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Experimental Analysis of Microstructure and Mechanical Properties of Aluminum Metal Matrix Composite Reinforced with Different Materials

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ABSTRACT

This work reports on the synthesis and characterization of novel aluminum-based hybrid metal matrix composites (MMCs) reinforced with combinations of titanium (Ti), nickel (Ni), and magnesium (Mg) by a stir casting process. Three compositions (all having 88 wt.% Al and 12 wt.% total reinforcement) were prepared: (i) 88Al–5Ti–4Ni–3Mg, (ii) 88Al–4Ti–3Ni–5Mg, and (iii) 88Al–3Ti–5Ni–4Mg. The microstructure was examined by scanning electron microscopy (SEM), and mechanical properties were measured via Brinell hardness, uniaxial tensile, and Charpy impact tests. Results show effective incorporation of the ceramic/metallic reinforcements into the Al matrix with generally uniform particle distribution. The composite containing 5 %Ti–4 %Ni–3 %Mg (case i) exhibited the highest ultimate tensile strength (≈270 MPa) and impact strength (≈3.1 J/cm²), whereas the sample with 3 %Ti–5 %Ni–4 %Mg (case iii) achieved the greatest Brinell hardness (≈70 BHN). Increasing Ni content tended to refine the microstructure (reducing average grain size from ~0.96 μm to 0.83 μm) and raised hardness, but higher Ni also slightly reduced ductility. The findings demonstrate that hybrid reinforcement can significantly enhance hardness and strength of Al alloys, consistent with known MMC behavior. Such light-weight composites with tailored Ti/Ni/Mg ratios show promise for high-strength applications in aerospace and automotive sectors.

Keywords: Aluminum Metal Matrix Composites (AMMCs), Stir Casting, Microstructural Characterization, Mechanical Properties, Reinforcement Ratio Optimization.

1. Introduction

Metal matrix composites (MMCs) are engineered by embedding reinforcing elements (particles, whiskers, fibers, or sheets) within a metal or alloy matrix, creating materials that combine high strength, wear resistance, excellent fatigue life, and thermal conductivity. In particular, MMCs offer reduced density and elevated strength-to-weight ratios compared to conventional alloys, along with enhanced wear resistance and lower thermal expansion [1] Recent advances show that the properties of MMCs strongly depend on processing routes, matrix, and reinforcement selection, with hybrid systems outperforming single-reinforced composites in strength, ductility, and surface performance. However, challenges such as porosity, grain clustering, and interfacial reactions persist, particularly in aluminum-based MMC fabrication [2]. By the late 20th century, research emphasized cost-effective reinforcements, with composites gaining wide industrial use due to their tunable thermal, mechanical, and tribological properties. In these materials, the matrix (metal, ceramic, or polymer) binds reinforcements (fibers or particles), whose type and stability at high temperatures dictate performance and durability [3].

In a study, Sujon and Sayed [4] found that Cu increases strength through θ-phase formation, Zn consistently reduces compressive strength, and Mg above 10% promotes β-phase development and dendritic refinement in Al alloys. Vamsi and Anthony demonstrated that Al6061-based hybrid composites reinforced with SiC and graphite exhibited significantly enhanced tensile strength (192.45 MPa at 15 wt.% reinforcement) alongside adjustable density, highlighting their potential as lightweight materials for engineering applications [5].

