

## Investigation of microstructural, mechanical, and electrical characteristics of CuNi5W alloy synthesized by warm compaction

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### Abstract

In the Electric Discharge Machining (EDM) process, electrode materials require high electrical conductivity and sufficient mechanical strength. These electrodes can be fabricated by the Powder Metallurgy (PM) technique from copper-based alloys. The electrode strength can be improved by adding refractory materials through a properly selected warm compaction parameter, such as temperature and pressure compaction. The study focused on analyzing microstructural changes, compressive strength, hardness, and electrical behavior of the alloy. High-purity (Cu, Ni, W) elements were synthesized by warm compaction with different penetration loads and temperatures to produce CuNi5W alloys. The physical, mechanical, and electrical testing were carried out at room temperature. The results indicate that incorporating tungsten (W) into Cu-Ni-based alloys, combined with higher compaction temperatures and pressures during warm compaction, leads to an improvement in density, hardness, and electrical conductivity. The optimum values for these properties were achieved in the Cu-Ni-W-based alloy compacted at 250°C and 250 MPa. The CuNi5W alloys exhibited a microstructure characterized by a solid solution matrix in which tungsten particles were evenly distributed, playing a key role in enhancing the hardness of the model CuNi5W-based alloy.

### Keywords:

Alloys, electrical conductivity, microstructure, mechanical properties, warm compaction.

### 1 Introduction

Pure copper and its alloys are essential materials in engineering, notably for fabricating electrical components such as Electric Discharge Machining (EDM) electrodes [1]. These components require both excellent electrical conductivity and adequate mechanical strength. The combinations of Cu and Ni, along with the addition of other elements that can act as strengthening agents and the correct selection of process parameters successfully improve the mechanical properties [2]. The characteristic improvement of the alloys can be done by various methods, such as the addition of elements like Si, Gr, Al, SiC, Cr, Ti, and B4C [3]. The addition of refractory elements such as W into Cu alloy improves the hardness, as the increase in the W elements increases the hardness, while the addition of Cu tends to decrease resistivity and hardness [4], and varying the proportions of Cu-Ni-Si-(Ti) has a significant impact on the resulting hardness [5]. Furthermore, material candidates for EDM electrode materials have been developed by a combination of Cu-Ni-W synthesized by powder metallurgy method with 735°C sintering temperature and 7 tons of compaction load [6]. The parameters of a powder metallurgy contribute to improving the characteristics of the alloys. Among the key processing parameters,

sintering temperature plays a significant role; higher temperatures tend to improve both the densification and strength of Cu-Ni-Ti alloys [7]. The compaction stages of powder are also important; the increases in compaction load result in better mechanical properties of the Cu-Ni alloy [8]. The cold compaction method has been employed to produce various model alloys, including Cu-Ni-W with different tungsten contents [9]. In another study, Cu-Al-Ni-Ag alloys were synthesized using cold compaction at 400 MPa for 5 minutes, followed by vacuum sintering with two holding stages at 150°C and 550°C (each for 30 minutes) until reaching a final temperature of 850°C, and subsequently subjected to quenching. The results showed that water quenching led to higher hardness and ultimate compressive strength [10]. A uniform distribution of the Y<sub>2</sub>O<sub>3</sub> nanoparticles within a Cu-matrix was observed with process parameters using cold compaction at 700 MPa, subsequent high temperature sintering at 950°C [11]. The compaction model in the powder metallurgy technique is mainly divided into two methods based on temperature, namely cold compaction [12] and warm compaction [13], and further hot compaction, which is a combination of high temperature and pressure at the same time. The most influential factors in the hot compaction method are pressure and temperature. These two variables produce denser material with a higher density than that produced by cold compaction [14].

