. Below here, the composition changes into a more intricate and grainier region, revealing the different material elements which comprise the workpiece. A red rectangular box labeled as "Selected Area 1" is utilized to highlight certain areas of focus, indicating that this specific area is the primary subject of detailed analysis. The images from the SEM are used for material analysis.

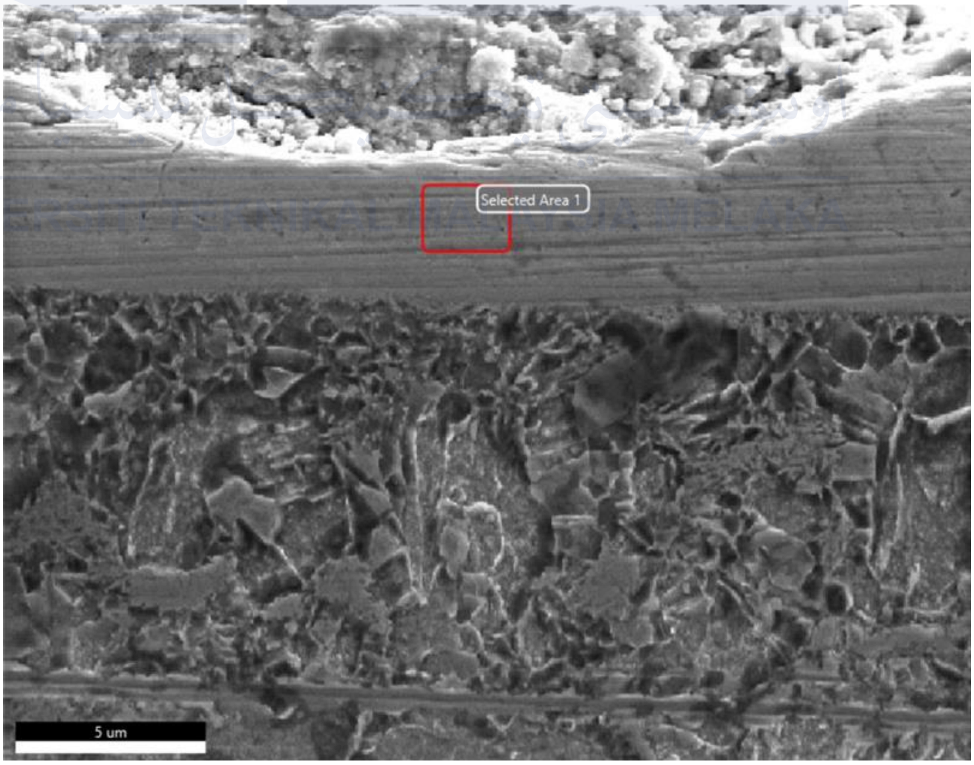


Figure 4.5: SEM image for 3tons result

Based on Figure 4.6, the weight percentage of copper (Cu) in the analysis is 73.6%. This high percentage indicates that a significant portion of the sample's mass is attributed to the Cu coating layer on the mild steel workpiece. In summary, the weight percentages obtained in the analysis reflect the relative mass contributions of carbon, iron, and Cu in the sample. The presence of carbon and iron is the main characteristic of mild steel, while the high percentage of Cu confirms migration of Cu from the PM electrode on the mild steel workpiece. Figure 4.7 shows the Energy Dispersive X-ray Spectroscopy (EDX) Spectrum for the result obtained.

