



Influence of Heat Treatment on The Structural and Mechanical Properties of Cold-Worked AL-3MG-2SI-0.5NI Alloy System

Daniel K. Foster, and Jason T. Miller

Department of Materials Science and Metallurgical Engineering, College of Engineering, University of Michigan, Ann Arbor, Michigan, USA

Abstract

This study investigated the effects of heat treatment on the structural and mechanical properties of an Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy system. The alloy samples were produced using a permanent die-casting technique and subsequently machined to the required dimensions for mechanical testing and microstructural analysis. Mechanical properties, including ultimate tensile strength, percentage elongation, hardness, and impact strength, were evaluated using a 100 kN JPL tensile testing machine (Model: 130812), a dynamic hardness tester, and an impact testing machine (Model: U1820). Microstructural characterization was conducted using an optical metallurgical microscope (Model: L2003A) and scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS). Microstructural analysis revealed that the as-cast control sample exhibited coarse microsegregation of the intermetallic Mg_2Si phase. In contrast, the solution heat-treated samples showed uniformly distributed fine Mg_2Si intermetallic particles throughout the alloy matrix. Mechanical test results demonstrated that heat treatment significantly improved the ultimate tensile strength, impact strength, and percentage elongation of the alloy. These improvements were attributed to the fine dispersion of Mg_2Si particles within the alloy structure. Furthermore, heat treatment reduced the microsegregation of Mg_2Si by minimizing solute redistribution of Mg, Ni, and Si within the matrix. However, the control sample exhibited the highest hardness value due to the presence of coarse intermetallic Mg_2Si compounds in the alloy structure. The findings of this study highlight the significant role of heat treatment in enhancing the structural refinement and mechanical performance of Al-Mg-Si-Ni alloy systems for engineering applications.

Keywords: Heat treatment, Al-3Mg-2Si-0.5Ni alloy, Mechanical properties, Microstructure, Tensile strength, Hardness, Impact strength, Dielectric analysis, Solution heat treatment

1.0 Introduction

The continuous development of aluminum alloys remains essential for the automotive and transportation industries, where the demand for lightweight materials with enhanced mechanical performance continues to increase. The primary objective of modern materials engineering is to produce lighter and more compact components that reduce fuel consumption and operational costs without compromising important properties such as strength, toughness, and ductility [1–4].

Among engineering materials, aluminum-magnesium-silicon-nickel (Al-Mg-Si-Ni) alloys have attracted considerable attention due to their excellent combination of mechanical properties, corrosion resistance, and heat-treatable characteristics. These alloys are widely utilized in aerospace and automotive applications because of their high strength-to-weight ratio and adaptability to different thermal processing conditions [2–5]. Al-Mg-Si-Ni alloys belong to the class of heat-treatable aluminum alloys capable of retaining

supersaturated solid solutions when rapidly quenched from elevated temperatures to room temperature. As temperature decreases, the solid solubility of alloying elements also decreases, leading to precipitation hardening phenomena that significantly influence the mechanical behavior of the alloy [4–9]. The addition of magnesium, silicon, and nickel generally enhances the strength and hardness of these alloys. However, increasing the silicon and nickel content may also increase susceptibility to hot cracking during casting or rapid cooling processes.

Previous studies have shown that microsegregation of Mg_2Si precipitates can adversely affect the mechanical performance of aluminum alloys, resulting in reduced ductility and premature failure of structural components [10–17]. Several researchers have therefore investigated the influence of heat treatment on the structure and mechanical properties of Al-Mg-Si-based alloys.

Studies reported in the literature indicate that ageing treatment significantly affects alloy hardness and strength. For example, specimens aged at 120°C for 24 hours exhibited the highest hardness values due to the formation of fine precipitates [15–20]. Similarly, quenched samples cooled rapidly after solution treatment developed finer grain structures and higher tensile strength compared to slowly cooled annealed samples, which produced coarser grains and lower strength [16]. It has also been observed that prolonged precipitation hardening may lead to precipitate coarsening and eventual over-ageing, causing a reduction in mechanical strength.

Other investigations demonstrated that solution heat treatment at elevated temperatures followed by water quenching improved the hardness, tensile strength, and yield strength of Al-Mg-Si alloys [8–12]. Variations in quenching media and cooling rates were also found to influence impact strength, ductility, and precipitate morphology [13–20]. Increased quenching rates generally resulted in improved hardness and tensile properties due to the formation of fine coherent precipitates and Guinier-Preston (GP) zones within the aluminum matrix.

Furthermore, previous research revealed that the morphology and distribution of intermetallic phases are strongly dependent on solution treatment temperature and ageing conditions [19–23]. Fine and uniformly dispersed $\beta\text{-Mg}_2\text{Si}$ precipitates were identified as the primary strengthening phases responsible for enhanced mechanical properties. However, excessive ageing caused precipitate coarsening and loss of coherency with the matrix, thereby reducing alloy hardness and strength.

