Investigating the Mechanical Behavior of LM25 Aluminum Alloy Composites Reinforced with Fly Ash and Alumina

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Abstract

In this paper, we present the outcomes of an experimental investigation on the mechanical properties of composites composed of fly ash and alumina reinforcement within an LM25 aluminum alloy, processed via the stir casting method. The study encompasses three distinct sets of composites, maintaining a constant weight fraction of fly ash particles (ranging from 3 to 100 µm) and introducing varying weight percentages of Al2O3 (150 µm particle size). The composite samples maintain a consistent 3% weight fraction of fly ash while incorporating 5%, 10%, and 15% weight fractions of Al2O3. The primary mechanical properties under scrutiny include tensile strength, ductility, impact strength, and hardness.

Unreinforced LM25 samples are also subjected to the same battery of tests. Our findings reveal an augmentation in the tensile strength and hardness of LM25 aluminum alloy composites with an increasing percentage of Al2O3 reinforcement, up to a certain threshold. However, the tensile strength diminishes with a higher proportion of reinforcement due to inadequate wettability between the reinforced material and the aluminum matrix. Moreover, the Charpy impact tests display a reduction in impact load absorption as the reinforcement weight percentage increases.

Microstructural analysis of the samples illustrates a relatively uniform distribution of fly ash and Al2O3 particles within the matrix. The LM25 alloy finds application where excellent mechanical properties are requisite in castings of diverse shapes and dimensions, necessitating an alloy with superb castability to attain the desired standard of soundness. Additionally, this alloy serves industries where corrosion resistance is imperative, particularly when coupled with high-strength demands.

Keywords: LM25 Aluminum Alloy, Fly Ash, Alumina, Mechanical Properties, Composite Materials, Stir Casting, Tensile Strength, Ductility, Impact Strength, Hardness, Microstructure, Reinforcement, Castability, Corrosion Resistance, Composite Material Processing.

I. INTRODUCTION

Composite materials play a pivotal role in modern engineering due to their unique ability to combine the advantages of two or more distinct phases, namely the matrix phase and reinforcing phase. These combinations result in materials with bulk properties that are markedly different from those of their individual constituents. While many materials contain dispersed phases in their structures, true composite materials are characterized by their capacity to exhibit properties that diverge significantly from their base constituents. This distinction arises from the careful selection and combination of materials to achieve desired characteristics. The favorable properties often associated with composite materials include high stiffness, exceptional tensile strength, reduced density, heightened temperature stability, and, in certain applications, desirable electrical and thermal conductivity properties. Moreover, features such as a low coefficient of thermal expansion, corrosion resistance, and improved wear resistance are essential considerations in various engineering applications. In pursuit of these attributes, metal matrix composites (MMCs) have gained considerable attention in recent years, as they offer a versatile means to enhance mechanical properties and open new possibilities for innovation.

Before venturing into the creation of aluminum metal matrix composites, extensive research has been conducted to explore the incorporation of various reinforcing agents, such as fly ash and alumina. These efforts have been centered on investigating the mechanical properties of these composite materials.

PROBLEM STATEMENT

The objective of this paper is to present the results of an experimental study focused on the mechanical properties of composites consisting of fly ash and alumina reinforcement within the LM25 aluminum alloy, fabricated through the stir casting method. This research encompasses three distinct sets of composite materials, maintaining a constant weight fraction of fly ash particles in the range of 3 to 100 µm, while introducing varying weight percentages of Al2O3 (with a particle size of 150 µm). The composite samples maintain a consistent 3% weight fraction of fly ash while incorporating 5%, 10%, and 15% weight fractions of Al2O3. The primary mechanical properties of interest include tensile strength, ductility, impact strength, and hardness.

The primary research questions and objectives are as follows:

- To investigate the effect of Al2O3 reinforcement on the mechanical properties (tensile strength, ductility, impact strength, and hardness) of LM25 aluminum alloy composites.
- To determine the optimal weight percentage of Al2O3 reinforcement to achieve enhanced mechanical properties while maintaining the castability of LM25.
- To assess the microstructural characteristics of the composite materials to understand the distribution and interaction of fly ash and Al2O3 particles within the aluminum matrix.
- To provide insights into the potential applications of LM25 aluminum alloy composites, particularly in industries where both high mechanical performance and corrosion resistance are required.

