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ORIGINAL CONTRIBUTION

Enhancing Mechanical Properties of Al-6061-Cu/Mg−Al_2O_3/SiC Composites: A Comparative Study of Stir Casting and Ultrasonic Casting Techniques

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Abstract Aluminum composites with improved mechanical properties are highly sought after in various industries. Two main methods, stir casting and ultrasonic casting, are used to create these composites. Stir casting involves mechanically stirring reinforcement materials into a molten aluminum matrix, while ultrasonic casting uses vibrations to disperse reinforcements in the molten metal. Understanding the differences between these techniques and their impact on mechanical properties is crucial for optimizing composite fabrication. This article presents a comprehensive comparison of stir and ultrasonic casting procedures and evaluates their impact on the characteristics of aluminum composites. This study involved the fabrication of aluminum metal matrix composites (AMMCs) utilizing both traditional stir casting and ultrasonic-assisted stir casting techniques. The latter method utilized an ultrasonic probe to overcome the limitations of the earlier technique by introducing ultrasonic energy. The AMMCs were produced using CuMg/SiC/Al_2O_3 microparticles with concentrations ranging from 2 to 16%, increasing in increments of 2%, and with a size of 60 µm. The study conducted a thorough evaluation and comparison of the mechanical and physical characteristics of composites produced using both procedures. It specifically examined the impact of filler content on the density of AMMCs. The microstructural examination showed that the CuMg/SiC/Al_2O_3 microparticles were evenly distributed when the ultrasonic probe was utilized. The experimental results clearly demonstrated a significant improvement in the mechanical and physical qualities as a result of using the ultrasonic-assisted stir casting technique. By exploring the methodology, key parameters, and experimental results, this study offers valuable insights into the selection and optimization of casting techniques for the production of high-performance aluminum composites.

Keywords Aluminium metal matrix composite (AMMC) · MgCu/Al_2O_3/SiC reinforcement · Ultrasonic stir casting · Physical properties · Mechanical properties

Introduction

The casting procedure is critical in producing aluminium composites with good mechanical characteristics. Stir casting and ultrasonic casting are two prevalent procedures in this industry. Let's look at the differences between these processes and how they affect the mechanical characteristics of the final composites. Researchers have gradually changed their attention from monolithic materials to composite materials in response to worldwide demand for lightweight, environmentally friendly, high performance, and wear and erosion resistant materials over the last two decades [1, 2]. Aluminium matrix composites (AMMCs) are significant lightweight materials used in various technical applications. AMMCs are frequently used in applications that need a combination of high quality, efficient heat conduction, effective damping properties, and low density [3, 4].

Advanced Metal Matrix Composites (AMMCs) exhibit high temperature and corrosion resistance, making them

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suitable for applications requiring lightweight materials due to their exceptional strength-to-weight ratio. Several studies have been undertaken to improve the mechanical properties of AMMCs. In their study, Jayaseelan et al. [5] examined the performance characteristics of an aluminium composite reinforced with 5% CuMg/SiC/Al_2O_3. They utilized both powder metallurgy and stir casting techniques. The results revealed that the stir casting samples exhibited superior performance compared to the powder metallurgy specimens. The kind and amount of the reinforcement also significantly affect the mechanical and wear characteristics of the composites. In their study, Miyajima and Iwai [6] examined how various reinforcements, such as SiC/Al_2O_3, Cu whisker, and Mg particles, influenced the physical properties of powder metallurgy composites. The researchers noted that the quantity and kind of reinforcement had a substantial influence on the performance of the composite materials they generated. Furthermore, they found that these materials may be employed to enhance the wear resistance of metal matrix composites (MMCs). Aluminium alloy (AA) commonly utilizes hard fired particles (such as Al_2O_3 and CuMg) and soft particles (typically graphite) as reinforcements, making them the most frequently employed Metal Matrix Composites (MMCs). Abdullah et al. [7] shown that the addition of particles to AA composites resulted in significant improvements in the strength and hardness of aluminum and its alloys, while causing a major decrease in flexibility and malleability. This can have a substantial influence on the safety and reliability of components made using Additive Manufacturing and Metal Casting (AMMC) techniques. Idrisi and Mourad [8] employed the stir casting technique to fabricate AMMCs with different weight fractions of CuMg micro (5% and 10%) and nanoparticles (1% and 2%), thereafter subjecting them to wear analysis. The researchers discovered that the addition of 2 weight percent nanoparticles significantly improved the wear resistance of AMMC. Purohit et al. [9] conducted tensile experiments on an aluminium CuMg composite to analyze its mechanical properties. They changed the weight fraction of CuMg in the AA from 5 to 30%. The composite is strengthened with 15% CuMg.

The most dominant component was particles. Singla et al. [10] employed a two-stage mixing method in the stir casting technique to produce a CuMg particulate metal matrix composite (MMC) based on aluminum. The weight of CuMg was varied at different levels (5%, 10%, 15%, 20%, 25%, and 30%). According to the research, the concentration of CuMg had a positive effect on both the impact strength and hardness, leading to an increase in both properties. Moreover, the mechanical properties exhibited a loss of 38% as the CuMg weight was increased, while the most significant outcome was observed at a CuMg/SiC/Al_2O_3 weight of 34%. Researchers have employed a range of manufacturing procedures, with stir casting being the most cost-effective and efficient method.

However, a crucial step in the creation of composites is the homogeneous dispersion of reinforced particles. Because of their high viscosity and low wettability, reinforced particles are exceedingly difficult to distribute uniformly in the matrix phase. An important need for uniform particle dispersion is a longer stirring period; nevertheless, this might cause oxidation and gas production in the matrix. Therefore, it's crucial to stir less while creating composites of higher quality.

Ultrasonic vibrations, which produce an ultrasonic cavitation effect, have recently been employed to equally mix reinforcement particles [11]. It can scatter the formed agglomeration of CuMg microparticles and diminish crack-like flow [12–14], affecting the fracture toughness and mechanical properties of the composite. These ultrasonic vibrations are powerful enough to break apart the clusters into little fragments and distribute them evenly throughout the molten metal. This implosive influence with locally raised temperature for short periods of time contributes to improved wettability between the molten metal and the reinforcement [15–17]. Ultrasonic vibration has a very localised influence. As a result, ultrasonic vibration cannot be used to manufacture AMMCs reinforced with microparticles on their own. By combining the two procedures, the individual drawbacks of stir casting and ultrasonic casting may be avoided. Thus, the stir casting process was coupled with ultrasonic treatment in this study to make AMMCs reinforced with microparticles. These are the most cost-effective methods for producing composite particles. The base material was Al6061, and the reinforcement was CuMg microparticles. To test the effect of ultrasonic treatment, samples were made with varied CuMg concentration and two distinct stir casting procedures (with and without an ultrasonic probe). Additionally, mechanical properties such as tensile strength, compressive strength, hardness, and density were compared.

