International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 06 June 2025
Page No: 2727 - 2737
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0405

Study of Thermal and Mechanical Properties in Al-Mg Alloys for Lightweight Thermal Applications

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Abstract
Aluminium and Magnesium alloys are highly valuable due to their mechanical strength, corrosion resistance, and machinability, making them ideal for lightweight applications in aerospace and automotive thermal systems. This study investigates the thermal and mechanical behaviour of aluminium-magnesium (Al-Mg) alloys with varying magnesium content. Two alloy compositions Al 90% + Mg 10% (Sample 1) and Al 80% + Mg 20% (Sample 2) were analysed using a guarded hot plate apparatus for thermal conductivity, Brinell hardness testing, tensile strength measurement, and optical microscopy for microstructural evaluation. Results showed that Sample 1 exhibited higher thermal conductivity due to a finer and more uniform microstructure, while Sample 2 demonstrated superior mechanical properties such as higher hardness and tensile strength, attributed to solid solution strengthening and refined grain structure. Microstructural analysis revealed that increased magnesium content promotes grain refinement and precipitate formation, affecting both heat transfer and mechanical performance. The findings highlight the critical role of alloy composition and microstructure in tailoring Al-Mg materials for lightweight thermal and structural applications.

Keywords: *Aluminium Alloy, Microstructural Analysis, Thermal Conductivity, Hardness, Temperature Distribution.*

1. Introduction

Aluminium is widely used in aerospace, automotive, and thermal applications due to its lightweight and good thermal conductivity. Aluminium (Al) alloys were used as heatproof and heat-dissipation components in automotive and communication industries, with growing demand for higher thermal conductivity [1]. It plays a vital role in the aerospace industry due to their low density, which reduces aircraft weight and enhances fuel efficiency and load capacity. These alloys can be strengthened through alloying and heat treatment, making them well-suited for high-load and vibration environments. It offers excellent resistance to corrosion and fatigue, ensuring long-term durability in challenging aerospace conditions. Their recyclability contributes to sustainable development efforts. High-strength aluminium alloys remain crucial in the aerospace sector, driven by advancements in processing and strengthening techniques despite the growing use of composite materials [2]. The addition of magnesium improves mechanical strength, corrosion resistance, and machinability, making Al-Mg alloys commercially valuable. Bian et al.2022 [3], have proposed a minor alloying strategy involving copper and calcium in pure magnesium, addressing challenges such as poor cold formability, corrosion

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resistance, and high cost, leading to significant improvements in material performance. Thus the aluminium and magnesium is major role in thermal application. The study of magnesium (Mg) alloys has improved an understanding of corrosion mechanisms, compositional and microstructural optimization, mechanical performance enhancement, and control of degradation rates in advanced technique. Recent research on Mg alloy thermal conductivity has identified key factors such as solute atoms, heat treatment, mechanical deformation, and temperature as influencing factors [4]. Solution treatment tends to reduce thermal conductivity, whereas aging and annealing treatments enhance it. Deformed Mg alloys generally exhibit higher thermal conductivity along the transverse direction compared to the extrusion or rolling directions. Huang et al.2023 [5] demonstrated that the thermal conductivity of Mg-1.5, Zn-0.3, Ca-x, Al-0.2Mn alloys decreases with increasing aluminium content, with the highest value of 140 W/(m·K) observed in the 0.2 wt% Al alloy. Shittu et al.[6] investigated the role of magnesium in improving the mechanical properties of 1200-Aluminium (Al-Fe-Si) alloy used in household utensils. They showed that magnesium acts as an effective dispersion strengthening agent, enhancing the alloy's hardness and tensile strength, though with a slight reduction in impact strength. The Al-Mg alloy is highly valued in the motor vehicle industry due to its excellent corrosion resistance, weldability, and high strength-to-weight ratio. Microstructural characterization was conducted using scanning electron microscopy and optical microscopy to examine various magnesium concentrations after solidification and to monitor grain size evolution. It revealed that increasing the magnesium content from 0 to 5 wt.% led to a threefold increase in hardness, along with a 48% decrease in electrical conductivity[7]. Al-Mg alloys are recognized for their potential in lightweight thermal applications due to their mechanical and thermal properties, but several research gaps exist. Notably, there is limited understanding of how thermal and mechanical behaviours interact under real-world conditions, such as cyclic thermal loading and thermal-mechanical fatigue. Most studies concentrate on thermal conductivity or mechanical strength, neglecting the optimization of alloy composition, particularly magnesium content, to balance both properties. The influence of microstructural features like grain size and phase distribution on enhancing thermal and mechanical performance is not well understood. The temperature-dependent behaviour of Al-Mg alloys at elevated temperatures remains underexplored, and predictive models linking alloy composition to final properties are lacking. Many studies use standard testing methods that fail to replicate actual application environments, underscoring the need for more specific evaluations. Addressing these gaps is essential for developing advanced Al-Mg alloys for high-performance lightweight thermal systems in automotive, aerospace, and electronic applications. This study to investigate how varying magnesium content affects the thermal conductivity and hardness of aluminium. The following section presents a critical review of this work.

