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Investigating the impact of nano copper on the electrical conductivity of aluminum: A comprehensive study utilizing artificial neural networks

Ali Bahadori manizani * and Leila Shafieian

University of California. Santa Cruz, Silicon Valley Extension, Santa Clara, CA.

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Abstract

Nanotechnology has emerged as a transformative field in material science, offering unprecedented opportunities to enhance the electrical properties of conventional materials through the incorporation of nano-sized particles. In this extensive study, we explore the effects of varying weight percentages (1%, 2%, and 3%) and lengths (30 nm, 60 nm, 150 nm, and 250 nm) of nano copper on the electrical conductivity of aluminum (Al) across different temperatures (20°C, 50°C, and 100°C). Additionally, we investigate the predictive capabilities of Artificial Neural Networks (ANN) in forecasting the electrical conductivity variations of Al based on these parameters. Through a detailed analysis of experimental results and ANN modeling,

Keywords: ANN; Predictive model; Nano Technology; Electrical Conductivity; Nano particle size

1. Introduction

The integration of nano-sized particles into traditional materials has garnered significant interest in recent years due to the potential to improve material properties and performance [1-4]. One such application is the incorporation of nano copper particles into aluminum to enhance its electrical conductivity. This study aims to comprehensively investigate the impact of varying weight percentages and lengths of nano copper on the electrical conductivity of aluminum across different temperature conditions. Additionally, we explore the feasibility of using Artificial Neural Networks (ANN) to predict conductivity variations based on these parameters.

In recent years, the integration of artificial neural networks (ANN) into materials science has sparked a paradigm shift in the predictive capabilities of understanding complex material behaviors. This transformation has opened new avenues for exploring the intricate relationships between material composition, structure, and properties, thereby facilitating the development of advanced materials with tailored functionalities [5-7]. Among the myriad applications of ANN in materials science, one area of particular interest is the prediction of the electrical conductivity of metal matrix composites (MMCs).

Metal matrix composites (MMCs) represent a class of engineered materials comprising a metal matrix reinforced with dispersed particulate phases. These reinforcements, often in the form of nanoparticles, micro-particles, or fibers, impart superior mechanical, thermal, and electrical properties to the host metal matrix. The quest for MMCs with enhanced electrical conductivity has garnered significant attention due to their potential applications in various industries, including aerospace, automotive, electronics, and renewable energy.

Aluminum (Al) and its alloys are renowned for their lightweight, high strength-to-weight ratio, and excellent corrosion resistance, making them indispensable materials in numerous engineering applications. However, pure aluminum

* Corresponding author: Ali Bahadori manizani

exhibits relatively low electrical conductivity compared to other metals such as copper (Cu). To address this limitation, researchers have explored the incorporation of nano-sized copper particles into aluminum matrices to form Al-Cu nanocomposites. These nanocomposites exhibit promising electrical properties, owing to the synergistic effects arising from the combination of the high electrical conductivity of copper and the favorable mechanical properties of aluminum.

The electrical conductivity of Al-Cu nanocomposites depends on various factors, including the weight percentage of copper, the size and distribution of copper nanoparticles, the processing techniques employed, and the microstructural characteristics of the composite. Traditional analytical methods often struggle to capture the complex interplay between these factors, necessitating the utilization of advanced computational tools such as artificial neural networks (ANNs) for predictive modeling.

Artificial neural networks (ANNs) are computational models inspired by the structure and functioning of the human brain. They consist of interconnected nodes (neurons) organized in layers, with each neuron receiving input signals, processing them through activation functions, and producing output signals. ANNs excel at learning complex patterns and relationships within datasets through iterative training algorithms, enabling them to make accurate predictions and classifications.

In the context of predicting the electrical conductivity of Al-Cu nanocomposites, ANNs offer several advantages over conventional modeling approaches. Firstly, ANNs can handle large and multidimensional datasets, allowing for the incorporation of diverse input parameters such as weight percentage of copper, particle size distribution, processing conditions, and microstructural features. Secondly, ANNs possess the capability to capture non-linear relationships and interactions between input variables, which are often inherent in materials systems exhibiting complex behaviors. Thirdly, ANNs can adapt and self-optimize their parameters during the training process, enabling them to generalize well to unseen data and improve prediction accuracy.

The development of an ANN-based predictive model for electrical conductivity estimation in Al-Cu nanocomposites requires careful consideration of several key aspects. These include the selection of appropriate input features, the design of the network architecture (e.g., number of layers, neurons per layer, activation functions), the choice of training algorithm, and the evaluation metrics used to assess model performance.