The casting process is particularly important when it comes to the production of aluminum composites that have favorable mechanical properties [18]. Stir casting and ultrasonic casting are two processes that are frequently used in this sector of the economic sector. Researchers have steadily switched their focus from monolithic materials to composite materials in response to the global need for lightweight, environmentally friendly, high-performance, and wear and erosion-resistant materials over the past two decades [19]. This movement has occurred as a result of materials that are resistant to wear and erosion. Aluminum matrix composites, also known as AMMCs, are major lightweight materials that are utilized in a variety of technological applications. These applications require a mix of high quality, efficient heat conduction, effective damping qualities, and low density within their materials. Because of their remarkable strength-to-weight ratio, Advanced Metal Matrix Composites (AMMCs) are appropriate for applications that require lightweight materials with high temperature and corrosion resistance. This makes them suitable for applications that require lightweight materials [20].

A number of investigations have been carried out with the purpose of enhancing the mechanical properties of AMMCs. For example, Jayaseelan et al. investigated the performance characteristics of an aluminum composite reinforced with 5% CuMg/SiC/Al_2O_3 by employing both powder metallurgy and stir casting processes [21]. They discovered that stir casting samples demonstrated improved performance compared to powder metallurgy samples. In their research, Miyajima and Iwai investigated the ways in which several reinforcements, including SiC/Al_2O_3, Cu whisker, and magnesium particles, influenced the physical properties of powder metallurgy composites. They found that the kind of reinforcement and the quantity of reinforcement had a significant impact on the performance of the overall composite [22]. Stir casting is the most cost-effective and efficient approach; nevertheless, it has difficulties in uniformly dispersing reinforced particles because to its high viscosity and low wettability. This might result in oxidation and gas formation if the stirring process is sustained for an extended period of time. Recent years have seen an increase in the use of ultrasonic vibrations for the purpose of enhancing particle dispersion by ultrasonic cavitation [23]. This technique helps to break up clusters and enhances wettability. It is possible to alleviate the unique limitations of each approach by combining stir casting with ultrasonic treatment, which has the potential to result in composites of greater quality. In this study, the effect of ultrasonic treatment on Al6061 AMMCs that have been reinforced with CuMg microparticles is investigated [24]. The mechanical parameters of the samples, including tensile strength, compressive strength, hardness, and density, are compared across samples that have varying concentrations of CuMg and different stir casting processes.

Material and Methods

Materials

The 6061-aluminum alloy is a widely used material known for its excellent mechanical properties and weldability. It is a lightweight, non-heat treatable, high Mg–Al wrought alloy and is broadly used in automobile and marine applications. Its chemical composition typically includes the following elements in Table 1.

Table 1 Chemical composition of 6061 Al alloy

Element	Composition range (%)
Aluminum (Al)	Balance
Magnesium (Mg)	0.8–1.2
Silicon (Si)	0.4–0.8
Iron (Fe)	Up to 0.7
Copper (Cu)	0.15–0.4
Manganese (Mn)	Up to 0.15
Chromium (Cr)	0.04–0.35
Zinc (Zn)	Up to 0.25
Titanium (Ti)	Up to 0.15

AMMC Fabrication Processes

Simple Stir Casting Process

Figure 1a illustrates the straightforward stir casting procedure that was employed. Initially, the 6061 Al matrix was liquefied in a 4 kg clay graphite crucible utilizing an electrical furnace operating at a temperature of 765 °C, which exceeded the melting point of the aluminium alloy [18]. For the melting process, a mechanical stirrer with a blade positioned at a 90° angle from the shaft axis was used to agitate the molten metal. Slag powder was injected into the aluminum when it reached the point of becoming liquid to remove the slag component. Next, the slurry was purged of gas by utilizing Argon gas. The temperature of the molten substance was reduced below the liquidus temperature of 670 °C during the process of removing gas. After completing the procedure, the surface was cleaned once more, and the temperature of the melt was measured to have increased to 770 °C [19]. SiC microparticles that had been preheated were introduced into the molten metal at different weight percentages at the same temperature in order to produce composite materials with varying compositions. Subsequently, the slurry was heated to a temperature higher than its liquidus temperature and subjected to automatic swirling for approximately 10 minutes at an average speed of 550 revolutions per minute. Ultimately, the liquefied combination was transferred into pre-warmed mild steel disc molds using a ladle.

Ultrasonic Simple Stir Casting Process

Both the standard stir casting technique and the ultrasonic-assisted stir casting approach employ a comparable process. In this procedure, an ultrasonic probe was substituted for the stirrer once the molten metal had been thoroughly blended, as depicted in Fig. 1b. The molten metal was subjected to ultrasonic treatment using a high-power ultrasonic

Fig. 1 Stir Casting and Ultrasonic Stir Casting

vibration apparatus (model VCX 1500, Sonics and Materials, USA), while maintaining a processing temperature of 620 °C. The ultrasonic therapy apparatus had a power of 2 kilowatts and operated at a frequency of 20 kilohertz. After placing a warmed ultrasonic horn with a diameter of 19 mm approximately 15–20 mm beneath the surface of the molten material, ultrasonic treatment (UST) was carried out using 1.5 kW of power for a duration of 180 s. Multiple dendrites with several branches might develop within the casting as it solidifies, leading to a reduction in the mechanical properties of the composite. The use of ultrasonic vibration to the casting process eradicated this particular dendritic pattern. Vibrations might uniformly disperse particles in the casting and disrupt the dendritic structure. Figure 2 depicts the flowchart illustrating the methodology employed in the stir casting process with the aid of ultrasonic help.

Composite Fabrication

The fabrication process of the composite material involving Al-6061 matrix metal pieces and B4C particles followed a specific experimental setup. The Al-6061 metal pieces were first cleaned and melted in a crucible up to 770 °C to produce a super-heated state in an electric-resistance furnace procured from Steel Plant, Visakhapatnam, India. The composite fabrication involved the introduction of preheated Cu/Mg/Si particles (sized approximately 80–100 microns) of MMC, into the superheated matrix melt. Experiments were conducted separately for varying weight percentages (2, 4, 6, 8, to 16 wt%). Stirring was utilized during the integration of these AMMC's and persisted thereafter to guarantee appropriate and consistent dispersion. The total duration of stirring (T, minutes) was calculated by adding the time required for incorporating the reinforcement (T1, minutes) to the time taken to finish the addition of the MMC (T2, minutes). The time of heating and stirring had a substantial impact on the dispersion of AMMC particles in the metal matrix solution. Inadequate heating duration may result in partial fusion of the matrix material, whereas overly extended stirring durations may lead to the separation of AMMC along the crucible wall or the formation of clusters, which can have a detrimental impact on the dispersion and size of the AMMC particles. The authors manually adjusted the feeding and stirring times of the particles for each weight percentage of AMMC in order to obtain a uniform distribution, as determined by their observations. A two-step agitation method was employed, consisting of a 10-min agitation period to disperse the AMMC particles individually, followed by a 15-min cooling period to achieve a partially solid state. Subsequently, the composite mixture was heated to a temperature of 750 °C and agitated for an extra duration of 5 min. The stirring rates were adjusted between 300 and 350 rpm based on the incorporation and distribution status of AMMC, which was continuously monitored during the process. Moreover, an ultrasonic probe was utilized to create cavitation effects in the composite mix by generating high-intensity ultrasonic sound waves. These waves formed cavitation bubbles within the liquid matrix melt, facilitating the breakup of AMMC clusters and ensuring homogeneous dispersion throughout the liquid metal. The experimental approach aimed to optimize the dispersion of AMMC particles within the Al6061 matrix, considering various factors such as heating duration, stirring times, and the use of ultrasonic cavitation to achieve a uniformly distributed composite material.

