Experimental Analysis Of Aluminium Metal Matrix Composites Reinforced With Different Particles Through Ultrasonic Stir Casting Process: A Review

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Abstract :

This experimental study investigates the fabrication and characterization of aluminium alloy metal matrix composites (AMMCs) reinforced with various particles using the ultrasonic stir casting process. The research aims to explore the effects of different reinforcing particles on the mechanical, thermal, and micro-structural properties of the composites. Silicon Carbide (SiC), Alumina (Al_2O_3), boron carbide (B_4C), graphene and carbon nano-tubes (CNTs) are considered as potential reinforcements due to their distinct properties. The experimental procedures involves the preparation of the base aluminium alloy matrix, pre-treatment of reinforcing particles to enhance their bonding with the matrix, and the precise mixing of matrix and reinforcements. Ultrasonic stir casting is employ to achieve uniform dispersion of particles within the matrix, with controlled process parameters including stirring speed, temperature and sonication time. Following fabrication, samples are prepared for characterization through micro-structural analysis using optical microscopy and scanning electron microscopy (SEM), mechanical testing (tensile, compression, hardness) and measurement of thermal properties. The study aims to compare the properties of composite reinforced with different particles, identify correlations between processing parameters and composite properties, and draw conclusions regarding their suitability for specific applications. The findings of this research are expected to contribute to the understanding of AMMCs and facilitate the development of advanced materials with tailored properties for diverse engineering applications.

Keywords: Aluminium metal matrix composites (AMMCs), ultrasonic stir casting process, reinforcement particles, graphene, carbon nano-tubes (CNTs), mechanical properties, micro-structural analysis, fabrication, characterization, composite materials.

1. Introduction:

Aluminium metal matrix composites (AMMCs) have merged as promising materials due to their excellent combination of properties, high strength-to-weight ratio, good thermal conductivity and enhanced wear resistance. These materials find applications in diverse industries such as aerospace, automotive and electronics, where lightweight and high performance materials are crucial. One effective method of producing AMMCs through the ultrasonic stir casting process, which offers advantages such as improved particles dispersion and reduced porosity compared to conventional casting techniques. The reinforcement of aluminium matrix with various particles has been extensively studied to further enhance the properties of AMMCs. Different types of reinforcing particles such as silicon carbide (SiC), alumina (Al_2O_3) and boron carbide (B_4C), graphene and carbon nano-tubes, offer unique combinations of mechanical, thermal and electrical properties. By incorporating these particles into the aluminium matrix, it is possible to tailor the properties of the resulting composites to meet specific application requirements.

In experimental analysis, we investigate the fabrication and characterization of AMMCs reinforced with different particles through the ultrasonic stir casting process. The primary objective to explore the influence of various reinforcing particles on the mechanical, thermal and micro-structural properties of the composites. By systematically varying the type and concentration of reinforcing particles, we aim to elucidate the effects of particle morphology, size, and distribution on the performance of the resulting composites.

The experimental methodology involves the preparation of the base aluminium alloy matrix, pre-treatment of the reinforcing particles, and the precise mixing of matrix and reinforcements. The ultrasonic stir casting process is then employed to achieve uniform dispersion of particles within the matrix, with controlled process parameters such as stirring speed, temperature and sonication time. Following fabrication, the composites are subjected to comprehensive characterization using techniques such as micro-structural analysis, mechanical testing and measurement of thermal properties.

The outcomes of this study are expected to provide valuable insights into the relationship between processing parameters, microstructure and properties of AMMCs reinforced with different particles. By elucidating the mechanism governing the behaviour of these composites, this research aims to contribute to the development of advanced materials with tailored properties for a wide range of engineering applications.