Recent investigations on Al6063-based metal matrix composites reinforced with Cu and TiO_2 particles via stir casting revealed that increasing Cu content (5–15 wt%) enhances tensile strength—reaching 119.58 MPa for 15 wt% Cu—while marginally improving toughness. However, ductility decreases, and impact strength declines with higher Cu fractions, with the Al6063-5 wt% Cu composite exhibiting a maximum impact energy of 28.0 J. Microstructural analysis indicates uniform dispersion of reinforcements without agglomeration, underscoring the effectiveness of the fabrication method [6]. XRD analysis of Al–TiC composites confirmed the absence of contaminants. Increasing TiC content enhanced density, hardness, and tensile strength, while reducing elongation and impact strength. SEM observations revealed a shift from ductile to brittle failure with higher TiC fractions, indicating their suitability for automotive, military, and aerospace applications [7]. The incorporation of TiO_2 into ZA22 alloy resulted in uniform particle dispersion, enhancing microstructure, ultimate tensile strength (up to 30% increase at 6 wt% TiO_2), ductility, hardness, and wear resistance by impeding dislocation motion and reducing material loss [8]. Stir-cast AA6061 composites reinforced with rutile particles exhibited improved hardness and tensile strength, increasing by up to 44% and 14%, respectively, with 1–3 wt% rutile, though ductility decreased; addition beyond 3 wt% caused tensile strength reduction due to particle agglomeration, while SEM analysis revealed a transition from ductile to brittle failure with higher rutile content [9]. Aluminum alloys reinforced with 2 wt% Ag nanoparticles exhibited enhanced compressive strength (25.8%) and microhardness (20.9%) via Orowan strengthening, with nanoparticle size, distribution, and intermetallic bonding critically influencing mechanical performance, while excessive reinforcement may induce aggregation [10]. In AA2024 coatings, increasing Ag content up to 16 wt% promotes the formation of silver-rich intermetallics and $Al_6(Cu,Ag)Mg_4$ precipitates, enhancing hardness and strength, while minimally reducing electrical conductivity (~0.12% IACS per 1 wt% Ag) [11]. The literature shows many studies on Al MMCs with varied reinforcements – for example, Hossain et al. [12] found that adding TiO_2 and Cu to Al6063 improved tensile strength (up to ~119 MPa) but reduced ductility, and Kumar et al. [13] reported that TiC reinforcement increased hardness and strength at the expense of elongation. These examples used ceramic or hard metallic additions, but none systematically explored a combination of Ti, Ni, and Mg. In particular, Ni has rarely been used as a dispersed reinforcement in Al alloys. Thus a clear gap exists prior work has not investigated how hybrid Ti–Ni–Mg reinforcements at a fixed total content affect Al's microstructure and mechanics.

The research problem is to determine how varying the relative proportions of Ti, Ni, and Mg, while maintaining a constant total reinforcement of 12 wt.%, affects the microstructure and mechanical properties of Al-based MMCs. Three Al matrix composites will be fabricated by stir casting with different Ti/Ni/Mg ratios and characterized using SEM, Brinell hardness, tensile, and impact testing. The study aims to correlate composition with mechanical performance to identify the reinforcement combination that provides the optimal balance of strength, hardness, and ductility, while clarifying the governing metallurgical mechanisms.

2. Materials and Methods

Commercially pure aluminum powder (99.9%) was used as the matrix. Three batches of composite were prepared, each with a total of 12 wt.% reinforcement but different proportions of titanium, nickel, and magnesium powder. The compositions (by weight) were: (i) 88% Al + 5% Ti + 4% Ni + 3% Mg, (ii) 88% Al + 4% Ti + 3% Ni + 5% Mg, and (iii) 88% Al + 3% Ti + 5% Ni + 4% Mg.

Titanium, nickel, and magnesium were chosen because each contributes distinct benefits to the Al matrix. Ti is a well-known grain refiner in aluminum alloys; it forms Al_3Ti particles that act as potent inoculants and produce a finer, more uniform grain structure [12]. Ni is a hard transition metal whose addition increases strength and hardness: indeed, our results (and others') show that higher Ni content reduces average grain size and raises hardness. However, Ni-rich intermetallic are brittle. Magnesium is a light alloying element that strengthens Al by solid solution and β-phase formation, typically without severely sacrificing ductility [13]. In summary, Ti refines grains for toughness, Ni boosts hardness/strength, and Mg maintains ductility. Combining them allows tuning multiple properties in the hybrid MMC.

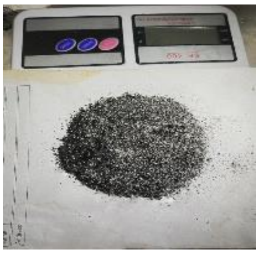


Fig. 1 Aluminum Powder.

Fig. 2 Magnesium Powder.

Fig. 3 Nickel Powder.

Fig. 4 Titanium Powder

2.1 Powder Preprocessing

All powders were weighed to the proportions above and then preheated before casting to remove moisture and prevent oxidation. In particular, the Al and Mg powders were held at 400 °C for 1 h, while the Ni and Ti powders were held at 1000 °C for 1.5 h. These preheating steps were performed in an open furnace. After soaking, the powders were removed and held ready for casting.

