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RESEARCH ARTICLE

# Mechanical properties and wear resistance of SiC-reinforced aluminium matrix composite with nickel addition

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**ABSTRACT -** This study aims to analyze the effect of nickel addition on SiC-reinforced aluminum matrix composites in terms of mechanical properties (hardness and tensile strength), wear rate and microstructure produced through the casting process. The aluminum matrix used in this study is Al6061 and Al2024 with a concentration of 15 wt% SiC (silicon carbide) and nickel additions of 1, 3 and 5 wt%. The casting process uses a metal mold, mold temperature of 673.15 K, a stir-casting speed of 350 rpm and a pouring temperature of 923.15 K. The results of this study indicate that the addition of nickel increases hardness, tensile strength and wear resistance. Al2024/SiC with nickel addition exhibits higher hardness and wear resistance than Al6061/SiC under the same nickel addition. The highest hardness value in Al2024/SiC with 5% nickel is 113.78 HV with a wear rate of 0.05 mg/s. However, Al6061/SiC with nickel addition demonstrates better tensile strength and strain, with the highest tensile strength in Al6061/SiC + 5% Ni recorded at 282 MPa. The results of the microstructure examination shows that nickel addition can refine grains, particularly in Al6061, which contributes to the improvement in mechanical properties. SEM/EDS analysis confirms that Ni is evenly distributed and there is no agglomeration in either Al6061 or Al2024.

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*Nickel*
*Hardness*
*Tensile strength*
*Wear resistance*

## 1. INTRODUCTION

Metal Matrix Composite or MMC is a composite material with at least two distinct constituents, one of which is metal [1], [2]. Aluminum is one of the common metals used as a matrix in the fabrication of metal matrix composites due to its light mass [3], [4], [5]. However, aluminum alloy are generally considered soft and exhibit limited hardness and wear resistance. Nevertheless, their durability can be significantly improved by reinforcing them with particulate reinforcements such as SiC, $Al_2O_3$, and $B_4C$. The resulting material, which consists of aluminum alloy reinforced with these particles, is known as an Aluminum Matrix Composite (AMC). Aluminum Matrix Composite (AMC) is one of the most widely used types of Metal Matrix Composites (MMCs) in industry due to its light weight, high durability, and excellent mechanical properties. These include high strength, superior wear resistance, low thermal expansion, and good electrical conductivity, which make AMCs a potential substitute for conventional aluminum alloys [6].

The strengthening of composite materials depends on several key variables, including: (1) the preparation method, such as purification and activation of the constituent materials; (2) the mixing process, which involves factors like temperature, technique, mixing uniformity, composition of the reinforcement, and the use of wetting agents; and (3) the advanced processing methods, such as sintering, extrusion, compaction, thixoforging, and other post-treatment techniques [7], [8], [9], [10]. AMC fabrication mostly uses molten processing, especially stir casting because of its simplicity and scalability for industrial applications [11]. In the synthesis of Aluminum Matrix Composites (AMCs), stir casting is considered a relatively low-cost method (compared to other techniques such as powder metallurgy and spark plasma sintering); it also offers flexibility in processing conditions and reinforcement options [12].

In the production of Aluminum Matrix Composites (AMCs), commonly used reinforcing materials include silicon carbide (SiC) and alumina ($Al_2O_3$), which are ceramic materials known for their superior mechanical properties. The incorporation of SiC particles, in particular, can significantly enhance the tensile strength, hardness, density, and wear resistance of aluminum and its alloys [13], [14], [15], [16].

The common problem encountered in the development and production of Aluminum Matrix Composite (AMC) is that agglomeration and porosity often occur. Another problem encountered is the improved mechanical strength of AMC is frequently accompanied by a reduction in ductility. According to Zhu *et al.*, an inherent trade-off exists between increased ductility and decreased tensile strength due to microstructural changes during mechanical property optimization [17]. To address the common challenges found in Aluminum Matrix Composites (AMCs), such as reduced ductility and particle agglomeration, additional reinforcing elements need to be introduced into the matrix. Among these, magnesium is one of the most frequently used elements due to its effectiveness in enhancing the mechanical properties of AMCs. Magnesium plays a major role as an effective oxygen scavenger, reacting with the oxygen present on the surface of the

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dispersoid. This reaction thins the gas layer, thereby improving wetting and reducing the tendency for agglomeration [18], [19].

Research by Yadav attempted to embed nickel particles into an aluminum Matrix Composite (AMC) using the Friction Stir Processing (FSP), and it shows that the reinforcement of nickel particles leads to a threefold increase in the yield strength while an appreciable amount of ductility is retained. The nickel particles also are uniformly dispersed in the AMC which resulted significant grain refinement of the matrix [20]. That is consistent with the intrinsic properties of nickel that can easily combine with various other metals. Nickel can function both as a base metal and as an alloying element in various ferrous and non-ferrous systems. It also provides excellent resistance to corrosion, heat, stress-corrosion cracking, and electrical degradation, and acts as an austenite stabilizer. [21].

The addition of nickel to aluminum matrix composites (AMCs) can enhance mechanical properties without reducing ductility. However, the influence of nickel addition in AMCs produced by the stir casting method has been explored only to a limited extent. Therefore, this study investigates the effect of nickel addition on improving the mechanical properties and wear resistance of Al–SiC composites fabricated by the stir casting method.

## 2. MATERIALS AND METHODS

The materials employed in this study comprised: (1) aluminum alloys Al 6061 and Al 2024 as the matrix materials; (2) silicon carbide (SiC) as the reinforcement; and (3) nickel (Ni) and magnesium (Mg) as reinforcement addition. Prior to the casting process, all equipment was carefully inspected to ensure proper functioning and cleanliness.

Table 1. Composition of aluminum 6061

| Al | Mg | Cu | Fe | Mn | Si | Zn | Ni |
|---|---|---|---|---|---|---|---|
| 97.5 | 1.1 | 0.25 | 0.38 | 0.07 | 0.78 | 0.06 | 0 |

Table 2. Composition of aluminum 2024

| Al | Mg | Cu | Fe | Mn | Si | Zn |
|---|---|---|---|---|---|---|
| 92 | 1.46 | 5.08 | 0.22 | 0.82 | 0.23 | 0.18 |

Aluminum 6061, aluminum 2024, silicon carbide (SiC), nickel (Ni), and magnesium (Mg) were pre-weighed according to the predetermined compositions.