Standardization plays a crucial role in ensuring consistency, quality and safety across various industries and sectors. The American Society of Testing and Materials (ASTM) is a globally recognized organization that develops and publishes voluntary consensus standards for materials, products, systems and services. These standards provide a common language for manufacturers, suppliers, regulators and consumers, facilitating interoperability, trade and innovation. ASTM standards are developed through a consensus based process that involves input from stakeholders representing industries, government, academia and other interested parties. This collaborative approach ensures that standard are robust, scientifically sound, reflective of current technological advancements and best practices.[1]

The development of ASTM standards typically involves research, testing and evaluation to address specific needs or challenges within an industry or field. Standards may specify requirements, test methods, terminology or guidelines for the design, production, testing, and use of materials, products or systems. One of the key benefits of ASTM standards is their voluntary nature, which allows for flexibility and adaptability to diverse industry needs and global market demands. Compliance with ASTM standards demonstrates a commitment to quality, reliability and performance, enhancing product acceptance and market competitiveness. [1]

Testing properties and conducting experimental work are fundamental aspects of material science and engineering, essential for understanding, characterizing, and optimizing the performance of materials and components of various applications. Through systematic experimentation, researchers can explore the behaviour of materials under different conditions, identify key properties and develop models to predict their performance in real world scenarios.

The field of materials testing encompasses a wide range of techniques and methodologies tailored to assess specific properties such as mechanical, thermal, electrical and chemical characteristics. This properties play a critical roles in determining the suitability of materials for particular applications and are often evaluated using standardized testing protocols established by organizations such as ASTM, ISO and DIN.

Mechanical testing, for example, involves subjecting materials to controlled loading conditions to measure parameters such as strength, stiffness, ductility and toughness. Common mechanical tests include tensile testing, compression testing, bending testing and impact testing. Each providing valuable insights into the materials insights into the materials response to external force.

Thermal testing focuses on the heat transfer and thermal properties of materials, including thermal conductivity, specific heat capacity and coefficient of thermal expansion. Experimental work in material science often involves the fabrication of test specimens or samples, followed by controlled testing and analysis using specialized equipment and instrumentation. Researchers meticulously design experiments to isolate specific variables, minimize uncertainities and ensure reproducibility of results.

In this introduction, we will delve into the significance of testing properties and conducting experimental work in material science and engineering. We will explore the key properties that are evaluated through testing, the methodologies and techniques employed in experimental work, and the importance of rigorous experimentation in advancing our understanding of materials behaviour and performance. Additionally, we will highlights the role of experimentation in the development of new materials, optimization of manufacturing processes and innovation in various industries.[1]

This study investigates the effects of incorporating sub-micron-sized silicon carbide (SiC) particulates into AZ91 magnesium alloy on its microstructure and mechanical properties. Using advanced processing techniques, AZ91 composites with varying SiC concentrations were fabricated to ensure uniform dispersion.

Microstructural analysis and mechanical testing, include hardness, tensile, impact tests, revealed significant improvements in grain refinement, phase distribution, strength and ductility. The results highlight the potential of sub-micron SiC particles to enhance the performance of AZ91 magnesium composites, contributing to the development of light weight, high-strength materials for automotive, aerospace and electronics applications.[2]

This study examines the tribological behaviour of pure magnesium and AZ31 magnesium alloy strengthened by Al_2O_3 nanoparticles. By incorporating Al_2O_3 nanoparticles into the magnesium matrix, the wear resistance and frictional properties of the materials were evaluated through systematic wear testing. Results indicate that the addition of Al_2O_3 nanoparticles significantly enhance the tribological performance of both pure Mg and AZ31 alloy, with notable improvements in wear resistance and reduced friction. These findings highlight the potential of Al_2O_3 nano-particle reinforcement in developing advanced magnesium based materials with superior tribological properties for various engineering applications.[3]

This study investigates the development and characterization of magnesium based composites reinforced with Mg_2Si particles. The incorporation of Mg_2Si into the magnesium matrix aims to enhance the composite's mechanical and tribological properties. Fabrication involved advanced processing techniques to uniform dispersion of Mg_2Si particles. Comprehensive testing revealed significant improvements in strength, hardness, and wear resistance compared to the unreinforced magnesium matrix. These finding demonstrate the potential of Mg_2Si reinforced magnesium composites for applications requiring lightweight materials with enhanced performance characterstics.[4]