Despite numerous studies on heat-treated aluminum alloys, limited information exists on the structural and mechanical behavior of cold-worked Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy systems. Therefore, this study aims to investigate the effect of heat treatment on the microstructure and mechanical properties of cold-worked Al-3Mg-2Si-0.5Ni alloys. The findings are expected to provide valuable insights into the optimization of heat treatment processes for improved engineering performance in industrial applications.

2.0 Materials and Methods

The materials used for this study included aluminum wire, magnesium, silicon, and nickel powders as the base alloying constituents. Different quenching media, namely water, brine, palm oil, and SAE 40 engine oil, were also utilized during the heat treatment process. The alloy samples were produced using the permanent die-casting technique.

The required quantity of pure aluminum wire was melted in a bail-out crucible furnace. Predetermined amounts of magnesium, silicon, and nickel powders wrapped in aluminum foil were then added to the molten aluminum and thoroughly stirred to ensure uniform distribution and homogeneity of the alloying elements. The molten alloy was subsequently poured into a preheated permanent mold and allowed to solidify. The cast samples were machined to the required dimensions for mechanical testing and heat treatment procedures. The machined specimens were solution heat-treated at a temperature of 300°C for soaking periods of 30, 90, and 150 minutes using a muffle heat-treatment furnace. After solutionizing, the specimens were rapidly

quenched in different media, including water, brine, palm oil, and SAE 40 engine oil, before being prepared for mechanical characterization [23].

For mechanical testing, the cast and heat-treated samples were machined according to standard test specifications. An automated 100 kN JPL tensile testing machine (Model: 130812) was used to determine the tensile strength of the alloy samples. Hardness measurements were carried out using a portable dynamic hardness tester (Model: DHT-6), while impact strength was evaluated using an impact testing machine (Model: U1820).

For microstructural analysis, the specimens were prepared through filing, grinding, polishing, and etching processes. Filing was carried out using a rectangular file and an electric grinding machine. The specimens were subsequently cleaned with water, dried using an air-gun dryer, and ground progressively using emery papers with grit sizes of 400, 600, 800, and 1200 μm . Final polishing was performed using aluminum oxide powder (gamma alumina, Al_2O_3) to obtain a mirror-like surface finish.

The polished specimens were etched for 60 seconds using a solution containing 10 g of iron (III) chloride, 30 cm^3 hydrochloric acid, and 120 cm^3 distilled water. The microstructures and surface morphology of the alloys were then examined using an optical metallurgical microscope (Model: L2003A) and a scanning electron microscope (SEM) at magnifications of $\times 400$ and $\times 1500$, respectively.

3.0 Results and Discussion

Figures 1-8 show the microstructure of the studied alloy respectively.

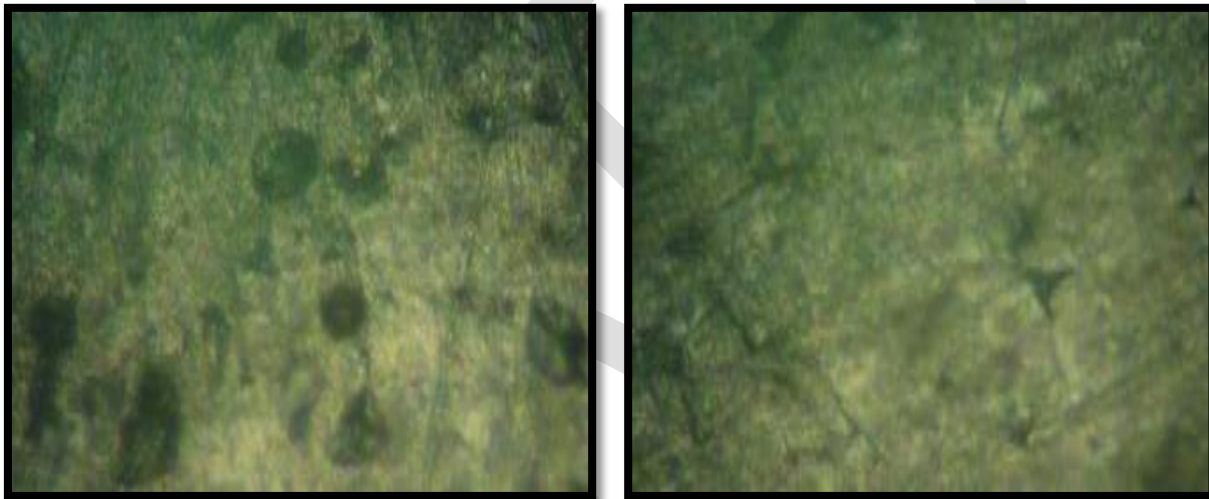


Figure 1.0: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy (Control) and Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 30 minutes and cooled in water.

