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Microstructural Characterization of AA7150–SiC Nano Metal Matrix Composites via Indirect Non-Contact Ultrasonic-Assisted Casting

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Abstract

The present study focuses on the fabrication and characterization of AA7150–SiC nano metal matrix composites (NMMCs) synthesized via an innovative indirect non-contact ultrasonic-assisted casting technique. Compared to conventional liquid-state casting routes, this ultrasonic-assisted methodology introduces high-intensity acoustic cavitation and micro-streaming fields into the melt. This phenomenon effectively overcomes cohesive van der Waals forces, thereby promoting uniform dispersion of the SiC nanoparticles and minimizing localized particle agglomeration to ensure a highly homogenous composite matrix. The microstructural architecture and interfacial characteristics of the fabricated nanocomposites were thoroughly evaluated using High-Resolution Transmission Electron Microscopy (HRTEM), confirming the spatial distribution of the nano-reinforcements and grain boundary conditions. Furthermore, the macroscopic mechanical response of the NMMCs was quantified through Rockwell hardness testing. This investigation establishes a comprehensive correlation between processing-induced nanoparticle dispersion, microstructural refinement, and the resultant mechanical performance of the AA7150–SiC system.

Keywords: Acoustic cavitation; Aluminum alloy 7150; High-resolution transmission electron microscopy (HRTEM); Metal matrix composites (MMCs); Nanocomposites; Silicon carbide (SiC); Ultrasonic casting.

1. Introduction

Several researchers have investigated the fabrication and characterization of aluminum-based metal matrix composites reinforced with ceramic particles to improve their mechanical and tribological performance. Zhang et al. (2006) studied the fabrication of aluminum matrix composites reinforced with ceramic particles and reported that uniform particle dispersion significantly enhanced hardness and tensile strength. Their findings highlighted the importance of controlling processing parameters to minimize particle agglomeration and achieve improved composite performance. Zhang et al. (2008) investigated the effect of reinforcement distribution on the microstructure and mechanical behavior of aluminum-based composites. The study revealed that homogeneous particle dispersion contributed to grain refinement and increased load transfer efficiency between the matrix and reinforcement, resulting in superior mechanical properties. Shehata et al. (2009) examined the influence of processing techniques on particulate-reinforced aluminum composites. Their results indicate that conventional casting methods often suffer from particle clustering and porosity formation, which adversely affect composite strength and wear resistance. The authors emphasized the need for advanced processing methods to achieve uniform reinforcement distribution. Sanaty-Zadeh (2012) reviewed various strengthening mechanisms in metal matrix composites and concluded that grain refinement, Orowan strengthening, thermal mismatch strengthening, and load transfer

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effects are the primary factors responsible for enhanced mechanical properties in nanoparticle-reinforced composites.

The study also highlighted the significance of nanoparticle dispersion in determining composite performance. Kumar et al. (2018) investigated SiC-reinforced aluminum alloy composites produced through stir casting and observed substantial improvements in hardness, tensile strength, and wear resistance with increasing SiC content. The enhancement was attributed to the hard ceramic particles acting as barriers to dislocation motion. Ramesh et al. (2020) fabricated nano-SiC reinforced aluminum alloy composites using ultrasonic-assisted processing. Their microstructural analysis confirmed uniform nanoparticle distribution and reduced porosity compared with conventional casting techniques. The composites exhibited improved hardness and wear resistance due to enhanced interfacial bonding between the matrix and reinforcement. From the available literature, it is evident that the mechanical and tribological properties of aluminum matrix composites are strongly influenced by the distribution of reinforcement particles and the fabrication technique employed. However, limited studies have focused on AA7150 alloy reinforced with nano-sized SiC particles using indirect non-contact ultrasonic-assisted processing. Therefore, the present work aims to develop AA7150–SiC nano metal matrix composites with improved particle dispersion and to investigate their microstructural, mechanical, and tribological characteristics.

2. Experimental Methodology

The fabrication of AA7150–SiC Nano Metal Matrix Composites was carried out using an indirect non-contact ultrasonic-assisted casting technique. The entire process consisted of three major stages: melting, mixing, and solidification. The objective of the process was to achieve homogeneous dispersion of SiC nanoparticles within the aluminum matrix and to minimize particle agglomeration during casting.

2.1 Melting Process

The AA7150 aluminum alloy was melted using a pit furnace. A pit furnace is a vertical cylindrical furnace commonly employed for melting metals intended for casting applications. The furnace consists of a steel shell lined internally with refractory bricks to withstand high temperatures. A removable lid covers the furnace, while a grate at the bottom facilitates combustion.