2. Critical Reviews

Al-Mg alloys provide a well-balanced mix of strength, corrosion resistance, and weldability, especially those in the 5000 series. These characteristics make them widely applicable across the marine, aerospace, transportation, and chemical industries. Strengthening in these alloys is primarily achieved through work hardening and solid solution strengthening, contributing to their excellent formability and resistance to harsh environments [8]. The addition of alloying elements further enhances the thermal and mechanical properties of Al-Mg alloys through mechanisms such as precipitation hardening, solid solution strengthening, and grain refinement [9]. Copper, silicon, and magnesium are essential elements in heat treatment that contribute to the formation of strengthening precipitates, which increase strength by preventing dislocation motion [10]. Zinc (Zn) forms solid solutions with aluminium and magnesium, enhancing strength by increasing lattice strain and inhibiting dislocation movement [11]. Similarly, titanium and scandium refine the grain structure, improving both strength and toughness [12]. Overall, alloying elements improve the mechanical strength of Al-Mg alloys while also influencing their thermal properties, including thermal conductivity and expansion. Metallic alloys

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often face a trade-off between strength and electrical conductivity due to the introduction of crystal structure imperfections during strengthening processes [13]. However, Limited research explores the thermal and mechanical properties of Al-Mg alloys, specifically their suitability for lightweight thermal management applications. Furthermore, the influence of various alloying elements on the thermal conductivity, thermal expansion, and their correlation with mechanical strengthening mechanisms (such as solid solution strengthening, precipitation hardening, and grain refinement) remains underexplored. This research aims to achieve the following objective.

- To investigate the temperature distribution and thermal conductivity from the sample's alloys.
- To study examines the impact strengthening mechanisms through hardness and tensile test.
- To explores the impact of microstructure variations on the thermal and mechanical properties of samples, focusing on grain structure, intermetallic phase distribution, and their correlation with conductivity, strength, and ductility.

3. Materials and Methods

Aluminium alloys fabricated using an induction heating furnace. The addition of over 10% and 20% of magnesium with aluminium (AA6063) effectively prevented oxidation and burning. Two samples are prepared to compare the effect of Mg in the aluminium as Sample-1(90% Al, 10% Mg) and Sample-2 (80% Al, 20% Mg). There are three work pieces in each sample. Density is calculated through the geometric methods. Hardness values are measured with the Brinell harness tester The measurement of indentation involves calculating the load (P), ball diameter (D), and impression diameter (d). Test force range taken from 250 kgf and a 5 mm diameter indenter. The work pieces placed on the respective position and the hardness test procedure was followed. The guarded plate apparatus is used to measure thermal conductivity based on Fourier's law of heat conduction. The specimen's surface temperatures were measured at equal distances along its height, with a readout of time and temperature, ensuring a ±10% accuracy. The measurement interval speed is 5 minutes. The materials properties are listed in Table 1. Universal testing machine (UTM) is used to determine the tensile strength and elastic modulus. The tensile stress of materials tested using UTM. A universal testing machine (UTM) is a versatile equipment used to test materials' mechanical properties under various conditions, featuring a crosshead, load indicator, speed control, and specimen mounting space. The work piece placed on respective location and followed the step-by-step procedure. The middle cross head moved up maximum speed of 300mm/min. The diameter of tensile test jaws ranges from 46 to 60 mm (Table 1).