Element	Weight %
C	16.3
Fe	10.0
Cu	73.6

Table 4. 4: Weight % for each element in coating layer (3 tons)

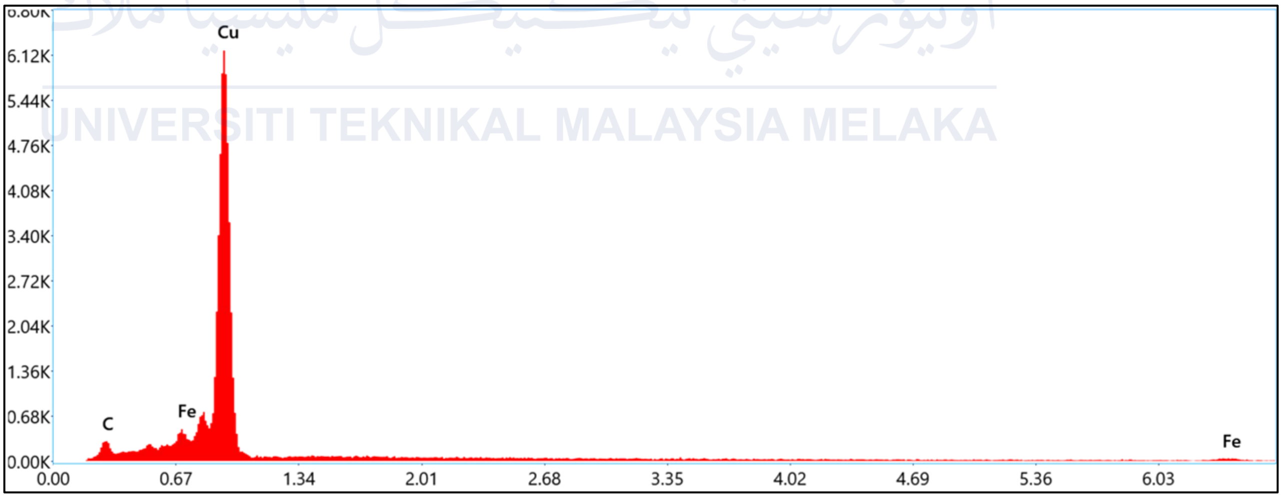


Figure 4. 6: EDX Spectrum for 3 tons

4.2.1.2 Compaction Pressure (4 tons)

According to Figure 4.8, "Selected Area 1," which can be seen as a red box, is in the uppermost layer of the image. The selected region has a more consistent and uniform arrangement structure compared to the surrounding area. The lines in this region show greater uniformity and density, indicating distinct characteristics and components within the wider area. On the other hand, the lower layer has a disordered and grainy structure, which is distinctly dissimilar to the organized pattern observed in the selected region. Here, we can differentiate the outer coating layer from the underlying material base layer.