Initially, a bed of coke was ignited and allowed to reach a stable combustion state. After achieving the desired furnace temperature, a crucible containing the aluminum alloy was placed inside the furnace and surrounded by additional coke. The furnace lid was then closed to maintain a controlled heating environment. The aluminum alloy was heated until complete melting occurred at approximately 660°C. The molten metal was subsequently maintained at the desired temperature before being transferred to the mixing chamber.

2.2 Mixing Process

The mixing stage involved the incorporation of SiC nanoparticles into the molten aluminum using a specially designed vibration-assisted mixing chamber. The equipment was developed to promote uniform nanoparticle distribution and prevent particle agglomeration.

Mixing Chamber Design: The mixing chamber consisted of the following components:

Nanoparticle Feeder: The nanoparticle feeder was designed to introduce SiC nanoparticles into the mixing chamber at a controlled rate. It incorporated a set of graded sieves that ensured the uniform flow and dispersion of nanoparticles into the molten aluminum stream.

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Molten Aluminum Feeders: Two molten metal feeders were positioned opposite each other on the mixing chamber. Their enlarged inlet geometry facilitated smooth and continuous delivery of molten aluminum into the chamber.

Copper Plates: Copper plates were installed at the entry points of the molten metal feeders. These plates reduced the flow velocity of molten aluminum, thereby providing sufficient residence time for effective mixing between the SiC nanoparticles and the aluminum matrix.

Helical Flow Guide: A helical guide was incorporated along the inner wall of the chamber to regulate the downward flow of the molten mixture. The helical configuration maintained a controlled flow rate and minimized particle agglomeration by promoting continuous mixing of the reinforcement particles.

Heating System: An external heating element was provided at the lower section of the chamber to maintain the molten state of aluminum throughout the mixing process. Continuous heating prevented premature solidification and ensured stable viscosity during particle incorporation.

Vibratory Mixing Unit: The entire mixing assembly was mounted on a sieve shaker that generated controlled vibrations. These vibrations enhanced the dispersion of SiC nanoparticles, prevented particle settling, and facilitated uniform distribution of reinforcement particles within the molten matrix.

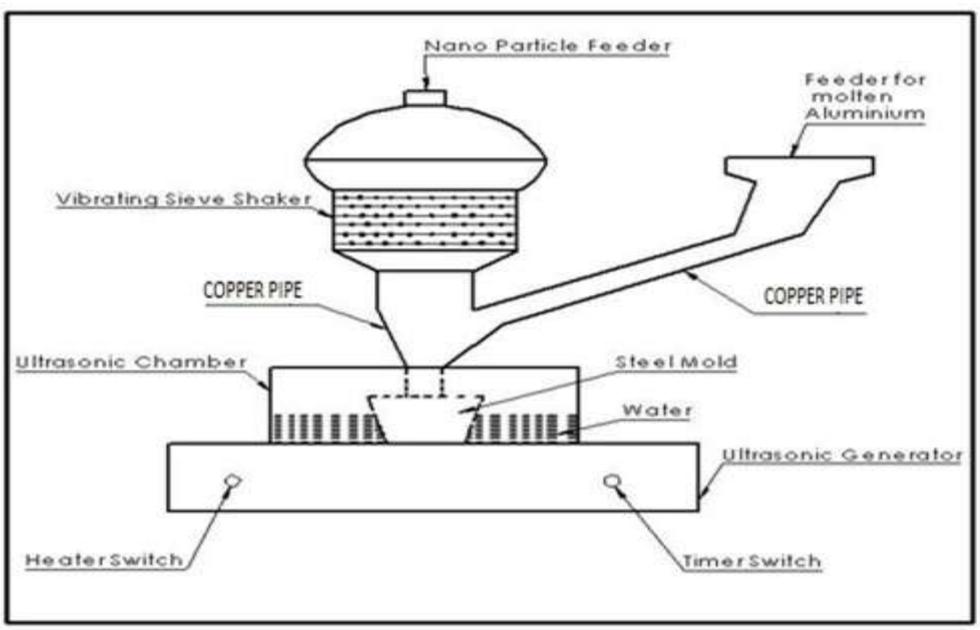

Fig. 1: Illustrates schematic diagram of experimental setup.