Table 1 Comparison of the Properties of Aluminium and Magnesium

Properties	Aluminium	Magnesium
Density [g/cm³]	2.7	1.7
Brinell hardness number (BHN)	75	106
Thermal conductivity [W/mK]	209	249
Elastic modulus [N/mm²]	70	45
Tensile strength [MPa]	276	260
Poisson ratio	0.34	0.271

The thermal conductivity of the Al-Mg alloy is determined using Fourier's law of heat conduction with the help of a guarded plate apparatus. The experimental setup comprises a centrally placed Al-Mg alloy sample, sandwiched between two heating plates, with appropriate insulation to minimize heat losses. Temperature sensors (PT100) are positioned at equal intervals along the height of the sample to measure the temperature gradient. Once the system reaches a steady-state condition, the temperature readings displayed on the digital panels are recorded, as shown in Fig. 1. The heat flow through the sample is calculated using the known dimensions and measured temperature difference. The thermal conductivity (κ) is determined using the following equations:

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$$V=\pi r^2 h \quad (1)$$
$$\rho=m/V \quad (2)$$
$$\kappa=(Q.dx)/(A.\Delta T) \quad (3)$$

Aluminium-magnesium alloy samples, each with a dimension of 50 mm × 50 mm, were placed on the base heater plate. Heat is supplied to the base, causing thermal energy to flow through the sample. The heating continues until a steady state is achieved. Surface temperatures are monitored at four positions (1, 2, 3, and 4) on the sample, and these measurement points are illustrated in Fig. 2. The heating coil has a capacity of 100–200 W, providing a uniform and controlled heat supply. Temperature is measured using PT100 sensors and thermistors attached to the sample surfaces, with an accuracy of ±1°C. Additionally, the microstructure of the alloy was examined using a LEICA DM6000M optical microscope.

Figure 1 Experiment Setup for Thermal Conductivity Measurement

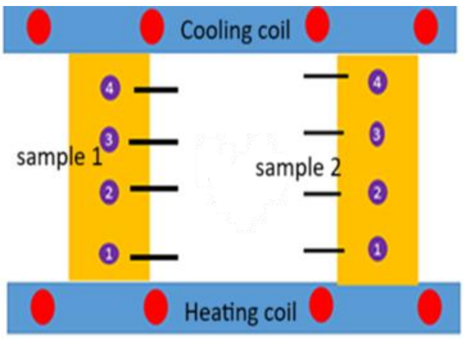

Figure 2 Schematic Diagram for Temperature Distribution Position in Sample Pieces

4. Results and Discussion

The experiment was conducted using a Guarded Hot Plate Apparatus to measure the thermal conductivity of Al-Mg alloy samples. This apparatus is specifically designed for steady-state thermal conductivity measurements of solid materials. The setup consists of a central hot plate (heating element) and a cooling plate, with the test samples placed in between. A guard heater surrounds the hot plate to minimize lateral heat loss and ensure one-dimensional heat flow through the sample.

Two Al-Mg alloy compositions were tested: Al 90% + Mg 10% and Al 80% + Mg 20%. These samples were placed in the sample chamber, which is thermally insulated to maintain stability. The apparatus is equipped with digital temperature displays and a temperature controller to regulate the heat input precisely. During the experiment, surface temperatures of the samples were recorded over time once a steady-state condition was achieved. Thermal conductivity was calculated using the known heat input, the physical dimensions of the samples, and the temperature gradient across the material. Additionally, the Brinell hardness test was used to measure the hardness of each sample, while tensile strength was estimated using a Universal Testing Machine (UTM). The microstructure of the samples was examined using an optical microscope (LEICA DM6000M) to analyse grain structure, which is important for evaluating mechanical properties. This method provides reliable and accurate measurements of thermal and mechanical properties. Among the samples tested, the 90% Al – 10% Mg alloy demonstrated superior thermal performance, making it suitable for lightweight thermal management applications. In contrast, higher magnesium content (20% Mg) resulted in reduced thermal conductivity, due to increased phonon or electron scattering mechanisms. The following section presents detailed results and discussion based on the experimental findings.

