



RESEARCH ARTICLE

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FABRICATION OF AL6061–SiC METAL MATRIX COMPOSITES VIA STIR CASTING: A RESPONSE SURFACE METHODOLOGY APPROACH TO MICROSTRUCTURE ANALYSIS

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ABSTRACT

To This study investigates the fabrication and microstructural characterization of Al6061–SiC composites using a Response Surface Methodology (RSM) approach to optimize stir casting parameters. Aluminum 6061 was used as the matrix material, while silicon carbide (SiC) particles with a size of less than 10 µm served as the reinforcement. The Aluminum Metal Matrix Composites (AMMCs) were produced through the stir casting technique, which is considered a cost-effective and efficient fabrication method. The composite samples were prepared according to the experimental design generated using the RSM Box–Behnken Design (BBD). The main processing parameters examined in this study were the reinforcement weight fraction (3.5 wt%, 7.0 wt%, and 10.5 wt%), melting temperature (625°C, 650°C, and 675°C), and stirring speed (225 rpm, 250 rpm, and 275 rpm). Microstructural examination carried out using a metallurgical microscope and high-resolution scanning electron microscope (SEM) indicated a relatively uniform dispersion of SiC particles within the aluminum matrix; however, minor particle agglomeration and porosity were also detected.



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I. INTRODUCTION

Metal matrix composites (MMCs) have gained considerable attention in recent decades due to their enhanced mechanical, thermal, and tribological properties compared with conventional alloys [1]. Among the various MMCs, aluminum matrix composites (AMMCs) are widely used because of their low density, high strength-to-weight ratio, good corrosion resistance, and excellent thermal conductivity [2]. Aluminum alloy Al6061 is particularly preferred as a matrix material because of its good formability, weldability, and mechanical performance [3]. Reinforcing aluminum alloys with ceramic particles such as silicon carbide (SiC) significantly improves hardness, wear resistance, and strength of the composite material [4]. The presence of hard SiC particles in the aluminum matrix restricts grain boundary movement and contributes to grain refinement during solidification, leading to improved mechanical properties [5]. Various fabrication techniques have been employed for the production of aluminum matrix composites, including powder metallurgy, squeeze casting, spray deposition, and stir casting [6]. Among these techniques, stir casting is considered one of the most economical and practical methods due to its simplicity and suitability for large-scale production [7]. In this method, reinforcement particles are introduced into molten aluminum and distributed uniformly through mechanical stirring [8]. However, the quality of the final composite depends strongly on several processing parameters such as melting temperature, stirring speed, and reinforcement percentage [9]. Improper control of these parameters may lead to particle agglomeration, poor wettability, and porosity within the composite structure [10].

Microstructural characteristics play a vital role in determining the mechanical and tribological performance of aluminum matrix composites [11]. A uniform distribution of reinforcement particles enhances load transfer efficiency between the matrix and the reinforcement, thereby improving strength and wear resistance [12]. Previous studies have reported that increasing the weight fraction of SiC particles improves hardness and wear resistance of Al6061 composites [13]. Furthermore, statistical optimization techniques such as Response Surface Methodology (RSM) have been widely applied to evaluate the combined effects of multiple process parameters and to identify optimal fabrication conditions [14]. The Box–Behnken design within RSM has proven effective in reducing the number of experiments while providing reliable prediction models for material processing studies [15]. Therefore, the present study focuses on the fabrication of Al6061–SiC composites using the stir casting method and investigates the influence of key process parameters on the microstructural characteristics. The Response Surface Methodology with Box–Behnken design is employed to systematically analyze the effects of reinforcement weight percentage, melting temperature, and stirring speed to achieve improved particle distribution and enhanced composite quality.