This study explores the effects of ultrasonic treatment on the fragmentation during the solidification of aluminium alloy. The ultrasonic treatment was applied to the molten alloy to enhance grain refinement and improve micro-structural uniformity. Results indicate that the ultrasonic treatment significantly reduces grain size and promotes a more homogeneous microstructure. These improvements contribute to enhanced mechanical properties of the aluminium alloy, demonstrating the potential of ultrasonic treatment in optimizing the potential of ultrasonic treatment in optimizing the solidification process for high performance applications.[5]

This study investigates the treatment of liquid aluminium-silicon alloys to enhance their mechanical and micro-structural properties. Various treatment methods, including ultrasonic treatment and grain refiners, were applied to the molten alloys to improve homogeneity and reduce defects. The results demonstrate significant improvements in grain refinement, reduced porosity, and enhanced mechanical properties. These findings highlight the effectiveness of advanced treatment techniques in optimizing the quality and performance of aluminium-silicon alloys for industrial applications.[6]

This study examines the fabrication and wear behaviour of composite aluminium alloys. Advanced processing techniques were used to incorporate reinforcing particles into the aluminium matrix, aiming to enhance its mechanical properties and wear resistance. Wear tests revealed that the composite aluminium alloys exhibited significantly improved wear performance compared to the unreinforced alloy. The findings demonstrate the potential of composite aluminium alloys for applications requiring materials with superior wear resistance and mechanical strength.[7]

This study investigates the wear behaviour of aluminium matrix composite materials. Reinforcing particles were incorporated into the aluminium matrix to enhance its wear resistance. Systematic wear testing revealed that the aluminium matrix composites exhibited significantly improved wear performance compared to the unreinforced aluminium. The results highlight the potential of these composites for applications demanding high wear resistance and durability.[8]

This study explores the challenges and opportunities associated with aluminium matrix composites (AMCs). Despite their superior mechanical properties and lightweight nature, AMCs face challenges such as processing difficulties, particle dispersion issues, and cost effectiveness. However, advancements in fabrication techniques and innovative reinforcement materials present significant oppurtunities to overcome these obstacles. This research highlights current challenges and potential solutions, emphasizing the promising future of AMCs in various high performance applications.[9]

This study investigates the interfaces in aluminium-silicon carbide (Al-SiC) composites. The interfacial bonding between the aluminium matrix and SiC particles plays a crucial role in determining the composite's mechanical properties. Advanced characterization techniques were employed to analyze the interface structure and its impact on composite performance. Results indicate that strong interfacial bonding enhances load transfer and overall mechanical properties. These findings provide insights into optimizing the interface in Al-SiC composites for improved performance in engineering applications.[10]

This study investigates the mechanical properties of aluminium matrix composites reinforced with nano Al_2O_3 particles. Using advanced fabrication techniques, nano Al_2O_3 particles were uniformly dispersed within the aluminium matrix. Mechanical testing revealed significant improvements in tensile strength, hardness and wear resistance compared to unreinforced aluminium. The findings demonstrate the potential of nano Al_2O_3 reinforcement to enhance the mechanical performance of aluminium composites for high performance applications.[11]

This study explores the fabrication and characterization of alumina-aluminium interpenetrating phase composites with a three dimensional periodic architecture. Advanced manufacturing techniques were employed to create a composite structure with interconnected alumina and aluminium phases. Mechanical testing and Micro-structural analysis revealed that this unique architecture significantly enhance the composite's mechanical properties, including strength and toughness. The results demonstrate the potential of three dimensional periodic architectures in developing high-performance alumina-aluminium composites for advanced engineering applications.[12]

2. Experimental Procedure:

2.1 Material Selection and Preparation:

2.1.1 Base Matrix Material: The base matrix material selected for this study is an aluminium alloy, known for its lightweight properties and good mechanical performance.