4.1. Impact of the Surface Temperature Distribution on the Al-Mg Alloy Samples

The applied load and the thermal conductivity of a material can significantly influence the surface temperature of an alloy sample. A high surface temperature gradient indicates increased thermal

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stress or elevated heat generation [14]. In this study, surface temperatures were measured to assess the heat transfer characteristics of Al-Mg alloy samples. Sample 1, containing a higher aluminium content (90% Al + 10% Mg), exhibited superior thermal conductivity, enabling more efficient heat transfer. This is attributed to aluminium's higher number of free electrons, which enhances energy transport within the material. The results show that the 90% Al + 10% Mg alloy consistently recorded higher surface temperatures across all four sensor positions than the 80% Al + 20% Mg alloy, indicating better thermal conductivity in alloys with lower magnesium content and displayed in Fig.3. Both samples showed increasing temperature trends over time, although the 90% Al sample's increase was more pronounced. This difference was more pronounced at greater sample heights (positions 3 and 4), emphasizing the influence of composition on thermal performance.

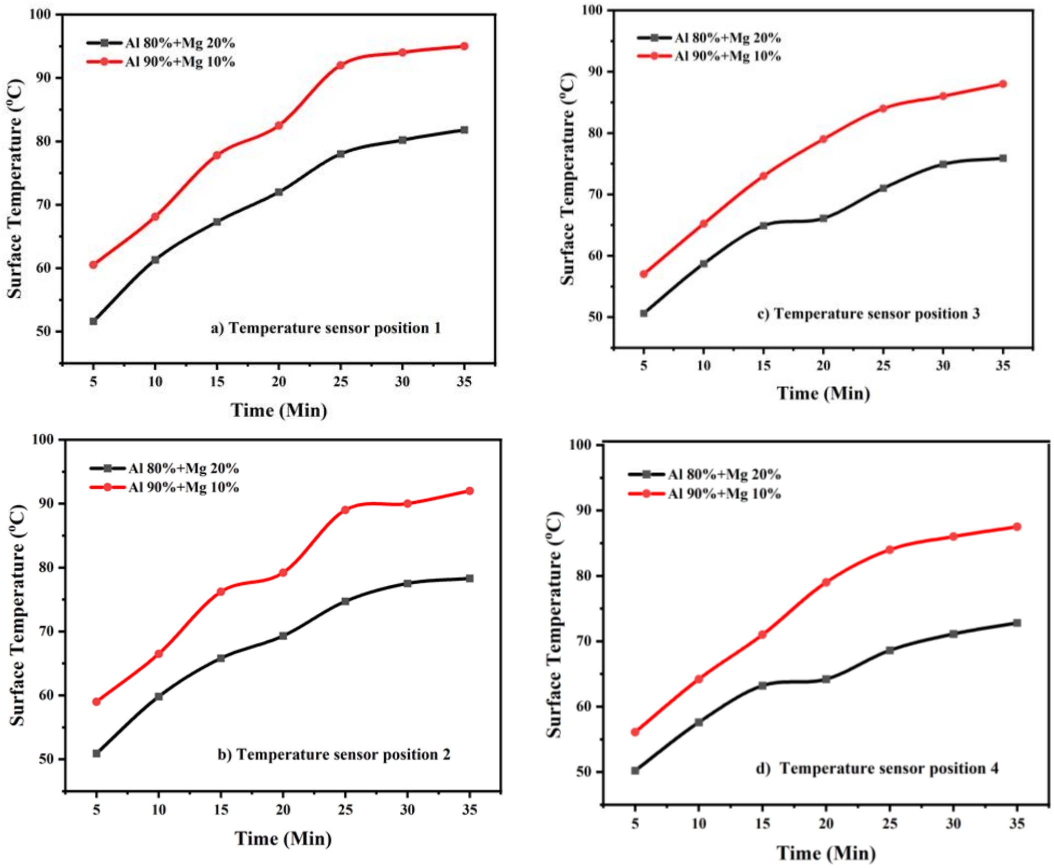

Figure 3 Comparison of Sample Surface Temperature in Different Positions a) h= 10 mm b) h=20 mm c) h=30 mm d) h=40 mm

4.2. Temperature Variations and their Impact on Heat Transfer in Al-Mg Alloy

Temperature variations along the length of the sample are primarily influenced by differences in heat transfer, internal heat generation, and inherent material properties. These factors result in uneven temperature distribution, which can affect the Sample 1 (90% Al + 10% Mg) and sample 2 (80% Al + 20% Mg) for mechanical behaviour and structural integrity during processes for thermal applications. External factors such as boundary conditions and process parameters influence temperature distribution in processes. The Fig.4 illustrates the comparison of an enhancement of temperature distribution in Sample 1 and Sample 2 at various heights (H = 10 mm to 40 mm) over time. As the height increases, the surface temperature rises more significantly, with the 40 mm position showing the highest temperature response in

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sample 1. This indicates improved heat transfer performance, due to the higher aluminium content in Sample 1. The steeper and more consistent temperature rise in Sample 1 suggests better thermal conductivity and more efficient energy transport through the material.