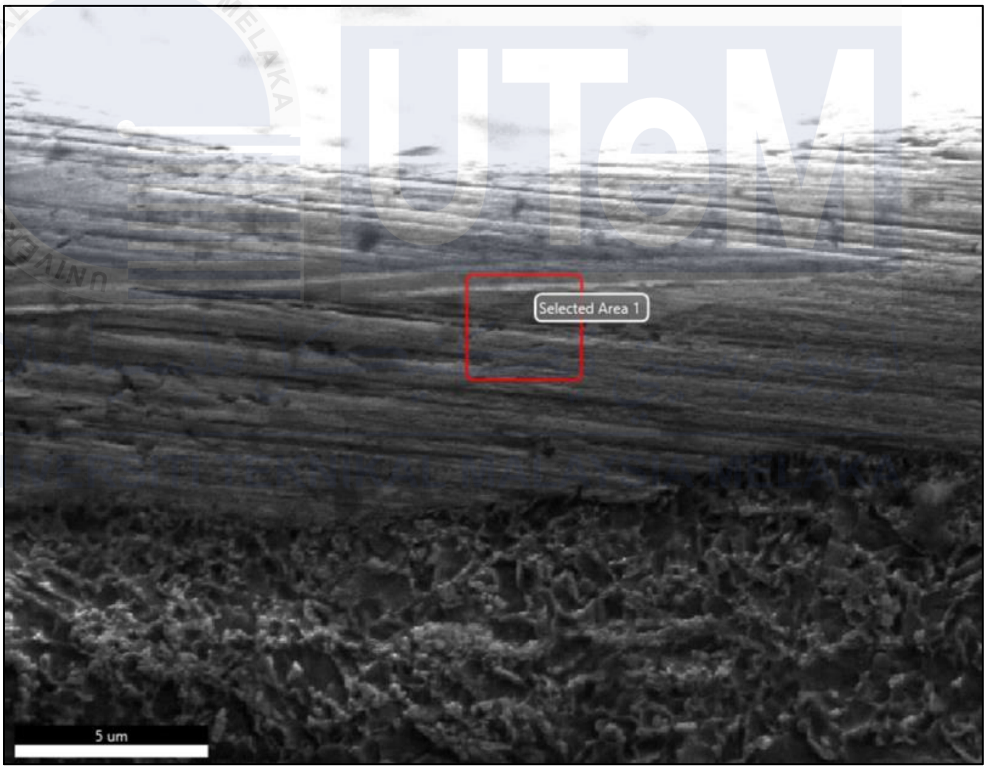


Figure 4. 7: SEM image for 4 tons

Figure 4.9 shows an in-depth description of four elements, including Carbon (C), Oxygen (O), Iron (Fe), and Copper (Cu), together with their respective weight percentages. The composition is as follows: Carbon comprises 20.0% of the whole weight, Oxygen constitutes 0.7% of the total weight, Iron represents 7.2% of the total weight, and Copper is the most prevalent element, accounting for 72.1% of the total weight. The oxygen found in the copper coating layer can be attributed to several factors. Normally, the copper oxidation process occurs when copper combines with oxygen in the air to create copper oxides, such as CuO or Cu_2O. In addition, the presence of oxygen could indicate that the coating has been exposed to an environment conducive to oxidation, such as air or moisture. Figure 4.10 shows the EDX Spectrum for 4 tons.

Element	Weight %
C	20.0
O	0.7
Fe	7.2
Cu	72.1

Table 4. 5: Weight % for each element in coating layer (4 tons)

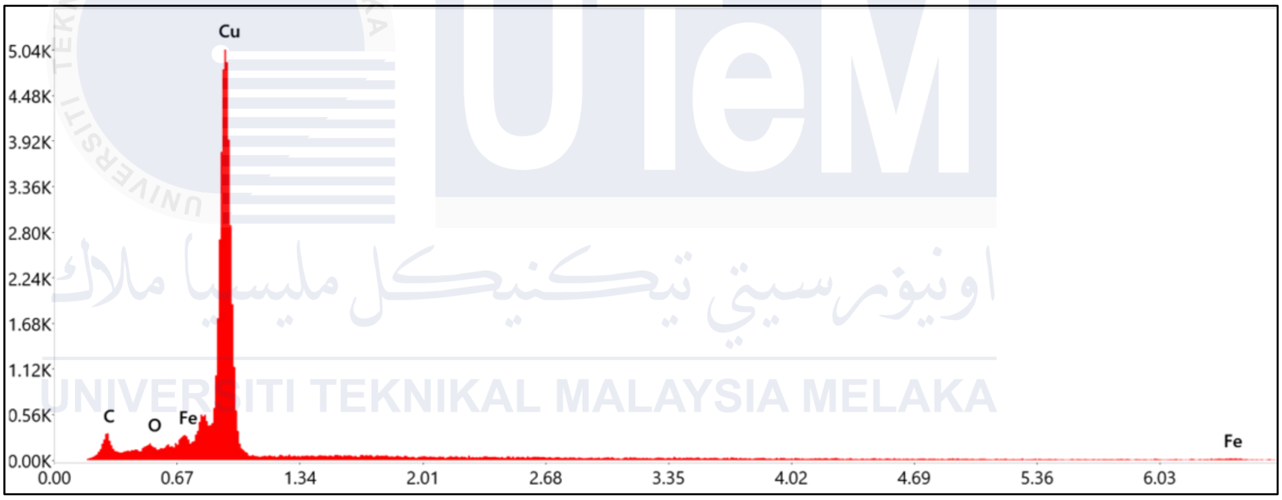


Figure 4. 8: EDX Spectrum for 4 tons

4.2.1.3 Compaction Pressure (5 tons)

Figure 4.11 shows a coating layered structure in the top area of the image, indicating the presence of different phases and layers inside the material. This occurrence may be related to a variety of factors, including differences in material compositions, deposition processes, or treatment conditions. The lower area of the image has a more porous and rough structure, indicating the presence of a different material phase and a different processing condition. The presence of this rough structure may indicate a greater degree of porosity and a different microstructural composition compared to the top layer. It is clear that the two layers are different elements, indicating that the top layer is the coating layer, and the bottom layer is the material base layer.