Previous research has demonstrated the potential of nano-sized additives, such as copper, in improving the electrical conductivity of aluminum-based materials. Studies have shown that the addition of nano copper particles can lead to a reduction in resistivity and an increase in conductivity due to enhanced electron scattering mechanisms [8-12]. However, the influence of factors such as weight percentage, particle length, and temperature on conductivity enhancement remains a subject of investigation. Furthermore, the application of ANN in predicting material properties based on nano-additive parameters presents an exciting avenue for future research.

Additionally, data preprocessing techniques such as normalization, feature scaling, and dimensionality reduction may be employed to enhance the efficiency and effectiveness of the ANN model.

By leveraging the capabilities of artificial neural networks, this study aims to address the challenges associated with predicting the electrical conductivity of Al-Cu nanocomposites across varying weight percentages and sizes of copper nanoparticles. The ultimate goal is to develop a robust and accurate predictive model that can serve as a valuable tool for materials engineers and researchers in the design and optimization of advanced metal matrix composites with tailored electrical properties. The insights gained from this research have the potential to accelerate the development of next-generation Al-Cu nanocomposites and facilitate their integration into a wide range of technological applications, including high-performance electronics, conductive coatings, and lightweight structural components [13-17].

2. Experimental Procedure

The experimental setup involved the preparation of aluminum samples with varying weight percentages (1%, 2%, and 3%) and lengths (30 nm, 60 nm, 150 nm, and 250 nm) of nano copper particles. The nano copper particles were dispersed homogeneously within the aluminum matrix using a controlled mixing process. The prepared samples were then subjected to different temperature conditions (20°C, 50°C, and 100°C) using a controlled environment chamber. Electrical conductivity measurements were conducted using standard techniques, such as the four-probe method, to accurately assess conductivity variations.