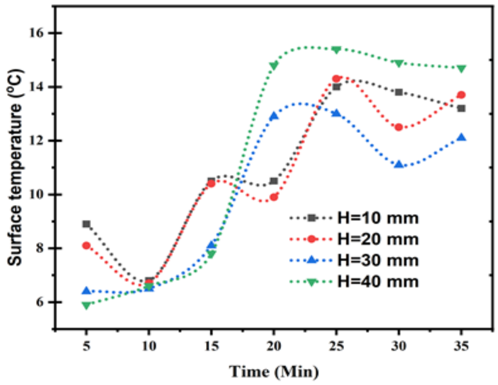

Figure 4 Comparison of an Enhancement of the Temperature Distribution from 1 To 2

4.3.Impact of The Thermal Conductivity On the Al-Mg Alloy Samples

In sample 1 has high content (90%wt) aluminium and less(10%wt) magnesium, thermal conductivity increases because aluminium has a higher concentration of free electrons than magnesium, making it a better heat conductor. The thermal conductivity of alloying elements Al-mg can be influenced by solid solution and precipitation transformations. The thermal conductivities for Sample 1 and Sample 2 were calculated to be 239.71 W/m·K and 224.73 W/m·K, respectively and displayed in Fig.5.

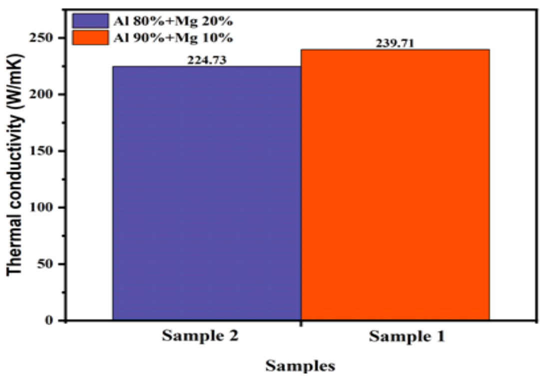

Figure 5 Comparison of Thermal Conductivity of the Al-Mg Alloy Samples

The minimal temperature difference in certain samples indicates higher thermal conductivity, indicating efficient heat conduction due to finer grain structures and better phase distribution. The root mean square (RMS) method confirmed the reliability and accuracy of the thermal conductivity results, with a measurement uncertainty of less than 5%. The steeper and more consistent temperature rise in Sample 1 suggests better thermal conductivity and more efficient energy transport through the material.

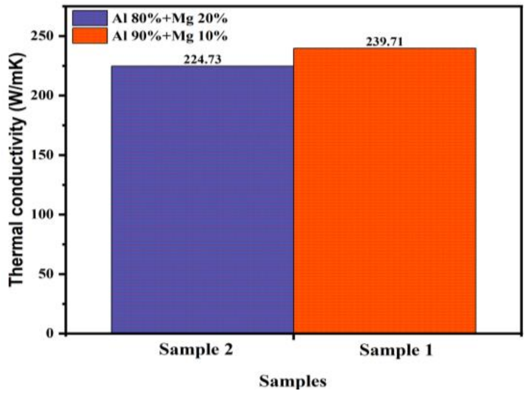

Figure 5 Comparison of Thermal Conductivity of the Al-Mg Alloy Samples

4.4.Impact of the Hardness on the Al-Mg Alloy Samples

Aluminium alloys with higher magnesium content exhibit increased hardness due to solid solution strengthening and precipitation hardening, as the larger magnesium atoms cause lattice distortions [15,16]. In this study, hardness tests were conducted under consistent loading conditions, with three readings taken for each sample to ensure accuracy and repeatability. The results revealed a clear difference in hardness between the two compositions. Sample 2, containing 20% magnesium, consistently showed higher Brinell Hardness Numbers (BHN) ranging from 115 to 113, while Sample 1, with 10% magnesium, recorded lower BHN values between 110 and 108 and displayed in Fig.6. The slight decreasing trend in both samples is attributed to variations in indentation diameters and time under load during Brinell testing, reflecting plastic deformation effects. The enhanced hardness in Sample 2 is primarily due to the increased magnesium content, which contributes to solid