Table 3. The weight percent of each constituent material

| Specimen Number | Aluminum Type | Addition Variation | | |
|---|---|---|---|---|
| | | Silicon Carbide | Nickel | Magnesium |
| I | Al 6061 | 15% | 1% | 0% |
| II | | | 3% | |
| III | | | 5% | |
| VII | | | 0% | 3% |
| IV | Al 2024 | | 1% | 0% |
| V | | | 3% | |
| VI | | | 5% | |
| VIII | | | 0% | 3% |

The casting method was carried out by referring to various studies on casting parameter optimization [12], [22], [23], [24]. The processing method used in this study was stir casting. Initially, the materials were melted at a temperature of 993.15 K. Subsequently, the molten materials were stirred using a stir casting mixer at a speed of 350 rpm. While stirring, the SiC powder was added to the melted material. After that, the nickel powder was also poured into the mixture and stirring continued. Finally, the fully mixed material was poured into a preheated mold at 673.15 K. This stirring step was essential to promote the even distribution of the reinforcement particles within the molten matrix. The stir casting setup is illustrated in Figure 1.

The prepared specimens were subsequently subjected to Vickers microhardness testing, tensile testing, wear testing, and metallographic analysis. The microhardness test was conducted in accordance with ASTM E384, using an applied load of 0.2 kgf and a dwell time of 5 seconds, with five indentations performed on each specimen. Tensile testing was conducted using three specimens for each composition in accordance with ASTM E8/E8M-16a (subsize tensile test specimen), as presented in Figure 2.

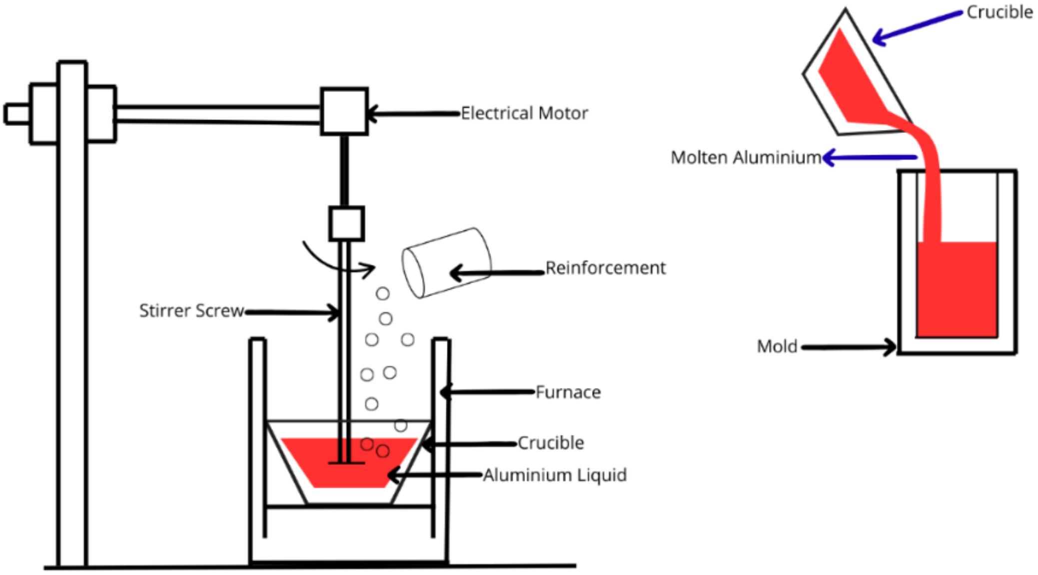


Figure 1. Stir casting equipment and scheme

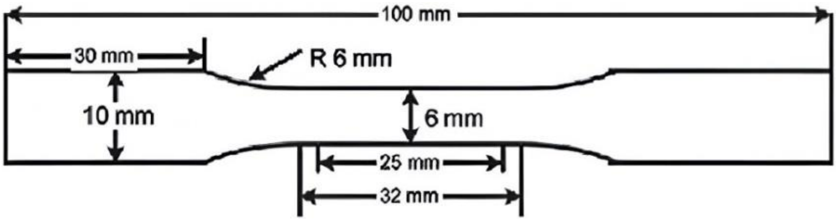


Figure 2. ASTM E8/E8M-16a (subsize tensile test specimen)

Wear testing was conducted using the abrasive wear method with a duration of 150 seconds and a load of 255 g, while the disk rotated at a speed of 3 revolutions per second and a sliding distance of approximately 169.6 m. Metallographic analysis involved polishing the specimens with sandpaper up to 1000 grit, followed by etching with Keller's reagent. The etchant solution was composed of 25 ml deionized water, 5 ml HF, 7.5 ml HCl, and 12.5 ml $HNO_3$. Specimens were immersed in the etchant for 40 seconds, rinsed with alcohol, and subsequently washed with deionized water. Microstructural observations were performed using an Olympus LEXT 3D Measuring Laser Microscope OLS4100 at 100× magnification, followed by further analysis with SEM/EDS.

## 3. RESULTS AND DISCUSSION

### 3.1 Cast Product

Figure 3 shows the cast product, which conforms accurately to the shape of the mold. No visible defects were observed. The specimen will subsequently be sectioned into multiple parts for use in wear testing, microhardness testing, and microstructural analysis.

Figure 3. AMC cast product

### 3.2 Hardness Value

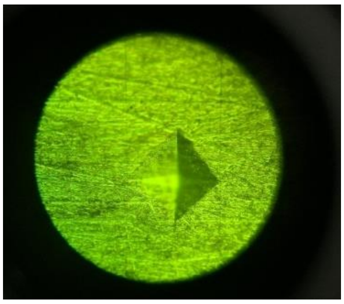


Figure 4. Microscopic indentation

Table 4 presents the hardness values obtained from five indentations on each specimen, averaged to obtain a representative value, and these averaged values were compared to illustrate the effect of nickel addition on the hardness of silicon carbide-reinforced Aluminum Matrix Composites (AMCs), as shown in Figure 5. It can be observed that the addition of nickel significantly increases the hardness values in both Al 6061 and Al 2024 composites. For equivalent nickel content variations (1%, 3%, and 5%), the hardness values of Al 2024 composites are consistently higher than those of Al 6061. The highest hardness recorded was for the Al 2024 composite (Specimen VI) measuring 113.78 HV, compared to 68.88 HV for the corresponding Al 6061 composite (Specimen III) with the same composition.