The fabrication of ultrafine-grained Cu-0.8 wt.% C bulk alloys was achieved through spark plasma sintering at 800°C, starting from nanocrystalline powders produced by high-energy mechanical milling [15]. Processing parameters, such as manufacturing under hot press conditions (1030°C, 40 MPa, 1 h) with nitrogen gas protection and sintering in a vacuum furnace (10 mbar, 2 h, 950°C), were reported to improve the hardness of (CuNiSi)-xAl alloys [16]. Conversely, an increase in compaction pressure during the processing stage alters the compressive strength of Al-Si-Cu-based alloys [17]. Additionally, the applied pressure during compaction in powder metallurgy is believed to play an important role in the final density improvement of the alloys. The geometrical aspect ratio, calculated from the sample's height and diameter, is strongly correlated to the compaction properties, density, and hardness of sintered Cu powder [18]. Particularly for warm compaction, this method uses low temperature with easier-to-control parameters, process, and control oxides or contaminants. Furthermore, the FeSiCr composite with a warm compaction process reduces internal porosity, as well as strengthens microstructural homogeneity [19]. Warm compaction at 130°C can increase plasticity, green density, and stress uniformity to exceed the performance of cold compaction [20] and the densification mechanism and microstructure evolution of TiC/316L composite with warm compaction stabilizes the shape and can reduce defects [21] were reported.

It has been clearly established that the parameters involved in the compaction process significantly shape the behavior of model alloys. However, the study on the introduction of warm compaction with different loads on the synthesis of the Cu-Ni alloy with the addition of 5 wt.%W and its effect on the characteristics of the model alloys is still limited. The present study focuses on investigating the role of the warm compaction temperature and load on mechanical properties such as hardness, compressive strength, microstructure, and electrical conductivity.

### 2 Materials and methods

In this study, the model CuNi5W alloy was produced by using powder metallurgy through a warm compaction process. High purity powders (> 99.0%) consisting of transition elements (Cu, Ni) act as a matrix and reinforcement W element, which have (30~40) μm particle size as the starting material. The schematic stages of the powder metallurgy process as shown in Fig. 1. The Cu and Ni have been used as a matrix with a 90/10 Cu/Ni ratio of 95 wt.% of their constituent element and an additional 5 wt.% W. These powders were mixed using horizontal milling, in which a hard steel ball with 8 mm diameter was used as grinding media with a 10:1 Ball-to-Powder Ratio (BPR). The mixing process was performed at 300 rpm

for 2 h, after which the blended powder was warm-compacted at sample temperatures (°C) labeled C1–C3 and pressures (MPa) labeled T1–T3 (see Table 1). The 95(CuNi)-5 wt.%W alloys were divided into six model alloys according to pressure and temperature

parameters. The green compact material was further sintered at 770°C for 120 minutes to obtain final densification. The specimen preparation and standard material are referred to ASTM B 925-03 [22] for each mechanical testing.

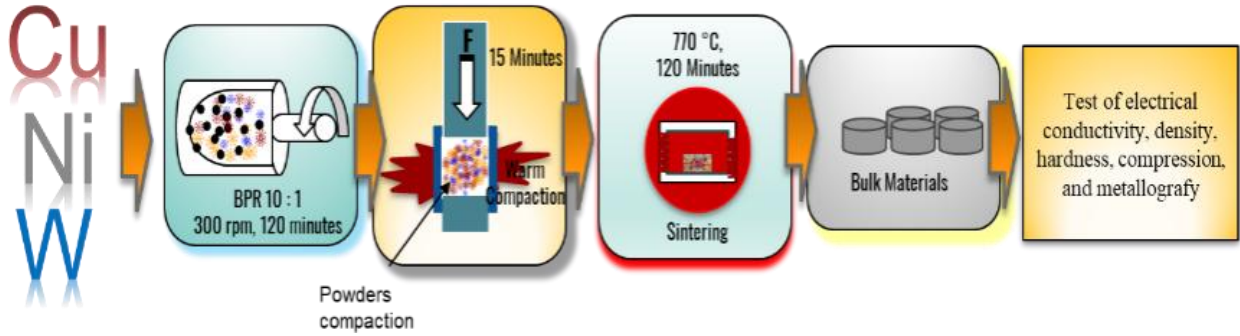


Fig. 1. The schematic representation of the synthesis stages of the Cu-Ni-W model alloy and its testing.