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solution strengthening by distorting the aluminium lattice and impeding dislocation motion. Additionally, the higher Mg content promotes grain refinement and precipitate formation, further enhancing mechanical strength. This observed increase in BHN with magnesium content confirms the effectiveness of alloying in optimizing the mechanical properties of aluminium-based materials. The next section displays the analysis of the sample's tensile strength. Figure 6 shows Comparison of Brinell Hardness in the Al-Mg Alloy Samples

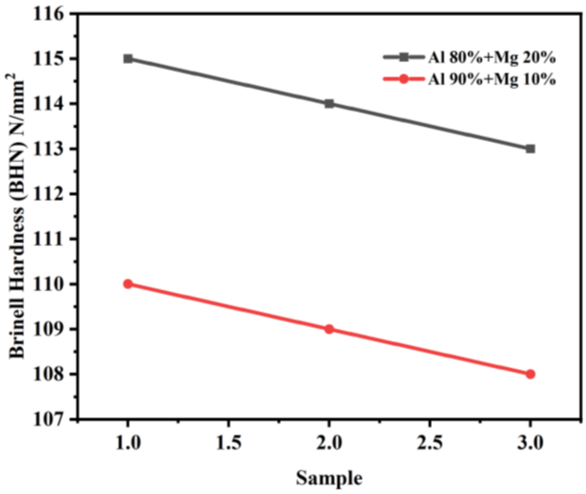

Figure 6 Comparison of Brinell Hardness in the Al-Mg Alloy Samples

4.5.Effect of Tensile Strength in the Al-Mg Alloy Samples

Tensile strength in Al-Mg alloy samples refers to the maximum tensile stress a material can endure before failure, providing a key measure of its resistance to stretching forces. In this study, tensile testing was conducted to evaluate and compare the mechanical performance of two alloy compositions Al 90% + Mg 10% and Al 80% + Mg 20% highlighting how magnesium content influences their load-bearing capacity and indicated in Fig.7 Sample 2, with a higher magnesium content (20%), exhibited a slightly greater ultimate tensile strength, reaching approximately 390–400 MPa, compared to 370–380 MPa for Sample 1. This increase is primarily attributed to solid solution strengthening and potential grain refinement, both of which impede dislocation motion and enhance mechanical strength. Beyond the yield point, both samples demonstrated stable plastic deformation up to the onset of necking. The strain at failure remained relatively similar, indicating that the addition of magnesium enhances strength without significantly compromising ductility at the tested concentrations. Notably, Sample 2 showed marginally higher resistance to strain localization, suggesting improved toughness. The near-identical behaviour in the elastic region reflects similar elastic moduli, dominated by the aluminium matrix. However, the higher peak stress observed in Sample 2 confirms that increased magnesium content substantially enhances tensile performance, making it a more favourable choice for structural applications demanding high strength-to-weight efficiency. Figure 7 shows Comparison of Tensile Strength Test Analysis in the Al-Mg Alloy Samples

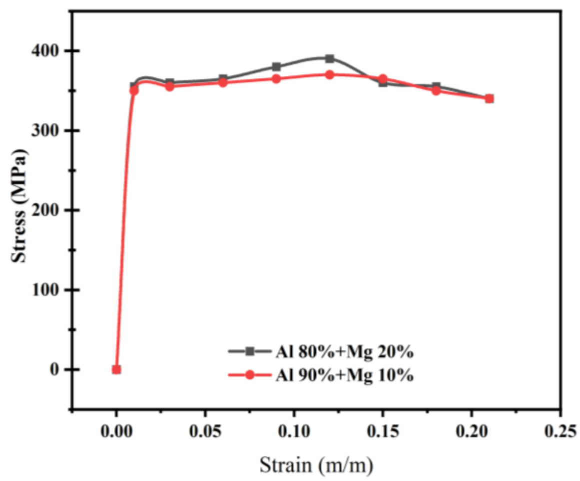

Figure 7 Comparison of Tensile Strength Test Analysis in the Al-Mg Alloy Samples

4.6.Effect of Microstructural Analysis in the Al-Mg Alloy Samples

Microstructural analysis provides critical insight into the internal grain structure, phase distribution, and morphology of Al-Mg alloys, which directly influence their mechanical and thermal properties. In this study, optical microscopy revealed that increasing magnesium content led to finer grains and a more uniform microstructure, indicating enhanced grain refinement. This refinement results from magnesium's ability to restrict grain growth during solidification. Sample 2 (Al 80% + Mg 20%)