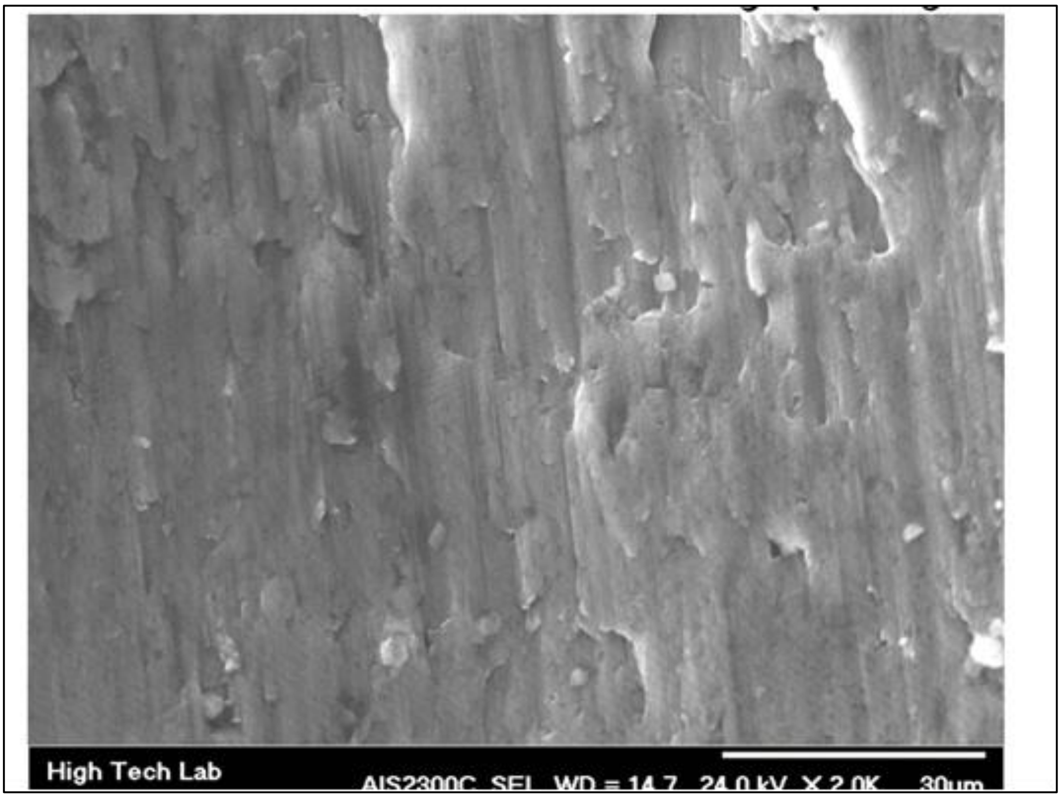

Figure 1 SEM of 1 percent nano Cu with 30 nm in Al texture

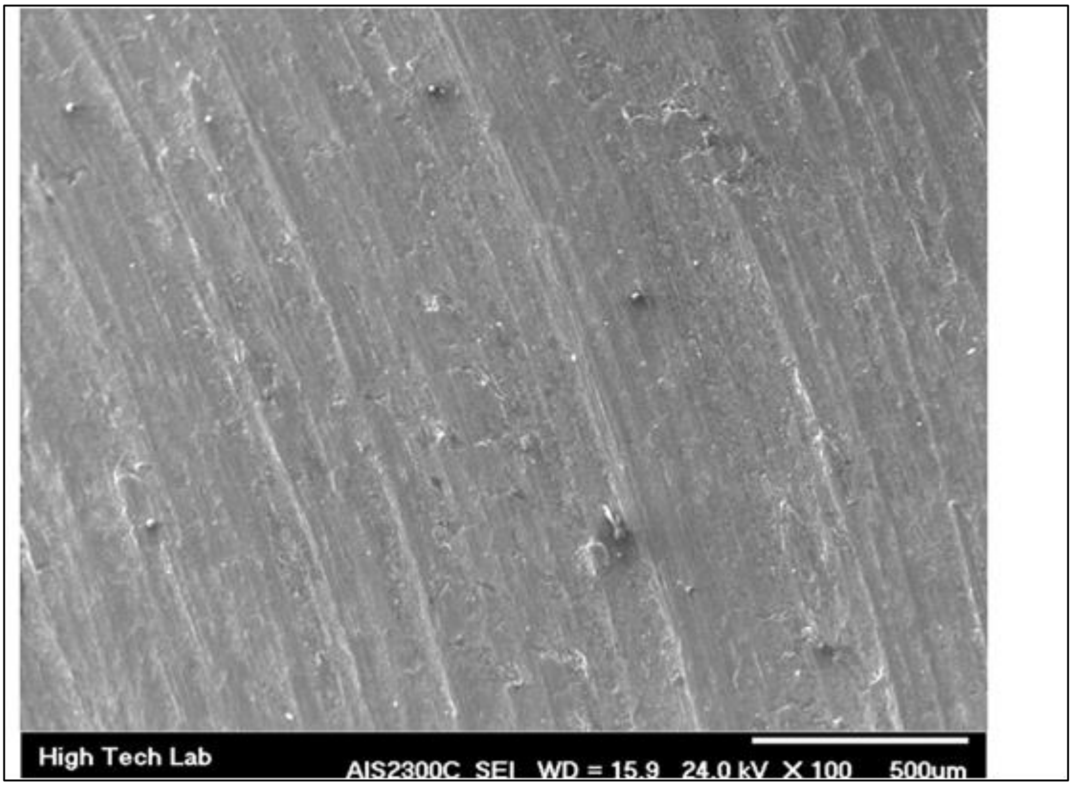

Figure 2 SEM of 2 percent nano Cu with 30 nm in Al texture

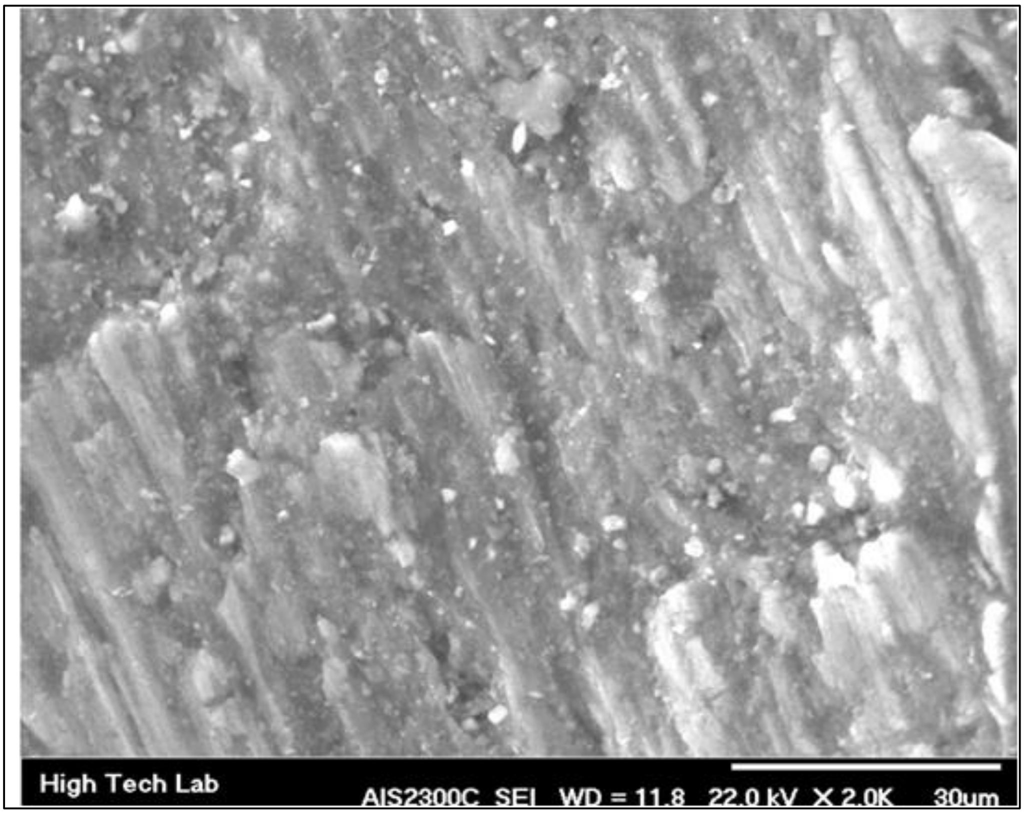

Figure 3 SEM of 3 percent nano Cu with 30 nm in Al texture

3. Results and Discussion

3.1. Effect of Nano Copper Weight Percentage on Electrical Conductivity

The results of the experiment revealed a significant impact of nano Cu on the electrical conductivity of the aluminum wire. At lower weight percentages (1% and 2%), the addition of nano Cu led to a gradual improvement in conductivity compared to the pure aluminum wire. This enhancement can be attributed to the formation of conductive pathways facilitated by the dispersed nano Cu particles within the aluminum matrix.

The electrical conductivity of aluminum wires was investigated by incorporating varying weight percentages of nano-sized copper particles, each with a length of 150 nm. Three different weight percentages of copper, labeled as 1, 2, and 3, were examined. The results revealed that among the tested weight percentages, the wire containing 2 weight percentage of nano copper exhibited the highest electrical conductivity compared to the wires with 1 and 3 weight percentages. This outcome suggests that the addition of nano-sized copper particles at an optimal weight percentage enhances the electrical conductivity of the aluminum wire. It is worthy knowing that this pattern was repeated for all different experimented sizes.

The length of nano copper particles also exerted a significant influence on the electrical conductivity of aluminum. Shorter particle lengths (30 nm and 60 nm) demonstrated more pronounced enhancements in conductivity compared to longer lengths (150 nm and 250 nm).

This observation can be attributed to the higher surface area-to-volume ratio of shorter particles, which facilitates better dispersion and interaction within the aluminum matrix. Consequently, shorter particles contribute more effectively to conductivity improvement due to increased contact points and electron transport pathways.