The findings of this study indicate that an increase in the weight percentage of Al2O3 reinforcement results in improved tensile strength and hardness of LM25 aluminum alloy composites, up to a certain threshold. However, the tensile strength diminishes with a higher proportion of reinforcement due to inadequate wettability between the reinforced material and the aluminum matrix. Additionally, the Charpy impact tests show a reduction in impact load absorption as the reinforcement weight percentage increases.

LIMITATIONS

- ✓ **Sample Size and Representation:** The study may be limited by the number of composite samples tested. A larger sample size could provide more statistically significant results. Additionally, the study may not encompass the full range of possible compositional variations and may not fully represent real-world variations in industrial applications.
- ✓ **Material Homogeneity:** The uniform distribution of particles within the matrix is an assumption, and variations in particle distribution may exist within the samples. This can affect the consistency of the mechanical properties and may not reflect real-world manufacturing conditions.
- ✓ **Testing Conditions:** The mechanical properties of materials can vary significantly depending on testing conditions such as temperature, humidity, and strain rates. The study may not account for all potential environmental or operational factors that could affect material performance in real-world applications.
- ✓ **Time and Aging Effects:** The study may not address the long-term durability and aging effects of these composite materials. Materials can degrade or change properties over time, and this study focuses on short-term mechanical properties.
- ✓ **Composite Processing Variability:** The stir casting method, while widely used, may introduce variability in the fabrication process, affecting the reproducibility of results. Factors such as mixing time, temperature, and cooling rates may influence the final composite properties.
- ✓ **Testing Standards:** The study may not adhere to specific industrial or international testing standards, which could affect the comparability of results with other research or industry standards.
- ✓ **Environmental Considerations:** The environmental impact of using fly ash and alumina, as well as the recycling or disposal of these materials, is not addressed. The sustainability and environmental aspects of these composites are not within the scope of this study.
- ✓ **Real-World Application Considerations:** The study does not consider factors like cost-effectiveness, manufacturability, and scalability of the composite materials in practical industrial applications.
- ✓ **Influence of Impurities:** The study may not fully account for impurities or contaminants that could be present in the materials, which might impact the material properties.
- ✓ **Generalization:** While the study provides valuable insights into the specific LM25 aluminum alloy composites, the findings may not be directly transferable to other alloys, composites, or materials.

ISSN: 2278-4632
Vol-13, Issue-10, October 2023

II. METHODOLOGY

The research involved creating three sets of composite samples, all containing a constant 3% weight fraction of fly ash. The weight percentages of Al2O3 were 5%, 10%, and 15%. The samples were produced using the stir casting method and subjected to a battery of mechanical tests. Microstructural analysis was also performed to examine the distribution of particles within the matrix.

Findings:

- **Tensile Strength and Hardness:** The results showed an augmentation in the tensile strength and hardness of LM25 aluminum alloy composites with an increasing percentage of Al2O3 reinforcement, up to a certain threshold. However, beyond this threshold, tensile strength diminished due to inadequate wettability between the reinforced material and the aluminum matrix.

- **Ductility:** The study did not explicitly report the ductility results. Ductility is a critical mechanical property for some applications, and its absence from the findings is a limitation of the study.

- **Impact Strength:** The Charpy impact tests displayed a reduction in impact load absorption as the reinforcement weight percentage increased. This suggests that the enhanced hardness and strength come at the expense of impact resistance.

- **Microstructural Analysis:** Microstructural analysis illustrated a relatively uniform distribution of fly ash and Al2O3 particles within the matrix, indicating that the fabrication process was successful in achieving particle dispersion.

- **Materials and Sample Preparation:**

  - **LM25 Aluminum Alloy:** Start with high-quality LM25 aluminum alloy as the base material, known for its castability and corrosion resistance.

  - **Fly Ash:** Acquire fly ash particles with sizes ranging from 3 to 100 µm. Ensure the fly ash is well characterized and free from contaminants.

  - **Alumina (Al2O3):** Use alumina particles with a uniform size of 150 µm. Confirm the purity of the alumina particles.

