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***Research paper***

# The Effect of Powder Metallurgy Parameters on Electrical Conductivity of Copper-Nickel-Tungsten Electrode

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## Abstract

Powder metallurgy is a manufacturing process to produce a specific shape of product by using powder as the raw material. Using this technology powder can be mixed with different types of powder material to enhance the properties of the product as required. In addition, properties such as thermal, electrical and microstructure properties of the material can be efficiently controlled by controlling a numbers of parameters such as compressive load, particle size and sintering temperature of the process. This research discusses the effect of the pressure applied, the temperature of sintering, and the powder composition on the electrical conductivity of the Electrical Discharge Machining (EDM) electrode produced by powder metallurgy. Three different powder types of Copper (Cu), nickel (Ni) and tungsten (W) were mixed in this experiment with several ratios to produce the composite metal product. Several compressive load were tested to produce green compact electrode which are 7 tons, 8 tons and 9 tons. Three different sintering temperatures of 635ºC, 685ºC and 735ºC were also tested in sintering process of the green compacted electrode. In this experiment it was found that all investigated parameter significantly influenced the response. Through the analysis, the optimum electrical conductivity of EDM electrode was obtained by using 7 tonne, 5% W, and 735°C, for compaction load, composition, and temperature respectively. The highest electrical conductivity obtained is 16.425 µOhm cm.

***Keywords***: *Powder metallurgy; Electrical conductivity; Density; Porosity; Microstructure; EDM electrode*

## 1. Introduction

A composite is made by physically combine two or more materials to produce a structural property that is not exist in any individual material. Metal matrix composites are composite materials comprising of at least two basic parts. One being a metal and the other part may be a different metal or another material, such as ceramic or organic compound. It can be produced by dispersing a reinforcing material into a metal matrix. For the last two decades, metal matrix composites (MMC's) have grown great importance and their application have gradually become well known [1, 2].

EDM is a machine that is using electrode to produce the electrical sparks for material removal process. This sparking process is occurred in between electrode and work piece [3, 4]. The important characteristic of the electrode includes; electrical conductivity, thermal conductivity and temperature resistivity. Powder metallurgy (PM) is one of electrode manufacturing processing technology in which the metal powder is compacted into desired electrode shape and sintered to form a solid piece. Electrical discharge machine (EDM) electrode production using powder metallurgy believed as able to produce product that meets the require specification. In powder metallurgy process of Copper-Tungsten (Cu-W), transition metal such as Nickel (Ni) is usually added to lower the activation energy of sintering, that consequently lowered the sintering temperature [5]. This process is called solid state activated sintering [6]. In Cu-W composites, addition of Ni provide better wettability and adhesion of W and Cu was found [5, 7]. Recently it was mentioned that the Cu-Ni electrode provides better surface finish then the ordinary Cu-W electrode especially in micro-EDM of Polycrystalline Diamond (PCD) [4, 8] . The Ni will not only act as the activator during solid phase sintering but also theorized acting as the graphitization catalyst during Electrical Discharge Machining of PCD[9].

Manufacturing of EDM electrodes usually done by using conventional alloying techniques which is casting. However, this techniques are fit only for less complex formed electrodes [10]. In fact, high differences in melting temperature of alloying materials gives challenge to the casting process. Composites with 10 to 40 Wt% Cu are commonly produced by infiltration technique; while at higher Cu contents, a pure powder metallurgy route is used, so that the two powders are blended, pressed, and subsequently sintered in solid state [11] . In the case of Cu-Ni-W production, Copper with vaporisation temperature of 1083˚C [12] is expected to vaporize first before tungsten began to melt at temperature 3422℃ [7]. Hence, powder metallurgy is believed to provide better ability in combining several alloying materials. Powder metallurgy process included mixing process, compaction process and solid-state sintering process as shown in figure 1.