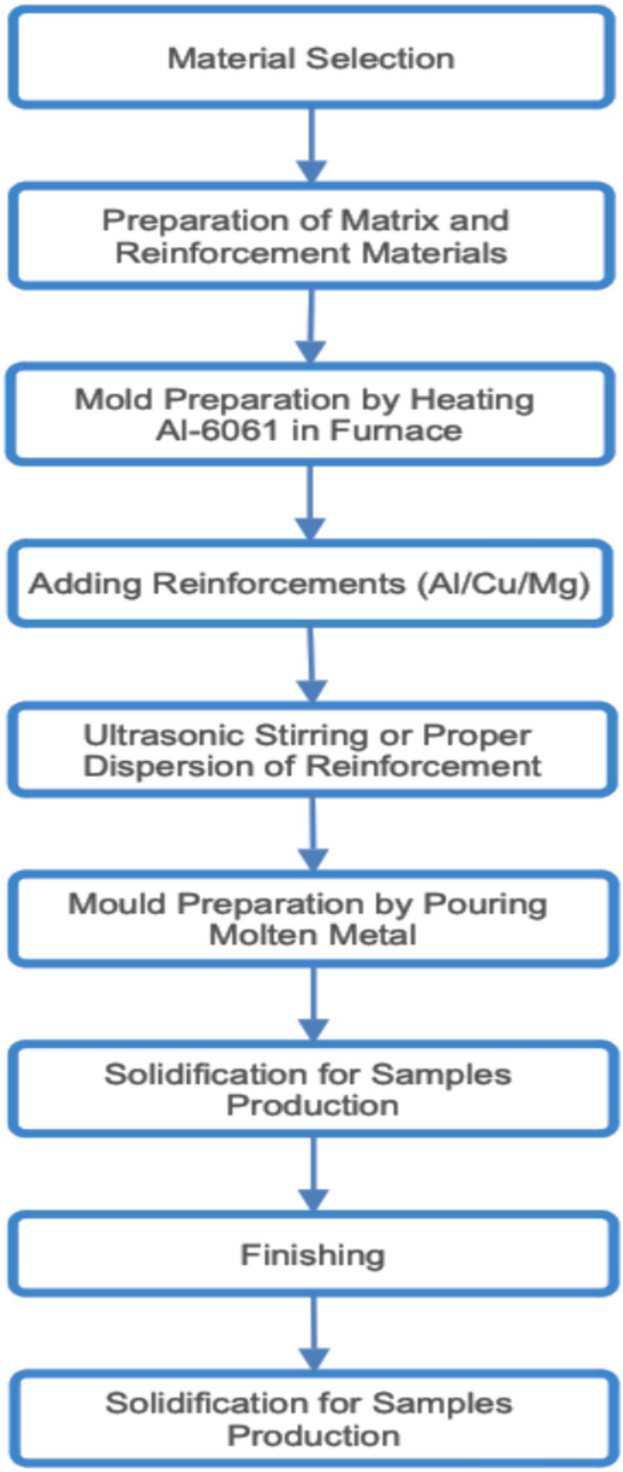


Fig. 2 Schematic diagram of methodology of Ultrasonic stir casting process

To address the challenge of uniform particle dispersion, researchers often utilize the Rule of Mixture to predict the mechanical properties of composites. The Rule of Mixture is a generalized formula used to estimate the properties of a composite material based on the properties and proportions of its constituents. The formula is expressed as:

$$Pc = VmPm + VfPf$$

where Pc is the property of the composite, *Vm* and *Vf* are the volume fractions of the matrix and the reinforcement respectively, and *Pm* and *Pf* are the properties of the matrix and the reinforcement respectively.

Recently, ultrasonic vibrations have been employed to enhance particle dispersion through ultrasonic cavitation, which breaks apart clusters and improves wettability. Combining stir casting with ultrasonic treatment can mitigate the individual drawbacks of each method, leading to higher quality composites. This study investigates the effect of ultrasonic treatment on Al6061 AMMCs reinforced with CuMg microparticles, comparing mechanical properties such as tensile strength, compressive strength, hardness, and density across samples with varied CuMg concentrations and different stir casting procedures.

Characterization of AMMC's

Density

The Rule of Mixtures is a method for determining a composite material's density by taking into account the volume fractions and densities of each of its constituent parts. When calculating composite materials' overall attributes based on the quantities and features of their component materials, the Rule of Mixtures is a simple technique to use. This method makes the assumption that the components in the composite are evenly distributed and do not interact. The Rule of Mixtures yields an approximate density for the composite material by adding the products of the volume fractions and densities of each component. This method is fundamental and frequently used to estimate not just density but also mechanical strength, thermal conductivity, and other attributes in composite materials.

To calculate the density of an aluminum metal matrix composite (MMC) containing Al6061 alloy, copper (Cu), magnesium (Mg), and silicon carbide (SiC), considering the densities of each component and their respective volume fractions within the composite.

The formula for calculating the density of the composite material is:

$$\text{Density of MMC} = \sum_{i=0}^{n} n(\text{Volume Fraction of Component } i) \times (\text{ Density of Component } i)$$

Let's assume the following volume fractions and densities for the components:

Aluminum (Al6061): Density ≈ 2.7 g/cm^3
Copper (Cu): Density ≈ 8.96 g/cm^3
Magnesium (Mg): Density ≈ 1.74 g/cm^3
Silicon (Si): Density ≈ 2.33 g/cm^3

Suppose the volume fractions (percentages by volume) of each component in the composite are:

Al6061: 88%
Cu: 4%
Mg: 4%
SiC: 4%

Using the formula:

$$\begin{aligned}\text{Density of MMC} =&(0.88 \times \text{Density of Al6061})\\&+ (0.04 \times \text{Density of Cu})\\&+ (0.04 \times \text{Density of Mg})\\&+ (0.04 \times \text{Density of Si})\end{aligned}$$

Substituting the given densities

$$\begin{aligned}\text{Density of MMC} =&\left(0.88 \times 2.7\,\text{g/cm}^3\right) + \left(0.04 \times 8.96\,\text{g/cm}^3\right)\\&+ \left(0.04 \times 1.74\,\text{g/cm}^3\right) + \left(0.04 \times 2.33\,\text{g/cm}^3\right)\\=& 2.376\,\text{g/cm}^3 + 0.3584\,\text{g/cm}^3 + 0.0696\,\text{g/cm}^3 + 0.0932\,\text{g/cm}^3\\=&2.8972\,\text{g/cm}^3\end{aligned}$$

Therefore, based on the volume fractions of 4% each composition (Al6061: 88%, Cu: 4%, Mg: 4%, Si:4%), the density of the aluminum metal matrix composite containing Al6061/Cu/Mg/SiC/Al_2O_3 would be approximately 2.8972 g/cm^3.

Hardness

As part of the Brinell hardness testing technique, the samples were metallographically finished using emery sheets of varied grit sizes to provide an accurate measurement of hardness. In the test, a 2 mm diameter indenter ball was exposed to 190 kg applied force and a 6-s dwell duration. Five independent readings were acquired at various locations across the sample, and average values were then computed and considered for analysis.