2.3 Solidification Process

The solidification setup consisted of an ultrasonic generator, an ultrasonic chamber, a steel mould, and a heating filament. The ultrasonic generator operated at a frequency of 35 kHz and supplied ultrasonic vibrations during the casting process. The steel mould was preheated prior to casting to minimize thermal stress and prevent mould cracking. The mould was then placed inside the ultrasonic chamber, which was partially filled with water to facilitate efficient transmission of ultrasonic waves. The chamber was continuously vibrated at a frequency of 35 kHz during casting. Molten AA7150 alloy and SiC nanoparticles with an average particle size of approximately 12.3 nm were simultaneously introduced into the vibrating

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mould from the mixing chamber. Immediately after pouring, a heating filament was positioned above the molten metal surface to delay solidification and prolong the interaction between ultrasonic waves and the molten composite. Ultrasonic vibration was maintained for approximately five minutes to promote uniform nanoparticle dispersion, reduce particle clustering, and enhance wettability between the matrix and reinforcement. The application of ultrasonic energy during solidification contributed to grain refinement, improved microstructural homogeneity, and enhanced interfacial bonding between the aluminum matrix and SiC nanoparticles. The resulting AA7150–SiC nanocomposites were subsequently subjected to microstructural and mechanical characterization to evaluate the effectiveness of the developed processing technique.

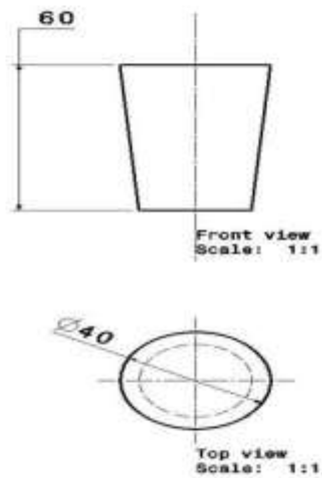

Fig. 2: Illustrates schematic diagram of sample prepared during experiment.

The ingots were cut into smaller samples as shown in Figure 3. Fig. 3 (b) shows the locations of samples cutout from the ingot at different locations for Rock Well hardness tests.

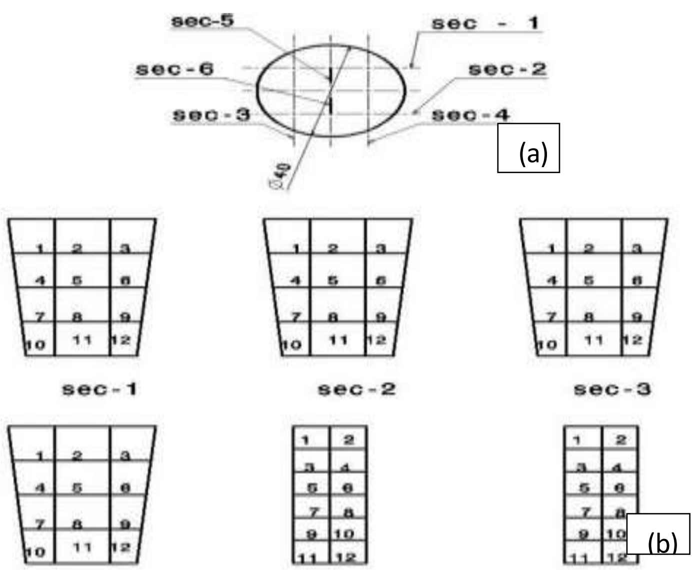

Fig. 3: Illustrates schematic diagram of sectioning of sample prepared during experiment.

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Rockwell Hardness Test: The Rockwell hardness test method, as defined in ASTM E-18, is the most commonly used hardness test method. The Rockwell method measures the permanent depth of indentation produced by a force/load on an indenter. First, a preliminary test force (commonly referred to as preload or minor load) is applied to a sample using a diamond indenter. The Rockwell hardness was measured on the polished samples using steel ball indenter of 1.588 mm diameter with a load of 100kgf. The reported value is an average reading taken at different locations on the 6 sections on the specimens.

Table 1: Hardness distributions of Al-Sic Nano composites.

SECTION	SAMPLE	MAX HRB	MIN. HRB	MEANHRB
1	1	97	82	90.75
2	2	94	81	88.41
3	3	90	81	85.83
4	4	92	83	87.33
5	5	95	84	89.25
6	6	97	87	93.25

Analysis of HRTEM and phase images of Al-Sic Nano nanoparticles: For TEM analysis High Resolution TEM (JEOL, JEM-2100) was used. The TEM operated at an accelerating voltage of 200 kV. Bright field images of Nano-particulates spread in the Al matrix were taken and selected area diffraction patterns were recorded. EDAX was also carried out.