It was also found that the hardness values of specimens with the addition of magnesium were relatively similar to those with the addition of nickel in both Al 6061 and Al 2024. The addition of nickel to aluminum can reduce the grain size. This behavior aligns with the Hall–Petch effect, which describes the relationship between grain size and the strength of polycrystalline materials. This principle states that the smaller the grain size, the higher the strength and hardness of the material [25]. The addition of nickel to Al 2024 can lead to the formation of the AlCuNi phase, which possesses hard characteristics, thereby resulting in a higher hardness value in Al 2024 compared to Al 6061.

Table 4. Hardness value results

| Specimen Number | Aluminum Type | Addition Variation | | | Hardness Value (HV) |
|---|---|---|---|---|---|
| | | Silicon Carbide | Nickel | Magnesium | |
| I | Al 6061 | 15% | 1% | 0% | 59.78 |
| II | | | 3% | | 56.48 |
| III | | | 5% | | 68.88 |
| VII | | | 0% | 3% | 58.16 |
| IV | Al 2024 | | 1% | 0% | 106.94 |
| V | | | 3% | | 111.34 |
| VI | | | 5% | | 113.78 |
| VIII | | | 0% | 3% | 109.04 |

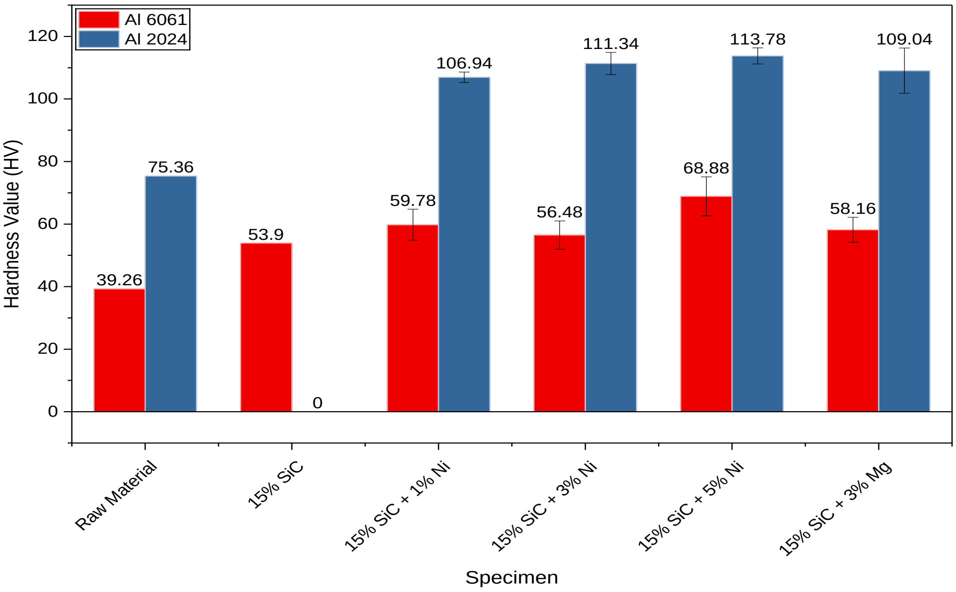


Figure 5. Hardness value comparison

### 3.3 Tensile Strength

This test utilized three samples from each specimen to obtain accurate data, in accordance with the ASTM E8/E8M-16a standard for subsize tensile test specimens, and the cast product sample before and after the test is shown in Figure6.

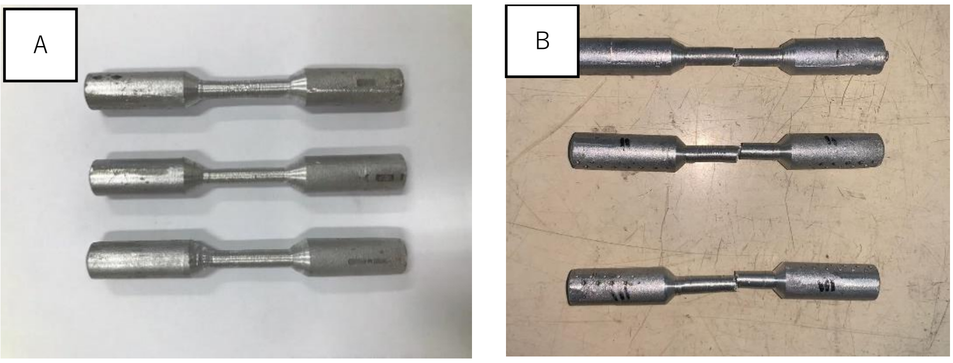


Figure 1. Tensile specimens; (A) Before testing, (B) After testing

Table 5 presents the averaged tensile strength and strain values obtained from three samples of each specimen, and the comparison of these values is illustrated in Figure 7 and Figure 8. In Figure 7 below, it is observed that the tensile strength of the Aluminum Matrix Composite (AMC) increases in both the Al 6061 and Al 2024 matrices. This trend is directly proportional to the results obtained from the hardness test. The highest tensile strength was achieved in Al 6061(Specimen III), recording a tensile strength of 282 MPa. This value is higher than that of Al 2024 (Specimen VI) with the same addition, which exhibited a tensile strength of 239 MPa.