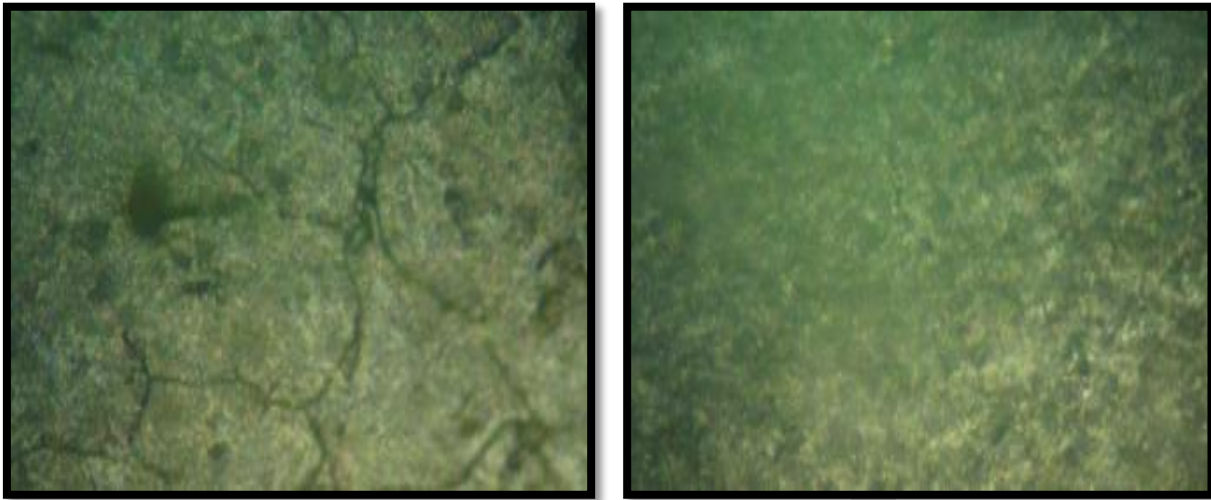


Plate 2: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 90minutes and cooled in water and Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 150minutes and cooled in water.

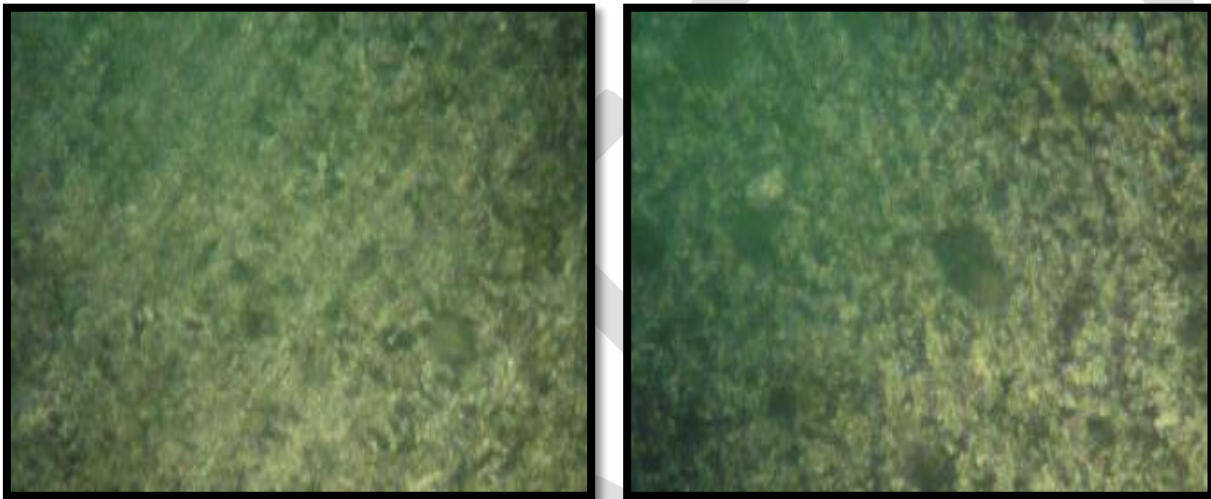


Plate 3: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 30minutes and cooled in brine and Plate 6: Micrograph of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 90minutes and cooled in brine.