**Figure 1:** Method of the process of powder metallurgy

Due to its ability to produce good surface finish of Polycrystalline diamond (PCD) in EDM, Copper Nickle (Cu-Ni) electrode was regarded as candidate to replace Copper Tungsten (Cu-W) in EDM electrode application. Adding W into Cu-Ni is expected to further improve the wear resistance property of the electrode material. This research was designed to determine the suitable powder metallurgy parameter to produce new Cu-Ni-W electrode. The response of interest in this investigation is the electrical conductivity of the newly developed electrode.

Ni has a significant effect on the physical properties and mechanical properties of Cu-Ni. Cu-Ni alloys show a strong tendency to absorb gas as Ni content and temperature rise. It is known that the solubility of hydrogen and oxygen is rapidly decreasing during the transition to solid state and the pores and the vent holes then occur, since the gas is usually unavailable [13]. This is because the W is a refractory metal with a high melting point and Cu has a good thermal conductivity, as shown in Table 1 [14].

**Table 1:** Physical and properties of Copper, Nickel and Tungsten

| | **Copper** | **Nickel** | **Tungsten** |
|---|---|---|---|
| **Molecular formula** | Cu | Ni | W |
| **Molecular weight (g/mol)** | 63.546 | 58.71 | 183.84 |
| **Density (g/cm$^3$)** | 8.9 | 8.9 | 19.3 |
| **Melting Point ($^o$C)** | 1083 | 1455 | 5900 |
| **Thermal Conductivity (W/m.K)** | 385 | 90 | 180 |
| **Electrical Conductivity (μohm.cm)** | 1.7 | 7 | 5.28 |

This paper discusses the effects of powder metallurgy parameters on electrical conductivity of Cu-Ni-W composites. Therefore, in this research, development of Copper-Nickel Tungsten electrode properties was believed to give better improvement in EDM of PCD in comparison to the present available electrodes.

## 2. Methodology

### 2.1. Material Preparation

Raw powders of Cu (100 wt.% and 45µm), Ni (99 wt.% and 45µm) and W (99.95wt.% and 10µm) were used as raw materials. Zinc stearate was used as a lubricant in this experiment. The Coarse and fine-grained elements of Cu-Ni-W powder metals containing 5 wt.%, 15wt.% and 25 wt.% of W was at first mixed and blended into a fully homogeneous mixture by using a ball milling machine.

Table 2 shows the variation of Cu-Ni-W used in which the ratio of Cu to Ni in Cu-Ni is 70:30. Mixing process was carried out at constant rate of 200rpm for 2hr to produced homogenous mixture. Figure 3 shows the ball milling machine and ceramic beaker used for mixing process.

**Table 2:** Variation of Cu-Ni-W

| **Composition, Wt.%** | |
|---|---|
| **Cu-Ni** | **W** |
| **95** | 5 |
| **85** | 15 |
| **75** | 25 |


**Figure 2:** Ball milling machine and ceramic beaker

### 2.2. Compaction Process

The compaction process is the main process in this research in which the mixed powder is compacted to form green compact product. The high load that applied to the powder creates bonding that maintained the shape of electrode. Figure 3 shows the hydraulic press machine. The compaction load of 7 tonne, 8 tonne and 9 tonne were used in this study.

**Figure 3:** Hydraulic press machine

### 2.3. Sintering Process

The green compacts were sintered in a tube furnace with the presence of argon gas at varied temperatures; 635°C, 685°C and 735°C . Figure 4 shows the cycle for this sintering process.