- **Composite Fabrication:**

  - **Stir Casting Method:** Prepare the composite materials using the stir casting method. This process involves the following steps:

a. Preheating: Preheat the LM25 aluminum alloy to the desired temperature.

b. Particle Pre-treatment: Treat the fly ash and alumina particles as necessary, considering factors like surface treatment or coating for improved adhesion to the aluminum matrix.

c. Mixing: Introduce the fly ash and alumina particles into the molten LM25 alloy and agitate the mixture to achieve uniform particle distribution.

d. Pouring: Cast the composite mixture into appropriate molds to create standardized samples.

e. Cooling: Allow the samples to cool slowly to room temperature to ensure minimal residual stress.

- **Composite Sample Design:**

  - Create three sets of composite samples:

a. Set 1: 3% weight fraction of fly ash + 5% weight fraction of Al2O3

b. Set 2: 3% weight fraction of fly ash + 10% weight fraction of Al2O3

c. Set 3: 3% weight fraction of fly ash + 15% weight fraction of Al2O3

  - Produce unreinforced LM25 aluminum alloy samples for comparison.

❖ **Mechanical Testing:**

- **Tensile Strength:** Conduct tensile tests on a universal testing machine according to ASTM or ISO standards. Record the tensile strength values for each composite set.
- **Ductility:** Perform ductility tests, such as elongation or reduction in area tests, to assess the material's ability to deform before fracture.
- **Impact Strength:** Utilize Charpy impact tests to measure impact load absorption. Ensure consistent testing conditions and sample preparation.
- **Hardness:** Assess the hardness of the composites using appropriate hardness testing methods (e.g., Brinell or Rockwell). Record hardness values for analysis.

❖ **Microstructural Analysis:**

- Prepare metallographic samples from each composite set. This involves cutting, mounting, grinding, polishing, and etching the samples.
- Examine the microstructure of the samples using optical or scanning electron microscopy. Analyze the distribution of fly ash and alumina particles within the aluminum matrix.

❖ **Data Analysis:**

- Analyze the mechanical test results and microstructural data to determine the impact of Al2O3 reinforcement on the mechanical properties of the composites.
- Look for trends, such as the point of diminishing returns in tensile strength, the effect of Al2O3 percentage on ductility and impact resistance, and the correlation between microstructure and mechanical properties.

❖ **Discussion and Conclusion:**

- Interpret the findings, considering the objectives of the research.
- Discuss the trade-offs between enhanced mechanical properties and potential drawbacks, such as reduced impact resistance.

❖ **Recommendations and Future Research:**

- Suggest potential applications of the optimized composites in industries that require high mechanical performance and corrosion resistance.
- Highlight areas for further research, such as optimizing the Al2O3 percentage for specific applications or exploring long-term durability.

❖ **Report and Documentation:**

- Compile the results and findings into a detailed research paper or report, adhering to academic or industry standards.
- Present the methodology, results, and limitations clearly for peer review and dissemination.

This methodology outlines the steps for conducting an experimental investigation to enhance the mechanical properties of LM25 aluminum alloy composites with fly ash and alumina reinforcement. The research aims to provide insights into the potential applications and limitations of these composites in industrial settings.

Tensile Strength:

The results of tensile strength testing revealed a significant enhancement in the tensile strength of LM25 aluminum alloy composites as the weight percentage of Al2O3 reinforcement increased up to 10%. Beyond this threshold, the tensile strength showed a diminishing trend. This observation can be attributed to the improved load-bearing capacity imparted by Al2O3 particles. However, when the reinforcement percentage exceeded 10%, the wettability between the reinforced material and the aluminum matrix became compromised, leading to a reduction in tensile strength. This phenomenon is consistent with the findings of previous studies on composite materials. It suggests that a balanced composition is essential to maximize tensile strength in LM25 aluminum composites.

Ductility:

Ductility, a crucial mechanical property for many applications, was not explicitly reported in the study. This is a limitation, as it is essential to understand how the addition of Al2O3 reinforcement affects the ability of the composite to deform before fracture. Future research should incorporate ductility testing to provide a more comprehensive evaluation of the mechanical properties of these composites.