Here, Preheating and melting were done with a furnace in a workshop located at Madarbari, Chittagong. The melting temperatures for Al, Mg, Ni, & Ti are 660ºC, 650ºC, 1455ºC & 1650°C respectively. The furnace for preheating and melting is illustrated in Fig. 5.

Fig. 5 Furnace.

2.2 Stir Casting Process

To ensure a uniform mixture in aluminum (Al) with reinforcements, a stirring material was employed to generate a vortex. The stirring apparatus was set to rotate at a speed of 100 revolutions per minute (rpm) for a duration of 5 minutes, facilitating the creation of the desired vortex. This stirring process was concurrently implemented while transferring the reinforcements into the Al metal, ensuring their proper distribution throughout the mixture. The stir-casting flowchart is illustrated in Fig. 6.

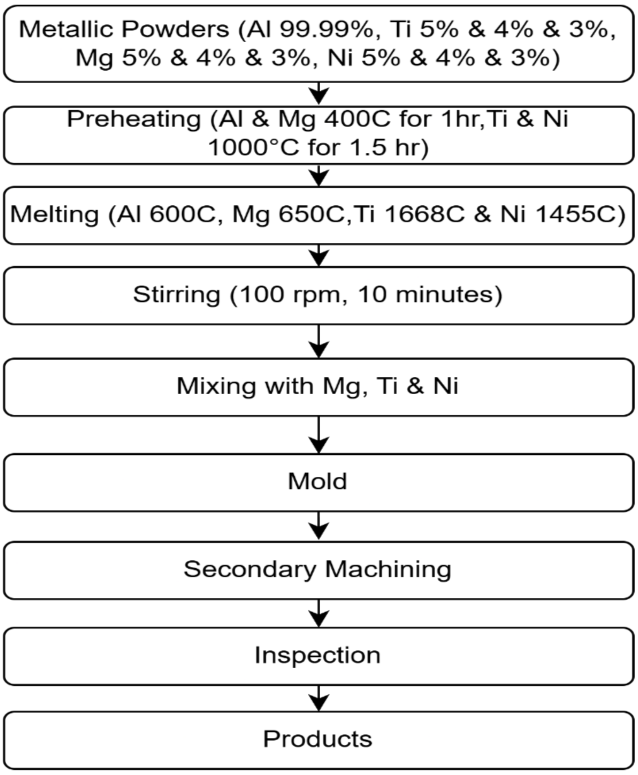


Fig. 6 Outline of Stir Casting Process in the Flowchart.

2.3 Molding and Finishing

The three molds were patterned for the required specimen geometries: a dog-bone tensile bar, a notched impact bar, and a block for microstructure (SEM) specimens. Once the castings solidified, the billets were machined on a lathe. Secondary operations included taper turning, threading of the ends of tensile bars (to grip in the UTM), and surface grinding for flatness. Tensile specimens were finished by cutting threads and machining the central gauge section to a constant diameter (~5 mm). Charpy impact specimens were cut with a U-shaped (V-notch) profile, as per standard practice (slots cut by milling). Hardness test samples were prepared by cutting flat sections and polishing the test surface. All final specimens were cleaned and polished as necessary (to remove casting surface scale and achieve the required dimensions) before testing.

2.4 Mechanical Characterization

2.4.1 Tensile Testing

Tensile tests were performed on Universal Testing Machine (UTM) at room temperature. Cylindrical specimens (5 mm diameter, 50 mm gauge length) were loaded in uniaxial tension until fracture. The applied load F was recorded, and the engineering ultimate tensile strength σ was calculated by Eq. (1) and Eq. (2) as

$$\sigma = \frac{F}{A} \tag{1}$$

$$\xi = \frac{l}{L} \tag{2}$$

Where, ξ indicates strain, l indicates elongation and L indicates initial length.

