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Correlatory Study of the Structural and Mechanical Performance of Ti/Nd Modified Al-3%Li Alloy

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Abstract: **Aluminium-lithium alloys remain an important class of lightweight structural materials due to their good strength-to-weight ratio and corrosion resistance. However, their mechanical performance is strongly influenced by microalloying additions that control grain structure and intermetallic formation. This study therefore investigates the synergistic effect of varying Ti/Nd ratios on the mechanical and microstructural properties of cast Al-3wt%Li alloy. Aluminium, lithium, titanium and neodymium powders were weighed by percent composition, melted in a steel crucible furnace, alloyed, stirred and cast into moulds. Tensile, yield, elongation and hardness tests were performed using ASTM E8M-04 standards, alongside optical and SEM microstructural evaluations. Results showed that tensile strength reached its peak when Ti = 1.2 wt% and Nd = 0.2 wt%, before decreasing with further additions. Hardness increased from 39.5 BHN (control) to 71.1 BHN at optimal Ti/Nd combinations, while elongation decreased from 12.20% to 6.57% at higher Ti content. Grain refinement, increased α-Al matrix volume and modification of β-Al_3Mg_2 morphology were observed, but excessive Ti/Nd caused grain coarsening and reduced ductility. The findings demonstrate the potential application of optimized Ti/Nd ratios in improving lightweight alloy components for aerospace and automotive structural use.**

Keywords: **Aluminium-lithium alloy, Titanium, Neodymium, Grain refinement, Mechanical properties.**