The characteristics of 95(CuNi)-5 wt.%W alloys were investigated by varying the testing conditions. The bulk density of the model alloys was measured using Archimedes' principle. The mechanical properties of the specimen consist of a hardness test with a Vickers hardness tester, TMTECK HV-1000D, based on the ASTM E384 [23] standard, with a load of 100 g, and a compression test conducted with a loading rate of 5 mm/min at room temperature. The electrical conductivity properties of the model alloys were measured using a Keithley machine. Meanwhile, the microstructural observation of the specimen was performed using a Metallurgical Microscope at 100x magnification, with type Rax Vision No.545491, MM-10A, 230V-50Hz has been used.

Table 1. Compaction condition for the synthesis of 95(CuNi)5W alloy

Alloys designation	P (MPa)	T (°C)
(CuNi)W-C1	190	150
(CuNi)W-C2	220	150
(CuNi)W-C3	250	150
(CuNi)W-T1	250	100
(CuNi)W-T2	250	200
(CuNi)W-T3	250	250

### 3 Results and discussion

#### 3.1 Microstructure of the alloys 95CuNi-5 wt.%W

Fig. 2 presents the microstructure observation of the CuNi-based alloys, in which the microstructure consists of three main areas, namely a reddish color indicating the Cu-rich phase, a light green area representing the CuNi solid solution phase, and dark regions corresponding to porosity. Fig. 2(a)-Fig. 2(c) shows the microstructure of the 95(CuNi)-5wt.%W alloys with different compaction pressures. In Fig. 2(a), the microstructure of the (CuNi)W-C1 model alloy with 190 MPa compaction pressure, a non-homogeneous distribution of the CuNi and Cu-rich phases with small porosities less than 10 μm dispersed in the microstructure. An increase in compaction pressure up to 250 MPa results in a slightly denser microstructure and reduced porosity. The addition of 5 wt.%W tungsten is hard to detect by OM, but with their high melting temperature, these elements are believed to disperse between CuNi and Cu-rich phases, and they can act as dispersion strengthening [24]. The microstructure of the (CuNi)W-T1 alloy at different compaction temperatures (100-250°C) is presented in Fig. 3(a)-Fig. 3(c). It can be seen that the introduction of temperature during the compaction process contributed to microstructure evolution, which in a more homogeneous distribution of CuNi and Cu-rich phases. On the other hand, a homogeneous distribution of the finer oxides and porosities was obtained with compaction temperature 100-200°C. In addition, the increase of temperature to 250°C promoted larger oxide particles. This fact increases more oxidation in the (CuNi)W-T3 alloy. Temperature plays an important role in the oxide formation [25]. Higher compaction temperatures were reported to generate

more oxides in the Cu-7.0Ni-1.75 Si-0.5 Cr alloys [26]. The relationship between compaction pressure and sintering temperature on the shape and size of porosity in metal powder-based alloys has been reported in previous studies [27]. Varying factors could influence the microstructure of an alloy, not only processing parameters but also the alloying content of the model alloys.