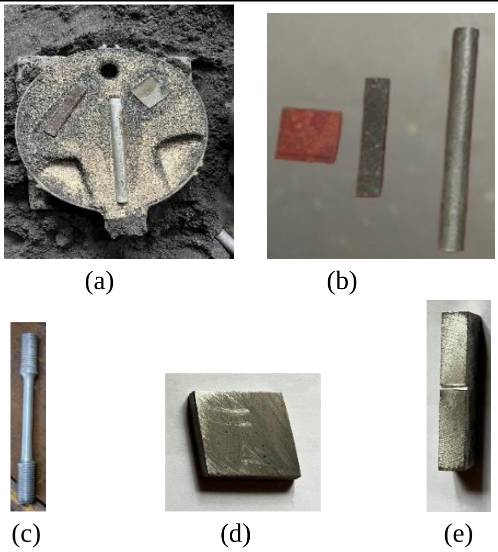


Fig. 7 (a), (b) Pattens for making molds. (c) Tensile Test Specimen, (d) Hardness Test Specimen, (e) Impact Test Specimen.

2.4.2 Hardness Testing (Brinell)

The Brinell hardness of each composite was measured using a Brinell hardness testing machine. Each test employed a 10 mm diameter hardened steel ball indenter (tungsten carbide), pressed into a flat specimen surface. A test load (typically in the range 500–3000 N) was applied for 10–30 s. After indentation, the impression diameter d was measured, and the Brinell Hardness Number (BHN) was calculated by Eq. (3)

$$\text{BHN}=\frac{2P}{\pi D(D-\sqrt{D^2-d^2})} \tag{3}$$

2.4.3 Impact Testing

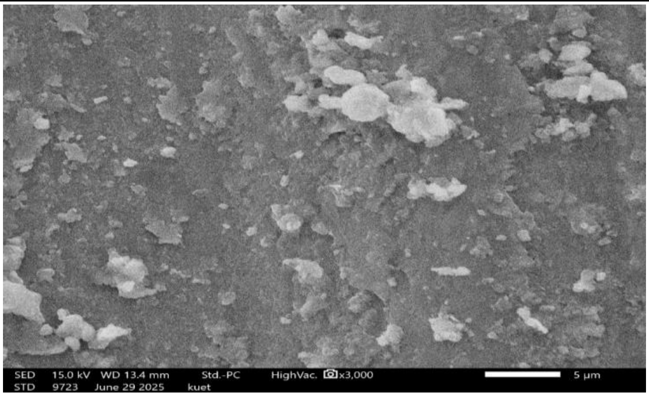
Charpy V-notch impact tests were conducted on a digital impact testing machine (pendulum type). Standard Charpy specimens with a V-notch (typically 2 mm deep) were prepared from the composite bars. In each test the pendulum was released to fracture the specimen, and the absorbed energy E (in J) was recorded directly by the machine. The impact strength was calculated by dividing the absorbed energy by the cross-sectional area at the notch (resulting in units of J/cm²).

2.4 Microstructural Analysis

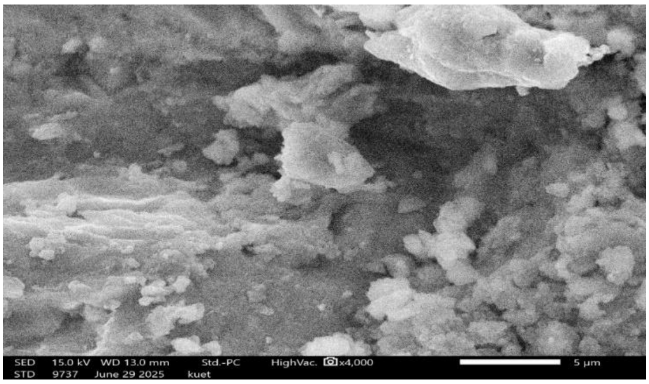
Microstructure and reinforcement dispersion were examined by scanning electron microscopy (SEM).