Table 5. Tensile strength and strain results

| Specimen Number | Aluminum Type | Addition Variation | | | Tensile Strength (Mpa) | Strain Value (ε) |
|---|---|---|---|---|---|---|
| | | Silicon Carbide | Nickel | Magnesium | | |
| I | Al 6061 | 15% | 1% | 0% | 233 | 3.05 |
| II | | | 3% | | 262.3 | 4.24 |
| III | | | 5% | | 282 | 3.85 |
| VII | | | 0% | 3% | 273 | 3.32 |
| IV | Al 2024 | | 1% | 0% | 231 | 3.36 |
| V | | | 3% | | 258 | 2.98 |
| VI | | | 5% | | 239 | 3.36 |
| VIII | | | 0% | 3% | 244.3 | 2.7 |

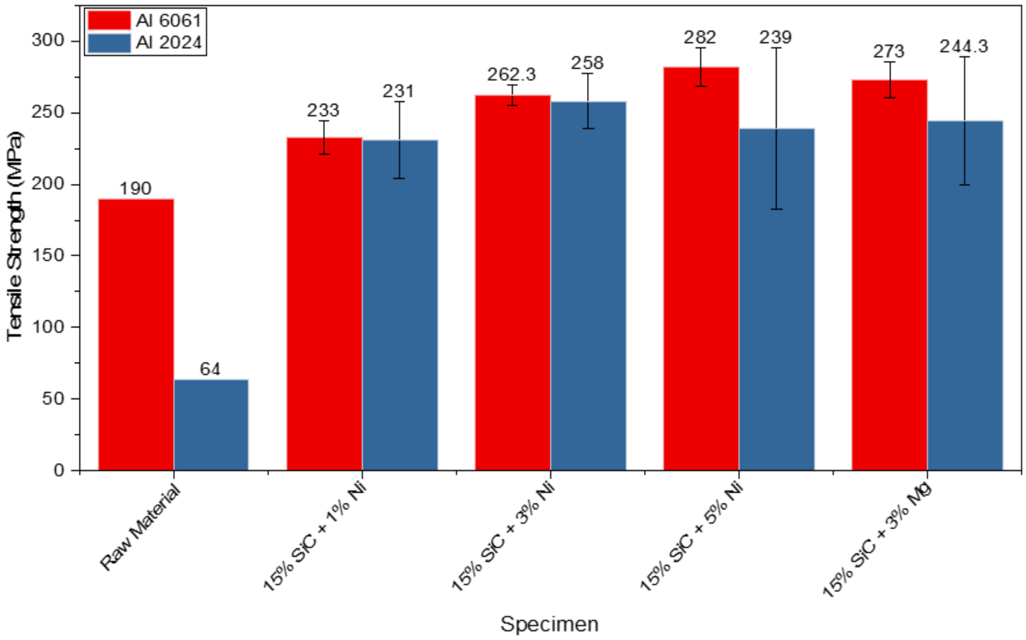


Figure 7. Tensile strength comparison

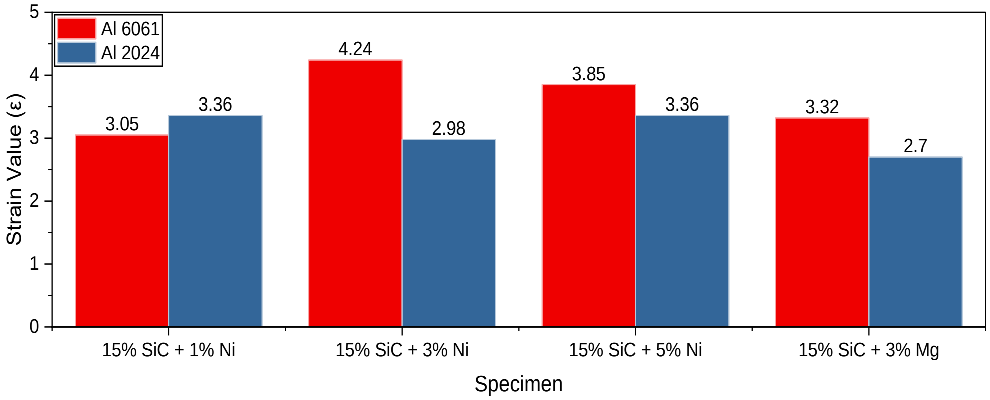


Figure 8. Strain value comparison

The influence of nickel addition on tensile strength is greater than that of magnesium. In contrast to the hardness results, the tensile strength of Al 6061 is observed to be higher than that of Al 2024. In certain cases, materials exhibiting high hardness may not necessarily possess high tensile strength, particularly if their internal microstructure does not facilitate effective resistance to tensile loads [26], [27], [28], [29], [30]. Although there is a tendency that hardness and tensile strength are directly proportional in many materials, this relationship is not universal. Each material can exhibit different characteristics depending on the physical and chemical factors that affect its mechanical properties. Therefore, such testing remains necessary to accurately assess the influence of incorporating new materials into Aluminum Matrix Composites (AMC) on their mechanical properties. The tensile strength of Al 2024 exhibits larger deviation, indicating a more fluctuating tensile strength value. This may be attributed to the presence of porosity or the agglomeration of SiC particles within the matrix.

### 3.4 Wear Resistance

Table 6 presents the wear rate results for each silicon carbide reinforced aluminum matrix composite (AMC) specimen with nickel addition, and the obtained values were subsequently compared, as illustrated in Figure 9. It can be observed in Figure 9 that Al 6061 exhibits a higher wear rate compared to Al 2024. This indicates an inverse correlation between the wear rate and the hardness values. Overall, the test results indicate a clear correlation between the wear rate and the hardness of the material. Specifically, an inverse relationship was observed, whereby an increase in material hardness corresponds to a decrease in wear rate [31], [32], [33]. The addition of SiC to AMCs enhances wear resistance due to its high hardness, load-bearing capability, and its role in improving the microstructure. With a good distribution of particles, the wear rate can be significantly reduced compared to conventional aluminum alloys. The addition of nickel to Al 2024 acts as a precipitate that enhances both hardness and wear resistance, attributable to the formation of the hard Al-Cu-Ni second phase [34], [35], [36], [37], [38], [39].