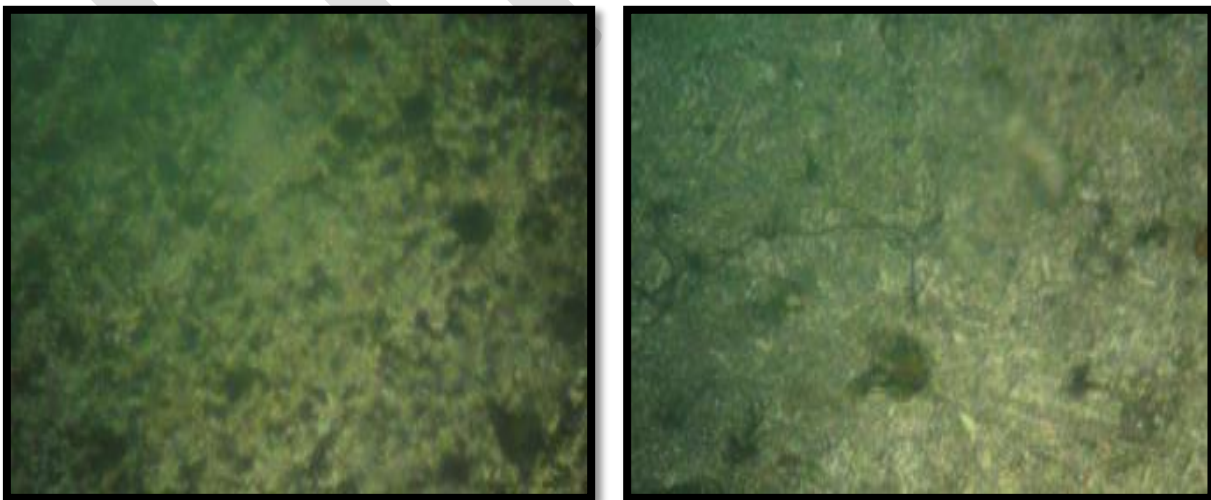


Plate 4: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 150minutes and cooled in brine and Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 90minutes and cooled in palm oil.

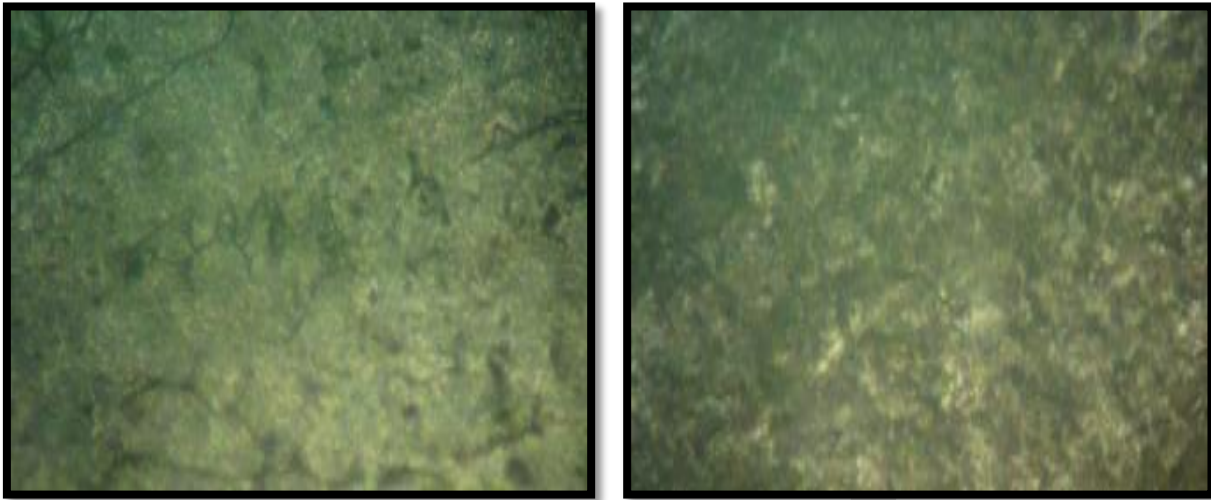


Plate 5: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 150minutes and cooled in palm oil and Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 30minutes and cooled in SAE40.