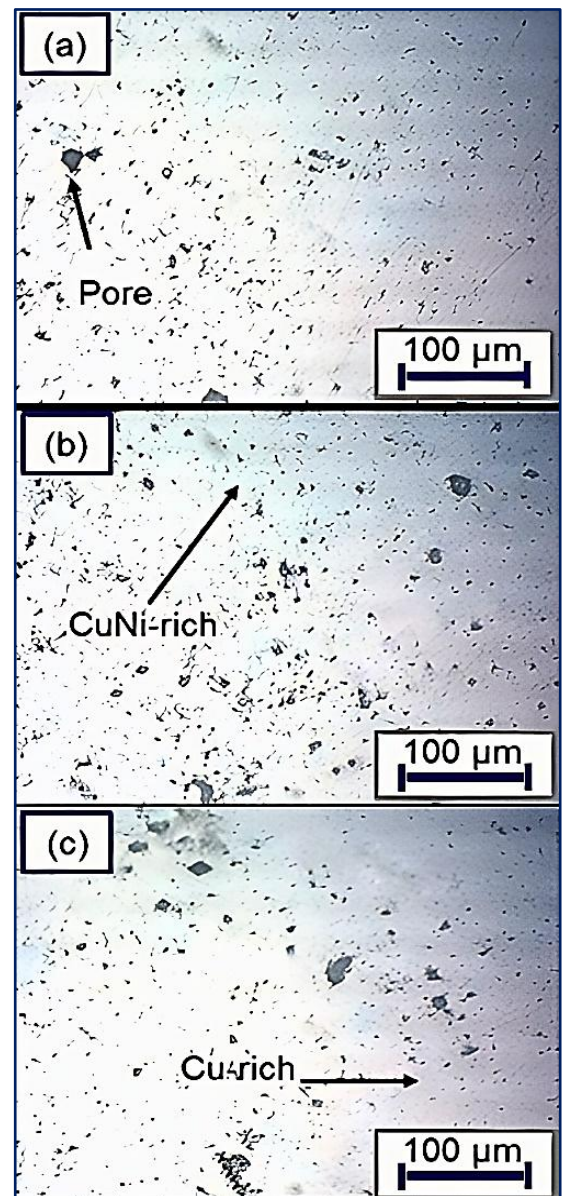


Fig. 2. Microstructure of 95(CuNi)-5 wt.%W alloys at varying compaction pressures: (a) 190 MPa, (b) 220 MPa, and (c) 250 MPa.

The introduction of varying warm compaction parameters has an impact on the quality of the compact material, but it is not significant. Furthermore, the characteristics of the model alloys are influenced

by the sintering process at high temperatures. Densification occurs through diffusion during the sintering process [28]. The changes in the microstructure occurred significantly after sintering and influenced the characteristics. The effect of compaction clearly has an influence on microstructural changes; it has been reported that increasing compaction pressure tends to reduce the formation of porosity in Cu-based alloys, which will certainly have a good effect on alloy characteristics such as mechanical properties and electrical conductivity [29]. The increased amount of porosity has a negative impact on the thermal conductivity, electrical, and mechanical properties of the material [30]. The presence of porosity is a common problem in powder metallurgy techniques, where the infiltration of oxygen or other contaminants during the powder mixing process promotes the formation of porosity, oxides, and carbides during sintering [10].