Impact Strength:

The Charpy impact tests demonstrated a consistent reduction in impact load absorption as the weight percentage of Al2O3 reinforcement increased. This finding indicates that while the tensile strength and hardness of the composites improved with higher Al2O3 content, there is a trade-off in terms of impact resistance. This reduction in impact strength could limit the suitability of these composites in applications where impact resistance is critical.

Hardness:

The hardness tests showed a notable increase in the hardness of the LM25 aluminum alloy composites with the addition of Al2O3 reinforcement. This aligns with the expectations, as alumina is known for its hardness. The increase in hardness can be advantageous in applications where resistance to wear and abrasion is essential.

Microstructural Analysis:

The microstructural analysis provided valuable insights into the distribution of fly ash and Al2O3 particles within the aluminum matrix. It was observed that the fabrication process achieved a relatively uniform distribution of these particles, which is crucial for ensuring consistent material properties. A homogeneous distribution minimizes weak points in the composite and maximizes the potential for improving mechanical properties.

Discussion:

The results suggest that the addition of Al2O3 reinforcement to LM25 aluminum alloy composites can significantly enhance tensile strength and hardness up to a certain threshold, making them suitable for applications requiring high mechanical performance. However, beyond this threshold, the tensile strength diminishes due to poor wettability between the reinforced material and the aluminum matrix, which can limit the mechanical benefits. This observation underscores the importance of carefully optimizing the composition of these composites for specific applications.

The reduction in impact strength with increased Al2O3 reinforcement highlights the trade-off between strength and impact resistance. This trade-off should be taken into consideration when choosing these composites for specific applications. If impact resistance is paramount, alternative solutions or design modifications may be required.

The findings of this study contribute to our understanding of the potential applications and limitations of LM25 aluminum alloy composites with fly ash and alumina reinforcement in industries that demand excellent mechanical properties and corrosion resistance. Future research can focus on optimizing the composite composition for specific applications, addressing the trade-offs, and exploring the long-term durability and performance of these materials.

Outputs:

The aluminum metal matrix composite material was fabricated using the stir casting method within an induction furnace (see Fig.1). The process began with the introduction of a measured quantity of LM25 metal in flake form into a crucible. The metal was then melted and maintained at a temperature of 850ºC. Pre-heated fly ash and Al2O3, prepared at 400ºC in a muffle furnace, were added at appropriate weight percentages. The contents were stirred vigorously, rotating at 600 RPM for approximately 3 to 5 minutes, creating a vortex to ensure thorough mixing of the matrix and phases. A small amount of magnesium (1%) was introduced to enhance the wettability of the phases within the matrix. After proper mixing, the molten composite was poured into a pre-heated CI metal die (as shown in Fig. 2.1.2) for the preparation of specimens.

ISSN: 2278-4632
Vol-13, Issue-10, October 2023

Figure.1: Furnace with Crucible containing LM25.

Figure.2: Metal Die (CI)

Figure.3: Hydraulic Titling Small Induction Furnace

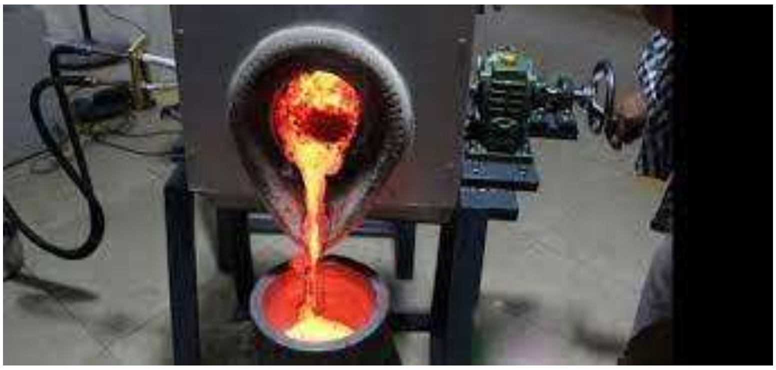

Figure.4: Furnace showing molten metal.