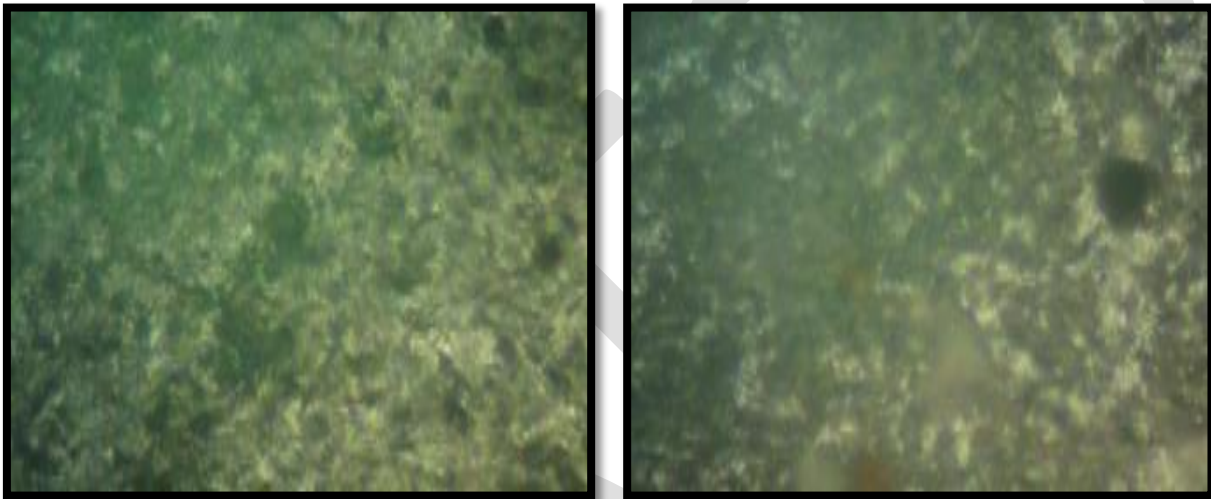


Plate 6: Micrographs of Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 90minutes and cooled in SAE40 and Al-3wt%Mg-2wt%Si-0.5wt%Ni soaked for 150minutes and cooled in SAE40.

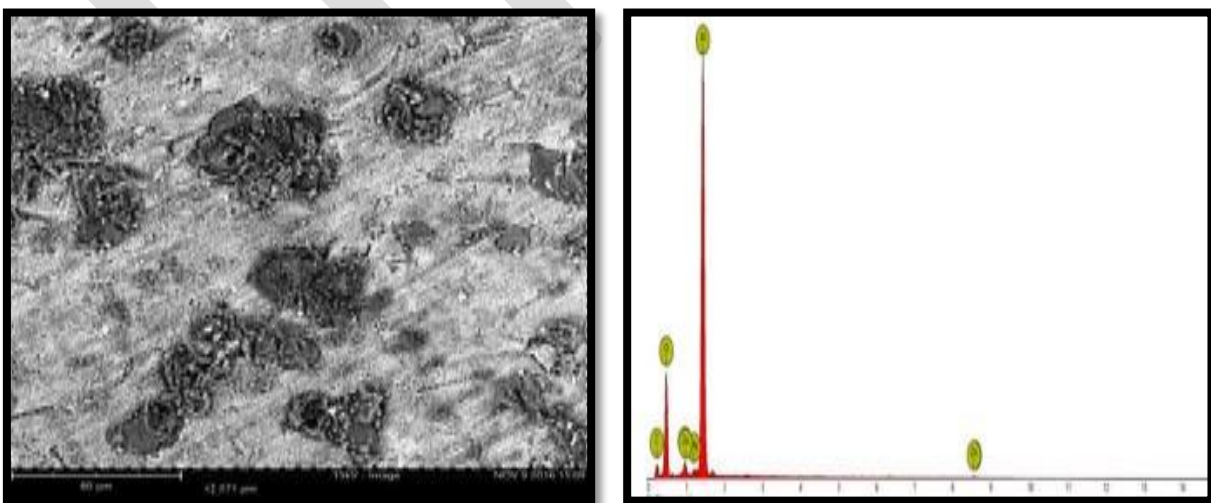
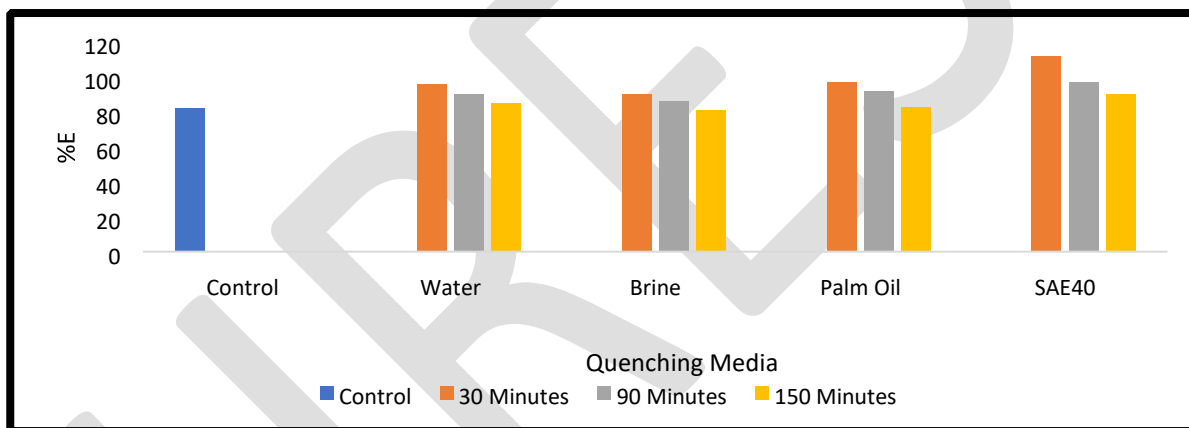


Figure 7: Micrograph (SEM) of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy soaked for 30minutes and cooled in water and EDS spectrum of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy.

