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Investigation of Mechanical Characteristics of Aluminum Metal Matrix Composite Reinforced with Copper and Nickel

Jobayat Isteyak Riyadh, Shafin Ahmed, Showrov Dev Nath, Sheikh Muhammad Humayun Kabir*

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chittagong-4349, Bangladesh

ABSTRACT

Aluminum metal matrix composites reinforced with varying proportion of Cu and Ni has been fabricated using stir casting process and analyzed their mechanical characteristics and microstructures. Three compositions have been investigated - 90% Al with 8% Cu and 2% Ni, 90% Al with 7% Cu and 3% Ni, and 90% Al with 6% Cu and 4% Ni. Scanning Electron Microscope (SEM) test is conducted to validate the distribution of reinforcements in Al. The captured SEM micrographs at 2000x, 5000x and 20000x magnification has shown uneven distribution of Cu and Ni in the composites. Grain size distribution analysis using ImageJ software has indicated a heterogeneous nature of the observed composites, with a mean grain diameter of 0.305 microns and a standard deviation of 0.094 microns. Furthermore, hardness test, tensile strength test and impact strength test has been conducted for analyzing the mechanical properties for varying proportions of reinforcements. The composite with 7% Cu and 3% Ni has exhibited the highest Brinell hardness number (70.25 BHN) and ultimate tensile strength (59.84 MPa), but impact strength for this composition was the lowest (2.9 Jcm^{-2}). Impact strength is highest for composite with 6% Cu and 4% Ni (3.2 Jcm^{-2}). Given their enhanced mechanical properties and high strength-to-weight ratio, these composites can be utilized in the automotive, aerospace and defense industries.

Keywords: Composite Fabrication, Aluminum Metal Matrix Composite, Microstructural Analysis of Composite

1. Introduction

Composite materials are combinations of two or more insoluble constituents, resulting in superior properties compared to those of the individual components. Compared to conventional materials like steel, composites are stronger and lighter [1]. A composite material typically consists of two phases: the matrix, which is a continuous phase, and one or more discontinuous reinforcing phases. The matrix is commonly made of ceramics, metals, or polymers, while fibers and particles serve as reinforcements. The choice of reinforcement depends on the application; for instance, tougher reinforcements are employed for components requiring high wear resistance, while softer reinforcements, like graphite and molybdenum, are used for components that need lubricating properties. Both the matrix and the reinforcements significantly influence the composite material's properties. While the reinforcement enhances the overall performance of the matrix, it is the matrix that holds the reinforcement in place and maintains the desired shape. To ensure structural integrity, the composite's components must not interact at high temperatures, which could lead to material failure [2].

Composites can be classified, according to the matrix material, into the following categories: metal matrix composite (MMC), ceramic matrix composite (CMC), and polymer matrix composite (PMC) [3]. In metal matrix composites (MMCs), materials such as aluminum (Al), magnesium (Mg), titanium (Ti), and copper (Cu) are commonly used as matrix elements. Various types of MMCs include particle-reinforced MMCs, short fiber or whisker-reinforced MMCs, and continuous fiber or sheet-reinforced MMCs [4].

Aluminum metal matrix composites (AMMCs) are composite materials composed of more than two constituents with varying chemical compositions, which can be in macro, micro, or nano forms. These constituent materials do not dissolve in the matrix, and the mechanical behavior of the composite is influenced by the percentage of reinforcement and the composition of the matrix material. This property has made AMMCs valuable in various engineering and functional applications [5]. In AMMCs, aluminum alloys serve as the matrix material (continuous phase), which can be enhanced by incorporating single or multiple reinforcement particulates (discrete non-metallic ceramics) such as silicon carbide (SiC), magnesium (Mg), copper (Cu), nickel (Ni), alumina (Al_2O_3), graphite, titanium dioxide (TiO_2), and boron carbide (B_4C). These composites exhibit greater strength than the base alloy material, which is crucial for the rapid development of technologies across various application domains. Recent studies have shown that the ability of MMCs to modify physical properties, such as density and thermal expansion, alongside mechanical characteristics, by altering the phases of their constituent materials, has achieved significant research interest [6].

The primary processes for the manufacturing of aluminum metal matrix composites (AMMCs) at an industrial scale can be categorized into solid-state and liquid-state processes. Solid-state processes include techniques such as Powder Metallurgy, Diffusion Bonding, and Physical Vapor Deposition [1]. The Powder Metallurgy process involves several steps, including powder production, blending, compaction, sintering, and finishing operations [7].

In recent years, there has been extensive research on the production and characterization of stir cast aluminum MMCs.