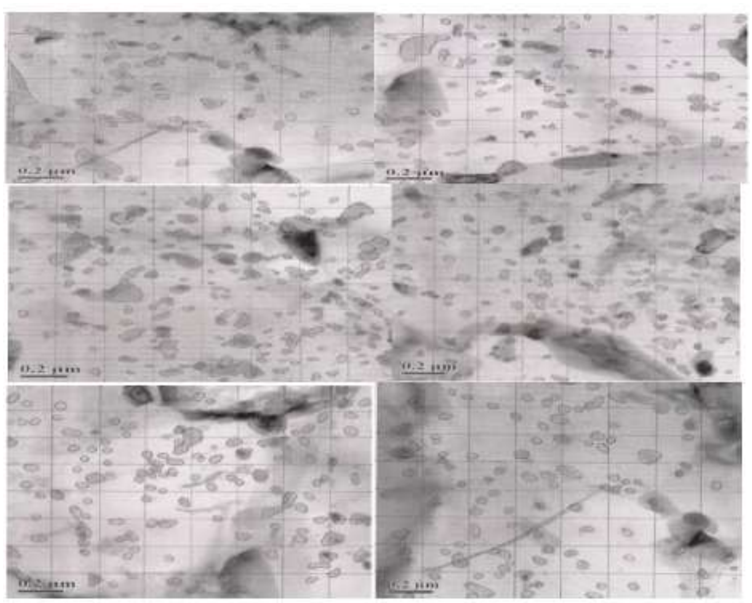

Fig. 4: HRTEM micrograph divided into number of cells according to scale.

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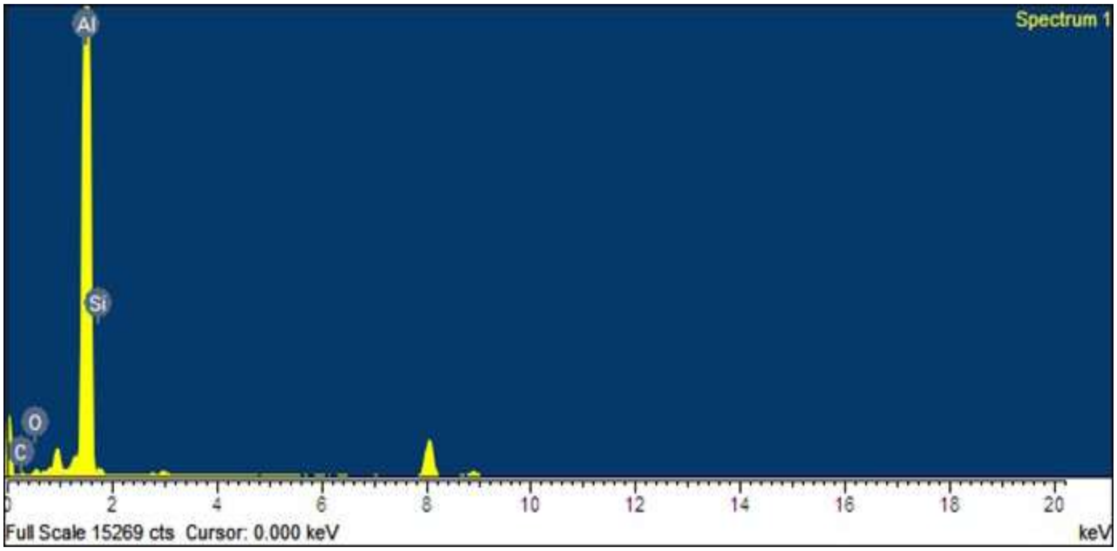

Fig. 5: TEM micrographs of Al-Sic Nano composites.

Table 2: Depicts Particle Distribution of Individual HRTEM Figure of Different Section of cast ingot.

SECTION	MAX NO. OF PARTICLE	MIN NO. OF PARTICLE	MEAN OF PARTICLE	VOLUMETRIC FRACTION (IN%)
1	14	1	3.75	6.63
2	14	1	3.82	6.75
3	8	1	3.95	6.99
4	9	1	2.96	5.25
5	10	1	2.87	5.08
6	8	1	2.98	5.26

High resolution micrograph of various sections of 6 samples was done with the help of HRTEM. Some of those were chosen randomly for analysis. From analysis average volumetric fraction came to be 5.99.

Field Emission Scanning Microscopy & Energy Dispersive X-ray Analysis (FESEM&EDX): The casted specimen is polished and etched as per the standard metallographic procedure. The microstructures of color etched specimens were observed using a scanning electron microscope (FESEM). Silicon Carbide (Sic) analyzed by scanning electron microscope was shown in Figure 7 with average size of 10 microns.