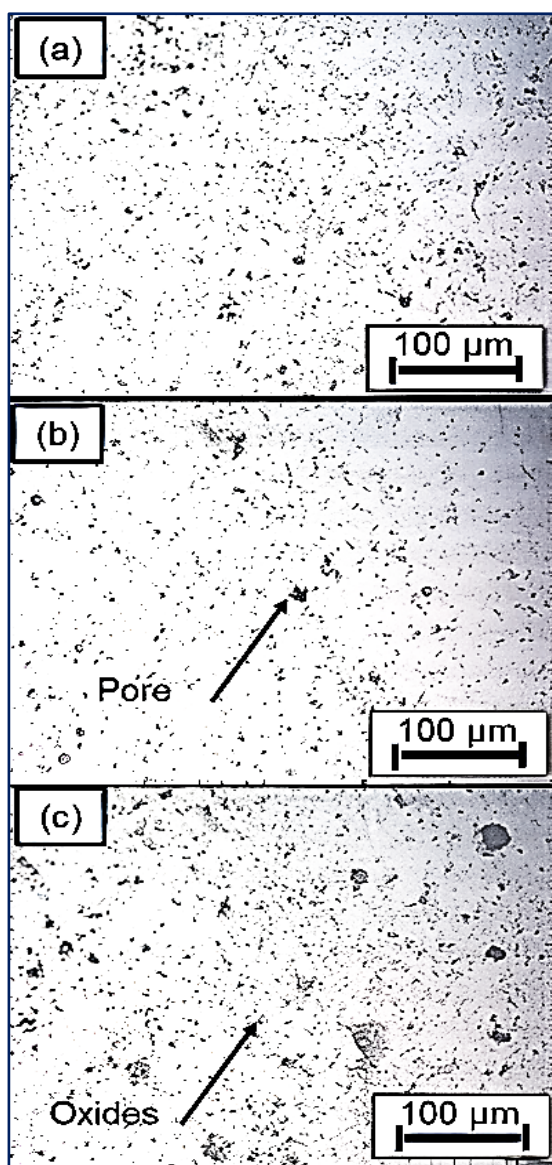


Fig. 3. Microstructure of alloy 95% CuNi-5 wt.%W with temperature compaction variations (a) 100°C, (b) 200°C, and (c) 250°C.

### 3.2 The density of the 95(CuNi)-5 wt%W model alloy

Fig. 4 shows the density of (CuNi)W alloys. A maximum density of 7.89 g/cm<sup>3</sup> was obtained through warm compaction at 200°C under a pressure of 250 MPa. On the contrary, a low density of 7.1 g/cm<sup>3</sup> was obtained at a compaction temperature of 100°C and pressure of 250 MPa; this result indicates that warm compaction at the temperature level T1 (100°C) is not effective in increasing the particle density during powder compaction. This result corresponds to the microstructure in Fig's 2 and 3, in which the highest density is correlated with low porosity in the microstructure, as shown in Fig. 3(b). Fig. 5 shows the Relative Density (RD) of the model (CuNi)W

alloys; these results correspond well with the density as shown in Fig. 4, the highest obtained with the introduction of the 250 MPa and 250°C compaction temperature. It is observed that with increasing compaction pressure, the relative density of the model alloy also slightly increases. The increase in relative densities is believed to be associated with improved temperature and compaction efficiency during warm compaction as shown in Fig. 5. The increase in absolute and relative density can be explained by the role of temperature in increasing the adhesive mobility of (CuNi) and W powder particles [31]. The higher temperatures encouraged denser particle rearrangement, reduced the number of micropores, and supported tighter inter-particle bonds before the sintering process [32]. In contrast, the low density in sample (CuNi)W-T1 shows that heating is not enough to overcome inter-particle binding, even causing early oxide formation, especially in Cu or Ni, which interferes with the solidification process.

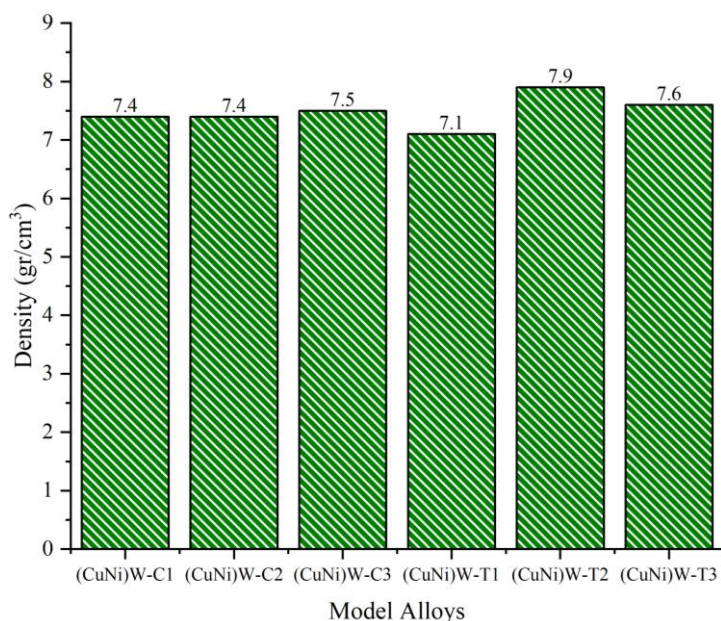


Fig. 4. Densities of varying (CuNi)W model alloys.