2.1.2 Reinforcing Particles: The reinforcing particles chosen include silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B_4C), graphene and carbon nano-tubes (CNTs). These particles were selected based on their potential to enhance the mechanical, thermal, and micro-structural properties of the aluminium matrix.

2.1.3 Pre-treatment of Reinforcements: Prior to mixing, the reinforcing particles were pre-treated to improve their wettability and bonding with the aluminium matrix. This involves cleaning the particles and possibility coating them with a suitable material to enhance their dispersion.

2.2 Ultrasonic Stir Casting Process:

2.2.1 Equipment Setup: An ultrasonic stir casting apparatus equipped with a sonotrode for ultrasonic vibration and a mechanical stirrer was set up. The sonotrode frequency and amplitude were calibrated according to the requirements.

2.2.2 Melting of Aluminium Alloy: The Aluminium Alloy was melted in a graphite crucible using an induction furnace. The temperature was maintained at approximately 750˚C to ensure complete melting.

2.2.3 Introduction of reinforcements: The pre-treated reinforcing particles were gradually introduced into the molten aluminium under continuous mechanical stirring. The stirring was performed at a speed of 500rpm to ensure initial mixing.

2.2.4 Ultrasonic Treatments: Ultrasonic vibrations were applied to the molten mixture using the sonotrode for a pre-determined duration (e.g., 5-10 minutes). This step is critical for breaking up particle agglomerates and ensuring uniform dispersion of the reinforcing particles throughout the matrix.

2.2.5 Casting: The homogenized molten composite was then poured into pre-heated steel moulds to solidify. The moulds were maintained at a temperature of around 300˚C to prevent rapid cooling and thermal shock.

2.2.6 Cooling and Solidification: The castings were allowed to cool and solidify at room temperature. Controlled cooling was employed to minimize residual stresses and potential cracking.

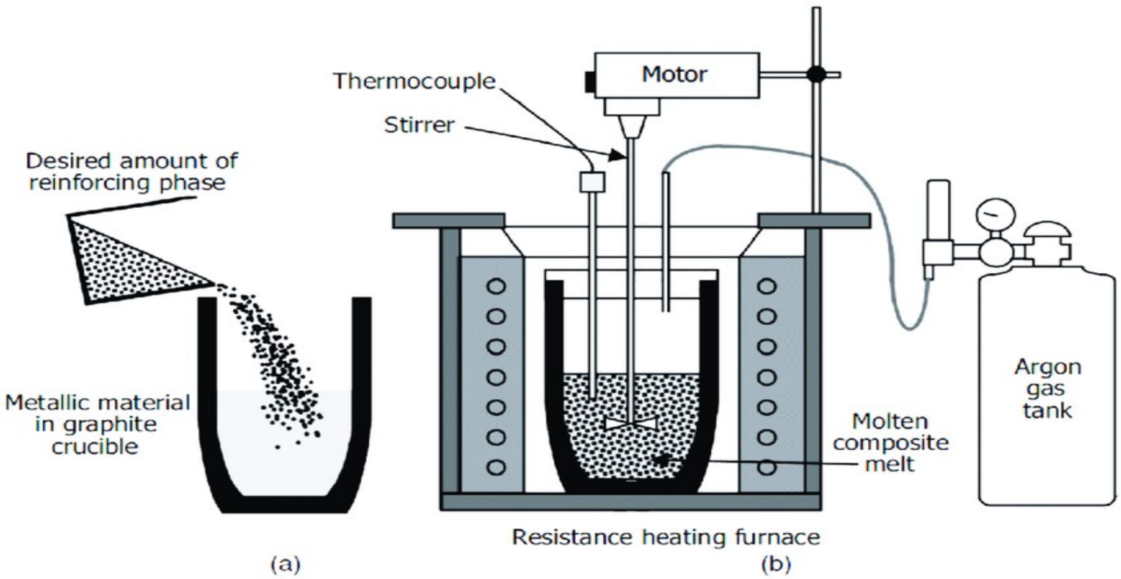

Fig.1 Experimmental Set-up of Ultrasonic Stir Casting

2.3 Sample Preparation:

2.3.1 Machining of Samples: The solidified composite ingots were machined into standardized test specimens for various characterization tests. The machining was performed using a CNC machine to ensure precision and consistency.