Tensile Strength

Al–Cu/Mg/SiC/Al_2O_3 composite specimens were manufactured in compliance with ASTM E8-08 requirements and put through tensile testing utilising a Universal Testing Machine at room temperature (27 °C). The specimens were firmly gripped between the machine's top and lower jaws. Throughout the test, the upper jaw moved upward, applying strain on the sample until it fractured. After the fracture, the tensile strength was ascertained, and the associated calculated Young's modulus computed. Tensile was evaluated while maintaining a regulated crosshead speed of 1.6 mm/min.

Compression

In accordance with ASTM E9-09 standards, compression tests were performed on composite specimens made of Al6061–Cu/Mg/SiC/Al_2O_3. Using an INSTRON testing equipment, the specimens were evaluated at ambient temperature (27 °C). The specimens were positioned between two flat plates during the testing process, and the maximum failure load was determined by applying compression force. The crosshead speed during the test was 2 mm/min.

Fatigue

The fatigue behavior of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites (MMCs) was comprehensively investigated in accordance with ASTM E466 standards, employing rigorous fatigue testing methodologies. The experimental procedures followed ASTM E466 guidelines, enabling precise force-controlled constant amplitude axial fatigue tests to evaluate the fatigue characteristics of the MMCs. This study aimed to assess the material's endurance limit, fatigue life, and other crucial fatigue-related properties, contributing valuable insights into the composite's mechanical performance and durability under cyclic loading conditions.

Flexure

Flexural testing was conducted on Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites (MMCs) following ASTM E290 standards to evaluate their bending behavior on an UTM. The ASTM test procedure provided standardized conditions for assessing the flexural properties of these composite materials, allowing for a systematic examination of their resistance to bending forces. This study aimed to analyze the flexural strength, modulus of elasticity, and other mechanical characteristics of the MMCs, providing valuable insights into their structural performance and suitability for specific engineering applications.

Microstructural Analysis

The microstructural examination performed through Carl Zeiss Scanning Electron Microscopy (SEM) delivered valuable insights into the dispersion of reinforcing elements within the Aluminum Matrix Composites (AMCs) under scrutiny. Preceded by meticulous sample preparation involving precise polishing to 0.05 µm and brief etching with a 2.5 vol% nitric acid in ethanol solution at room temperature (290 K), a fine layer of Au was applied to enhance conductivity for scanning electron microscope imaging.

Results and Discussions

Prior to delving into the comparison and results of mechanical properties between stir casting and ultrasonic casting, it is essential to acknowledge the significance of investigating the mechanical properties of metal matrix composites, particularly those fabricated using stir casting and ultrasonic casting methods. These composites, comprising Al-6061/Cu/Mg/SiC/Al_2O_3, hold promise for various engineering applications due to their enhanced strength, hardness, and fatigue resistance. Understanding the influence of fabrication techniques and reinforcement percentages on these properties is crucial for optimizing composite performance and guiding material design. Through meticulous examination and comparison of tensile strength, hardness, fatigue strength, and density, insights can be gleaned to inform future manufacturing processes and advance the development of high-performance materials tailored to specific industrial needs. Therefore, a comprehensive analysis of the experimental results and discussion thereof is imperative to elucidate the relative merits of each casting method and reinforcement percentage in shaping the mechanical characteristics of these composite materials.

Tensile Test

Eight readings were recorded for each method of samples which are given in the Fig. 3.

The plot illustrates the comparison of tensile strengths between two different fabrication methods, stir casting and ultrasonic casting, for Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites (MMCs) with varying weight percentages of reinforcing particles. As the weight percentage of the reinforcing phase increases from 2 to 16%, both fabrication techniques show an overall trend of enhancing the tensile strength of the composites. In the case of stir casting, the tensile strength gradually increases from 110.05 MPa at 2% reinforcement to 137.05 MPa at 16% reinforcement. Conversely, the ultrasonic casting method exhibits a similar increasing trend, with the tensile strength escalating from 118 MPa at 2% reinforcement to 145 MPa at 16% reinforcement.

Notably, From the Fig. 3 it can be observed that the ultrasonic casting technique generally demonstrates higher tensile strengths across most weight percentages compared to stir casting, indicating its potential effectiveness in achieving improved mechanical properties, particularly at higher reinforcement levels. This comparative analysis highlights the influence of fabrication techniques and reinforcement percentages on the tensile strength of Al-6061/Cu/Mg/Si metal