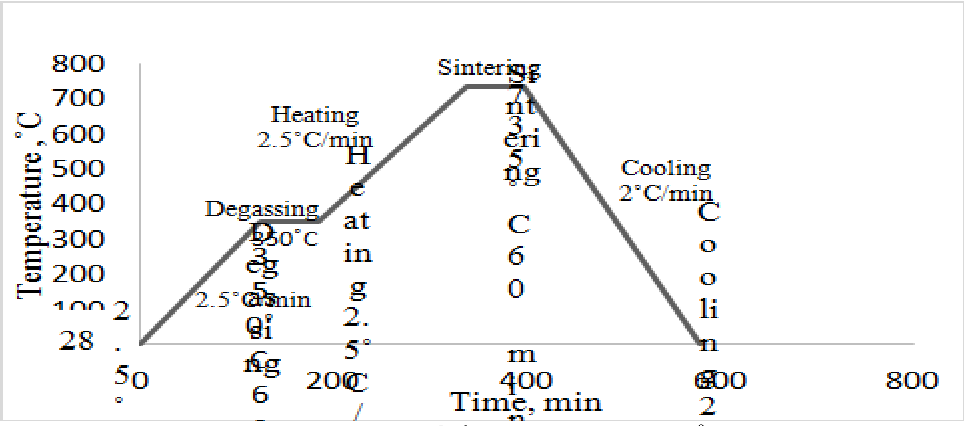


**Figure 4:** Heating Cycle for sintering process at 735 °C

### 2.4. Experimental Analysis

In this research, the data obtained from experimental will be analyzed by 2-level Full Factorial Design of Experiment (DOE). Electrical conductivity is an important characteristic of EDM electrode. The higher the electrical conductivity of the electrode is, the faster is the charging process of the electrode (better energy supply rate). This ensures bigger energy will be supplied during the pulse-ON duration of EDM. Figure 5 shows the 4-point probe Pro4 used for the electrical conductivity test.


**Figure 5:** 4-point probe Pro4

## 3. Result and Discussion

### 3.1. ANOVA Analysis

All responses were statistically analyzed through Analysis of Variance (ANOVA) to determine the significant factors including single and interaction. Total number of 19 experiments were implemented in this research. Figure 6 shows half-normal probability graph for Electrical Conductivity analysis.

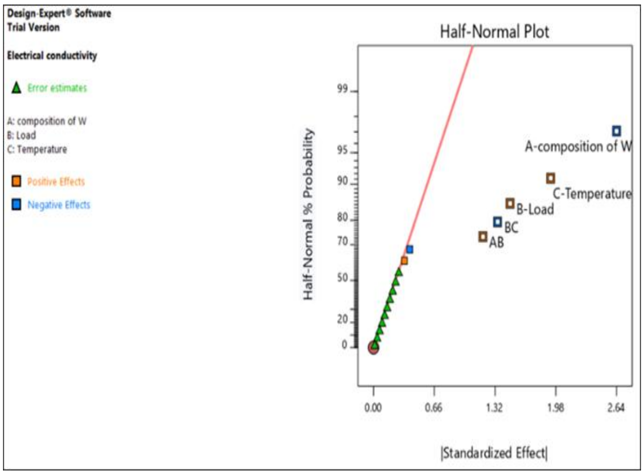


**Figure 6:** Half-Normal Plot for electrical conductivity

Table 3 shows the revised ANOVA for electrical conductivity test. From the ANOVA analysis, the lack of fit value was not significant, means that the data for the experiment are matched well with the model. The lack of fit value is 0.3833. The curvature was found as not significant as the p-value of 0.8475 was obtained. Therefore, no axial points are needed to be added for the additional analysis. This indicates that the 3-dimensional response plot of the experimental model is in a linear plane graph. This analysis also shows the significant effect of the major factors that termed as A, B, C and interactions between two factors which are AB and BC (the affect is categorized as significant effect if the p-value of less than 0.05 is obtained).