1. INTRODUCTION

Aluminum, a non-ferrous metal, has a unique combination of properties which makes it one of the most versatile, economical, and attractive metallic elements for a broad range of uses - from soft, highly ductile wrapping foil to the most demanding engineering applications (Davis, 2001). Aluminum excels among other non-ferrous metals because of its high specific weight, resistance to corrosion etc. Al–Li alloys amongst aluminum alloys have been mainly used in aerospace and vehicle industries due to good combined properties such as weldability, high ductility, medium strength, and excellent corrosion resistance (Wang et al, 1989). However, in the presence of magnesium (Li), the formability, welding characteristics, and corrosion resistance of Al alloys may be adjusted to some degree, but this can also reduce the toughness and formability of Al due to the presence of the brittle b-Al3Li2 phase and poor ductility (Kaufman, 2004). Al-Li alloys are used in non-heat treatable, sand, permanent mold and die castings. These alloys show good corrosion resistance in most natural fresh waters and in chemical media. Efforts have been made by various researchers towards refining and improving the structure and mechanical performance of Al–Li alloys through controlled alloying and heat treatment. Recent reviews emphasize that Adjusting microalloying levels—especially Ti and rare-earth elements—strongly influences the mechanical response of Al–Li systems (Hajjioui, 2022). The balance between lightweight and ductility depends on precipitate distribution and solidification kinetics. Refinement of grain size using Ti-based inoculants improves yield strength and hardness without compromising toughness (Zhang et al., 2024). This makes microalloying optimization a key route for achieving high-performance Al–Li alloys. Kurt et al. (2016) studied the effect of different concentrations of Ti and Mg on the microstructure and mechanical properties of Al–Li–Ti alloy, showed that the highest hardness value achieved was 80 HBN, for Al–6Li–3Ti alloy. The optimum concentration of Mg and Ti was 4 and 2wt. %, respectively. Kro´l et al, (2017) investigated the Structure and properties of aluminum–magnesium casting alloys after heat treatment. The result showed that the influence of the heat treatment on structure and properties of aluminum castings increased the mechanical properties of aluminum alloys. Zhang et al, (2018) investigated the effects of Ag on the Microstructures and Mechanical Properties of Al-Mg Alloys. 5083 aluminum alloy can be strengthened by heat treatment with the addition of 0.6 wt% Ag. Ding et al. (2023) investigated the effect of Ti-based inoculants on Al–Cu–Mn alloys and observed that $TiAl_3$–Al_2O_3 dispersions improved both hardness and tensile strength by promoting uniform grain refinement. Their study confirmed that Ti particles act as heterogeneous nucleation sites, reducing dendrite arm spacing and enhancing overall mechanical stability. Similar mechanisms are relevant to Al–Li alloys, where controlled Ti additions can refine grains and improve formability. Excessive Ti, however, was found to promote coarse intermetallics that reduce ductility. Hence, optimizing Ti content is vital for balanced mechanical performance. Wang, et al. (2024) examined the dual grain-refinement effect in pure aluminum with micrometer TiB_2 additions and found a marked increase in tensile strength and hardness due to refined grains and uniform microstructures. The study revealed that TiB_2 particles enhanced solidification control by acting as effective nucleation sites. This finding reinforces the hypothesis that titanium-rich inoculants in Al–Li systems could improve strength and fatigue resistance. Furthermore, the authors emphasized the importance of synergistic alloying with rare-earths to further enhance microstructural stability. Wu et al. (2025) studied the effect of neodymium content and cooling rate on Al–Nd alloys, reporting that higher Nd concentrations and faster cooling led to finer $Al_{11}Nd_3$ intermetallics and improved hardness. Their results suggest that Nd additions contribute to increased strength through solid-solution hardening and precipitation strengthening mechanisms. In Al–Li systems, Nd can potentially modify δ'/Al_3Li precipitation behavior to increase thermal stability. Thus, combining Nd with Ti could improve both the microstructure and high-temperature strength of Al–Li alloys. Zhao et al. (2024) highlighted the dual effects of Ti on Al–Si alloys, showing that optimal Ti concentrations refine grains, while excessive Ti causes the formation of coarse intermetallics detrimental to ductility. Their observations mirror challenges seen in Al–Li blends, where microstructural control must prevent over-nucleation or clustering. The authors recommended compositional tuning and multi-element alloying, such as Ti and Nd co-addition, to achieve optimal mechanical properties. This reinforces the rationale for evaluating Ti/Nd ratio effects on Al–Li systems. Hao et al. (2024) reported that the addition of neodymium enhanced the thermal stability of precipitates in lightweight Al–RE alloys, maintaining fine intermetallic dispersion after high-temperature exposure. This improvement in thermal resistance directly correlated with higher hardness and yield strength retention during aging. Their work confirmed that rare-earth additions can retard grain coarsening and precipitation growth. Consequently, Nd acts as a stabilizing agent in microalloyed aluminum-lithium matrices. Liu, et al. (2023) reviewed the development of inoculants for aluminum alloys and concluded that Ti- and rare-earth-modified master alloys remain the most efficient grain refiners across diverse compositions. The authors noted that Ti/RE hybrid inoculants improve nucleation efficiency and resist solute poisoning better than single-element inoculants. These features make Ti–Nd combinations promising for refining Al–Li melts and ensuring consistent mechanical strength. Their work underpins the importance of investigating synergistic ratios of these elements. Baysal et al. (2025) examined the microstructure and mechanical behavior of aluminum alloyed with trace rare-earth elements, including neodymium, and found significant improvements in hardness, machinability, and corrosion resistance. The study attributed these effects to grain boundary modification and refinement. Although conducted on commercially pure aluminum, the insights are transferable to Al–Li systems where Nd acts as a microstructural modifier. The results demonstrate that rare-earth microalloying supports mechanical enhancement and improved environmental durability. Zhang et al. (2024) discussed modern chemical melt refinement processes and identified hybrid refiners (Ti + B + RE) as the future of aluminum alloy design. Their review revealed that rare-earth additions extend the efficiency range of TiB_2 refiners by modifying interface energy and nucleant morphology. Applying these mechanisms to Al–Li alloys can yield improved nucleation density and refined grain structure. This synergy supports systematic studies of Ti/Nd ratios to maximize strength and toughness. Zheng (2025) provided a comprehensive review on grain refinement advances, emphasizing nanoparticle and hybrid rare-earth–titanium inoculant systems for aluminum alloys. The work highlighted that dual-element refiners achieve superior refinement stability and mechanical uniformity compared to conventional single-element master alloys. It also stressed that optimizing the relative Ti/Nd ratio can minimize grain coarsening and improve tensile and fatigue performance. These conclusions align directly with current research into Ti/Nd synergy in Al–Li alloys (Zheng, 2025). This research is therefore aimed at investigating the synergetic effect of Titanium and Neodymium on the mechanical and micro-structural properties of cast Aluminum-Lithium (Al -3w% Li) alloys.

2. MATERIALS AND METHODS

2.1 Materials

The materials and equipment used in this research work are; Aluminum wire (99.99% purity), sourced from Cutix Plc, Nnewi, Anambra State Nigeria. Magnesium powder (99.9% purity), neodymium powder (98.7% purity), titanium powder (98.8% purity) were sourced from Shanghai Xinglu chemical company limited China. Others includes; Phase II 900-355 digital motorized Brinell hardness testing machine, Guangzhou Liss optical microscope(Model: L2003A), Ohaus analytical weighing balance (Model: FA-G), Instron universal tester (Model: 3367), Phenom ProX scanning electron microscope Pultra 1750 watchmakers lathe model, Medium crucible furnace. Electric grinding machine, Mixer, Scooping spoon, Hand gloves, Rammers, Blowers, Molding box, Digital camera, Hack saw, Silicon carbide papers, Aluminum oxide powder, Iron (III) chloride, Hydrochloric acid, Water, Electric grinder (ZMAK-GA5030/2), Hand file, Venier caliper, Bench vice.