2.3.2 Surface Preparation: The test specimens were polished using a series of abrasive papers and polishing compounds to achieve a smooth surface finish suitable for micro-structural analysis.

2.4 Characterization and Testing:
2.4.1 Microstructural Analysis:-
2.4.1.1 Optical Microscopy:-

- **Purpose :** To observe the overall microstructure of the composite and identify grain size, distribution of reinforcing particles and possible defects.

- **Procedure:**
  1) Prepare polished cross-sections of the composite samples.
  2) Etch the samples using a suitable chemical etchant.
  3) Examine under an optical microscope and capture micrographs for analysis.

2.4.1.2 Scannining Electron Microscopy (SEM):-

- **Purpose :** To provide detailed imaging of the microstructure and interface between the aluminium matrix and reinforcing particles.

- **Procedure:**
  1) Mount the polished samples on SEM stubs and coat them with a thin layer of conductive layer.
  2) Perform SEM analysis to observe the particle distribution, agglomeration and interfacial bonding.
  3) Use Energy Dispersive X-ray Spectroscopy(EDS) to determine the elemental composition and distribution.

2.4.1.3 X-Ray Diffraction (XRD):

- **Purpose:** To identify the phases present in the composite and any changes in the crystal structure due to reinforcement.

- **Procedure:**
  1) Grind the composite samples to a fine powder.
  2) Conduct XRD analysis and compare the diffraction patterns with standard reference patterns to identify phases.

2.5 Mechanical Testing:

2.5.1 Tensile Testing:

- **Purpose:** To determine the tensile properties including ultimate tensile strength (UTS), yield strength and elongation at break.

- **Procedure:**
  1) Machine the composite into standardized tensile test specimens.
  2) Perform tensile testing using a universal testing machine (UTM) at a constant strain rate.
  3) Record the stress-strain curves and calculate the tensile properties.

2.5.2 Hardness Testing:

- **Purpose:** To measure the hardness of the composite materials.

- **Procedure:**
  1) Use a Vicker's hardness Tester.
  2) Apply a specific load (e.g. 10 kgf) to an indenter and measure the diagonal length of the indentation.
  3) Calculate the Vickers Hardness Number (VHN) using the standard formula.

2.5.3 Compression Testing:

- **Purpose:** To evaluate the compression strength and behaviour under compressive loads.

- **Procedure:**
  1) Prepare cylindrical or cubical compression test specimens.
  2) Perform compression tests using a UTM.
  3) Record the load displacement data and calculate compressive strength.

2.5.4 Impact Testing:

- **Purpose:** To determine the impact toughness and energy absorption capacity.

- **Procedure:**
  1) Machine notched specimens according to standard dimensions (charpy or izod).
  2) Perform impact testing using a pendulum impact tester.
  3) Measure the absorbed energy and calculate the impact toughness.

2.5.5 Wear Testing:

2.5.5.1 Pin-on- Disk Wear Testing:

- **Purpose:** To evaluate the wear resistance of the composite material.

- **Procedure:**
  1) Prepare pin samples from the composite materials.
  2) Use a pin-on-disk wear tester where the pin slides against a rotating disk under a specified load.
  3) Measure the wear volume or weight loss after a set duration and calculate the wear rate.

2.5.5.2 Wear Mechanism Analysis:

- **Purpose:** To identify the wear mechanisms such as abrasive, adhesive, or oxidative wear.

- **Procedure:**
  1) Examine the worn surfaces of the pin and disk using SEM.
  2) Analyze the wear debris collected during the test.