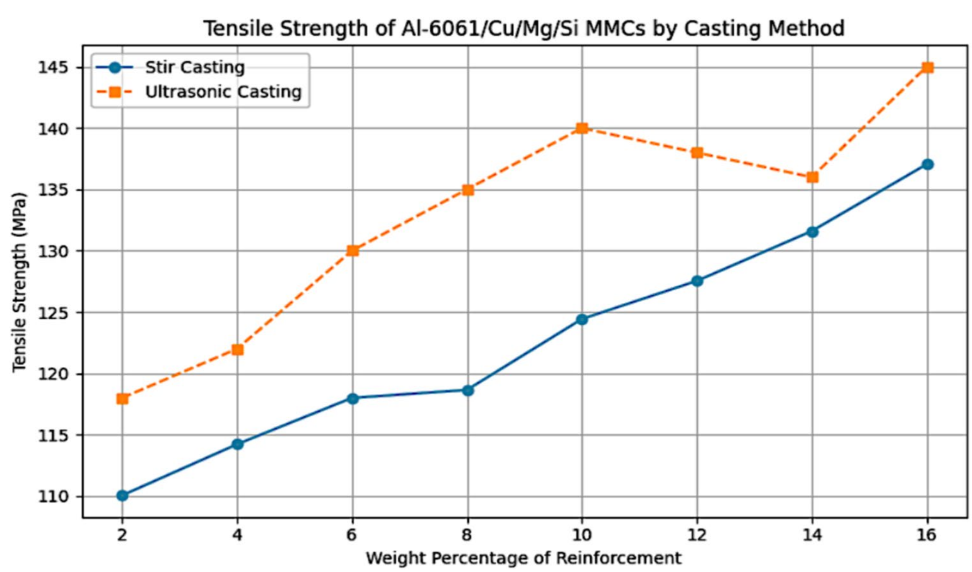


Fig. 3 Tensile strength comparison varying weight percentage in casting methods

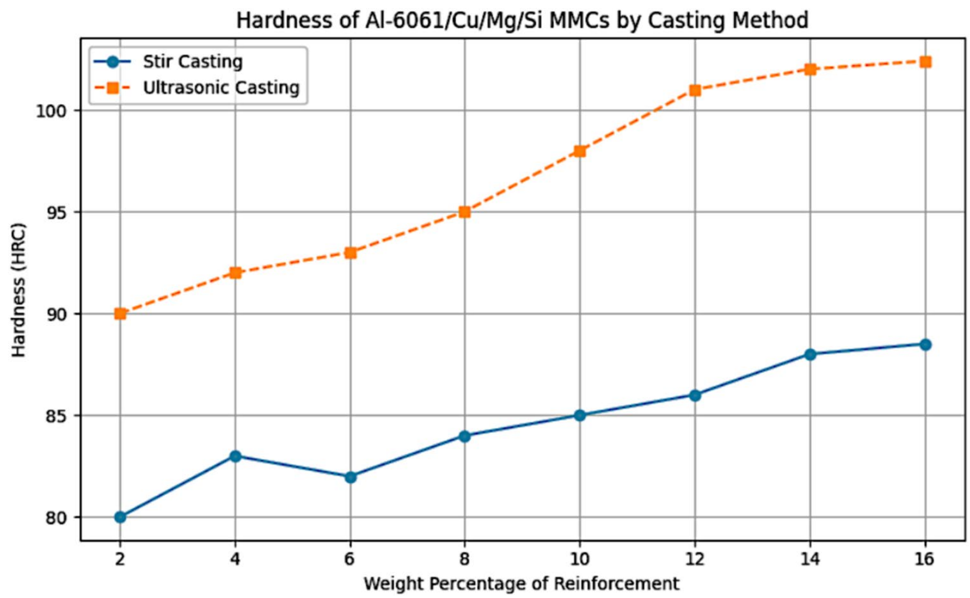


Fig. 4 Hardness comparison varying weight percentage in casting methods

matrix composites, providing valuable insights for material design and engineering applications.

Hardness

The plot as shown in Fig. 4 represents a comparison between the hardness values of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites (MMCs) processed through stir and ultrasonic stir casting methods across varying weight percentages of reinforcing particles. As the weight percentage of the reinforcing phase increases from 2 to 16%, both fabrication techniques demonstrate an overall trend of enhancing the hardness of the composites. In the case of stir casting, the hardness gradually increases from 80 to 88.5 HRC as the reinforcement content rises from 2 to 16%. Conversely, the ultrasonic stir casting method exhibits a similar ascending trend, with the hardness escalating from 90 to 102.4 HRC across the same weight percentages.

Notably, ultrasonic stir casting generally displays higher hardness values across most weight percentages compared to stir casting, suggesting its potential effectiveness in producing composites with increased hardness, especially at higher reinforcement levels. This comparative analysis highlights the influence of fabrication techniques and reinforcement percentages on the hardness of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites, providing valuable insights for material characterization and engineering applications.

Hardness and tensile strength are related but measured in different units. There is a general empirical correlation used to estimate tensile strength from hardness values for steels, which can also be used as an approximation for aluminum alloys. To convert hardness (HRC) to tensile strength (MPa), the following approximate formula can be used:

$$\text{Tensile strength}(\text{MPa}) = 3.45 \times \text{HRC}$$

Applying this conversion to the provided hardness values: For stir casting:

- At 2% reinforcement: $80 \times 3.45 \approx$ **276 MPa**
- At 16% reinforcement: $88.5 \times 3.45 \approx$ **305.3 MPa**

For ultrasonic stir casting:

- At 2% reinforcement: $90 \times 3.45 \approx$ **310.5 MPa**
- At 16% reinforcement: $102.4 \times 3.45 \approx$ **353.3 MPa**

So, the approximate tensile strength values corresponding to the given hardness values are:

- Stir casting: 276 MPa (at 2% reinforcement) to 305.3 MPa (at 16% reinforcement)
- Ultrasonic stir casting: 310.5 MPa (at 2% reinforcement) to 353.3 MPa (at 16% reinforcement)

These approximations help understand the relative improvements in mechanical properties due to the different casting techniques and reinforcement percentages.

Fatigue

The provided plots shown in Fig. 5 showcases a comparative analysis of fatigue strengths between Al-6061/Cu/Mg/

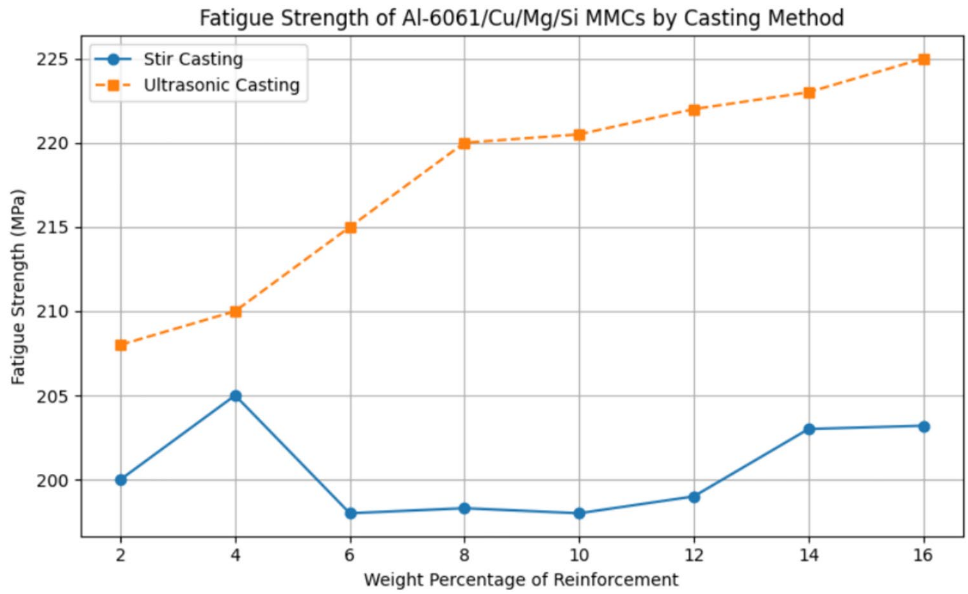


Fig. 5 Fatigue comparison varying weight percentage in casting methods

SiC/Al_2O_3 metal matrix composites (MMCs) fabricated via stir casting and ultrasonic stir casting techniques across various weight percentages of reinforcing particles. As the weight percentage of the reinforcing phase increases from 2 to 16%, both fabrication methods exhibit trends in enhancing the fatigue strength of the composites. For stir casting, the fatigue strength ranges from 200 MPa at 2% reinforcement to 203.2 MPa at 16% reinforcement. Contrastingly, ultrasonic stir casting demonstrates a similar trend, with fatigue strengths escalating from 208 MPa at 2% reinforcement to 225 MPa at 16% reinforcement.

Notably, ultrasonic stir casting generally reveals higher fatigue strengths across most weight percentages compared to stir casting, indicating its potential effectiveness in producing composites with improved fatigue resistance, particularly at higher reinforcement levels. This comparative evaluation sheds light on the influence of fabrication techniques and reinforcement percentages on the fatigue strength of Al-6061/Cu/Mg/Si metal matrix composites, offering valuable insights for engineering applications and material design.

The correlation between tensile strength and fatigue strength is evident in the mechanical behavior of Al-6061/Cu/Mg/SiC/Al2O3 metal matrix composites (MMCs) produced via different casting methods. Both tensile and fatigue tests reveal that increasing the weight percentage of reinforcing particles generally enhances the mechanical properties of the composites. For instance, as the weight percentage of reinforcement increases from 2 to 16%, the tensile strength in stir casting rises from 110.05 MPa to 137.05 MPa, while ultrasonic casting shows an increase from 118 to 145 MPa. Similarly, fatigue strength improves with higher reinforcement, with stir casting showing an increase from 200 MPa to 203.2 MPa and ultrasonic casting from 208 to 225 MPa. This parallel trend suggests that the improvements in tensile strength due to better load transfer and distribution among the reinforced particles also contribute to enhanced fatigue resistance, as the material can better withstand cyclic loading. The ultrasonic casting method, which demonstrates higher tensile strengths, also exhibits superior fatigue strengths across most weight percentages, indicating its effectiveness in producing composites with robust mechanical performance. This correlation highlights the interdependence of tensile and fatigue properties in the design and optimization of metal matrix composites for engineering applications.