2.2 Methods

2.2.1 Material Preparation

The first step of the experiment was to determine the mass by weight of the materials to be melted, in order to obtain the composition of Al-3%Li. This was done by weight percent calculation and the mass of each material was obtained using the weighing balance. The required weight percent of aluminum, magnesium, molybdenum, neodymium, zinc and nickel metals were calculated taking into consideration the total charge and the oxidation loss of the base metals. The calculated weight of the additives was measured using Ohaus analytical weighing balance(Model: FA-G), labeled and stored in batches based on the designed compositions.

2.2.2 Melting and Casting of Alloys

The steel crucible furnace was cleaned and ignited, after which the aluminum ingot was charged into the steel crucible pot. When the aluminum attained its melting temperature (660^0C), it was superheated to 750^0C to ease casting. Then the magnesium powder wrapped with aluminum foil was submerged into the molten aluminum using long scooping spoon and stirred properly. When the melting was completed, the crucible was left in the furnace for about 3 minutes to ensure uniform temperature of the alloy. The mould and ladle were already thoroughly dried and preheated. The melt was then stirred thoroughly with a steel rod, and then cast. The alloying elements were introduced into the parent liquid alloy and stirred manually from time to time in order to total dissolution of the alloying elements in the melt.

2.2.3 Machining of Samples

The machining operation was carried out using lathe machine (Pultra 1750 watchmakers lathe model). This was done by clamping the sample firmly on the lathe machine and cutting sliding along the entire length of the specimen to give the final desired dimension. The specimens for the tensile test were machined according to the ASTM E8M-04 standard dimension (120mm by 10mm), the gauge marks were scribed at the two ends separated by a distance of 50mm, using a punch.

2.2.4 Tensile Strength

Tensile Strength test was carried out at Engineering Materials Development Institute Akure. It was done with the use of Instron universal tester (Model: 3367) in accordance with ASTM E8M-04 standard. This test was carried out on the various specimen of total length of 120mm, 10mm diameter, 50mm gauge length, and 8mm gauge diameter 28mm. The tensile strength test was performed at room temperature by using Instron universal tester loading speed of 50mm/min. The specimen was fixed between the lower and upper jaw of the machine. The machine was then controlled to pull the specimen apart, putting the specimen under tension which caused the specimen to break at a breaking force. At the time of sample fracture, both the maximum tensile load and the extension were displayed in the machine scale. The ultimate tensile strength (UTS), yield strength and the percentage elongation (%E) of the alloy samples were calculated using equations 1, 2 and 3 respectively.

$$\text{Ultimate Tensile Strength} = \frac{\text{Ultimate Load, } P_{max}}{A_0\text{(Original Area)}} \qquad 1$$

$$\text{Yield Strength} = \frac{\textit{Load at yield point}}{\frac{\pi D^2}{4}} \qquad 2$$

$$\%\ \text{Elongation} = \frac{\Delta l \times 100}{L_o} \qquad 3$$

Where: P is load at any point up to the elastic limit, L_o is the gauge length, A_o is original area, ΔL is the elongation or change in L_o at any Load P.

2.2.5 Hardness Testing

Samples for Brinell hardness measurement were machined into a dimension of 15mm x 10mm x 10mm. The surfaces were ground and polished to obtain a smooth surface for the hardness measurement. The hardness measurement was performed by using Phase II 900-355 digital motorized Brinell hardness tester at Metallurgical Training Institute (MTI), Onitsha, Anambra State, Nigeria. The Brinell hardness measurement was done by the indenting of the polished surface of the samples with a diamond ball of 2.5mm diameter. Indentations were made on each sample surface under a load of 62.6.kg (612.9N) for 5s dwelling time. The Brinell hardness number of each measurement was calculated using equation 4.

$$BHN = \frac{\text{Force Applied}}{\text{Surface area of Indentation}} \qquad 4$$

$$BHN = \frac{L}{\left(\pi D/_2\right)\left(D - \sqrt{D^2 - d^2}\right)} \qquad 5$$

Where; L = Applied Force or Load (kg), D = diameter of steel ball (mm), d = Diameter of the Indentation (mm).

3. RESULTS AND DISCUSSION

3.1: Mechanical Property Result

The results of the mechanical property test is shown in table 1, and figures 1 - 4 below.

Table 1: Tensile Strength for Al-3%Mg Alloy with Ti/Nd Additions

Alloy Composition	Tensile Strength (MPa)	Elongation (%)	Yield Strength (MPa)	Hardness (BHN)
Al–3%Mg	153.4	12.20	99.71	39.50
Al–3%Mg – 1.2%Ti – 0.2%Nd	240.8	6.57	156.52	71.10
Al–3%Mg – 1.0%Ti – 0.4%Nd	225.8	7.12	146.77	67.56
Al–3%Mg – 0.8%Ti – 0.6%Nd	210.4	7.90	136.50	60.32
Al–3%Mg – 0.6%Ti – 0.8%Nd	176.3	8.20	114.59	48.80
Al–3%Mg – 0.4%Ti – 1.0%Nd	185.5	9.10	120.57	52.60
Al–3%Mg – 0.2%Ti – 1.2%Nd	191.6	7.23	124.54	57.80