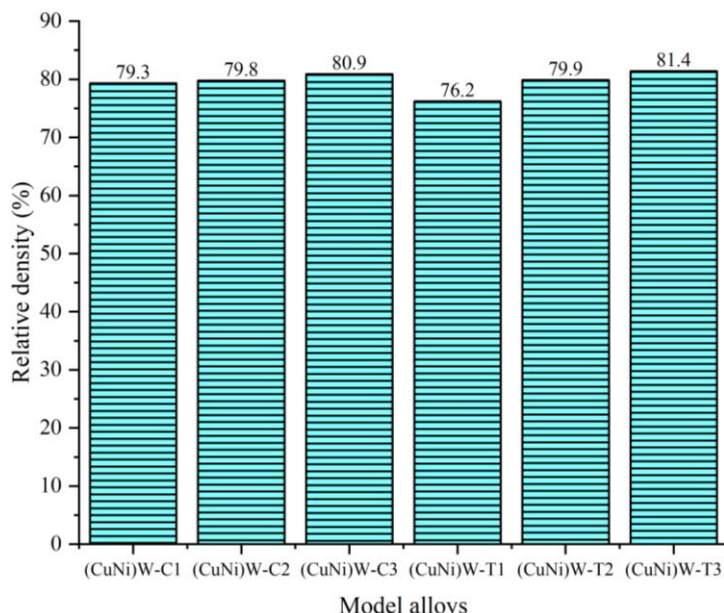


Fig. 5. Relative densities of model alloys.

### 3.3 Mechanical properties of the alloys 95CuNi-5 wt%W

Fig. 6 shows the hardness of the (CuNi)W model alloys; the increase in warm compaction temperature significantly increases the hardness. The (CuNi)W-T3 sample compacted at 250°C temperature and 250 MPa pressure shows the highest hardness, 100.2 HV obtained. The higher hardness is influenced by many factors such as density, porosity, solid solution phase formation, and dispersion strengthening of the alloys [33]. In this current study, both of the

(CuNi)W-C3 and (CuNi)W-T3 have a close to relative density. However, the higher hardness of the (CuNi)W-T3 obtained this fact probably correlated with solid solution formation and strengthening by nano-scale oxide formation within the microstructure. This indicates that a maximum compaction temperature is able to encourage plastic deformation between particles and increase intergranular bonds during the compaction process, finally resulting in a dense and better microstructure [34]. The (CuNi)W-T1 sample demonstrated the lowest hardness, 81.6 HV. In comparison with the increasing pressure in warm compaction design as (CuNi)W C1-C3 or (190-250) MPa, which gradually increases the hardness from 83.5~88.2 HV, nevertheless, it does not exceed the value observed in the (CuNi)W-T3 alloy. In addition, the presence of tungsten elements contributes to increasing hardness, but reduces the toughness of metal alloys such as Fe alloys containing 0.8 wt.% Cu [34].