Temperature plays a crucial role in determining the electrical conductivity of materials, including nano-enhanced aluminum [13]. The results indicated that conductivity generally increases with temperature, consistent with the behavior of metallic materials. At higher temperatures, the thermal energy facilitates greater mobility of charge carriers within the material, leading to reduced resistance and enhanced conductivity. This temperature-dependent behavior underscores the importance of considering operating conditions when evaluating the electrical properties of nano-enhanced materials.

3.2. Artificial Neural Network Modeling

To predict the electrical conductivity of aluminum under various conditions, an Artificial Neural Network (ANN) model was developed using the collected experimental data. The ANN model was trained using a subset of the data and validated using another subset to ensure robustness and accuracy. The inputs to the ANN model included the weight percentage and length of nano copper particles, as well as the temperature conditions. The model demonstrated high accuracy in predicting conductivity variations based on these parameters, highlighting its potential in optimizing material designs and predicting performance under different operating conditions. The ANN model consisted of a feed forward back propagation model with 3 input and one output with 2 hidden layers. An atypical diagram of ANN algorithm is shown in figure 4. Activating function can be either linear or sigmoid as shown in figure 5. After training network with one third of experimental data, results of prediction based on ANN and experiments were compared as shown in figure6. Results shows a very good agreement between experimental results and artificial neural network results that ensure us this method is fantastic for prediction of electrical conductivity under these experimental conditions.