Table 6. Wear test results

| Specimen Number | Aluminum Type | Addition Variation | | | Wear Rate (mg/s) |
|---|---|---|---|---|---|
| | | Silicon Carbide | Nickel | Magnesium | |
| I | Al 6061 | 15% | 1% | 0% | 0.08 |
| II | | | 3% | | 0.09 |
| III | | | 5% | | 0.11 |
| VII | | | 0% | 3% | 0.11 |
| IV | Al 2024 | | 1% | 0% | 0.08 |
| V | | | 3% | | 0.06 |
| VI | | | 5% | | 0.05 |
| VIII | | | 0% | 3% | 0.14 |

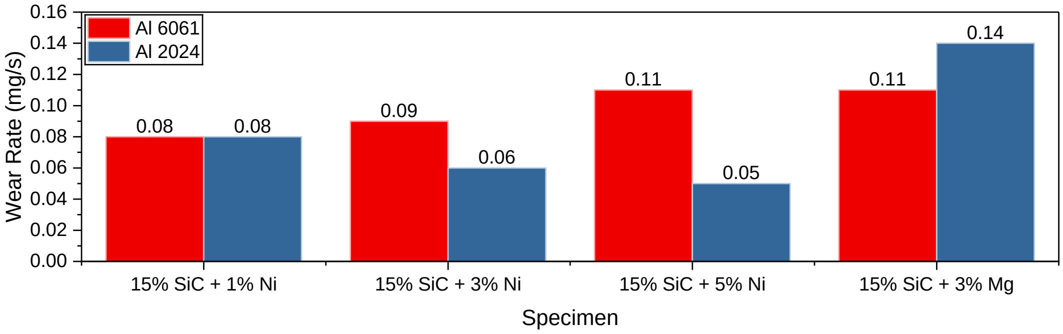


Figure 9. Wear rate comparison

### 3.5 Microstructural Analysis

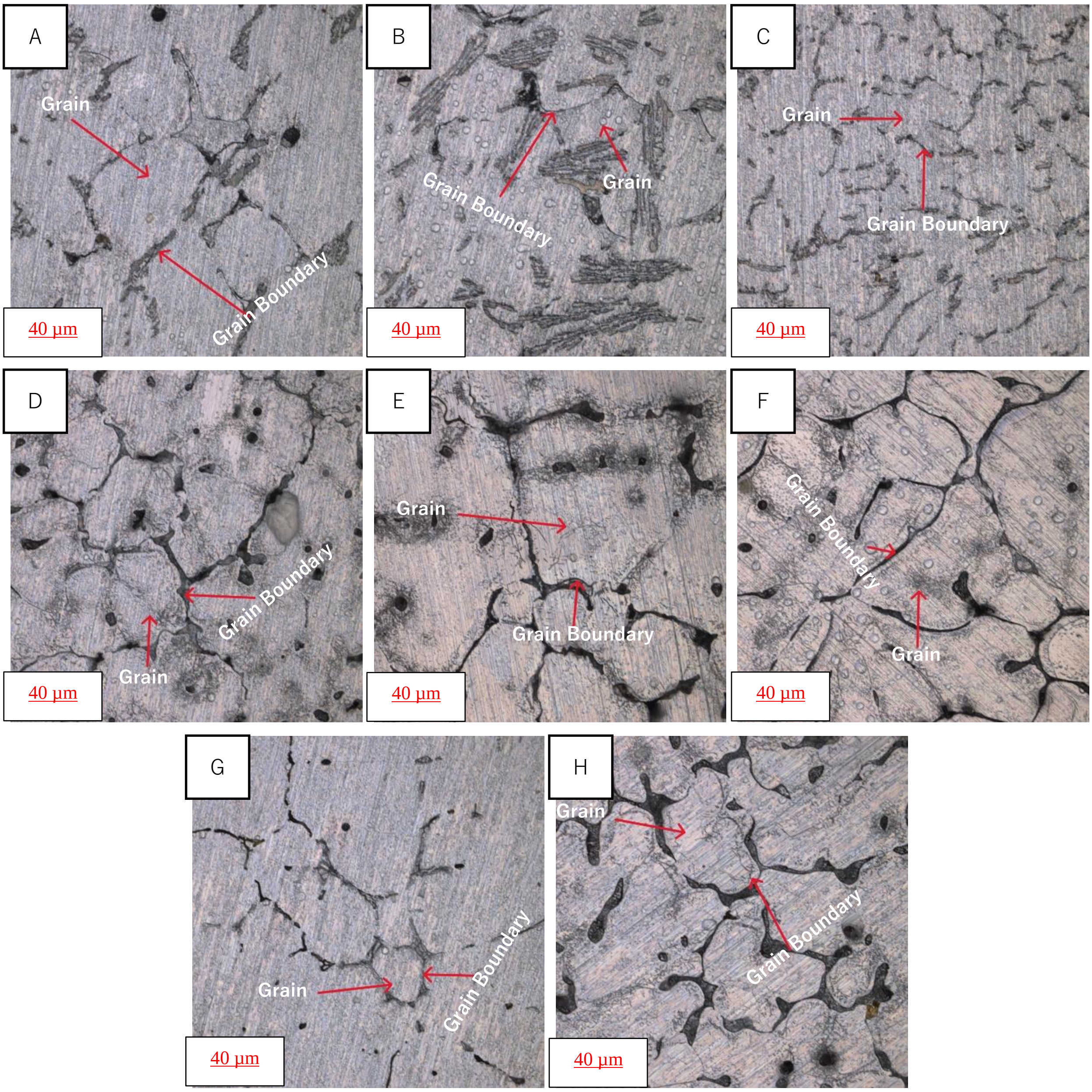


Figure 10. Microstructural analysis (40µm) (A) Specimen I, (B) Specimen II, (C) Specimen III, (D) Specimen IV, (E) Specimen V, (F) Specimen VI, (G) Specimen VII, (H) Specimen VIII

Figure 10 shows the microstructural analysis of nickel addition in silicon carbide-reinforced Aluminum Matrix Composites (AMCs). In the microstructure of Al 6061 + 15% SiC, shown in Figures 10(a), 10(b), and 10(c), it is observed that the grain size decreases progressively with increasing nickel content. Conversely, Figures 10(d), 10(e), and 10(f) present the microstructure of Al 2024 + 15% SiC with varying nickel additions, where the grain size appears relatively unchanged. Although both AMCs exhibit enhanced mechanical properties, the mechanisms differ. In Al 6061, the improvement is primarily attributed to grain refinement, whereas in Al 2024, it is due to the formation of a hard secondary phase, AlCuNi.