**Table 3:** Revised ANOVA of electrical conductivity

| Source | Sum of Squares | df | Mean Square | F-value | p-value | |
|---|---|---|---|---|---|---|
| **Model** | 64.46 | 5 | 12.89 | 25.24 | < 0.0001 | significant |
| A-composition of W | 27.90 | 1 | 27.90 | 54.62 | < 0.0001 | |
| B-Load | 8.81 | 1 | 8.81 | 17.24 | 0.0013 | |
| C-Temperature | 14.82 | 1 | 14.82 | 29.03 | 0.0002 | |
| AB | 5.66 | 1 | 5.66 | 11.07 | 0.0060 | |
| BC | 7.27 | 1 | 7.27 | 14.24 | 0.0027 | |
| Curvature | 0.0197 | 1 | 0.0197 | 0.0386 | 0.8475 | |
| **Residual** | 6.13 | 12 | 0.5107 | | | |
| Lack of Fit | 1.07 | 2 | 0.5348 | 1.06 | 0.3833 | not significant |
| Pure Error | 5.06 | 10 | 0.5059 | | | |
| **Cor Total** | 70.61 | 18 | | | | |

## 4. Page layout

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As shown in table 4, the Predicted $R^2$ of 0.7790 is in a reasonable agreement with the Adjusted R-square of 0.8770 as the different value is less than 0.2. The Adeq Precision of 16.3757 was found greater than 4, indicates an adequate signal.

**Table 4:** Value of R-Squared electrical conductivity

| | | | | |
|---|---|---|---|---|
| **Std. Dev.** | 0.7147 | | **$R^2$** | 0.9132 |
| **Mean** | 13.77 | | **Adjusted $R^2$** | 0.8770 |
| **C.V. %** | 5.19 | | **Predicted $R^2$** | 0.7790 |
| | | | **Adeq Precision** | 16.3757 |

### 3.2. Mathematical models

Mathematical models for each response were obtained as the following:
The final equation in terms of coded factors for electrical conductivity;
*Electrical conductivity (µ Ohm / cm) = 13.78 - 1:32 (A) + 0.7419 (B) + 0.9626 (C) + 0.5946 (AB) + 0.16779 (AC) - 0.6742 (BC)*
The final equation in terms of actual factors for electrical conductivity;
*Electrical conductivity (µ Ohm / cm) = - 66.66948 - 0.837426 (A) + 9.08646 (B) + 0.122091 (AC) + 0.0003335 (AC) - 0.013484 (BC)*

### 3.3. Optimum Condition

**Table 5:** Configuration Maximize Electrical conductivity

| Name | Goal | Lower Limit | Upper Limit | Lower Weight | Upper Weight | Importance |
|---|---|---|---|---|---|---|
| A:composition of W | is in range | 5 | 25 | 1 | 1 | 3 |
| B:Load | is in range | 7 | 9 | 1 | 1 | 3 |
| C:Temperature | is in range | 635 | 735 | 1 | 1 | 3 |
| Electrical conductivity | maximize | 9.077 | 17.382 | 0.870964 | 1 | 3 |
| Porosity | none | 2.3897 | 23.6989 | 1 | 1 | 3 |

| Number | composition of W | Load | Temperature | Electrical conductivity | Desirability | |
|---|---|---|---|---|---|---|
| **1** | **5.000** | **7.000** | **735.000** | **16.425** | **0.899** | **Selected** |
| 2 | 5.009 | 7.010 | 735.000 | 16.418 | 0.898 | |
| 3 | 5.000 | 7.018 | 735.000 | 16.416 | 0.898 | |
| 4 | 5.000 | 7.028 | 735.000 | 16.410 | 0.897 | |
| 5 | 5.087 | 7.000 | 735.000 | 16.410 | 0.897 | |
| 6 | 5.022 | 7.000 | 734.560 | 16.408 | 0.897 | |
| 7 | 5.000 | 7.049 | 735.000 | 16.399 | 0.896 | |
| 8 | 5.165 | 7.000 | 735.000 | 16.396 | 0.896 | |
| 9 | 5.000 | 7.000 | 733.872 | 16.392 | 0.895 | |
| 10 | 5.000 | 7.040 | 734.454 | 16.388 | 0.895 | |

Figure 7 shows the optimum 3D surface plot for optimum electrical conductivity. The optimum for electrical conductivity in this study is 16.425 µOhm cm when 7 tonne, 5% W, and 735°C for compaction load, composition, and sintering temperature respectively used as the processing parameter. This is due to the fact that increasing the composition of tungsten significantly caused to lower electrical conductivity[1]. However, as the compaction load and sintering temperature are also significant, different parameter combination believed as significantly altered the structural properties, brought into the significant different in electrical conductivity.