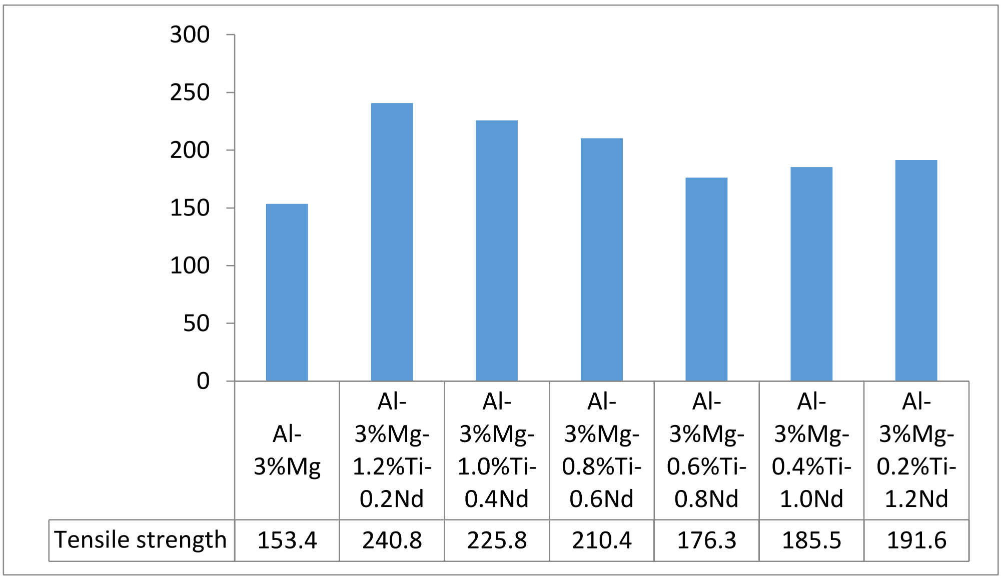

Figure 1: Effect of Ti and Nd on the ultimate tensile strength of Al-3%Li alloy.

From figure 1, it was observed that addition of all the alloying elements within the studied range of composition had significant effect on the tensile strength of the alloy. It was revealed that with the increase of Ti and Nd additions, the tensile strength increased first, when the concentration of titanium was 1.2wt% and neodymium was 0.2wt% then decreased gradually as the content of the additives were further increased up to titanium 0.6wt% and neodymium 0.8wt%. it was also observed that at titanium 0.4wt% and neodymium 1.0wt% the tensile strength started increasing again. Al–Li alloys are non-heat treatable aluminum alloys. These alloys are strengthened by Mg in solid solution. Magnesium is a primary alloying element and acts as an obstacle to the dislocation motion. The interaction of the solute atom-dislocation and/or the introduction of foreign atoms into a crystal lattice may result in strengthening of the materials (Huskins, Cao, and Ramesh, 2010). Thus the improvement on the tensile strength of the alloy was induced by grain refinement and solid solution strengthening processes. The additives served as growth-restriction elements and reduced the grain size of Al-3%Li alloy (Kurt *et al.*, 2016).

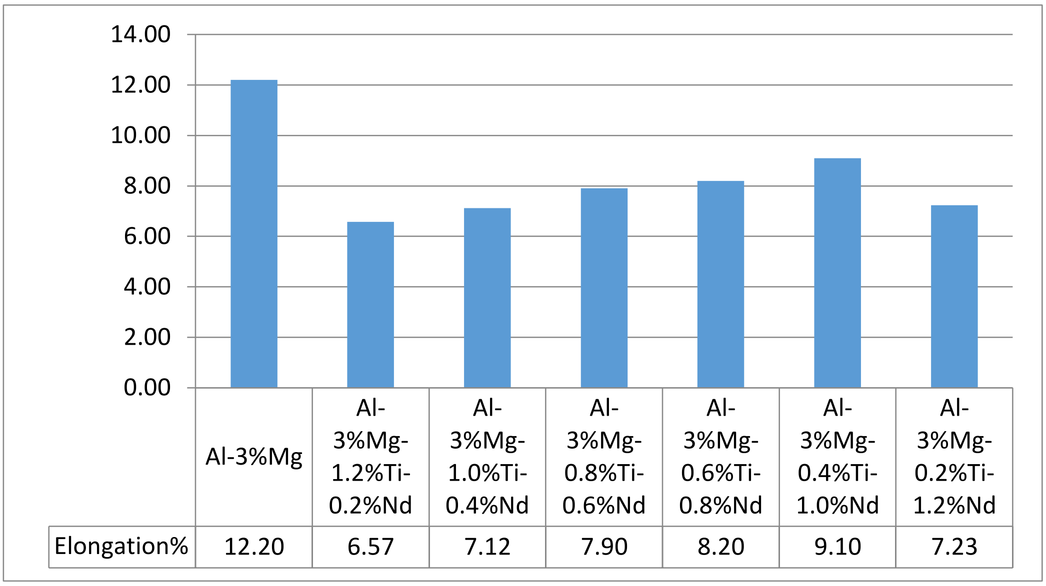

Figure 2: Effect of Ti and Nd on the elongation of Al-3%Li alloy.