*Corresponding Author Email Address: shafin.mech@gmail.com

Ahmed and Kadam developed aluminum metal matrix composites reinforced with copper, nickel, zinc, and silicon carbide to improve mechanical properties. Their study provided insights into metal matrix composites, contributing significantly to the field [8].

Guan et al. investigated aluminum matrix composites reinforced with Ni-coated graphene nanosheets using powder metallurgy. The study found significant improvements in hardness and tensile strength, with the graphene nanosheet content influencing both microstructure and mechanical properties. These findings highlight the potential applications of graphene-reinforced aluminum composites [9].

Kumar and Devi's research examined the mechanical properties of aluminum-copper metal matrix composites, focusing on tensile strength, hardness, and impact strength. [10]. Yadav and Bauri's study developed a nickel particle-reinforced aluminum matrix composite using powder metallurgy. The composite showed high ductility, suggesting its potential for industrial applications where ductility is essential. The research offers valuable insights into composite manufacturing with promising industrial implications [11].

Rao et al. developed dry sliding wear maps for AA7010 (Al–Zn–Mg–Cu) aluminum matrix composites. The authors focused on the effect of sliding speed and load on the wear behavior of the composite. The findings of the study revealed the critical wear mechanisms that occurred at specific load speeds. The paper stands out as a valuable contribution to the field, providing insights that can inform better design and usage of the 15 composite material. Overall, it can help researchers and industry professionals predict the durability of AA7010 material [12].

Kumar and Birru studied the impact of adding bamboo leaf ash to aluminum metal matrix composites using stir casting method. They tested the composites' tensile strength, hardness, and impact strength, finding significant improvements due to the bamboo leaf ash's unique morphology and even distribution. The research offers valuable insights into using bamboo leaf ash as a reinforcement material in aluminum composites [13].

Chebolu et al. fabricated Zn-Al-Cu/SiC/TiB_2 hybrid metal matrix composite using ultrasonic-assisted stir casting technique and analyzed tensile strength, yield strength and hardness. Microstructure was also investigated using SEM observation [14].

Maneiah et al. focused on optimizing the machining parameters for surface roughness in abrasive water jet machining of aluminum/magnesium hybrid metal matrix composites. Effective combination of machining parameters such as abrasive flow rate, standoff distance and traverse speed for achieving the desired surface roughness were investigated in this study [15].

Though aluminum metal matrix composites(AMMC) reinforced with Ni and Cu have been studied for their potential in lightweight and high-strength application, existing studies primarily focus on single reinforcements of composites with fixed reinforcement ratios. This study analyzes the influence of varying Ni and Cu reinforcement ratios on the mechanical and microstructural properties of AMMCs.

The objective of this research is to fabricate aluminum composites reinforced with Cu and Ni for enhancing the mechanical properties of the aluminum matrix. In this study, three different samples of different percentages of reinforcements are investigated for comparative analysis of their different characteristics. Furthermore, phase distribution of the composites is analyzed using Scanning Electron Microscopy (SEM) technique for observing distribution of reinforcements in the Al metal matrix.

2. Methodology

In this study, three samples are investigated. Percentage of Al is 90% in all three samples. 90% Al is used because of its capability to provide a lightweight matrix with excellent thermal and mechanical properties, essential for applications requiring a high strength-to-weight ratio. First sample contains 8% Cu and 2% Ni, second sample contains 7% Cu and 3% Ni and third sample contains 6% Cu and 4% Ni. Composite materials can be fabricated using several different techniques, such as lay-up operations, induction plasma deposition, physical vapor deposition, tape casting, stir casting, powder metallurgy, and quick solidification. These manufacturing techniques can be classified either as using continuously reinforced AMCs or as using discontinuously reinforced AMCs. Discontinuous-reinforcement AMCs are mostly used because they are inexpensive to manufacture. The stir-casting technique is selected for this study to create an Al-Ni-Cu composite, as it is cost-effective. In this technique, second-phase materials are added with molten metal matrix, which then solidifies to create a metal matrix composite. A flowchart illustrating the process is as followed:

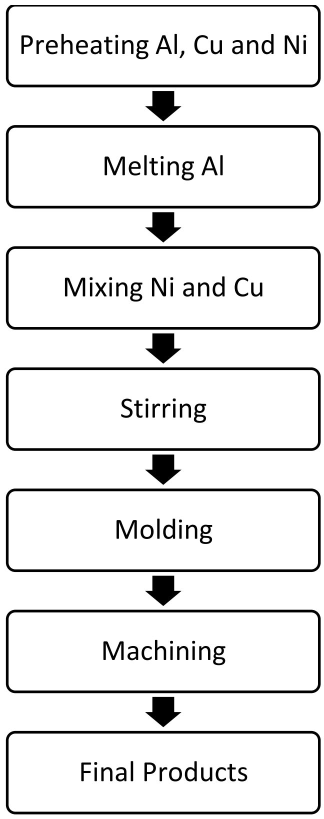


Figure 1. Flowchart of Stir Casting Process

At first, sample powders of Al, Ni, and Cu are obtained from a supplier. Afterwards, preheating is done to avoid oxidation. According to Jawalkar et. al [16], increasing preheating temperature prevents particle clustering in the composite matrix resulting in a reduced porosity. In this study, Al is preheated at 400ºC, and Cu and Ni is preheated at 1000ºC because melting point of Al, Cu and Ni is respectively 660ºC, 1085℃ and 1455℃.

After preheating, the melting process is carried out for melting Al, Cu and Ni. The melting point of Cu and Ni are respectively 1085ºC and 1455ºC, whereas Al melts at 660ºC. A furnace is used for this process. Once melting is completed, Al is stirred at a speed of 100rpm for 5 minutes in order to create a vortex in the molten Al. Meanwhile, the reinforcements are mixed with Al while the stirring process is running. It ensures the proper distribution of reinforcements in the Al metal matrix.

The liquid metal is poured into molds to obtain desired shape of the specimen. Three molds are used here. After solidification, final products are achieved. A total of eight samples are produced repeating this method. Several machining operations are further done such as thread cutting, taper tuning, grinding, and slot cutting.

After preparing specimen, Universal testing machine is used for performing tensile test according to ASTM E8 standard [17] and hardness test of the fabricated specimens and Digital Impact Test Machine is used for impact strength test according to ASTM E23 standard [17]. For investigation distribution of reinforcements in the metal matrix, Scanning Electronic Microscope (SEM) technique is performed.

For determining Brinell Hardness Number(BHN), stress and strain, following equations are used:

$$BHN = \frac{2P}{\pi g D(D-\sqrt{D^2-d^2})} \quad (1)$$

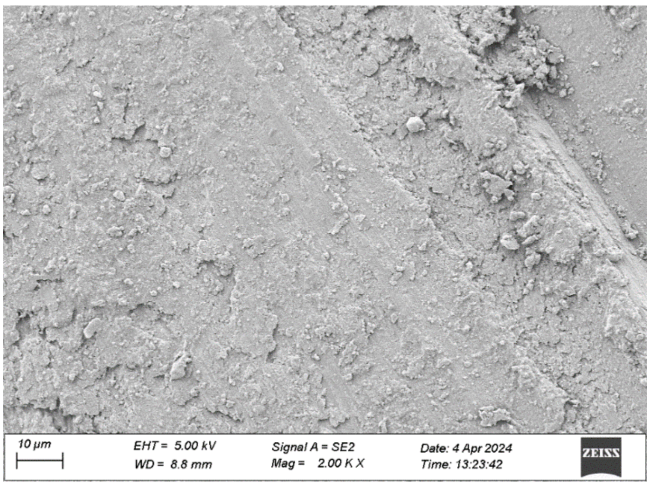
$$\sigma = \frac{F}{A} \quad (2)$$

$$\varepsilon = \frac{l}{L} \quad (3)$$

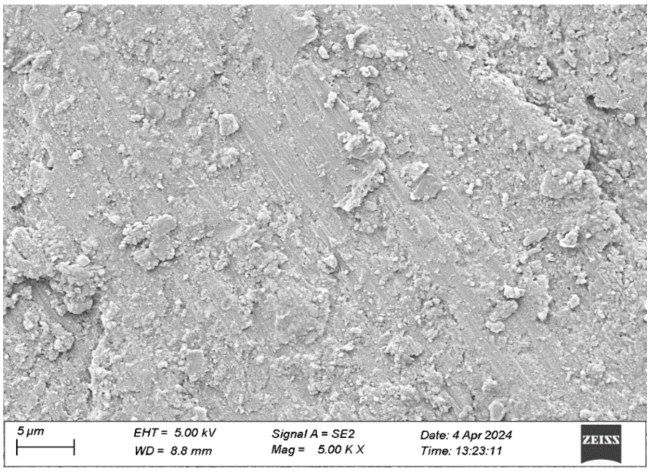
3. Result and Discussion

3.1 Distribution of Reinforcements

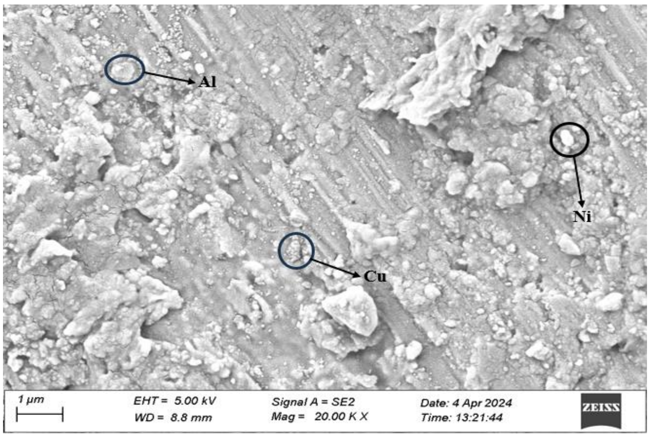
The sample consisting 90% Al, 7% Cu and 3% Ni was investigated by Scanning Electronic Microscope(SEM). Fig. 2(a), 2(b) and 2(c) show the SEM micrographs of the aforementioned sample which were captured at 2000x, 5000x and 2000x magnification respectively. From the SEM micrographs, it is observed that the maximum number of reinforcement particles in the Al matrix is distributed unevenly. It can be improved by improving the casting process.



(a)



(b)



(c)

Figure 2. SEM micrograph of 7% Cu and 3% Ni with (a) 2000x (b) 5000x and (c) 20000x magnification

3.2 Grain Size Distribution

Image J software is used for analyzing the grain size distribution for 7% Cu and 3% Ni. Afterwards, normal distribution curve analysis is performed as seen in fig 3, which demonstrated grain size heterogeneity resulting to its superior mechanical properties, consisting the highest tensile strength (59.84 MPa) and Brinell Hardness Number (70.25 BHN).

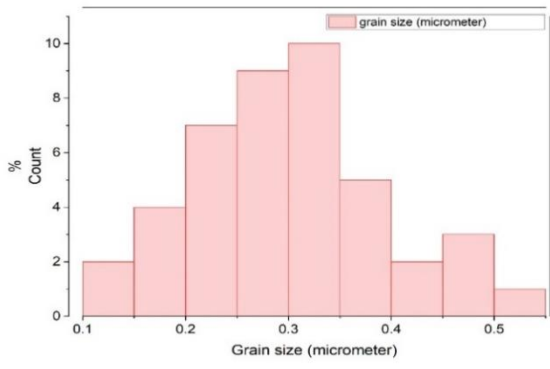


Fig 3. Normal Distribution Curve Analysis

Mean grain diameter is determined 0.305 microns with a standard deviation of 0.094. The curve demonstrates a significant presence of diverse grain sizes, highlighting the heterogeneous nature of the sample.

3.3 Brinell Hardness Number, Tensile Strength and Impact Strength

Comparison of Brinell hardness number for varying proportion of Cu and Ni is shown on figure 4. As observed from the graph, Brinell hardness number of the sample with 7% Cu and 3% Ni composition was the highest (70.25 BHN) compared to other two compositions.

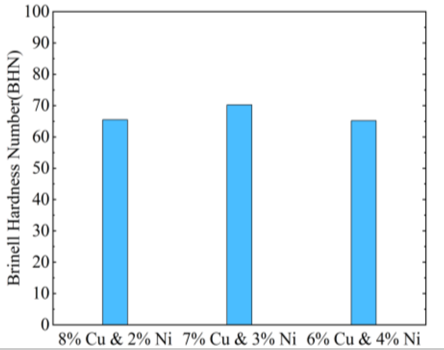
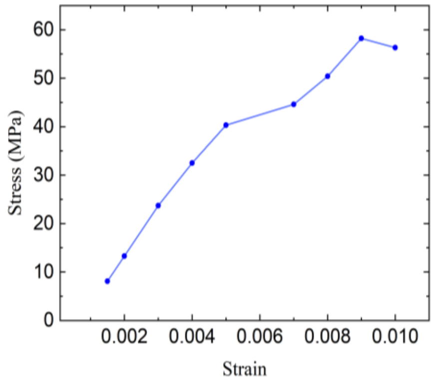
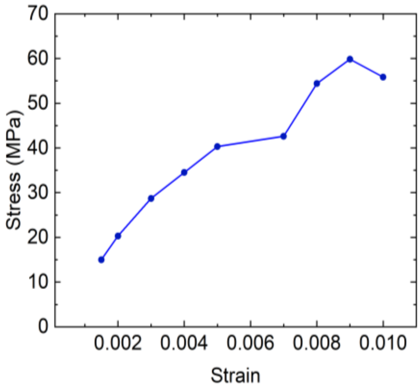