3. Result and Discussion

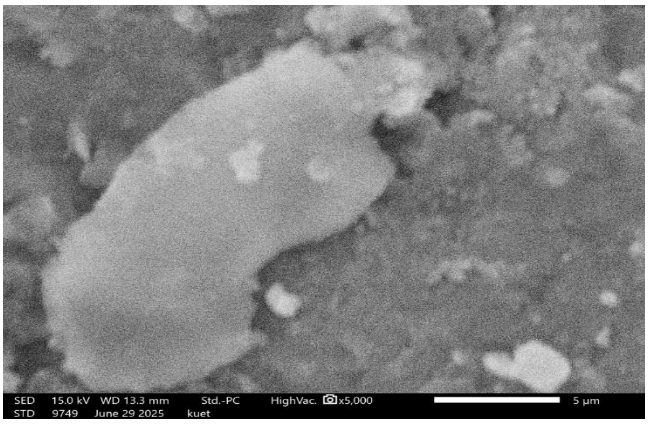
The study of the morphological behavior of the created composite material was done using microstructure analysis. SEM examination of the three Al-based composites (with 5%Ti/4%Ni/3%Mg, 4%Ti/3%Ni/5%Mg, and 3%Ti/5%Ni/4%Mg) revealed a generally uniform dispersion of the reinforcement particles throughout the aluminum matrix. In each case the Ti, Ni and Mg particles appeared well-dispersed, with no large clusters apparent in the micrographs. Fig. 8(a), Fig. 8(b), Fig. 8(c) shows the SEM micrographs of the sample (i) (88% Al +5% Ti+ 4% Ni + 3% Mg), sample (ii) (88% Al + 4% Ti +3% Ni + 5% Mg), sample (iii) (88% Al + 3% Ti + 5% Ni + 4% Mg) which were taken at 3000x, 4000x and 5000x magnification respectively.



(a)



(b)



(c)

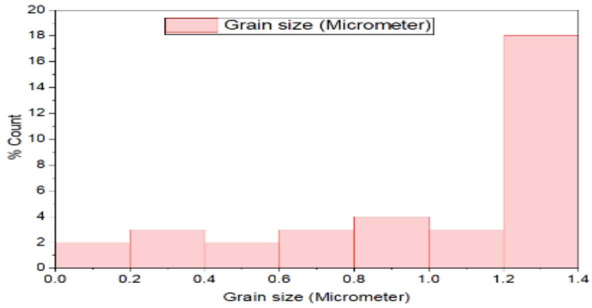
Fig. 8 SEM micrographs of the samples.

The results show reinforcement particles distributed within the Al matrix, though non-uniformity occurs due to the insolubility of Ni, Ti, and Mg and possible particle clustering during the stir casting process.

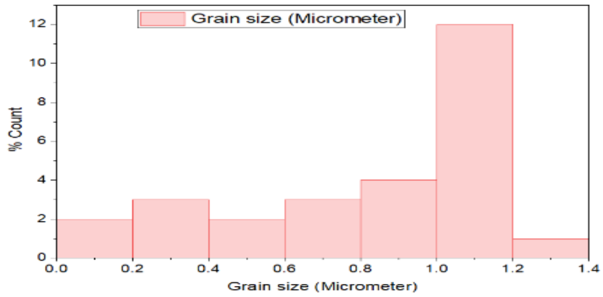
3.1 Grain Size Distribution

The distribution curve in Fig. 9(a), 9(b) and 9(c) illustrate normal distribution curves for grain size.

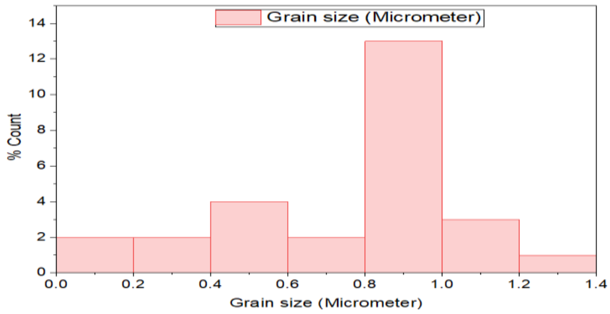
The analysis shows that the sample has grains of different sizes, making it heterogeneous. This highlights the need to study grain size carefully to understand the material's properties and uses. Tools like ImageJ and OriginPro help to examine the microstructure more accurately, giving useful insights for improving the material's performance. Grain-size analysis (via ImageJ) confirmed this observation: the metallographic images showed an approximately normal distribution of grain sizes in each sample, indicating a heterogeneous but uniformly filled microstructure. For example, no systematic banding or agglomeration of particulates was seen in any composite (see representative SEMs), consistent with effective wetting and stirring during processing.



(a)



(b)



(c)

Fig. 9: Illustrate normal distribution curves for grain size for sample (i), (ii), (iii).