From figure 2, It was noticed that as titanium addition increased the percentage elongation decreased from 12.20% to 6.57%, 7.12% till 7.90%. At 8.02% elongation starts to increase. before decreasing with additional increase in concentration of additives. This decrease in percentage elongation may be was attributed to the ability of the additives to refine grain size, thereby creating grain boundaries that impeded the dislocation motion in the alloy.

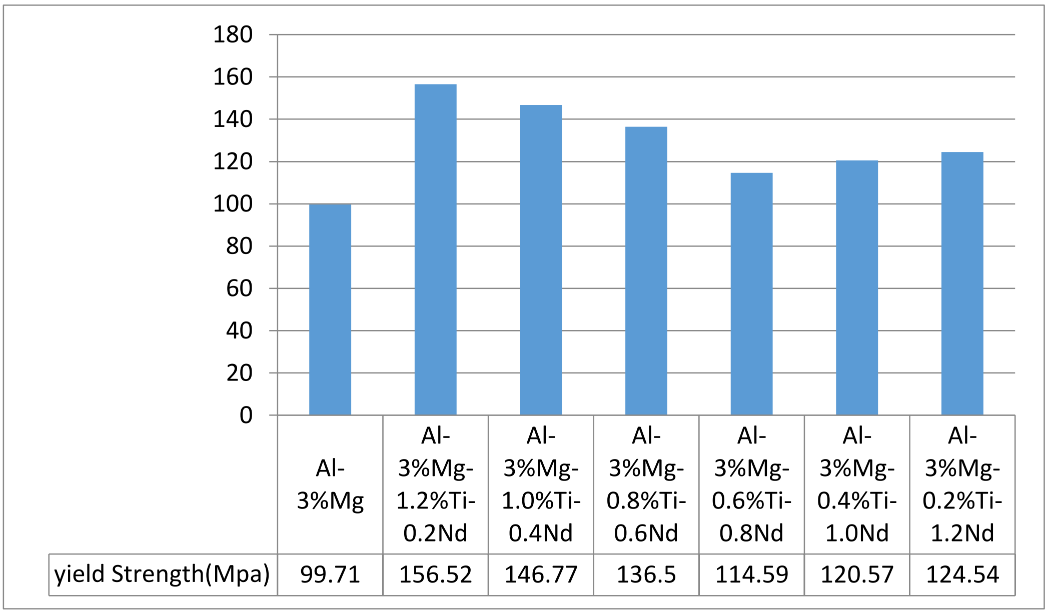

Figure 3: Effect of Ti and Nd on the yield strength of Al-3%Li alloy

From figure 3, the yield strength increased first when the concentration of titanium was 1.2wt% and neodymium was 0.2wt% then dropped down as the content of the additives were further increased. The result yield strength of Al-3wt% obtained was related to the size and morphology of α-Al and βAl_3Mg_2 intermetallic, because the yield strength of the alloy increases with the decrease in grain size, smaller grains have greater ratios of surface area to volume which means a greater ratio of grain boundary to dislocation (Kurt *et al.*, 2016).