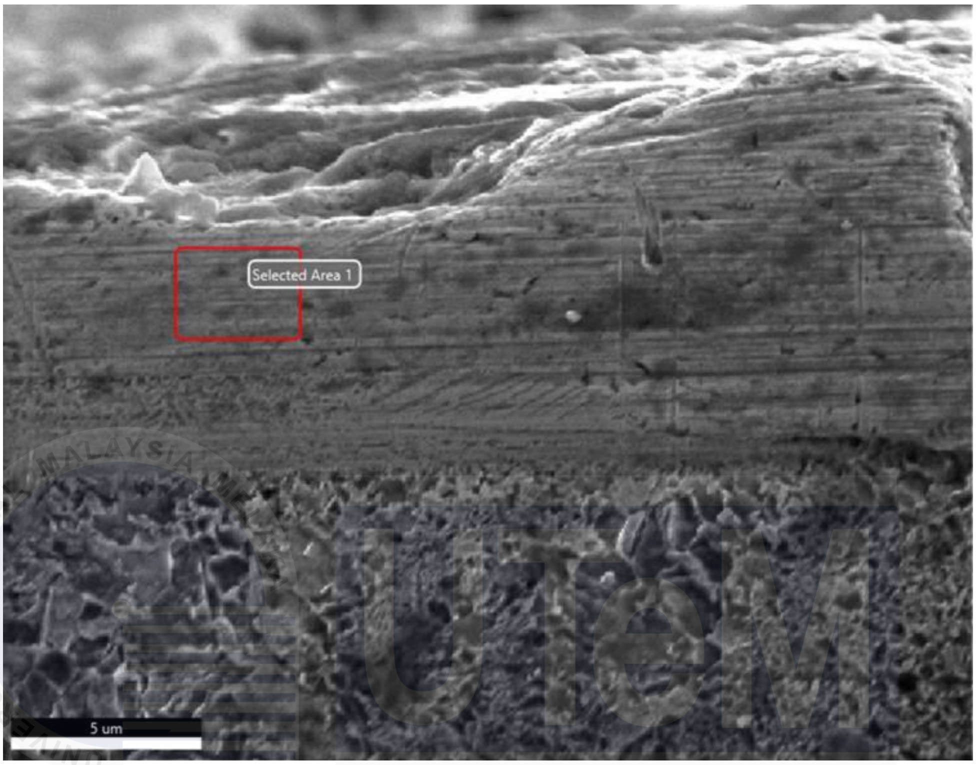


Figure 4. 9: SEM image for 5 tons

Figure 4.12 shows the weight percentage of three components, including C, Fe, and Cu, in the copper coating layer. Based on the data, Cu is the main element, comprising 65.1% of the total mass. A significant percentage indicates that Cu is the main element of the coating. The element C comprises 20.8% by weight, while Fe makes up 14.1%. The presence of C and Fe, although in smaller amounts than Cu, exists as base material elements. The presence of these additional components can affect the characteristics and performance of the copper coating, possibly affecting factors such as hardness, corrosion resistance and electrical conductivity. Figure 4.13 shows the EDX Spectrum for 5 tons.