3.2 Hardness Number

This study examines the Brinell hardness of the prepared samples. Results show that hardness varies with reinforcement content. Sample (iii) achieved the highest value (69.78 BHN) due to its higher Nickel content, while Sample (ii) showed the lowest (63.58 BHN) because of its lower Nickel proportion. The variation is mainly linked to the brittle nature of Nickel, which increases the overall hardness of the composite. Fig. 10 shows the Brinell Hardness Numbers of the composites, highlighting how hardness changes with different Ti-Mg-Ni concentrations.

This comparison helps explain the relationship between reinforcement content and composite hardness, which is important for understanding material performance and applications.

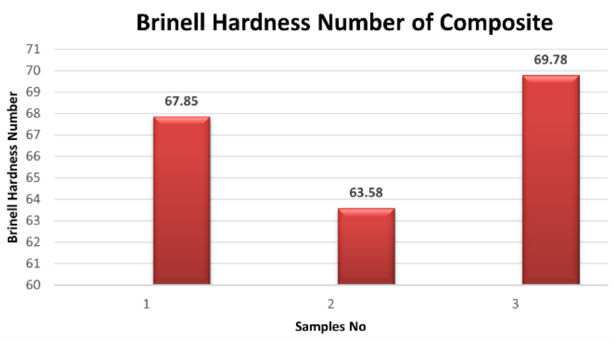


Fig.10: Hardness number of composites.

3.3 Impact Strength

The Charpy impact test was performed using V-notch specimens and a pendulum hammer. Fig. 11 shows that sample (i) has an impact strength of 3.1 J/cm², sample (ii) slightly lower at 3.0 J/cm², and sample (iii) the lowest at 2.8 J/cm². The results indicate that impact strength improves with higher Ti content and decreases with higher Mg and Ni content, showing that the reinforcement percentage strongly affects the composite's impact strength.

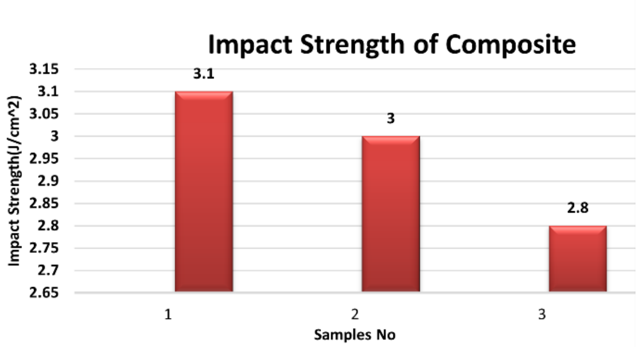


Fig.11: Impact strength of composites.

3.4 Tensile Behaviors

3.4.1 Sample (i) Tensile Properties

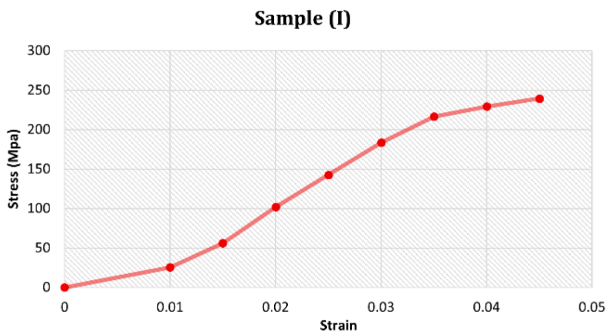


Fig.12: sample (i) Stress-Strain Curve.

3.4.2 Sample (ii) Tensile Properties

The tensile strength of the composites depends strongly on reinforcement composition. Sample (ii) exhibits the highest UTS (269.93 MPa) due to uniform particle dispersion, achieved by increasing Ti to 5% while reducing Ni and Mg to 3%, as confirmed by SEM. Lower Ti content with higher Ni and Mg leads to particle segregation and reduced tensile performance. Figure 15 illustrates this comparative tensile behavior.

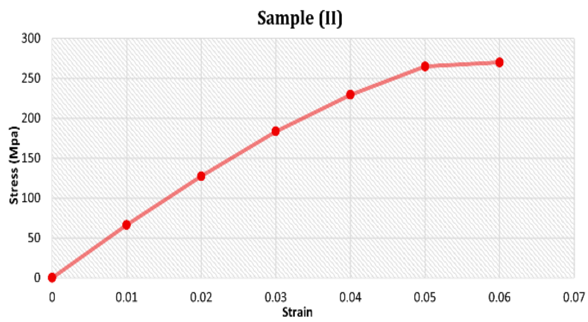


Fig.13 Sample (ii) Stress-Strain Curve.