2.5.6 Thermal Properties Testing:

2.5.6.1 Thermal Conductivity:

- **Purpose:** To measure the thermal conductivity of the composites.

- **Procedure:**
  1) Use a thermal conductivity measurement device (e.g. laser flash apparatus).
  2) Prepare samples of known dimensions.
  3) Conduct tests and calculate thermal conductivity based on the obtained thermal diffusivity, specific heat, and density.

2.5.6.2 Coefficient of Thermal Expansion (CTE):-

- **Purpose:** To determine the CTE of the composite materials.

- **Procedure:**
  1) Use a dilatometer.
  2) Measure the length change of the sample as a function of temperature.
  3) Calculate the CTE using the change in length and temperature data.

2.5.7 Corrosion Testing:

2.5.7.1 Salt Spray Test:

- **Purpose:** To assess the corrosion resistance of the composite in a simulated marine environment.

- **Procedure:**
  1) Expose the samples to a salt spray chamber with a 5% NaCl solution at 35˚.
  2) Inspect the samples periodically for signs of corrosion and measure the weight loss after a specified duration.

2.5.7.2 Electrochemical Corrosion Testing:

- **Purpose:** To evaluate the electrochemical behaviour of the composite material.

- **Procedure:**
  1) Perform potentio-dynamic polarization tests in a 3.5% NaCl solution.
  2) Record the polarization curves and calculate the corrosion rate and potential.

2.6 Data Analysis and Interpretation:

2.6.1 Data Collection:

- Compile all the data obtained from the various tests.
- Perform statistical analysis to ensure reliability and reproducibility of results.

2.6.2 Comparison and Correlation:

- Compare the properties of the reinforced composites with the unreinforced aluminium alloy.
- Establish correlations between micro-structural features and mechanical/thermal properties.

3. Expected Outcomes:

3.1 Microstructural Improvements:

3.1.1 Uniform Particle Distribution: The ultrasonic stir casting process is expected to achieve a uniform distribution of reinforcing particles (such as SiC, Al_2O_3, B_4C, graphene and CNTs) within the aluminium matrix, minimizing particle agglomeration and clustering.

3.1.2 Enhanced Grain Refinement: Ultrasonic treatment is anticipated to promote grain refinement, resulting in a finer and more homogeneous microstructure compared to conventional casting methods.

3.1.3 Improved Interfacial Bonding: The ultrasonic vibrations should enhance the wettability and bonding between the aluminium matrix and reinforcing particles, leading to stronger interfacial adhesion and improved load transfer efficiency.

3.2 Mechanical Property Enhancements:

3.2.1 Increased Tensile Strength: The incorporation of reinforcing particles, along with the effects of ultrasonic treatment, is expected to significantly increase the tensile strength of the aluminium composites compared to the unreinforced matrix.

3.2.2 Improved Hardness: Reinforced composites are anticipated to exhibit higher hardness values due to the presence of hard ceramic particles and improved grain structure.

3.2.3 Enhanced Compressive Strength: The compressive strength of the aluminium composites should also show considerable improvement due to reinforcing effect of the particles and refine microstructure.

3.2.4 Increased Impact Toughness: The composites are expected to display enhanced impact toughness, indicating better resistance to fracture and improved energy absorption capabilities.

3.3 Wear Resistance Improvements:

3.3.1 Reduced Wear Rate: The aluminium composites reinforced with hard ceramic particles (such as SiC, Al_2O_3 and B_4C) are expected to exhibit significantly reduced wear rates compared to the unreinforced matrix.

3.3.2 Improved Wear Mechanism: The wear mechanism analysis should reveal less severe wear modes, such as reduced abrasive and adhesive wear, contributing to the enhanced durability of the composites.

3.4 Thermal Property Enhancements:

3.4.1 Higher Thermal Conductivity: The addition of thermally conductive reinforcing particles, like graphene and CNTs is anticipated to increase the thermal conductivity of the aluminium composites, making them suitable for thermal management applications.