Density

The provided plot from the Fig. 6, illustrates a comparative analysis of density measurements between Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites (MMCs) fabricated through stir and ultrasonic stir casting methods, encompassing various weight percentages of reinforcing particles. As the weight percentage of the reinforcing phase increases from 2 to 16%, both fabrication techniques exhibit trends in the density variations of the composites. In the case of stir casting, the density measurements range from 2.7 g/cm^3 at 2% reinforcement to 2.75 g/cm^3 at 16% reinforcement. Conversely, ultrasonic stir casting demonstrates a slightly different trend, with density measurements escalating from 2.72 g/cm^3 at 2% reinforcement to 2.78 g/cm^3 at 16% reinforcement.

Notably, ultrasonic stir casting generally presents slightly higher density values across most weight percentages compared to stir casting, implying potential differences in the

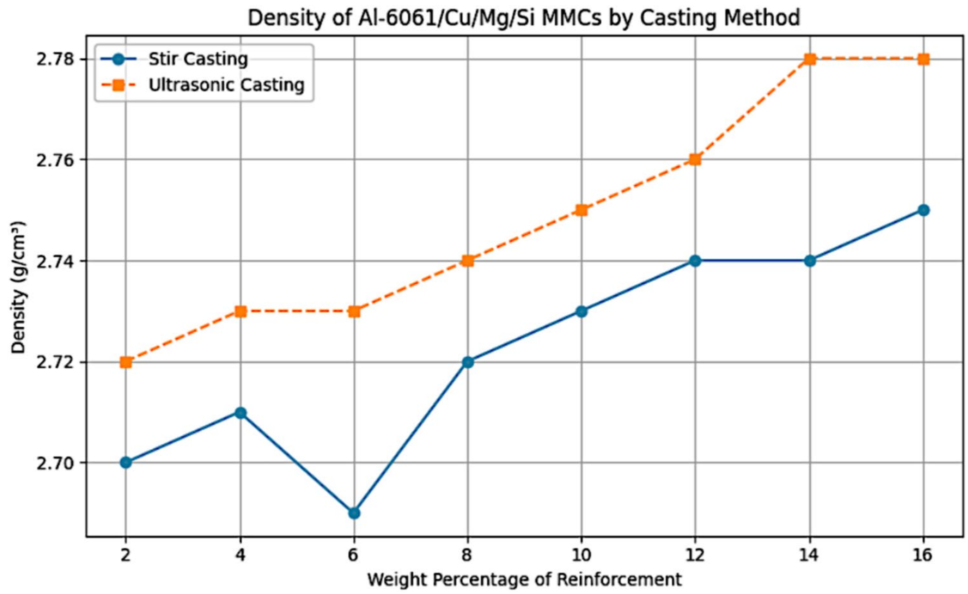


Fig. 6 Density comparison varying weight percentage in casting methods

material compaction or distribution of particles between the fabrication methods. This comparative analysis highlights the influence of fabrication techniques and reinforcement percentages on the density of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites, offering insights into material characterization for engineering applications and material design.

Microstructural analysis

The SEM analysis unveiled a non-uniform distribution of Si Cu Mg microparticles within the Al alloy matrix, indicating clustering and uneven dispersion. These observations suggest potential inconsistencies in mechanical properties due to the irregular distribution of reinforcing elements. To address this challenge and achieve more uniform dispersion, an ultrasonic probe was employed during the casting process. This insertion of ultrasonic energy aimed to enhance particle dispersion and distribution within the Al alloy matrix. By mitigating particle clustering and agglomeration, this ultrasonic treatment sought to augment the composite's overall homogeneity and potentially improve its mechanical properties. This microstructural scrutiny underlines the critical significance of achieving uniform reinforcement dispersion within the matrix to optimize the mechanical performance of Aluminum Matrix Composites. Furthermore, it highlights the efficacy of employing ultrasonic energy to ameliorate particle distribution, providing vital insights into refining casting techniques and optimizing the structural integrity of metal matrix composites. The second segment outlines the comparative microstructural analysis of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites created through distinct casting methods: It delineates the tendencies observed in particle distribution, size, and uniformity within the aluminum matrix for each technique. The discussion delves into the irregularities and potential clustering seen in the stir casting method, contrasting it with the superior homogeneity and finer particle dispersion achieved through ultrasonic stir casting. The paragraph elaborates on the consequential impact of microstructural variations on mechanical properties, emphasizing their critical role in dictating the overall performance and reliability of these metal matrix composites.

Figure 7a, b represents, the ultrasonic stir casting method, as compared to traditional stir casting, exhibits substantial advantages attributed to its capability in achieving a uniform dispersion of SiC Cu Mg particles within the metal matrix composite. Figure 7c and d show that agglomeration and clustering occur in stir casting due to poor wettability, high viscosity and a bulky surface-to-volume ratio inside the matrix phase, resulting in uneven particle distribution. Conversely, the ultrasonic treatment coupled with mechanical stirring enables superior dispersion. The summary of high-energy ultrasonic vibrations induces acoustic flowing and intense cavitation results, facilitating the even distribution of Cu and Mg particles among the aluminum matrix.

Figures 8a and b show SEM micrographs of an Al-6061 Cu/Mg alloy reinforced with 4% and 8% Cu/Mg SiC/Al_2O_3 particles, respectively. Figure 8a depicts a composite generated by traditional stir casting with multiple big and elongated grains. Figures 8c and d, on the other hand, show grain refinement caused by the use of sonic vibration. In another