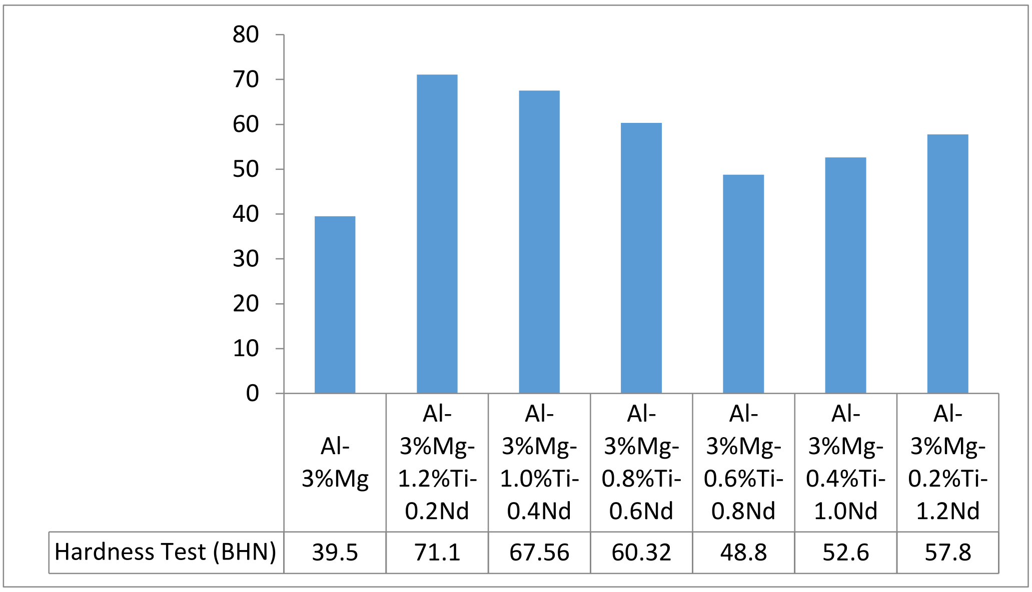

Figure 4: Effect of Ti and Nd on the hardness of Al-3%Li alloy

From figure 4, it was noticed that the hardness increased from 39.5BHN to 71.1BHN, 67.56BHN, 60.32BHN, 48.8BHN. 57.8BHN and 52.6BHN by addition of titanium and neogymium respectively before decreasing drastically with additional increase in concentration of Mo, Nd and Ti. This improvement in hardness was attributed to the ability of the additives to refine grain size and modification of βAl_3Mg_2 intermetallic in aluminum alloy since absence of other alloying elements beside magnesium paved way for the precipitation of βAl_3Mg_2 phase within the aluminum matrix as seen in aluminum-magnesium phase diagram.

3.2 Microstructural Evaluations

Plates: 1-5 are the results of analysis of the microstructural evaluations of Al-3wt% Mg alloys doped with Ti and Nd.

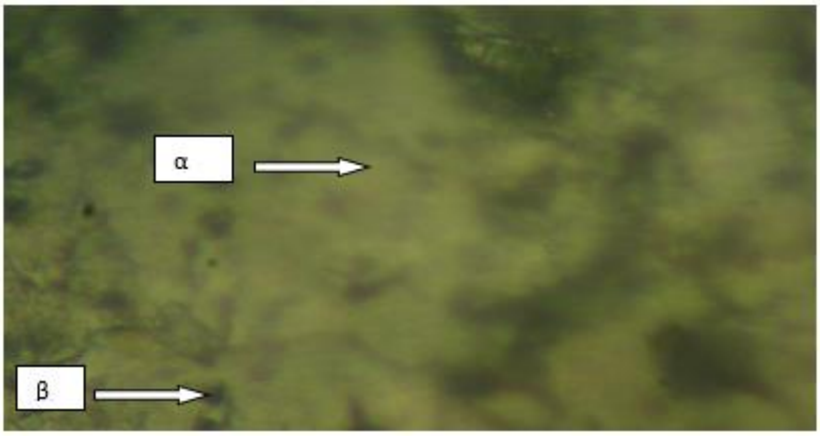

Plate 1: Micrograph of Al-3%wtLi (x400)

Plate 1 shows the microstructure of the control specimen (Al-3wt%Mg alloy) observed with the help of an optical microscope. The microstructure comprises of α- phase and β-phase (Shikun *et al.*,2015, Hosseiny, Emamy and Ashuri, 2015). The alpha phase is the region where magnesium formed a solid solution with the aluminum matrix while the beta phase is the intermetallic compound $\beta(Al_3Mg_2)$ which is the product of incomplete solid solubility. The α-phase is the light field region whereas the β-phase is the hard phase region. The Intermetallic phase compound existed in chains of coarse globular morphology separated from the solid solution by the grain boundary.

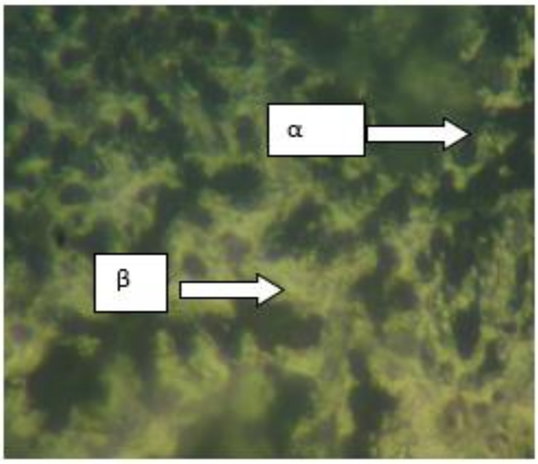

Plate.2: Micrograph of Al-3%wtLi-1.2wt% Ti-0.2wt%Nd (x400)