II. SELECTION OF MATERIALS AND METHODOLOGY

II.1 SELECTION OF MATERIALS

Aluminium 6061 is used as the base material in MMCs. It is mostly made of aluminum, with silicon and magnesium as the major alloying elements. Aluminium 6061 possesses good mechanical properties and excellent weldability. While the Al6061 matrix material demonstrates good corrosion resistance, its mechanical and tribological properties are not as significant. Therefore, enhancement of its mechanical and tribological characteristics is necessary. For this reason, aluminium alloy 6061 was selected as the matrix material in this investigation. The aluminium alloy Al6061 billet was procured in the form of billets. Silicon carbide belongs to a group of lightweight ceramic materials. It is extremely hard and, when used as a reinforcing material, can significantly increase the base matrix's hardness and resistance to wear. This material can withstand high temperatures (up to 1600°C) due to the strong bonding within the tetrahedral structure formed by carbon and silicon atoms in its crystal lattice. Based on these characteristics, chemically pure, green to bluish-black fine SiC powder was selected as the primary reinforcement.

II.2 DESIGN OF EXPERIMENT

This study utilizes the Box-Behnken Design to optimize the stir casting parameters for Al–SiC composites, concentrating on the critical process inputs and their levels as summarized in Table 1. Using the BBD, a quadratic model will be developed to investigate the connections between the final material characteristics and these process variables (such as tensile strength, hardness, Impact strength, Wear Rate and COF). The ultimate goal is to identify the optimal combination of parameters that leads to superior composite quality, enhancing the effectiveness and consistency of the stir casting process for Al–SiC composites.

Table 1: Controllable Factors in the Stir Casting Process.

Factors	Levels		
	-1	0	+1
Reinforcement RI(wt% SiC)	3.5	7	10.5
Melting or Stirring Temperature ST(°C)	625	650	675
Stirring Speed SS (rpm)	225	250	275

Source: Authors, (2026).

II.3 FABRICATION OF COMPOSITES

The Al6061–SiC MMCs in this study were produced using the stir casting method, a popular technique for manufacturing particle-reinforced aluminum composites due to its ease of use, cost efficiency, and scalability. The stir casting setup is illustrated in Figures 1. Conducting experimental Runs in Stir casting Process as listed in Table 2.

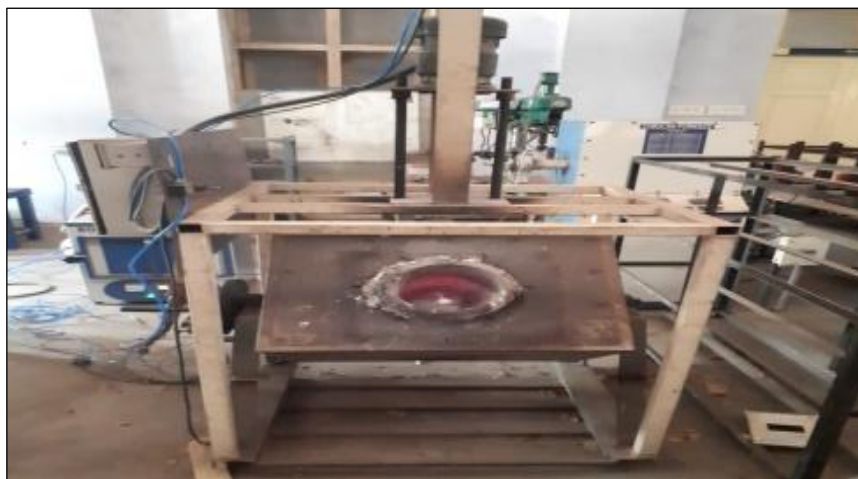


Figure 1: Experimental Framework for Stir Casting.

Source: Authors, (2026).

Table 2: Conducting Experimental Runs in Stir Casting.