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exhibited smaller and more closely packed grains compared to Sample 1, which improves hardness and tensile strength due to increased grain boundary area that impedes dislocation movement. It is shown in Fig 8 and Fig.9. The presence of Mg-rich precipitates in higher concentrations contributes to strengthening via the precipitation hardening mechanism. These microstructural changes confirm that alloy composition significantly affects performance, making microstructural analysis essential for optimizing material behaviour in engineering applications. The microstructural analysis of the Al-Mg alloys was carried out using optical microscopy at two magnifications: 100x and 500x.

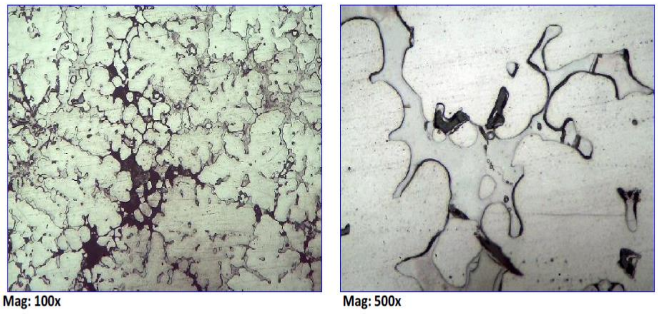

Figure 8 Microstructural Analysis of Sample-1 (90% Al, 10% Mg)

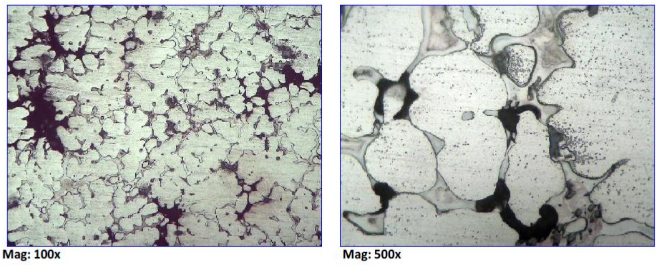

Figure 9 Microstructural analysis of Sample-2 (80% Al, 20% Mg)

4.6.1. Low Magnification (100x) Observations

At 100x magnification, the micrographs show a uniform distribution of the primary aluminium matrix interspersed with dark-etched intermetallic phases. These intermetallic regions are primarily concentrated along grain boundaries and junctions. The presence of these dark regions indicates the segregation of magnesium-rich phases and possibly Al_3Mg_2 intermetallic compounds, which typically precipitate during solidification.

Comparing the two sets of 100x images:

- The first set (top image) shows a finer distribution of second-phase particles, suggesting a relatively faster cooling rate or refined grain structure.
- The second set (bottom image) reveals larger clusters of intermetallic, due to slower cooling or higher magnesium content, allowing for more extensive segregation during solidification.

These structural differences imply that thermal conductivity may vary between the samples. Finer structures are generally more favourable for thermal applications due to improved uniformity and reduced thermal resistance across grain boundaries.

4.6.2. High Magnification (500x) Observations

At higher magnification (500x), the micrographs provide clearer insights into the morphology of the grain boundaries and intermetallic phases:

- In the first set, the grain boundaries are more rounded, and the intermetallic phases appear more isolated. This indicates more stable grain growth, which may be associated with improved ductility but could lower yield strength due to reduced obstruction to dislocation movement.
- The second set exhibits elongated and interconnected intermetallic phases forming a network along the grain boundaries. This morphology can influence mechanical strength and brittleness. Such networks may act as barriers to dislocation motion, enhancing strength but potentially lowering ductility.