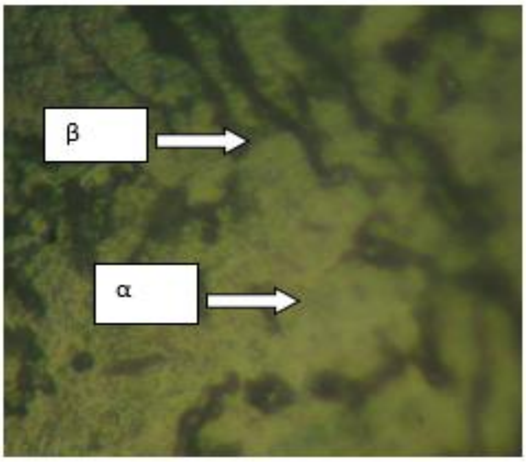

Plate 3: Micrograph of Al-3%wtLi-1.0wt% Ti-0.4Nd (x400)

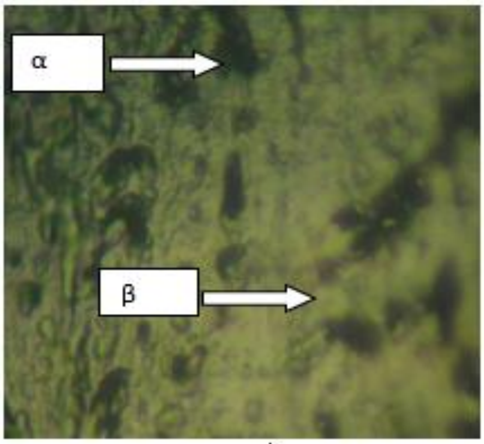

Plate 4: Micrograph of Al-3%wtLi-0.8wt%0.6Nd (x400)

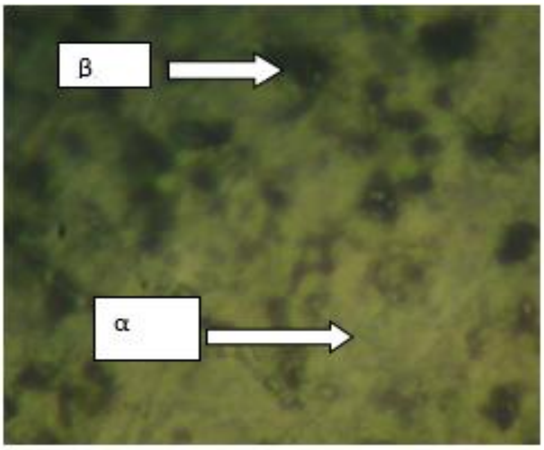

Plate 5: Micrograph of Al-3%wtLi-0.6wt% Ti-Ti-0.8Nd (x400)

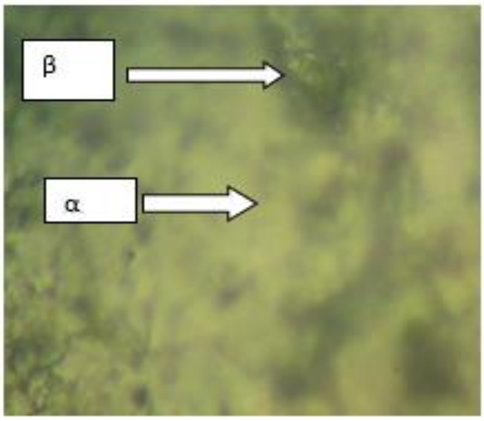

Plate 6: Micrograph of Al-3%wtLi-0.4wt%1.0wt% Nd (x400)

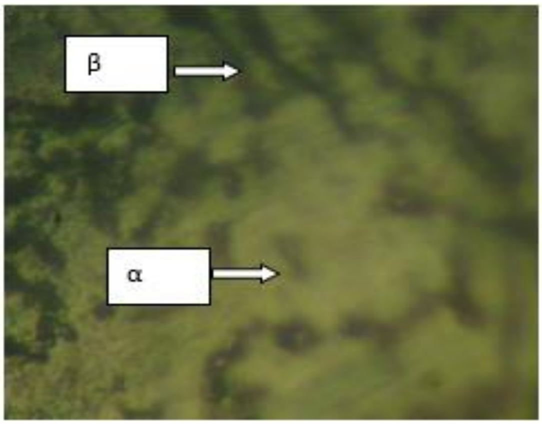

Plate 7: Micrograph of Al-3%wtLi-0.2wt% Ti-Ti-1.2 Nd (x400)

Plates: 2 - 7 depict the microstructure of aluminum -3wt% magnesium alloy doped with 0.17, 0.4, 0.75, 1.3, 2.5 and 6wt.% Ti/Nd observed with the help of an optical microscope. From the micrographs, microstructure of those alloys consists of α-Al matrix light field region and β(Mg_2Al_3) dark field region. As shown from plate 2 - 7, addition of neodymium to Al-3%Mg alloy resulted in changes in the morphology of the phase from coarse interconnected globular β(Mg_2Al_3) phase to fine equiaxed microstructure with homogenous distribution of the number of the primary α-Al phase, this resulted to reduction of average grain size. These microstructural modifications were beneficial to tensile strength, yield strength and hardness of the alloy. For instance the addition of 0.6wt% titanium and 0.8wt% neodymium significantly reduced the average grain size. The increased volume of α-Al matrix and the reduced average grain size improved the strength by solid solution strengthening and grain refinement. When the Ti and Nd content was above 0.6% and 0.8 respectively, coarsening of grain occurred this gave rise to increased average grain size as a result of increased intensity of β(Mg_2Al_3) phase.