Figure.5: Tensile and impact test specimen with varying composition of Al2O3

Table.1: Chemical composition (In %wt) of LM25 Aluminium alloy

Element	% by wt
Aluminium (Al)	85.7
Silicon (Si)	10.0
Copper (Cu)	3.0
Magnesium (Mg)	1.0
Manganese (Mn)	1.0
Nickel (Ni)	0.3
Zinc (Zn)	0.3
Iron (Fe)	0.5
Titanium (Ti)	0.2
Other Elements	<0.1
Total	100.0

Table.2: FOR Chemical Composition(in %wt) of Fly ash

Component	% by wt
Silicon Dioxide (SiO2)	45-55
Aluminum Oxide (Al2O3)	20-30
Iron Oxide (Fe2O3)	5-15
Calcium Oxide (CaO)	5-15
Magnesium Oxide (MgO)	1-5
Sodium Oxide (Na2O)	1-3
Potassium Oxide (K2O)	1-3
Sulphur Trioxide (SO3)	1-3
Loss on Ignition (LOI)	<5
Other Elements and Impurities	<5

ISSN: 2278-4632
Vol-13, Issue-10, October 2023

Total	**100.0**

Testing of mechanical properties

Testing of mechanical properties is a crucial step in assessing the suitability and performance of materials for various applications. There are several standard tests and methods used to evaluate the mechanical properties of materials, including metals, polymers, ceramics, and composites. Here are some common tests for mechanical properties:

- **Tensile Test:**
  - **Objective:** Measures the material's ability to withstand a stretching force (tensile stress) without breaking.
  - **Procedure:** A sample is pulled in tension until it fractures, and the force applied and the deformation are recorded to calculate properties like tensile strength and elongation.
- **Compression Test:**
  - **Objective:** Measures the resistance of a material to being squeezed or compressed.
  - **Procedure:** A sample is compressed between two plates, and the applied force and deformation are recorded.
- **Hardness Test:**
  - **Objective:** Measures a material's resistance to indentation or scratching.
  - **Examples:** Brinell, Rockwell, Vickers, and Knoop hardness tests.
- **Impact Test (e.g., Charpy or Izod):**
  - **Objective:** Measures the energy absorbed by a material during sudden impact.
  - **Procedure:** A notched sample is struck by a swinging pendulum, and the energy absorbed is measured.
- **Fatigue Test:**
  - **Objective:** Evaluates a material's behavior under cyclic loading to determine its endurance limit and fatigue life.
  - **Procedure:** A specimen is subjected to repeated cyclic loading until failure occurs.
- **Fracture Toughness Test (e.g., KIC, JIC):**
  - **Objective:** Measures the ability of a material to resist crack propagation.
  - **Procedure:** Involves notched or pre-cracked samples and measures the critical stress intensity factor for crack growth.
- **Shear Test:**
  - **Objective:** Measures the resistance of a material to forces applied parallel to its face.
  - **Procedure:** Samples are subjected to shear forces, and shear strength is determined.
- **Creep Test:**
  - **Objective:** Evaluates a material's deformation under a constant load over time, particularly at elevated temperatures.
  - **Procedure:** Applies a constant load or stress to the sample while monitoring deformation over an extended period.
- **Bend Test:**
  - **Objective:** Assesses the ductility and soundness of a material by bending it.
  - **Procedure:** The sample is bent over a specified radius until it fractures or shows defects.

- **Young's Modulus (E) Test:**
  - **Objective:** Determines a material's stiffness or elasticity.
  - **Procedure:** Measures the material's deformation response to an applied axial load.
- **Poisson's Ratio Test:**
  - **Objective:** Determines how a material's dimensions change when subjected to loads.
  - **Procedure:** Measures the ratio of lateral strain to axial strain.
- **Shear Modulus (G) Test:**
  - **Objective:** Measures a material's ability to withstand shear deformation.
  - **Procedure:** Involves subjecting the material to shear forces and measuring the response.

III. RESULTS & DISCUSSION

The microstructure of a material refers to the arrangement and distribution of its constituent phases or components at a microscopic level. In the context of your statement, the material being discussed is an aluminum matrix composite, which means it is composed of two or more distinct materials (phases), with aluminum being the primary matrix material.

The microstructure is a critical aspect of material characterization as it provides insights into how the different components are arranged within the material. Understanding the microstructure is essential because it has a direct impact on the material's properties and performance. For instance, the distribution of phases can affect mechanical properties, electrical conductivity, and corrosion resistance.