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Fig. 6: Energy Dispersive X-ray Analysis of Al-Sic Nano composites

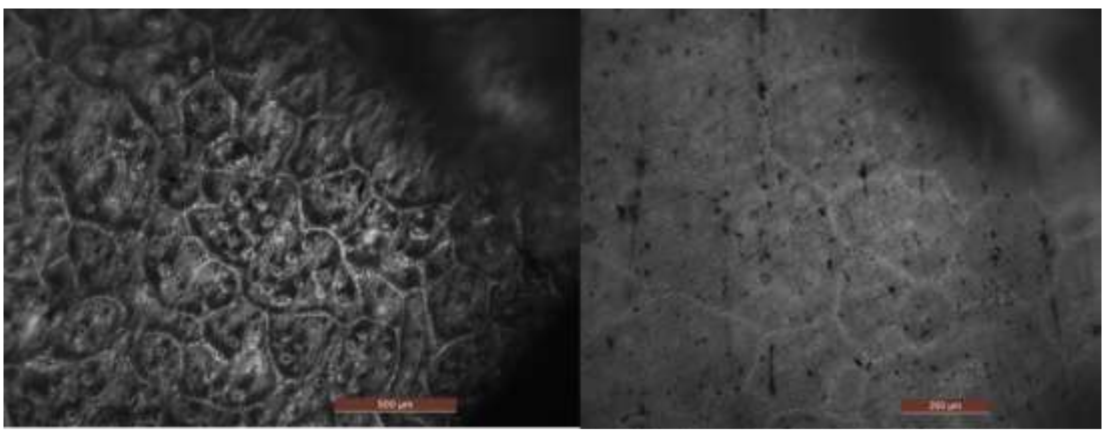

Fig. 8: Optical microscopy of Al-Sic Nanocomposites.

3. Result and Discussion

The hardness measurements obtained from different locations of the AA7150–SiC nanocomposite ingot indicate that the distribution of SiC nanoparticles is highly uniform throughout the casting. This suggests that the nanoparticles were effectively dispersed within the molten metal during the casting process. The segregation of some nanoparticles near the grain boundaries can be attributed to the pushing effect that occurs during solidification. As the grains grow, the advancing solid–liquid interface tends to reject and push the nanoparticles into the remaining liquid regions, leading to their accumulation at grain boundaries. This behavior is commonly observed in metal–ceramic composite systems where the particle engulfment velocity is lower than the grain growth velocity.

The microstructures of the fabricated composites clearly reveal a homogeneous distribution of SiC nanoparticles within the AA7150 aluminum alloy matrix. No evidence of significant porosity, cracks, or casting defects was observed, indicating the production of sound and high-quality composites. The absence of such defects can be attributed to the optimized processing parameters employed during composite fabrication, which enhanced wettability and particle dispersion.

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Energy Dispersive X-ray Spectroscopy (EDS/EDX) analysis further confirmed the successful incorporation of SiC nanoparticles into the aluminum matrix. The characteristic elemental peaks corresponding to silicon and carbon verified the presence of the reinforcement phase within the composites. In addition, Transmission Electron Microscopy (TEM) samples extracted from different regions of the cast specimen demonstrated a uniform dispersion of nanoparticles throughout the ingot. Quantitative analysis of High-Resolution Transmission Electron Microscopy (HRTEM) micrographs revealed a nearly constant volumetric fraction of SiC nanoparticles across the specimen. These observations collectively confirm that the SiC nanoparticles were distributed uniformly throughout the matrix, resulting in improved microstructural integrity and enhanced mechanical properties of the AA7150–SiC nanocomposites.

4. Conclusions

The hardness values measured at different locations of the AA7150–SiC nanocomposite ingot indicate a uniform distribution of SiC nanoparticles throughout the matrix. The minimal variation in hardness across the specimen confirms the effectiveness of the fabrication process in achieving homogeneous particle dispersion. This observation is further supported by the HRTEM micrographs, which reveal a consistent volume fraction of nanoparticles and their uniform distribution within the aluminum matrix. Compared with the parent AA7150 alloy, the composite material exhibited a significant increase in hardness due to the incorporation of hard SiC nanoparticles, which contribute to grain refinement and hinder dislocation movement. Furthermore, microstructural analysis showed an absence of noticeable porosity, indicating sound casting quality and effective wettability between the matrix and reinforcement. The lack of porosity and the strong particle–matrix interfacial bonding observed in the microstructure suggest efficient load transfer from the matrix to the reinforcement particles, resulting in enhanced mechanical performance. These results demonstrate that the developed AA7150–SiC nanocomposite possesses a uniform microstructure and superior hardness characteristics, making it suitable for high-performance engineering applications.

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