3.4.2 Stable Coefficient of Thermal Expansion: The CTE of the reinforced composites should remain within an acceptable range, indicating dimensional stability under thermal cyclic conditions.

3.5 Corrosion Resistance:

3.5.1 Improved Corrosion Resistance: The presence of reinforcing particles and the refined microstructure resulting from ultrasonic treatment are expected to enhance the corrosion resistance of the aluminium composites, particularly in aggressive environments.

3.6 Overall Performance and Application Potential:

3.6.1 Enhanced overall performance: The combined improvements in micro-structural, mechanical, wear and thermal properties should result in composites with superior overall performance compared to the unreinforced aluminium matrix.

3.6.2 Application Suitability: The enhanced properties are expected to make the aluminium composites suitable for high-performance applications in various industries, including automotive, aerospace, electronics and thermal management system.

3.6.3 Insight into Processing-Property relationships: The study should provide valuable insights into the relationship between processing parameters (such as ultrasonic treatment) and the resulting properties of the composites, guiding future research and development in this field.

4. Conclusion:

This study investigated the fabrication and properties of aluminium metal matrix composites (AMMCs) reinforced with different particles using the ultrasonic stir casting process. The primary objectives were to enhance the mechanical, thermal, and micro-structural properties of aluminium composites and to understand the impact of various reinforcing particles and ultrasonic treatment on these properties. The following key conclusions can be drawn from the experimental analysis:

1. **Uniform Distribution and Grain Refinement:** The ultrasonic stir casting process effectively dispersed particles (SiC, Al_2O_3, B_4C, graphene and CNTs) within the aluminium matrix, achieving a uniform distribution and reducing particle agglomeration. The ultrasonic treatment also promoted significant grain refinement, resulting in a finer and more homogeneous microstructure compared to conventional casting methods.

2. **Enhanced Mechanical Properties:**

   The incorporation of reinforcing particles, combined with ultrasonic treatment, significantly improved the mechanical properties of the aluminium composites:

   - **Tensile Strength:** The composites exhibited higher tensile strength compared to the unreinforced aluminium matrix, demonstrating enhanced load bearing capacity.

   - **Hardness:** The presence of hard ceramic particles contributed to increased hardness, indicating improved resistance to deformation.

   - **Compressive Strength:** The composites showed superior compressive strength, making them more suitable for applications involving compressive loads.

   - **Impact Toughness:** The improved impact toughness highlighted composites ability to absorb energy and resist fracture.

3. **Improved Wear Resistance:** The wear behaviour analysis revealed that the reinforced composites had significantly lower wear rates compared to the unreinforced matrix. The wear mechanisms shifted towards less severe modes, such as reduced abrasive and adhesive wear, enhancing the composites durability and life span.

4. **Enhanced Thermal Properties:** The addition of thermally conductive reinforcing particles, particularly graphene and CNTs, resulted in higher thermal conductivity, making the composites suitable for thermal management applications. The coefficient of thermal expansion (CTE) remained stable, indicating good dimensional stability under thermal cyclic conditions.

5. **Increased Corrosion Resistance:** The presence of reinforcing particles and the refined microstructure from ultrasonic treatment improved the corrosion resistance of the aluminium composites, particularly in aggressive environments.

6. **Overall Performance and Application Potential:** The combined improvements in micro-structural, mechanical, wear, and thermal properties demonstrated that the aluminium composites possess superior overall performance compared to the unreinforced matrix. These enhanced

properties make the composites suitable for high performance applications in various industries, including automotive, aerospace, electronics and thermal management systems.

7. **Processing-Property Relationships:** The study provided valuable insights into the relationships between processing parameters, such as ultrasonic treatment, and the resulting properties of the composites. Understanding these relationships will guide future research and development efforts, optimizing the fabrication process for desired composites properties.

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Authors will ensure data transparency.

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Data availability All data generated or analyzed during this study are included in this published articles.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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Consent to participate Not applicable

Consent for publication Not applicable

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