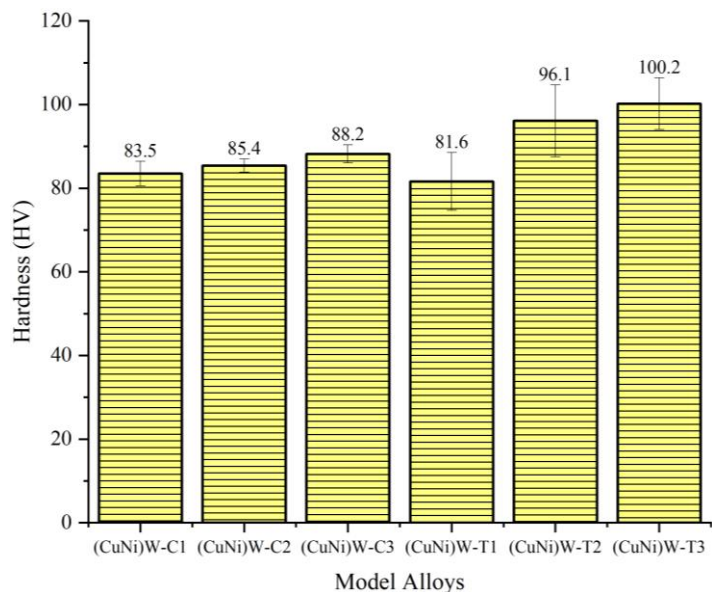


Fig. 6. Hardness of the model alloys under varying compaction pressures and temperatures.

The current investigation also included compression yield strength measurements. The results are presented in Fig. 7. It can be observed that variations in the compaction load promote an increase in the strength of the model (CuNi)W alloys. The (CuNi)W-C3 model alloy shows the highest strength with a value of 214.8 MPa. The increase in compaction pressure reduces porosity and produces a denser structure, thereby increasing resistance to plastic deformation during compression testing [35]. The model alloy (CuNi)W-T1 has the lowest strength, 182.08 MPa; the temperature might not have reached the minimum limit for particles to bind. This value increased at (CuNi)W-T2 to 204.1 MPa, but decreased at (CuNi)W-T3 (195.0 MPa). The decrease in strength at (CuNi)W-T3 (250°C) occurred, even though high temperatures and pressures were introduced during the processing. This phenomenon is likely correlated with the higher compaction temperature, which promotes increased oxide formation and consequently reduces strength. For instance, the presence of (Al, Cr) oxide layers weakens interfacial bonding and restricts plastic deformation, thereby contributing to the reduction in ductility and yield strength [36].

### 3.4 Electrical conductivity of the (CuNi)W alloy

Fig. 8 shows the electrical conductivity of the varying (CuNi)W alloy with differences in pressure and temperature compaction. The (CuNi)W-T3 alloy shows better electrical conductivity. This Cu-base alloy experienced a decrease of 39% in the conductivity in comparison to the IACS standard of the pure Cu (100% IACS) for the best model alloys in this current study. At a compaction temperature of 150°C, the electrical conductivity of the (CuNi)W alloy shows a linear increase with the increase of compaction pressure. The temperature influences the conductivity of the model

alloys, with the highest conductivity achieved by the compaction temperature of 250°C. This behavior indicates that moderate thermal activation during compaction promotes diffusion-assisted densification, resulting in a more continuous metallic network and improved atomic transport efficiency [37]. The peak conductivity observed at 250°C correlates strongly with microstructural evolution. At this temperature, probably sufficient localized heating enhances atomic diffusion at particle boundaries, which minimizes pore volume and improves metallurgical bonding without inducing extensive oxidation. This densification effect also coincides with enhanced mechanical performance, namely, a hardness of 100.2 HV (Fig. 6) and a compressive strength of 195.0 MPa (Fig. 7), both confirm the formation of a compact and well-bonded structure. The decrease in electrical conductivity is believed to be caused by the addition of nickel and tungsten alloys in (CuNi)W. Nickel and tungsten have lower electrical conductivity but better mechanical properties when compared to copper. Furthermore, the presence of defects and oxide formation also contributes to reducing the electrical conductivity of the alloys [38].