Figure 10(g) and 10(h) illustrate the effect of adding magnesium to the silicon-carbide reinforced aluminum matrix composite (AMC). In the case of Al 6061 + 15% SiC, the grain size appears relatively larger compared to that observed with nickel addition. Meanwhile, the addition of magnesium to Al 2024 + 15% SiC results in a grain size that is comparable to that of the nickel-added counterpart. These observations indicate that nickel has a more pronounced grain-refining effect than magnesium in Al 6061, whereas in Al 2024, the difference in grain size between the two additions is not significant.

Table 7. Average grain size results

| Specimen Number | Aluminum Type | Addition Variation | | | Average Grain Size (µm) |
|---|---|---|---|---|---|
| | | Silicon Carbide | Nickel | Magnesium | |
| I | Al 6061 | 15% | 1% | 0% | 48 |
| II | | | 3% | | 35 |
| III | | | 5% | | 27 |
| VII | | | 0% | 3% | 39 |
| IV | Al 2024 | | 1% | 0% | 30 |
| V | | | 3% | | 34 |
| VI | | | 5% | | 24 |
| VIII | | | 0% | 3% | 38 |

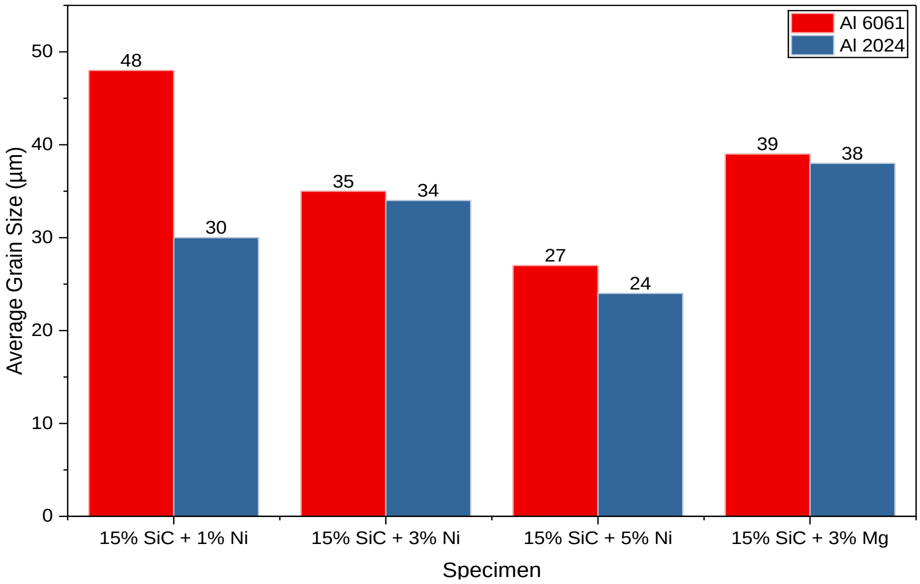
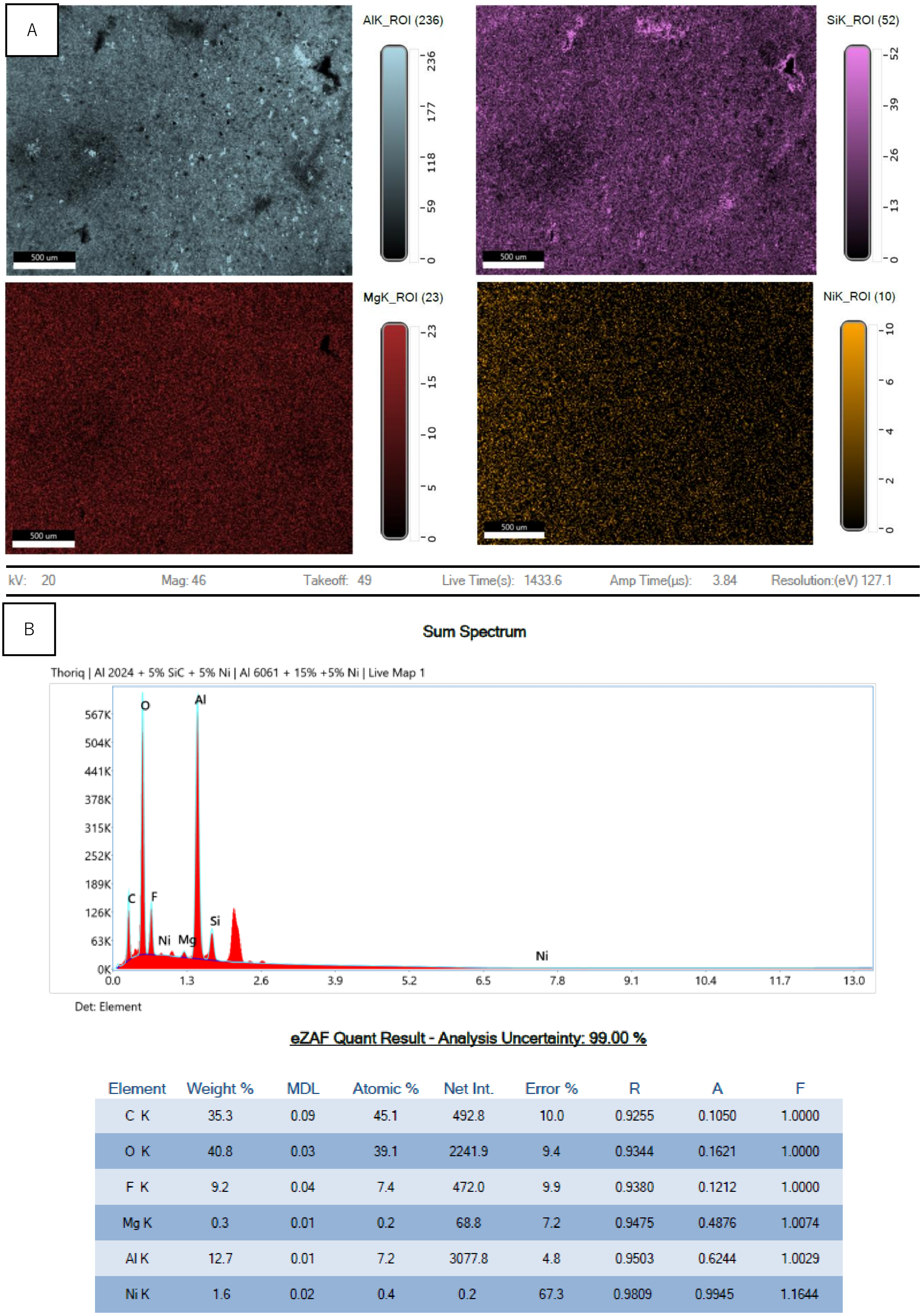