Element	Weight %
C	20.8
Fe	14.1
Cu	65.1

Table 4. 6: Weight % for each element in coating layer (5 tons)

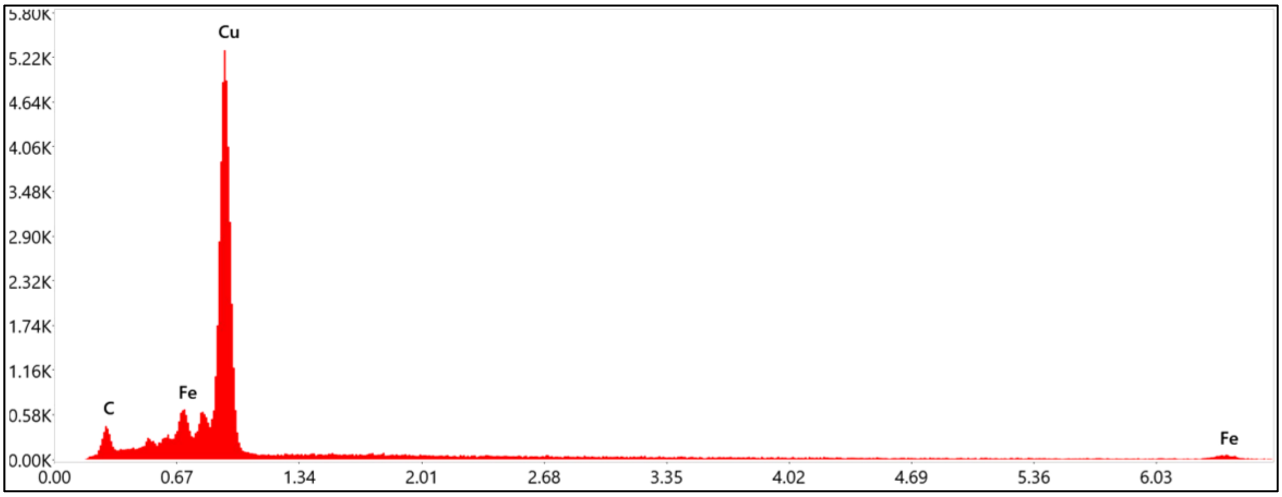


Figure 4. 10: EDX Spectrum for 5 tons

4.2.1.4 Comparison of Copper Weight % for Different Compaction Pressure

The experimental results for Cu weight % are shown in Table 4.4 and Figure 4.3, respectively. With increasing the compaction pressure from 3 tons to 4 tons, there was a slight decrease in the Cu weight percentage from 73.6% to 72.1%. This indicates that the increased pressure reduces the deposition of copper particles onto the mild steel surface, leading to a slight decrease in the copper content.

Nevertheless, when further increasing the compaction pressure to 5 tons, the copper weight percentage underwent a significant decrease, reaching 65.1%. This indicates that increased pressure leads to a lower deposition of copper particles onto the surface of mild steel, resulting in a more significant decrease in copper content. This trend is consistent with the findings of Ahmed et al. (2016). When the compaction pressure is increased, the powder particles become tightly bound together. During erosion, these particles erode as a cohesive mass and are deposited onto the workpiece.