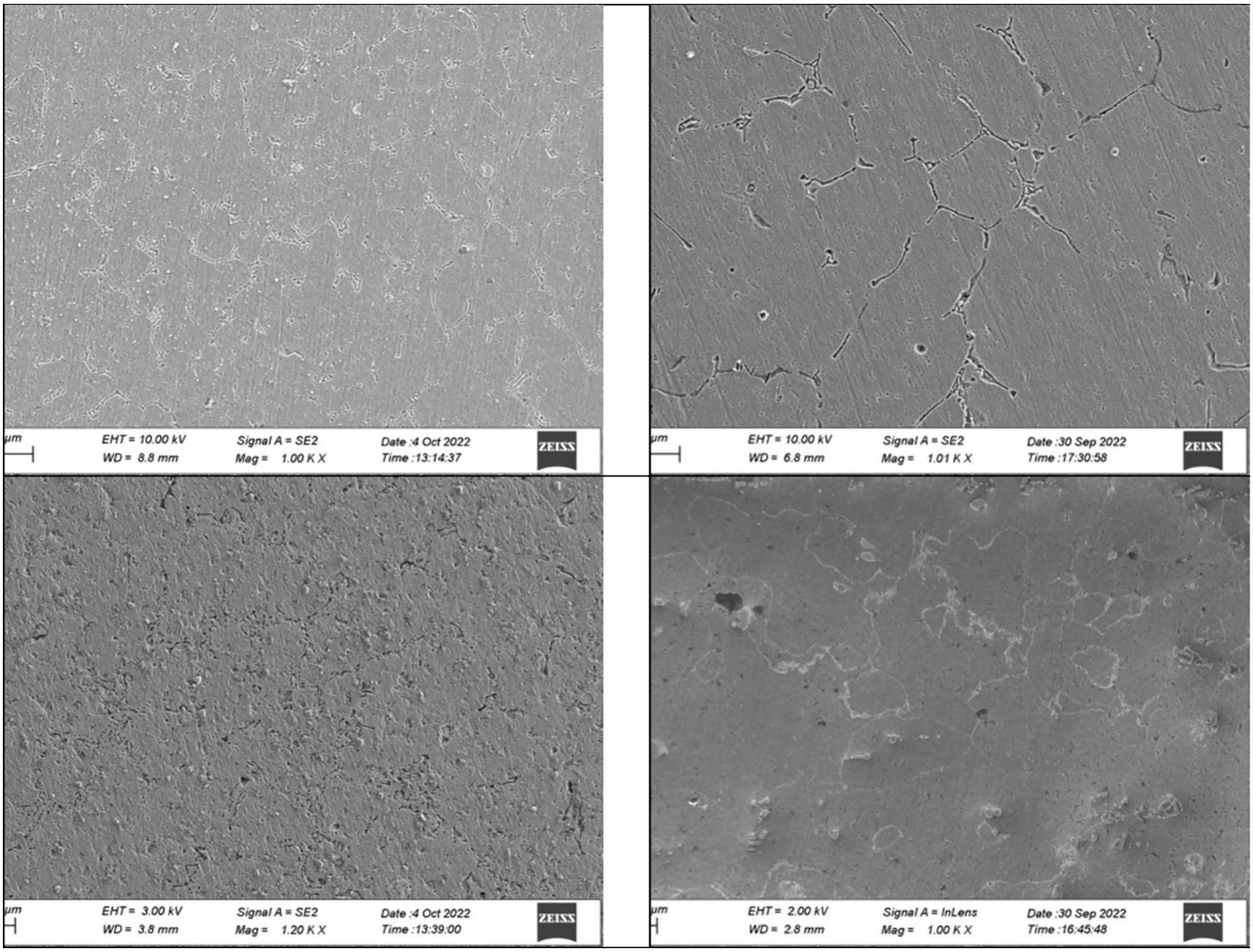


Fig. 7 Microstructures of Al-6061 Cu/Mg composite alloys reinforced with varying wt%

investigation, used semisolid stirring aided by ultrasonic vibration to manufacture magnesium matrix composites reinforced with Cu/Mg microparticles, resulting in a similar microstructure. The traditional mechanical stir casting process, on the other hand, efficiently integrates the reinforcing particles into the molten matrix material. When the churning stops, however, these particles tend to resurface and coalesce, producing clusters [21]. As a result, the ultrasonic dispersion of reinforcing particles varies from that obtained by traditional mechanical stir casting. This distinction is significant due to the inclusion of acoustic transient cavitation, a process that leads to the fragmentation of gas microbubbles in close proximity to clusters of reinforcement particles. The XRD observed for the process are shown in Figs. 9 and 10.

From Figs. 9 and 10, observed that stir casted Si and Mg can be observed in above lower fractions in the mixture whereas in the ultrasonic stir casting, spikes of equal mixture of Si and Mg along with Aluminium is found.

Consequently, these clusters disintegrate and scatter throughout the underlying material. Moreover, this technique facilitates the elimination of the gas layer adhering to the surface of the reinforcement particles and greatly enhances the capacity of the matrix material to spread and adhere to them. Ultrasonic events, such as short cavitation, effectively shatter clustered particles and distribute them evenly in the liquid phase. Researchers have noted similar nonlinear effects, such as acoustic streaming and cavitation, upon introducing ultrasonic energy into molten alloys, emphasizing their effectiveness in achieving homogeneous dispersion. Acoustic streaming, driven by an acoustic pressure gradient, induces highly effective stirring, while acoustic cavitation, characterized by microbubble formation

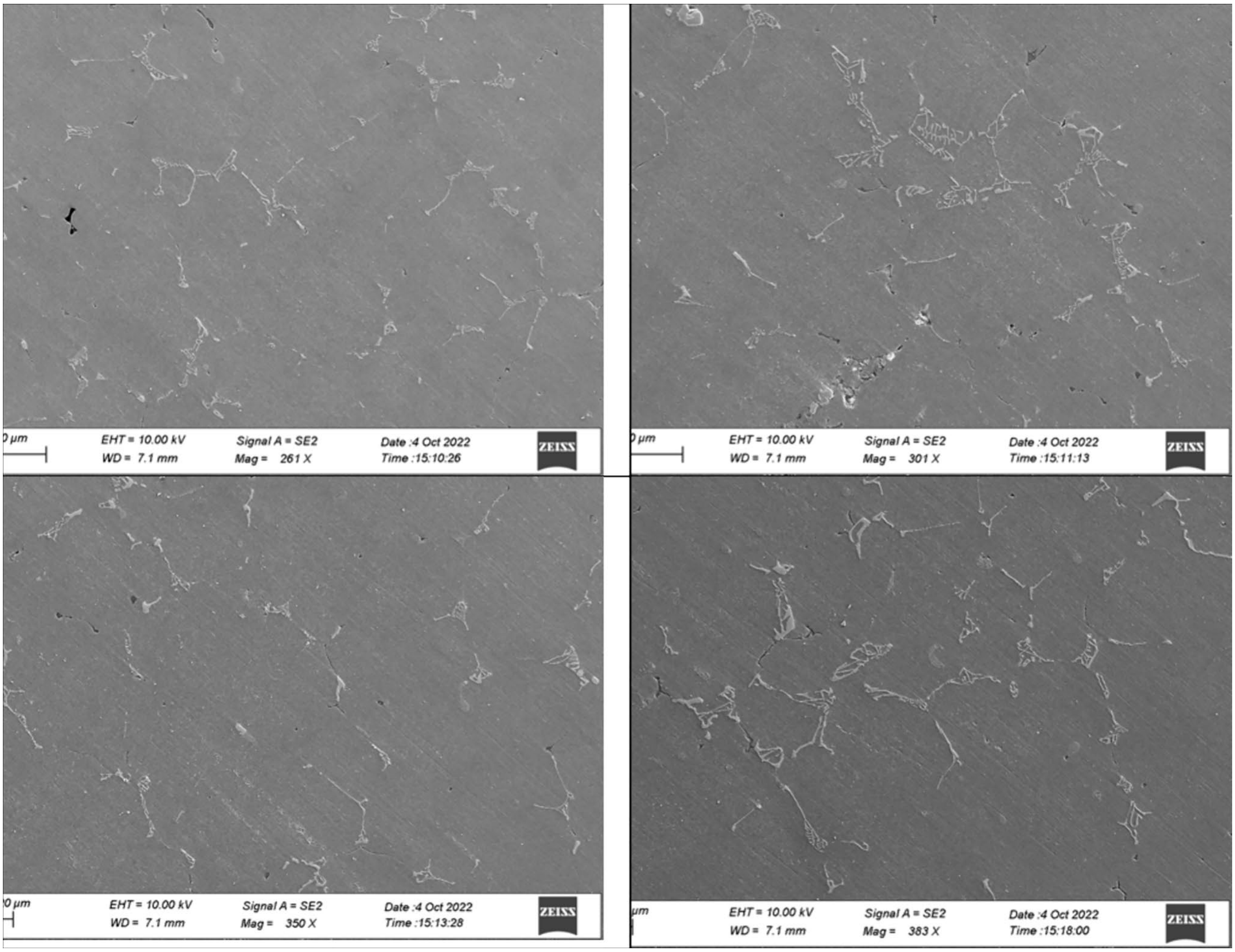
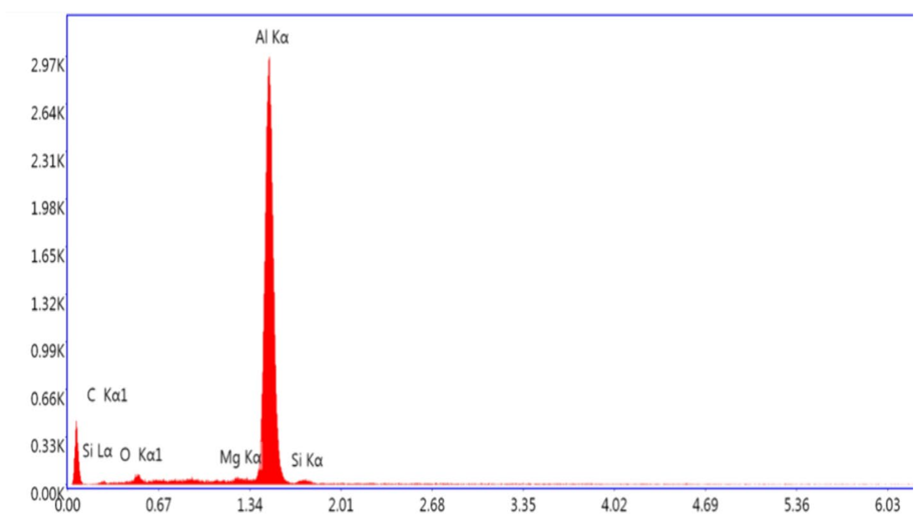