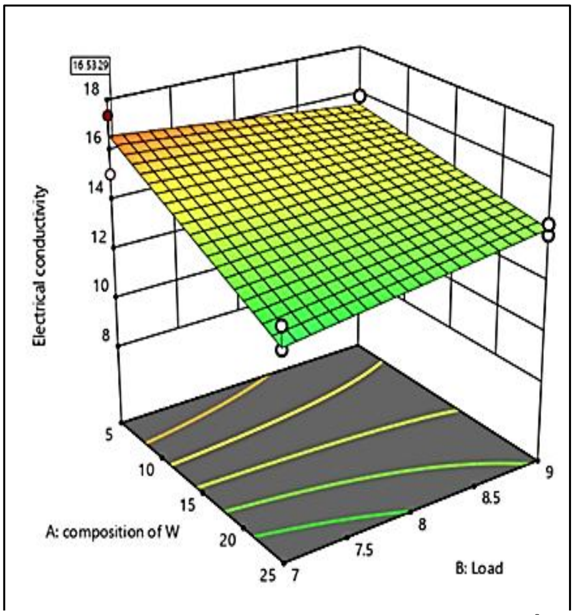


**Figure 7:** Optimum 3D surface electrical conductivity with the used of 735°C of sintering te

### 3.4. Confirmation testing

Confirmation test was done to validate the model. For this testing, the combination of parameters as shown in the table 6 were tested.

**Table 6:** Parameter used for confirmation test

| No | Composition of W, wt% | Load, tonne | Sintering Temperature °C |
|---|---|---|---|
| 1 | 10 | 8 | 685 |
| 2 | 20 | 8 | 685 |
| 3 | 15 | 7.5 | 685 |
| 4 | 15 | 8.5 | 685 |

Table 7 shows the predicted and experimental values obtained, Table 8 shows the errors calculated for each test performed. From the analysis, maximum of only 3.345% error was obtained. This model is in acceptable accuracy as the errors were within the prediction confident interval of 95%.

**Table 7:** The predicted and experimental value of Electrical Conductivity

| No | Predictable Responds for Electrical Conductivity (µOhm.cm) | Actual Responds for Electrical Conductivity |
|---|---|---|
| 1 | 14.4429 | 14.3410 |
| 2 | 13.1224 | 13.0156 |
| 3 | 13.4117 | 12.9631 |
| 4 | 14.1537 | 13.8521 |

**Table 8:** Experimental errors

| No | Different in Electrical Conductivity (µOhm.cm) | Error in Electrical Conductivity (%) |
|---|---|---|
| 1 | 0.1019 | 0.706 |
| 2 | 0.1069 | 0.815 |
| 3 | 0.4486 | 3.345 |
| 4 | 0.3016 | 2.130 |

## 4. Conclusion

Production of powder metallurgy requires certain parameters controls on temperature, load, and powder composition. Through ANOVA analysis, Main Factor, A (Composition), Main Factor B (Compaction load), and Main Factor C (Sintering Temperature) were significantly influenced the electrical conductivity of the electrode. From the optimization analysis, it can be concluded that the best parameter to obtain maximum electrical conductivity is 7 tonne, 5% W, and 735°C, for compaction load, composition, and sintering temperature respectively. The optimum result obtained for the electrical conductivity is 16.425 µOhm cm. The understanding is important as it will significantly influence the quality of the product. As this is a preliminary investigation, further investigation to explain the phenomenon is required. It was theorised that the electrical conductivity is not only caused by the W contents, but also due to some structural properties including the porosity density and other defects.

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