4.6.3. Implications on Thermal and Mechanical Properties

The observed microstructures directly influence the thermal and mechanical performance of the Al-Mg alloys:

- Thermal Conductivity: Finer grains and homogeneously distributed intermetallic phases, as seen in the first sample set, tend to enhance thermal conductivity due to reduced

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thermal barriers at grain boundaries.

- Mechanical Strength: The presence of continuous intermetallic networks can improve yield strength via grain boundary strengthening mechanisms but may introduce brittleness under mechanical loading.
- Ductility and Toughness: The second sample set's microstructure suggests higher ductility due to more equiaxed grains and isolated intermetallics, making it more suitable for applications involving mechanical stress.

4.7. Correlation Between Microstructure and Property Variations

A strong correlation was observed between the microstructural features of the Al-Mg alloy samples and their measured thermal and mechanical properties. The variations in grain structure, phase distribution, and intermetallic morphology played a critical role in influencing both thermal conductivity and mechanical behaviour.

4.7.1. Microstructure vs. Thermal Conductivity

Sample 1, which exhibited a finer and more uniformly distributed microstructure with interconnected intermetallic networks, demonstrated the highest thermal conductivity (239.71 W/m·K). This structure promotes more efficient heat transfer by minimizing the scattering of phonons at grain boundaries and interfaces. The uniformity of the grain boundaries allows for a continuous heat flow path, reducing thermal resistance across the material. In contrast, Sample 2 displayed a coarser grain structure with more isolated intermetallic phases. While this microstructure may reduce stress concentrations and improve ductility, it introduces more thermal barriers, resulting in a slightly lower thermal conductivity (224.73 W/m·K). This confirms that a refined microstructure with well-distributed phases enhances thermal performance, which is critical for lightweight thermal management applications.

4.7.2. Microstructure vs. Mechanical Properties

The intermetallic phase morphology affects mechanical behaviour. In Sample 1, the network-like intermetallics along grain boundaries contribute to grain boundary strengthening, enhancing yield strength. However, this may reduce ductility due to the potential for crack initiation at intermetallic clusters. Sample 2, with its more rounded grain boundaries and fewer interconnected intermetallics, exhibits improved toughness and ductility at the expense of reduced strength.

4.7.3. Integrated Understanding

The observed variations underline the importance of microstructural control in tailoring Al-Mg alloys for specific application requirements. Sample 1's refined microstructure is more suitable for applications requiring high thermal conductivity, such as heat sinks or thermal spreaders. Conversely, if mechanical flexibility and ductility are desired, Sample 2's coarser structure provides better performance. Therefore, optimizing alloy composition and processing parameters to achieve the desired microstructure is essential for balancing thermal and mechanical properties in Al-Mg alloys targeted for lightweight thermal applications.

Conclusion

This study successfully examined the influence of magnesium addition on strengthening mechanisms in aluminium alloys, specifically focusing on precipitation hardening and grain refinement. The results confirmed that increasing magnesium content enhances mechanical strength through solid solution strengthening and the formation of intermetallic compounds, which contribute to grain boundary strengthening. A clear trade-off between mechanical strength and thermal conductivity was observed. While the addition of magnesium improved hardness, it also led to a decrease in thermal conductivity due to increased impurity scattering and reduced electron mobility. This trade-off highlights the importance of composition optimization when designing alloys for thermal management applications. Among the tested compositions, aluminium with up to 10 weight percent magnesium was found to offer an optimal balance between mechanical strength and thermal efficiency. This makes it a promising candidate for lightweight components in energy systems where both structural integrity and effective heat dissipation are critical. Overall, the findings provide valuable insight into how alloy composition affects performance, supporting the development of Al-Mg alloys tailored for use in advanced thermal management systems. Future research should explore the incorporation of nano-reinforcements to further enhance properties without compromising thermal performance.

Acknowledgements

The authors would like to express their sincere gratitude to the faculty and technical staff of the Department of Mechanical Engineering, SRM Institute of Science and Technology, for their guidance, support, and access to laboratory facilities throughout this study. Special thanks are extended to the materials testing and microscopy labs for enabling the tensile, hardness, and microstructural analyses. The authors also appreciate the encouragement and valuable suggestions provided by colleagues during this work. Their insights significantly contributed to the completion of this research.

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International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 06 June 2025
Page No: 2727 - 2737
https://irjaeh.com
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