Fig. 8 Microstructures of Al-6061 Cu/Mg composite alloys reinforced with varying wt%

Fig. 9 Stir Cast



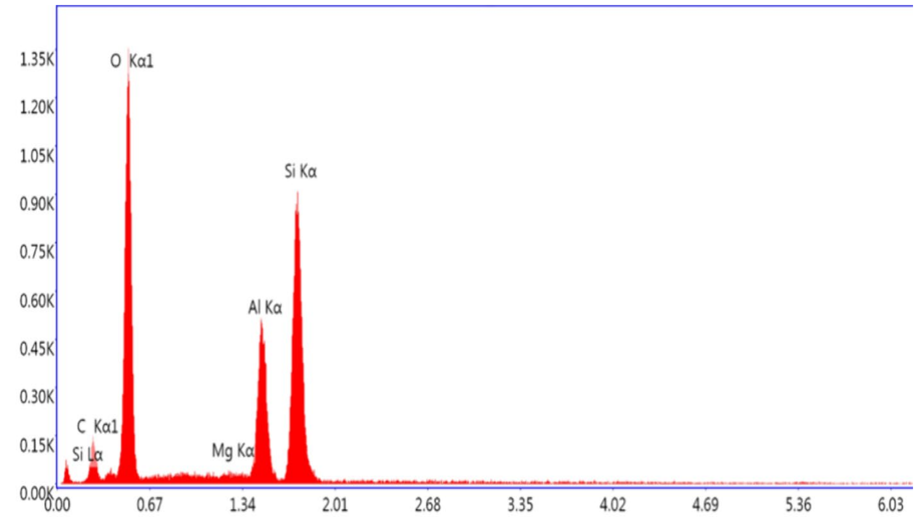


Fig. 10 Ultrasonic Stir Cast

and collapse under strong ultrasonic waves, contributes significantly to the dispersion process. The comprehensive and synergistic action of these ultrasonic-induced phenomena underscores the effectiveness and superiority of ultrasonic stir casting, ensuring enhanced dispersion and uniformity of reinforcing particles within the metal matrix composite.

Conclusions

The comparison between stir casting and ultrasonic casting techniques for fabricating Al/Cu/Mg SiC/Al_2O_3 metal matrix composites (MMCs) revealed significant differences in mechanical characteristics and microstructural attributes. Tensile strength exhibited an incremental trend with increasing weight percentage of reinforcing elements, with ultrasonic casting consistently demonstrating superior tensile strengths. Ultrasonic casting also showed higher fatigue strengths and hardness values across different weight percentages compared to stir casting. Density measurements displayed marginal differences, with occasional slightly higher densities observed in ultrasonic casting. Microstructural examinations indicated a more homogeneous dispersion of reinforcing particles within the matrix for ultrasonic casting, mitigating clustering and ensuring better mechanical integrity. Overall, ultrasonic stir casting exhibited enhanced mechanical properties and microstructural uniformity, underscoring its superiority for fabricating Al/Cu/Mg SiC/Al_2O_3 MMCs.

- Tensile strength incrementally increased with higher weight percentages, with ultrasonic casting consistently demonstrating superior strengths.
- Ultrasonic casting exhibited higher fatigue strengths and hardness values compared to stir casting.
- Density measurements showed marginal differences, with occasional slightly higher densities observed in ultrasonic casting.
- Microstructural examinations revealed a more homogeneous dispersion of reinforcing particles within the matrix for ultrasonic casting, mitigating clustering and ensuring better mechanical integrity.
- Overall, ultrasonic stir casting outperformed conventional stir casting in enhancing mechanical properties and microstructural uniformity, highlighting its superiority for fabricating Al/Cu/Mg/SiC/Al_2O_3 MMCs.

Ultrasonic casting consistently produces higher tensile strengths, hardness values, and fatigue strengths compared to stir casting, demonstrating its superior effectiveness in enhancing the mechanical properties of Al-6061/Cu/Mg/SiC/Al_2O_3 metal matrix composites. Both casting methods show an increasing trend in tensile strength, hardness, and fatigue strength as the reinforcement weight percentage increases from 2 to 16%, highlighting the positive effect of higher reinforcement content. The higher hardness values observed with ultrasonic stir casting suggest better dispersion and bonding of reinforcement particles, contributing to the improved mechanical performance of the composites. Both casting techniques exhibit a slight increase in density with higher reinforcement content, with ultrasonic casting showing slightly higher density values, indicating better material compaction and uniform particle distribution. These findings provide valuable insights for material design and engineering applications, emphasizing the benefits of ultrasonic casting for producing high-quality composites.

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Declarations

Conflict of interest The authors declare that they have no competing interests that could influence the work presented in the manuscript. All authors have contributed significantly to the conception, design, and interpretation of the study. Any sources of funding and conflicts of interest have been disclosed. The manuscript adheres to ethical standards, including the avoidance of plagiarism and the proper citation of sources where applicable.

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