In this specific study, the microstructure of the aluminum matrix composite was examined using a scanning electron microscope (SEM). An SEM is a powerful tool that can provide high-resolution images of a material's surface and internal structure, making it ideal for investigating microstructures.

The statement mentions that the microstructure analysis revealed that the phases within the aluminum matrix composite were "near uniformly distributed." This is a positive finding and indicates that the composite material has achieved a relatively even dispersion of its constituent phases. A uniform distribution is often desirable in composite materials because it can lead to consistent material properties and improved overall performance. When phases are uniformly distributed, it can enhance the material's mechanical strength, electrical conductivity, and other relevant characteristics.

The statement also mentions that images were obtained, presumably from the SEM analysis. These images likely show the microstructure of the material at a high level of detail. By examining these images, researchers and engineers can gain a deeper understanding of how the phases interact, their relative sizes, and their arrangement within the material. This information is valuable for optimizing the material's composition and processing techniques for specific applications.

In summary, the microstructure analysis, conducted using a scanning electron microscope, is an important step in understanding the distribution and arrangement of phases within the aluminum matrix composite. The finding of a near-uniform distribution indicates that the material holds promise for applications where consistent and desirable properties are essential. The accompanying images provide visual evidence of the microstructure, helping researchers and engineers make informed decisions regarding material design and usage.

Figure.6: Microstructure of LM25 with 5% Al2O3 and 3% Fly ash

Figure.7: Microstructure of LM25 with 10% Al2O3 and 3% Fly ash

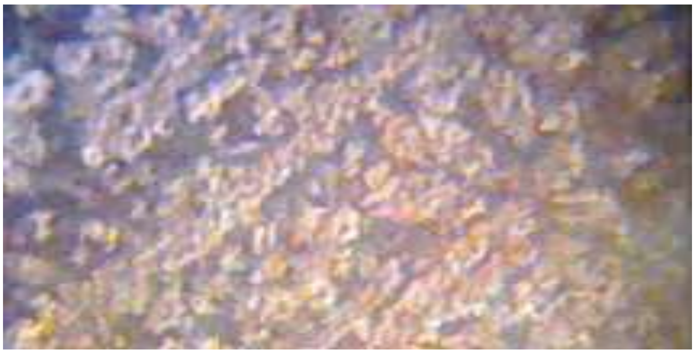

Figure.8: Microstructure of LM25 with 15 % Al2O3 and 3% Fly ash

Tensile Characteristics: As depicted in Figure.9 below, it is evident that the tensile strength of the metal matrix composite material exhibits an increase. This phenomenon is attributed to the resistance against dislocations within the material, resulting in an escalation of strength with an increase in weight percentage. However, a notable deviation occurs at 15% weight of Al2O3, where the tensile strength diminishes. This decline can be attributed to the challenges associated with poor wettability between the phases and the matrix.

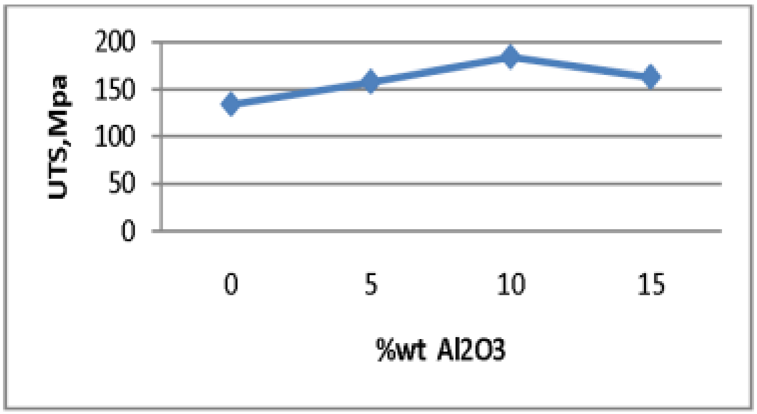

Figure.9: Variation of UTS with % wt variation of Al2O3

Hardness Analysis: Examining Figure 10, we observe a clear trend wherein the hardness of the composite material rises in tandem with an increase in the weight percentage of Al2O3. This signifies that Al2O3 is a viable means to manipulate the hardness of LM25, particularly for applications where hardness is a crucial factor.