Table 4. 7: Results for Cu weight %

Compaction Pressure (t)	**Weight %**
3	73.6
4	72.1
5	65.1

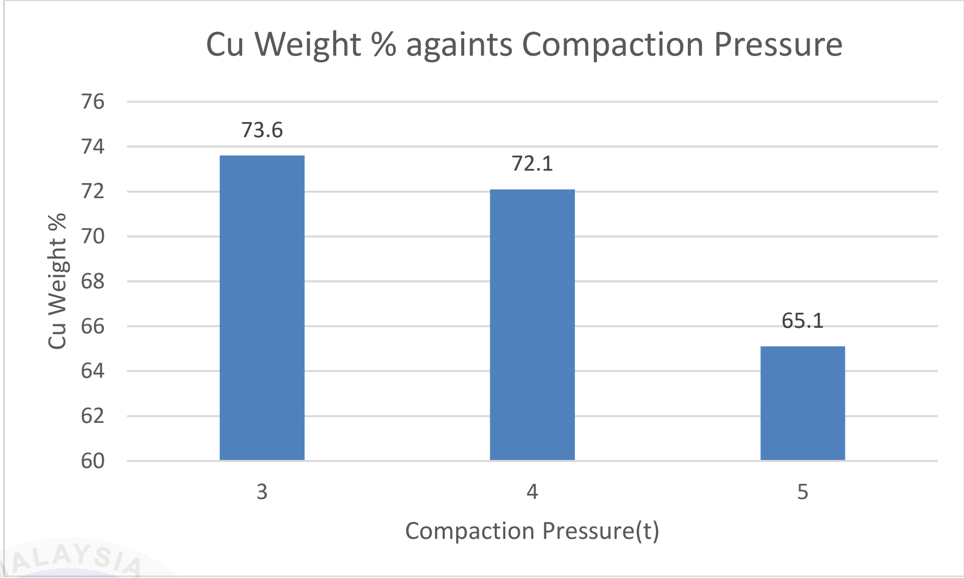


Figure 4. 11: Results for Cu weight %

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The main objective of this study is to examine how the application of compaction pressure and sintering temperature of PM electrode affect the formation of the deposition layer on mild steel. The results obtained offer useful insight into the correlation between these parameters to micro-hardness, copper weight % and the thickness of the deposited layer.

1. The microhardness results show that the maximum value is reached at a temperature of 650°C with an applied force of 3 tons, while the minimum value is seen at a temperature of 450°C with the same applied force of 3 tons. This finding shows that increasing the sintering temperature can increase the hardness of the layer formed. However, it is necessary to acknowledge that the compaction pressure also has a significant effect on the hardness of the material.

2. The maximum coating layer thickness achieved is 12.5 μm at a pressure of 5 tons and a temperature of 550°C, while the minimum thickness is 8.2 μm at a pressure of 3 tons and a temperature of 550°C. However, due to the uneven coating layers in 4 and 5 tons, the observed findings are opposite to the expected results.

3. The weight percentage of Cu reached its peak at 73.6% when the temperature was 550°C and the compaction pressure was 3 tons, while the lowest weight percentage of 65.1% was observed at 550°C with a compaction pressure of 5 tons. This finding shows that increasing the compaction pressure can reduce the weight percentage of Cu in the material.

In summary, this study offers significant insight into the correlation between compaction pressure, sintering temperature and deposited layer characteristics. These findings indicate that precise optimization of these parameters is essential to achieve the intended microhardness, copper weight %, and coating thickness in the EDC process.

5.2 Recommendation

1. Analyze the impact of different coating materials. This research focuses more on the use of copper as a coating material. Further investigation should be conducted to investigate the impact of other coating materials, such as nickel or chromium, on the characteristics of the deposited layer.

2. Investigate the impact of sintering duration. This research focused on the influence of sintering temperature on the characteristics of the layer that was deposited. Nevertheless, the duration of sintering is another significant factor that may influence the characteristics of the material. Further research should investigate the effect of different sintering durations.

3. Conduct a mechanical property testing. Increasing the scope of mechanical property tests, such as tensile strength, fatigue resistance, and wear resistance, would result in a more comprehensive understanding of the material's behaviors in different conditions.

5.3 Sustainable Design and Development

This research investigates the application of EDM using PM copper electrodes to improve the surface characteristics of mild steel. This approach is consistent with sustainable design principles by increasing the durability of mild steel, thus extending its lifespan and reducing the need for frequent replacement. The use of PM copper electrodes emphasizes the efficient use of materials and may reduce the environmental impact compared to conventional methods.

5.4 Complexity

This research involved a complex problem-solving task by investigating the interaction between different parameters such as compaction pressure and sintering temperature and their effect on mild steel properties. The detailed process, which involved the use of state-of-the-art machinery such as the Shimadzu Vickers Microhardness Tester and the FESEM Hitachi SU 5000, demonstrates the complexity of the engineering activities involved throughout the research.

5.5 Life Long Learning (LLL)

This research emphasizes the importance of life long learning by providing recommendations for further research. It recommends investigating the effects of various coating materials and sintering durations, as well as doing additional mechanical property tests. These suggestions indicate a dedication to continuous development and the acquisition of information in the field of material science.

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