Figure 4. Comparison of Brinell Hardness Number

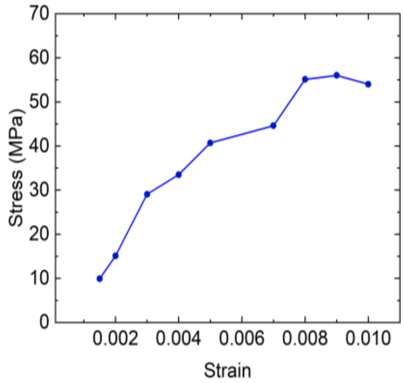
Figure 5(a), 5(b) and 5(c) demonstrates the stress-strain curve for 8% & Cu 2% Ni, 7% Cu & 3% Ni and 6% Cu and 4% Ni respectively. Ultimate tensile strength obtained from stress-strain curve is 58.20 MPa, 59.84 MPa and 56.02 MPa respectively and shown in figure 6. Notably, 7% Cu and 3% Ni composition exhibits the highest ultimate tensile strength. This finding provides valuable insights into optimum composition of aluminum metal matrix composites.



(a)



(b)



(c)

Figure 5. Stress-Strain curve for (a) 8% Cu and 2% Ni (b) 7% Cu and 3% Ni and (c) 6% Cu and 4% Ni

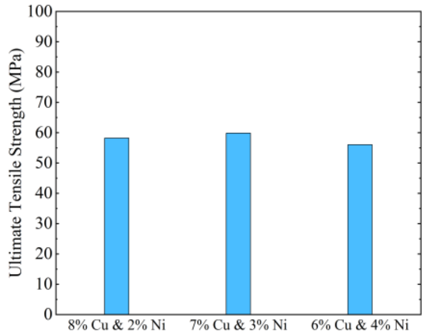


Fig 6. Comparison of Ultimate Tensile Strength

Fig 7 shows the comparison of impact strength for varying proportion of Cu and Ni. Sample containing 6% Cu and 4% Ni showed the highest impact strength (3.2 Jcm^{-2}) among all three samples. As noticeably, it is the lowest (2.8 Jcm^{-2}) for 7% Cu and 3% Ni, even though all other mechanical properties is the highest for this proportion of Cu and Ni. The lowest impact strength, despite its superior hardness and tensile strength, is due to the presence of brittle intermetallic phases, which may have reduced the material's ability to absorb energy during impact, leading to earlier crack initiation and propagation.

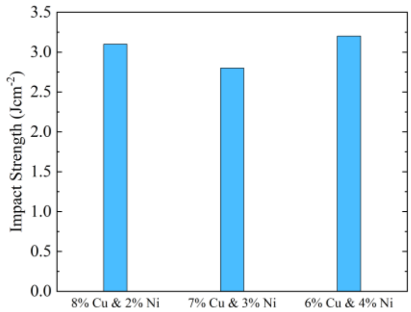


Fig 7. Comparison of Impact Strength

4. Conclusion

The main objective of this study was the fabrication of Aluminum Metal Matrix Composites reinforced with Cu and Ni. Stir casting process was used to combine the fine aluminum powder with different proportion of Ni and Cu. Distribution of Cu and Ni in Aluminum was investigated by conducting Scanning Electron Microscope(SEM) test. Tensile test, impact test and hardness test was also performed to analyze the mechanical properties for varying proportions of Cu and Ni. Based on the obtained results, following conclusions are drawn:

1) Distribution of Cu and Ni particles in the Aluminum was uneven. Mean grain diameter of the investigated sample was 0.305 microns. The samples were heterogeneous in nature, as standard deviation of the normal distribution curve was 0.094, indicating varying grain size in the sample.
2) 90% Al, 7% Cu and 3% Ni composition showed the highest Brinell hardness number and tensile strength, indicating the effectiveness of this composition in improving mechanical properties. However, 90% Al, 6% Cu and 4% Ni composition showed the highest impact strength.

In conclusion, this research provides a comprehensive insights of change of mechanical properties for varying proportion of reinforcements. However, effects of other reinforcement materials percentage should also be analyzed in future works. Investigating the influence of stirring parameters such as rpm and preheating temperatures should be investigated in future research.

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Nomenclature

D: Ball Diameter, mm
d: Diameter of the indentation, mm
P: applied load, kg
σ: Tensile strength
F: Applied Force, kN
A: Cross-sectional Area, mm^2
ε: Strain
l: Elongation
L: Initial Length