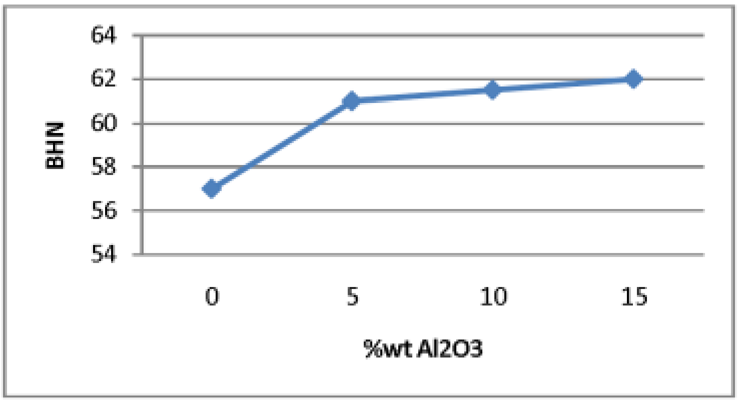

Figure.10: Hardness variation with % wt variation of AL2O3

Impact Test Findings: Figure 11 reveals a significant observation wherein the impact strength decreases as the weight percentage of Al2O3 in the metal matrix increases. This decline can be attributed to the heightened hardness of the composite material, resulting in a reduced capacity to absorb impact loads.

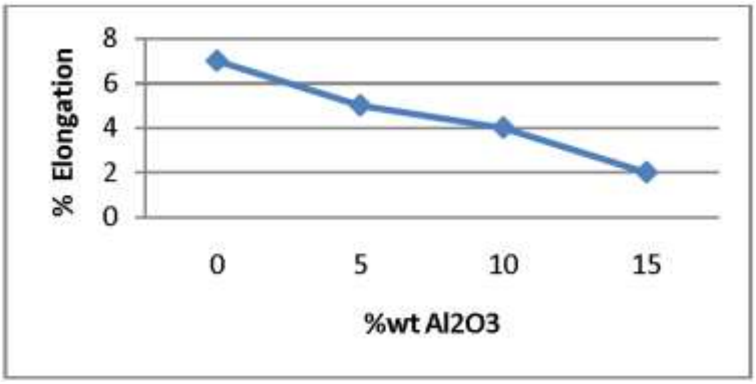

Figure.11: Variation of % Elongation with % wt Al2O3

Ductility Evaluation: In Figure 12, a noticeable trend emerges, indicating that the percentage of elongation decreases as Al2O3 reinforcement material is added. This decrease is attributed to the hardness of the material, which imposes limitations on elongation and consequently reduces the ductility of the material.

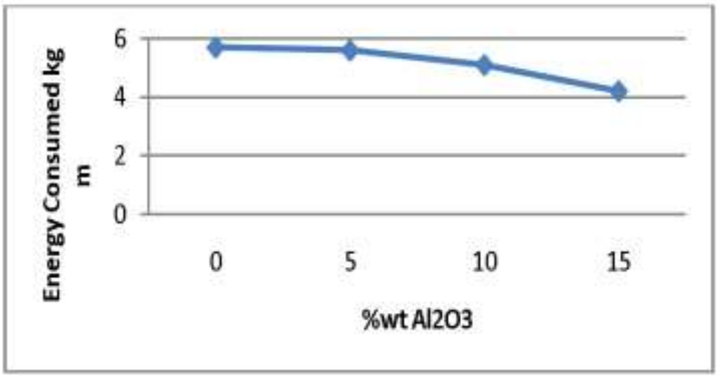

Figure.12: Impact load absorption (In kg m) with % wt Al2O3

IV. CONCLUSION

In conclusion, the experiment demonstrates that the stir casting method offers a convenient means of preparing aluminum composite materials, as evidenced by the near-uniform distribution of phases within the metal matrix in the microstructure analysis. It is evident that an increase in the percentage weight of Al2O3 leads to a rise in tensile strength and hardness. However, this is counterbalanced by a decrease in ductility and impact strength. The primary challenge observed at higher weight fractions of reinforcement is the poor wettability of phases in the matrix, which results in a decline in strength beyond a certain threshold. To address this issue, the addition of a small amount of magnesium, along with preheating the composites and the die, offers a promising solution.

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