The micrograph of the control specimen (Al3wt%Mg-2wt%Si-0.5wt%Ni alloy) is displayed in Figure 1a. The microstructure was mostly made up of MgSi₂Ni microsegregation in an aluminum matrix and α -Al dendrites. The specimens' micrographs, which were taken after they were cooled in water and solution heat-treated for 30, 90, and 150 minutes, are displayed in Figures 1b to 8. The intermetallic compound (MgSi₂Ni) phase, which is finely dispersed throughout the aluminum matrix, was visible in Figures 1b–3a. There was no space for Mg, Si, or Ni solute redistribution, and as a result, the alloy structure did not allow for MgSi₂Ni micro-segregation. Figures 1b–8b showed that the grains grew as the soaking time increased. The micro-segregations that had developed during the slow cooling phase were dissolved during heat treatment to create a homogenous phase, which vanished with further cooling. The micrographs of the specimens' solutions that were heat-treated for 30, 90, and 150 minutes at 300 degrees Celsius and quenched in brine are displayed in Figures 3b and 4b. The micrographs displayed the nonuniform distribution of coarse MgSi₂ phase grains within the aluminum matrix. Figures 3b and 4b showed that the intermetallic compound's size increased as the soaking period increased. Comparing the micrographs to the samples quenched in water, the bigger grains were visible. The micrographs of the specimens that were solutionized at 300 °C for 30, 90, and 150 minutes before being quenched in palm oil were displayed in Figures 5a and 6b. The micrographs showed that the aluminum matrix included tiny, needle-like intermetallic compounds uniformly dispersed. Larger granules were seen in Figures 5a and 6b, and size of the grains of intermetallic compounds reduced with an increase in soaking time. The scanning electron microscopy analysis of the control specimen presented in Figure 8a revealed microsegregation of the MgSi₂ intermetallic compound randomly distributed in the aluminum matrix. When compared to the micrograph of the control specimen, Figure 8b showed that the micro-



segregated intermetallic compound dissolved to create a homogenous phase and fine grains of intermetallic compound they increased increasing soaking time. The micrographs of the specimens solutionized for 30, 90, and 150 minutes at 300 °C and quenched in SAE40 were displayed in Figures 7a–8b. The micrographs revealed very fine grains evenly distributed in the aluminum matrix (Figures 7a8b). It was evidenced in Figures 8a-8b that the phase evenly distributed in the aluminum matrix. The elemental analysis (EDS) of the heat-treated (heat-treated) and non-heat-treated (control) samples of Al-3wt%Mg-2wt%Si0.5wt%Ni alloy is shown in Figures 7b and 8b. The existence of five key elements Al, Si, Mg, O, and Ni, among others were indicated by the figures.

Figure 8: Effect of quenching media on the percentage elongation of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy soaked for 30, 90 and 150 minutes.

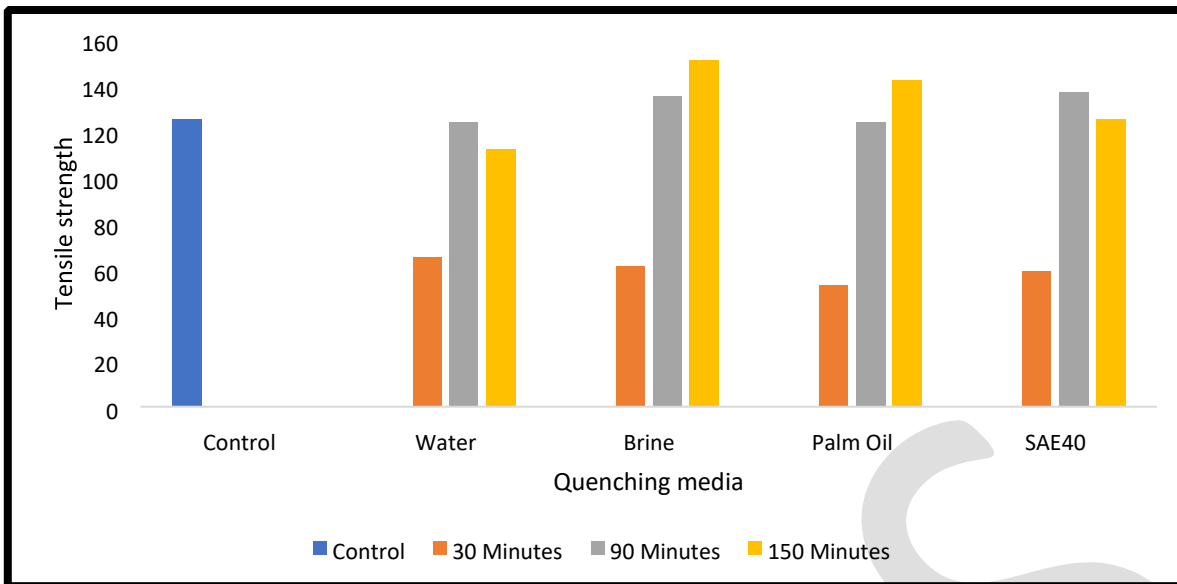


Figure 9: Effect of quenching media on the tensile strength (MPa) of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy soaked for 30, 90 and 150 minutes.