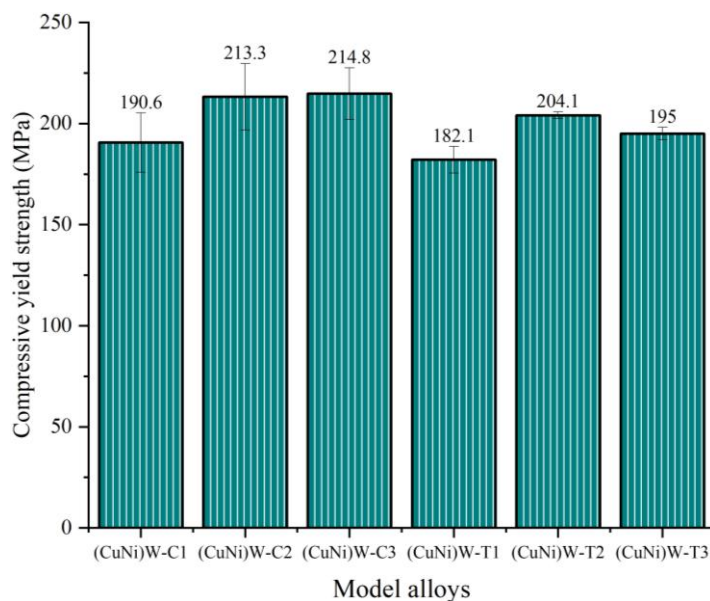


Fig. 7. Influence of compaction parameters on the compressive yield strength of the model alloys.

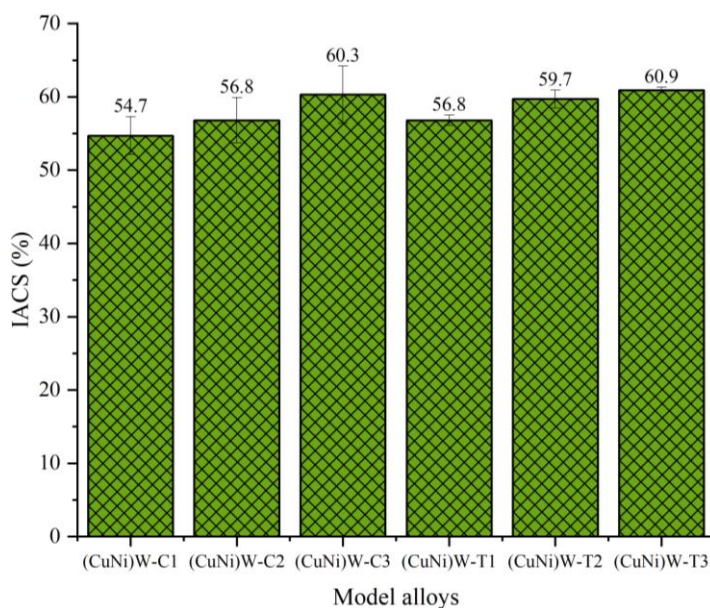


Fig. 8. The electrical conductivity of model alloys under varying compaction pressures and temperatures.

## 4 Conclusions

Based on the experimental results, it can be concluded that both of compaction load and warm processing temperature influence the characteristics of CuNi5W alloys. The CuNi with 5 wt.% W alloy

synthesized by warm compaction within the powder metallurgy route tends to marked improvements in the density, hardness, compressive strength, and electrical conductivity. The results showed that a temperature of 200°C combined with a compaction pressure of 250 MPa resulted in the highest density of 7.8 g/cm<sup>3</sup>, while a temperature of 250°C produced a maximum hardness of 100.2 HV and the highest electrical conductivity of about 61% IACS of pure copper. Meanwhile, the maximum compressive strength of 214.8 MPa was achieved at a pressure of 250 MPa. Microstructural observations suggest that heating during compaction enhanced inter-particle bonding, although signs of oxidation were observed at a temperature of 250°C. In summary, both tungsten addition and the warm compaction process significantly influence the microstructural characteristics, as well as their mechanical strength and electrical conductivity. Due to the limitation of this study to short-term laboratory observations, therefore future research should focus on evaluating long-term durability.

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