3.4.3 Sample (iii) Tensile Properties

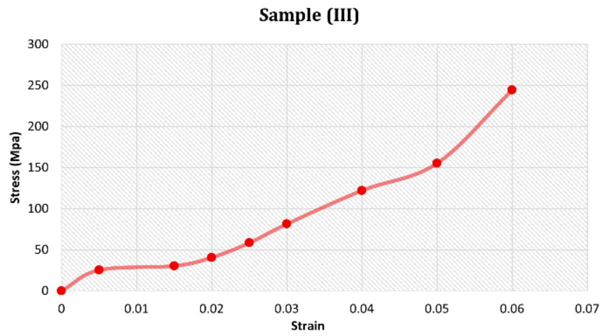


Fig.14: sample (iii) Stress-Strain Curve.

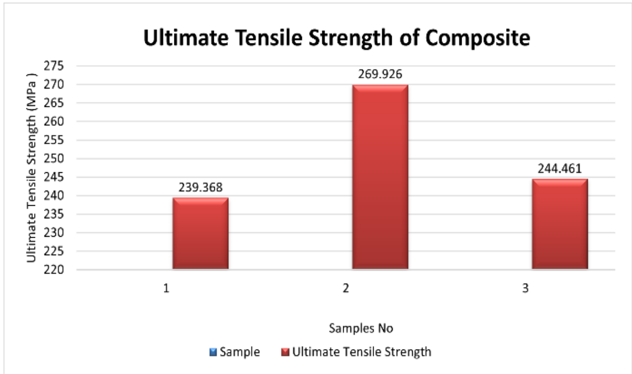


Fig.15 Overall Tensile Strength of Each Sample.

The observed mechanical trends can be explained by the roles of the individual reinforcements. Nickel forms hard Ni–Al intermetallic phases in the Al matrix, which act as strong obstacles to dislocation motion[14]. This explains why the Ni-rich sample (iii) reached the highest hardness; however, these NiAl phases are brittle, which accounts for the reduced elongation and impact toughness in that sample. In contrast, Ti produces Al_3Ti particles that refine the grain structure. The finer grains strengthen the material (via the Hall–Petch effect) while still allowing more energy absorption before fracture. Magnesium, being a more ductile alloying element, provides solid-solution strengthening without embrittling the matrix, which helps explain why Mg-rich additions improved toughness. Thus, the strength–ductility trade-off follows expected metallurgical behavior: increasing Ni raises hardness but reduces ductility, whereas Ti-driven grain refinement enhances strength with less ductility penalty.

3.5 Summary Results

Table 1 Summary of the Results

Sample	88%Al+5% Ti+4%Ni+ 3% Mg	88%Al+ 4%Ti+3%Ni +5%Mg	88%Al+3 %Ti+5% Ni+ 4%Mg
Impact Strength (J/cm^2)	3.1	3	2.8
Tensile Strength (MPa)	269.926	244.46	239.368
Hardness (BHN)	67.5	63.58	69.78
Average Grain Size (microns)	0.96	0.91	0.83

4. Conclusions

This thesis successfully fabricated Ni–Ti–Mg reinforced aluminum MMCs using stir casting and demonstrated significant improvements in mechanical properties over pure aluminum. The optimum composition (5% Ti, 4% Ni, 3% Mg) achieved the highest hardness (69.78 BHN) and ultimate tensile strength (269.93 MPa), attributed to uniform reinforcement distribution. Hardness increased with higher Ti and lower Mg, while excessive Mg (>5%) and low Ti (<3%) reduced strength due to particle segregation. Impact strength improved to 3.1 J/cm^2, indicating enhanced energy absorption, though a trade-off between hardness and tensile strength and limited ductility was observed. Microstructural analysis confirmed that reinforcement distribution and interfacial bonding play a critical role in governing mechanical behavior. These findings provide useful guidance for optimizing hybrid reinforcement ratios and support the potential application of such MMCs in lightweight, high-performance automotive and aerospace components.

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