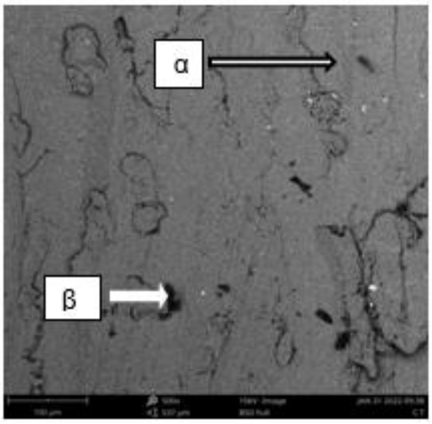

Plate 8: SEM micrograph of Al-3%Li+1.2wt%

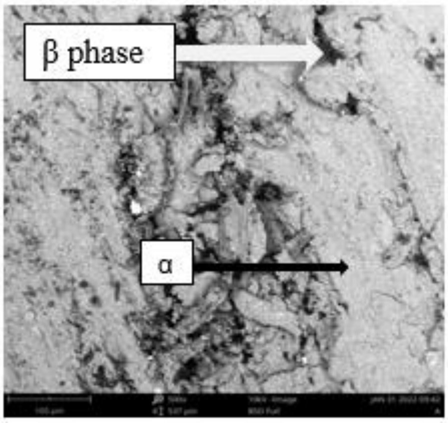

Plate 9: SEM micrograph of Al-3%Li Ti + 0.1wt%Nd.

Plate 8 shows the SEM micrograph of the control sample (Al-3%Mg alloy). It was revealed that the structure consists of α-phase and β phase. The α- phase is the region where Al formed solid-solution with the magnesium matrix while β phase is the intermetallic compound. The intermetallic phase Al_3Mg_2 exists in the form of globular. Plate 9 shows SEM of Al-3%Li +1.2wt% Ti + 0.1wt%Nd while figure 4.8 revealed the elements present. It was observed that microstructure of the all alloys consists of α phase and globular intermetallic phase of various sizes. The size and disposition of globular intermetallic phase present in the structure caused the reduction of mechanical properties of the alloy.

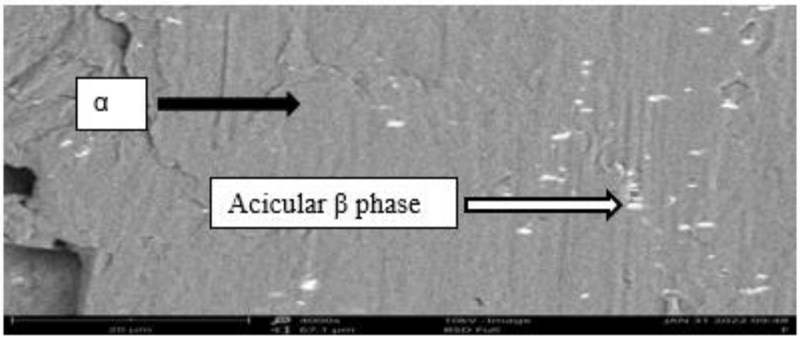

Plate 10: SEM micrograph of Al-3%wtMg-0.4wt% Ti-1.0wt% Nd

Plate 10 shows the SEM of Al-3%wtMg-0.2wt% Ti-1.2wt% Nd. It was observed that the microstructure of the alloy revealed α-phase surrounded by acicular β phase. The acicular β phase improved hardness but was detrimental to the ultimate tensile strength and ductility of the alloy.

4. CONCLUSION

The effect of micro-alloying on the mechanical properties of aluminum-Lithium (Al-3%Li) alloy was studied. From the study, it can be seen that the effect of micro-alloying on the mechanical properties of aluminum lithium alloy depends on the composition of the alloying elements. This was confirmed by the effects of the variation of each composition of the alloying element on the properties. The grain refinement and solid solution strengthening was responsible for the enhanced mechanical properties of the Al-3%Li doped with Ti and Nd. Additions of Ti and Nd above 0.6wt% and 0.8wt% respectively, generally improved the tensile strength of Al-3wt% alloy, mainly through microstructural refinement, a reduction of α-Al grain size and morphological changes in the detrimental shape of intermetallic compounds. The hardness of Al-3%Li alloy improved when Ti is above 0.6wt% and Nd content was greater than 0.8wt%. Also, for the studied alloy there was a reduction in elongation when compared to the control alloy (Al-3wt%Li). The additives do neither form any independent phase nor create any new phase with Al-3%Li alloy system.

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