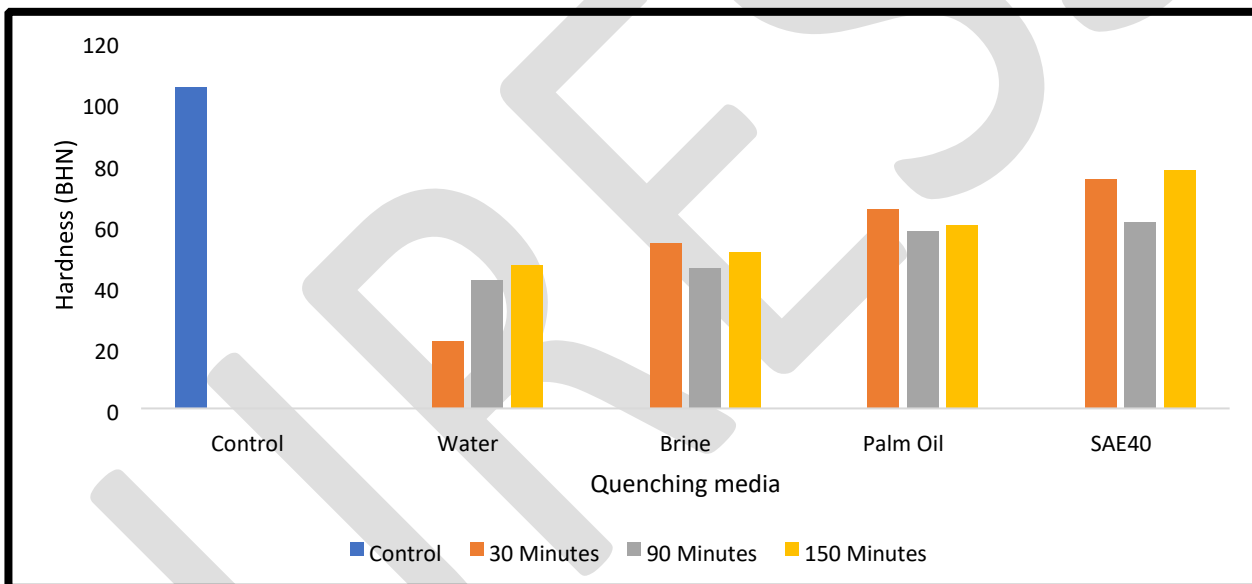


Figure 10: Effect of quenching media on the hardness (BHN) of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy soaked for 30, 90 and 150 minutes.

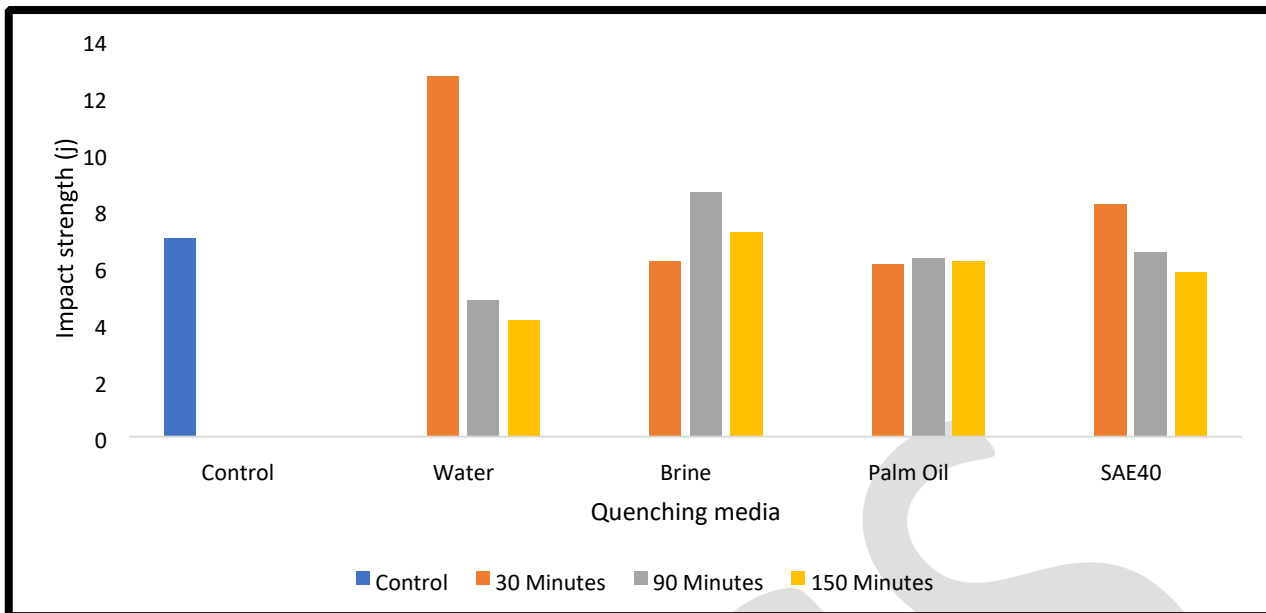


Figure 11: Effect of quenching media on the impact strength (j) of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy soaked for 30, 90, and 150 minutes.