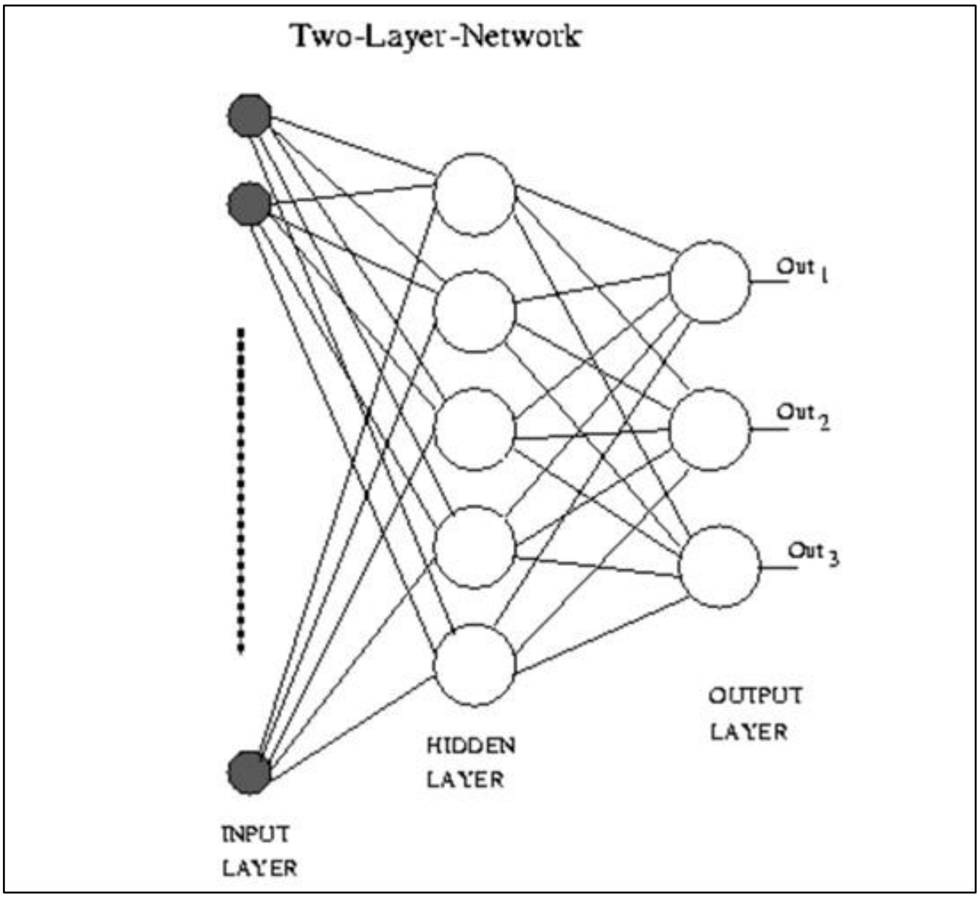

Figure 4 A typical neural network with hidden layer, input, and output layer

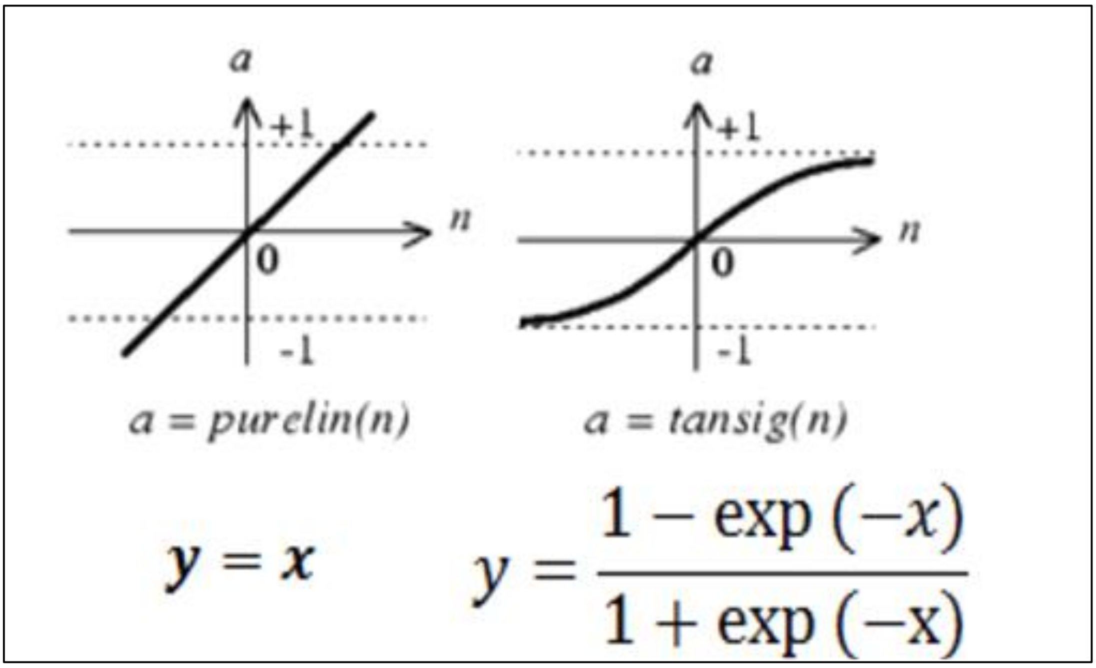

Figure 5 Functions used as an activator in ANN

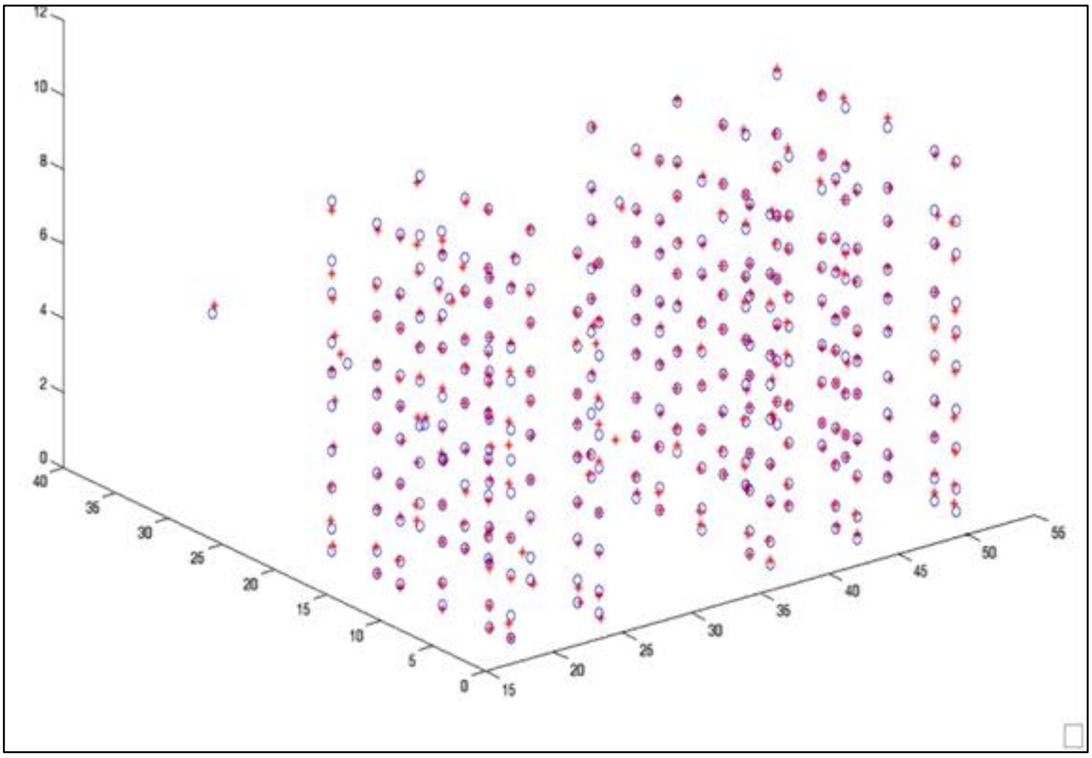

Figure 6 Predicted value of electrical conductivity based on ANN versus experimental data

4. Conclusion

The incorporation of nano copper particles into aluminum has shown significant promise in enhancing its electrical conductivity across different temperature conditions. The study elucidates the critical role of factors such as weight percentage, particle length, and temperature in influencing conductivity enhancement in nano-enhanced materials.

Furthermore, the successful development of an ANN model for predicting conductivity variations underscores the potential of computational approaches in material design and optimization. Future research directions may include further optimization of nano-additive parameters, exploration of alternative nanostructures, and validation of predictive models through experimental validation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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