Figure 11. Average grain size comparison

Figure 11 represents the average grain size of all Aluminum Matrix Composite (AMC) specimens. The quantitative results were calculated using the Heyn intercept method in accordance with ASTM E112, which involves determining grain size by counting the number of grain boundary intersections along a series of test lines [40]. Figure 11 illustrates the average grain size of aluminum matrix composite (AMC) specimens reinforced with 15% silicon carbide (SiC) and varied additions of nickel (Ni) and magnesium (Mg). The results indicate a clear grain refinement trend with increasing Ni content. In the Al 6061 matrix, the average grain size decreases significantly from 48 µm at specimen I to 27 µm at specimen III. A similar trend is observed in Al 2024, where grain size reduces from 30 µm to 24 µm across the specimen IV-VI. These findings suggest that the presence of Ni acts as an effective grain refiner, particularly in Al 6061, likely due to its influence on nucleation and growth restriction during solidification. Comparatively, the addition of 3% Mg results in relatively larger grain sizes—39 µm in specimen VII and 38 µm in specimen VIII, highlighting that Ni addition is more effective than Mg in grain size reduction. Furthermore, the data also show that Al 2024 generally achieves finer grains than Al 6061 under identical compositional conditions, especially at lower Ni concentrations. This grain refinement behavior is consistent with previously reported improvements in mechanical properties, such as hardness and wear resistance, indicating a strong correlation between microstructural refinement and performance enhancement in AMC systems.

Figures 12 and 13 present the SEM-EDS results, including elemental mapping, EDS spectrum, and corresponding elemental compositions. In Figure 12, the elemental distribution of the AMC specimen III shows that nickel is relatively uniformly dispersed, with no indication of phase separation or segregation. This suggests that Ni is either dissolved in the aluminum matrix as a solid solution or exists as fine precipitates. Similarly, Figure 13 illustrates that in the Al 2024-based AMC specimen VI, nickel is also evenly distributed. Notably, its distribution pattern closely follows that of copper (Cu), a principal alloying element in Al 2024, indicating the formation of Al-Cu-Ni intermetallic precipitates. These precipitates play a significant role in enhancing mechanical properties by acting as barriers to dislocation motion, thereby increasing the material's hardness [38]. Furthermore, the nickel distribution differs from that of carbon (C), suggesting that nickel does not bond with the silicon carbide and does not act as a wetting agent. Nonetheless, the presence of nickel still contributes positively to mechanical performance without compromising the bonding integrity between the matrix and the silicon carbide reinforcement.