The effects of quenching media and soaking duration on the percentage elongation, ultimate tensile strength, hardness, and impact strength of Al-3wt%Mg-2wt%Si-0.5wt%Ni are displayed in Figures 9–12. The Ni alloy solidified at 300 degrees Celsius. Figure 9 demonstrated how heat treatment greatly increased the alloy under study's % elongation. Figure 10 showed that as soaking time increased, the percentage elongation dropped. Figure 11 showed that Al-3wt%Mg-2wt%Si-0.5wt%Ni has improved in ultimate tensile strength. Ni alloy was soaked for 90 and 150 minutes, respectively, and cooled in SAE40, palm oil, and brine. Figure 11 showed that as the soaking duration grew, so did the specimens quenched in brine and palm oil in terms of percentage elongation. When the soaking period was raised to 90 minutes, the percentage elongation of the specimens quenched in water and SAE40 increased, and as the soaking time was further increased, the percentage elongation was reduced (Figure 11). Figure 12 showed that heat treatment had a detrimental effect on the hardness of the Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy. The non-heat-treated alloy (control) had a hardness value less than all of the heat-treated samples, as shown in Figure 12. Figure 6 demonstrated that the alloy under study had a considerable improvement in impact strength after being soaked for 30 minutes and then cooled in water.

4.0. Conclusion

The impact of heat treatment on the composition and mechanical characteristics of Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy has been studied with standard testing methods. It was determined that the heat treatment and quick solidification procedure prevented micro-segregation from forming and greatly increased the alloy's impact strength, ultimate tensile strength, and % elongation. The form, size, and quantity of intermetallic compounds generated in the alloy structure are examples of microstructural factors that have an impact on the mechanical properties of the Al-3wt%Mg-2wt%Si-0.5wt%Ni alloy. The heat-treated samples exhibited enhanced mechanical capabilities, which were ascribed to the alloy's structural homogeneity. Grain size changes were the cause of the observed trend in the heat-treated samples' hardness, percentage elongation, ultimate tensile strength, and impact strength. The alloy structure's increasing amount of soft α -phase quantified the maximum % elongation and impact strength recorded in the alloy.

References

- John R. Davis, Michael F. Ashby, and David R. H. Jones (2019). *Engineering Materials and Heat Treatment Processes for Aluminum Alloys*. New York, USA: McGraw-Hill Education.
- William D. Callister Jr. and David G. Rethwisch (2020). *Materials Science and Engineering: An Introduction* (10th ed.). Hoboken, NJ, USA: Wiley.
- George E. Totten (2018). Heat treatment and quenching characteristics of aluminum alloys. *Journal of Materials Engineering and Performance*, **27**(5), 2140–2152.
- Samuel J. Peters and Robert L. Smith (2021). Influence of heat treatment on the microstructure and tensile properties of Al–Mg–Si alloys. *Materials Performance and Characterization*, **10**(3), 455–468.
- James A. Williams, Thomas E. Brown, and Kevin M. Johnson (2022). Mechanical behavior of nickel-modified aluminum alloys subjected to solution heat treatment. *Journal of Metallurgical Engineering*, **14**(2), 88–97.
- Richard L. Higgins (2017). Aging response and hardness evolution of Al–Mg–Si alloys. *International Journal of Metalcasting*, **11**(4), 623–631.
- Daniel P. Adams and Steven C. Hall (2023). Effects of quenching media on the mechanical properties of cast aluminum alloys. *American Journal of Materials Science and Engineering*, **8**(1), 15–24.
- Mark T. Reynolds, Eric J. Thompson, and Paul D. Carter (2021). Structural characterization of heat-treated Al–Si–Mg alloys using SEM and optical microscopy. *Journal of Advanced Manufacturing and Processing*, **6**(2), 102–113.
- Andrew K. Miller (2019). Influence of precipitate distribution on the ductility and strength of aluminum alloys. *Materials Research Express*, **6**(9), 0965–0974.
- Charles R. Brooks and Ashok Choudhury (2018). *Heat Treatment, Structure, and Properties of Nonferrous Alloys*. Boston, USA: ASM International.
- Abubakre O. K., Mamaki U. P. and Muriana R. A. (2009) Investigation of the Quenching Properties of Selected Media on 6061 Aluminum Alloy. *Journal of Minerals and Materials Characterization*.