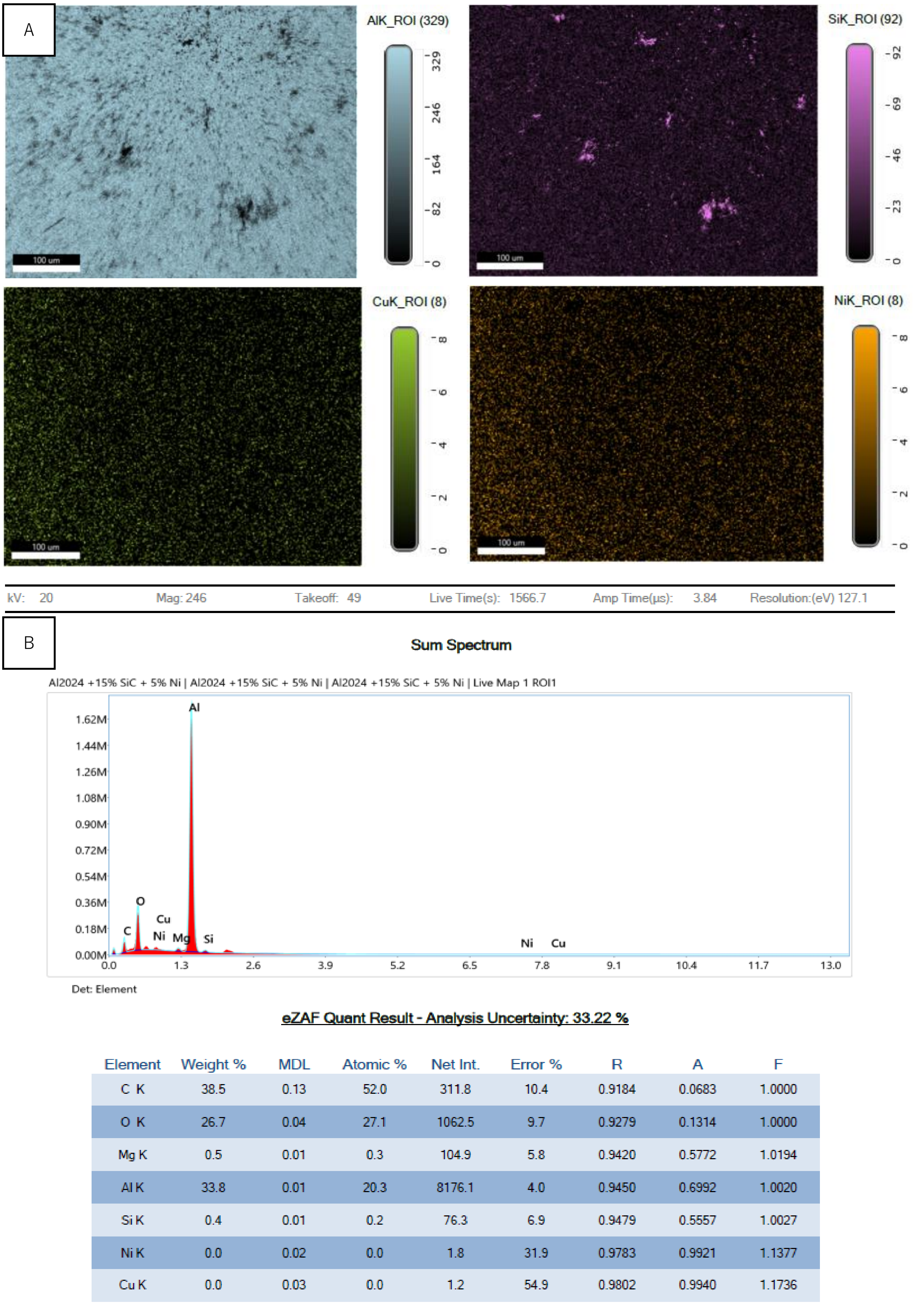


kV: 20 Mag: 46 Takeoff: 49 Live Time(s): 1433.6 Amp Time(µs): 3.84 Resolution:(eV) 127.1

eZAF Quant Result - Analysis Uncertainty: 99.00 %

| Element | Weight % | MDL | Atomic % | Net Int. | Error % | R | A | F |
|---|---|---|---|---|---|---|---|---|
| C K | 35.3 | 0.09 | 45.1 | 492.8 | 10.0 | 0.9255 | 0.1050 | 1.0000 |
| O K | 40.8 | 0.03 | 39.1 | 2241.9 | 9.4 | 0.9344 | 0.1621 | 1.0000 |
| F K | 9.2 | 0.04 | 7.4 | 472.0 | 9.9 | 0.9380 | 0.1212 | 1.0000 |
| Mg K | 0.3 | 0.01 | 0.2 | 68.8 | 7.2 | 0.9475 | 0.4876 | 1.0074 |
| Al K | 12.7 | 0.01 | 7.2 | 3077.8 | 4.8 | 0.9503 | 0.6244 | 1.0029 |
| Ni K | 1.6 | 0.02 | 0.4 | 0.2 | 67.3 | 0.9809 | 0.9945 | 1.1644 |

Figure 12. SEM-EDS test results of Specimen III (A) Elemental mapping, (B) EDS spectrum and elemental composition



kV: 20 Mag: 246 Takeoff: 49 Live Time(s): 1566.7 Amp Time(µs): 3.84 Resolution:(eV) 127.1

eZAF Quant Result - Analysis Uncertainty: 33.22 %

| Element | Weight % | MDL | Atomic % | Net Int. | Error % | R | A | F |
|---|---|---|---|---|---|---|---|---|
| C K | 38.5 | 0.13 | 52.0 | 311.8 | 10.4 | 0.9184 | 0.0683 | 1.0000 |
| O K | 26.7 | 0.04 | 27.1 | 1062.5 | 9.7 | 0.9279 | 0.1314 | 1.0000 |
| Mg K | 0.5 | 0.01 | 0.3 | 104.9 | 5.8 | 0.9420 | 0.5772 | 1.0194 |
| Al K | 33.8 | 0.01 | 20.3 | 8176.1 | 4.0 | 0.9450 | 0.6992 | 1.0020 |
| Si K | 0.4 | 0.01 | 0.2 | 76.3 | 6.9 | 0.9479 | 0.5557 | 1.0027 |
| Ni K | 0.0 | 0.02 | 0.0 | 1.8 | 31.9 | 0.9783 | 0.9921 | 1.1377 |
| Cu K | 0.0 | 0.03 | 0.0 | 1.2 | 54.9 | 0.9802 | 0.9940 | 1.1736 |

Figure 13. SEM-EDS test results of Al 2024 + 15% SiC + 5% Ni (A) Elemental mapping, (B) EDS spectrum and elemental composition

## 4. CONCLUSIONS

The effect of adding Ni to SiC-reinforced aluminum matrix composites can be concluded as follows:

a) The microhardness testing results demonstrate that the incorporation of nickel significantly enhances the hardness of the Aluminum Matrix Composite (AMC) in both Al 6061 and Al 2024. The highest hardness value was observed in specimen VI, reaching 113.78 HV. Furthermore, the addition of nickel yields higher hardness values compared to the specimens reinforced with magnesium, indicating its more pronounced strengthening effect.

b) The addition of nickel also results in an increase in strength in the Aluminum Matrix Composite (AMC) for both Al 6061 and Al 2024. Aluminum 6061 achieves the highest tensile strength of 282 MPa on the specimen III.

c) The addition of nickel improves the ductility of AMC for both Al 6061 and Al 2024. The highest ductility value, 4.24%, was obtained with the addition of 3% Ni in Al 6061 (Specimen II). This value is higher than the addition of 3% Mg, which yielded 3.32%. In Al 2024, the addition of 3% Ni resulted in a ductility value of 3.85%, which was also higher than the 2.7% obtained with the addition of 3% Mg.

d) Al 2024 with the addition of 15% SiC and Ni exhibits better wear resistance compared to Al 6061. Nickel is shown to be more effective than magnesium in enhancing wear resistance, particularly in Al 2024.

e) The addition of nickel (Ni) plays a role in refining the grains in the microstructure of Aluminum Matrix Composite (AMC). The addition of Nickel produces a refined microstructure that enhances mechanical properties. SEM results show that Nickel is evenly distributed and forms an Al-Cu-Ni phase which has hard properties.

## ACKNOWLEDGEMENTS

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## CONFLICT OF INTEREST

The authors declare no conflicts of interest

## AUTHORS' CONTRIBUTION

Muhammad Syahid (Conceptualization; Methodology; Writing - review & editing;)

M. Thoriq Ibnu Sina (Resources; Writing - original draft)

## AVAILABILITY OF DATA AND MATERIALS

The datasets generated and analysed during this study consist solely of experimental values obtained from laboratory testing. All relevant data are included within this published article. Additional information is available from the corresponding author upon reasonable request.

## ETHICS STATEMENT

This research did not involve human participants, animals, or sensitive data. Therefore, ethical approval and informed consent were not required.

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