Exp.No	Coded Value			Original Value		
	RI	ST	SS	RI (wt% SiC)	ST(°C)	SS (rpm)
1	-1	-1	0	3.5	625	250
2	-1	1	0	3.5	675	250
3	1	-1	0	10.5	625	250
4	1	1	0	10.5	675	250
5	-1	0	-1	3.5	650	225
6	-1	0	1	3.5	650	275
7	1	0	-1	10.5	650	225
8	1	0	1	10.5	650	275
9	0	-1	-1	7	625	225
10	0	-1	1	7	625	275
11	0	1	-1	7	675	225
12	0	1	1	7	675	275
13	0	0	0	7	650	250
14	0	0	0	7	650	250
15	0	0	0	7	650	250

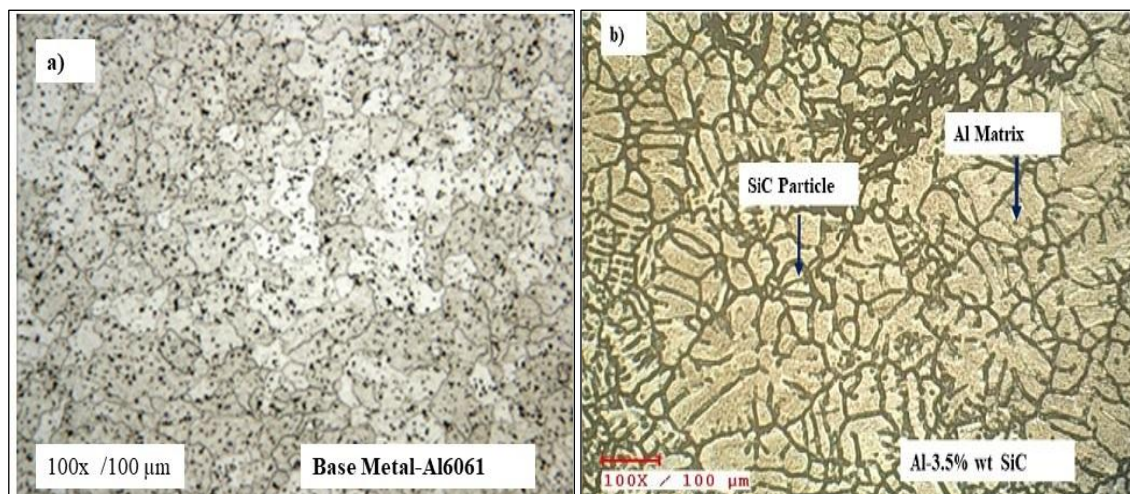
Source: Authors, (2026).

III. RESULTS AND DISCUSSION

III.1 MICROSTRUCTURAL ANALYSIS

The microstructure analysis of AL6061-SiC metal matrix composites (MMCs) using a metallurgical microscope (Dewinter Tech) involves a systematic sample preparation and examination process aimed at revealing the internal structural features of the composite material. The prepared sample is examined under a metallurgical microscope, beginning at low magnification (e.g., 100x) to investigate SiC particle shape, distribution, and interfacial bonding in the aluminum matrix. Microstructural features such as grain boundaries, particle clustering, porosity, and secondary phase formations are observed and, where applicable, captured using imaging software for further quantitative analysis. This procedure ensures a detailed and accurate characterization of the composite's microstructure, which is critical for understanding its mechanical properties and overall performance. The microstructure of the fabricated composite, shown in Figure 2 (b), was captured at 100× magnification with a scale of 100 μm. The matrix material, identified as AL6061, exhibits a typical dendritic solidification structure, characterized by primary α -Aluminum dendrites surrounded by an interdendritic eutectic network.

The regions highlighted by black circles represent the locations of reinforcing particles dispersed throughout the aluminum matrix. These areas appear darker, indicating the presence of secondary phases, which are most likely the silicon carbide (SiC) particles incorporated during the fabrication of the composite. Achieving a relatively uniform distribution of SiC particles within the matrix is essential for enhancing mechanical qualities like wear resistance, tensile strength, and hardness. The observed microstructure suggests good interfacial bonding between the AL6061 matrix and the SiC particles, which is necessary for effective load transfer under mechanical stress. Minimal porosity and segregation are evident, indicating a sound fabrication process and effective dispersion of reinforcement. The existence of SiC particles inhibits the grain growth of the aluminum matrix, contributing to the refinement of the microstructure and thus improving the overall performance of the mechanism. This analysis confirms the successful incorporation of 3.5 wt% SiC into the AL6061 alloy, directly correlating to the enhancements in mechanical properties observed during hardness, tensile, and impact testing.



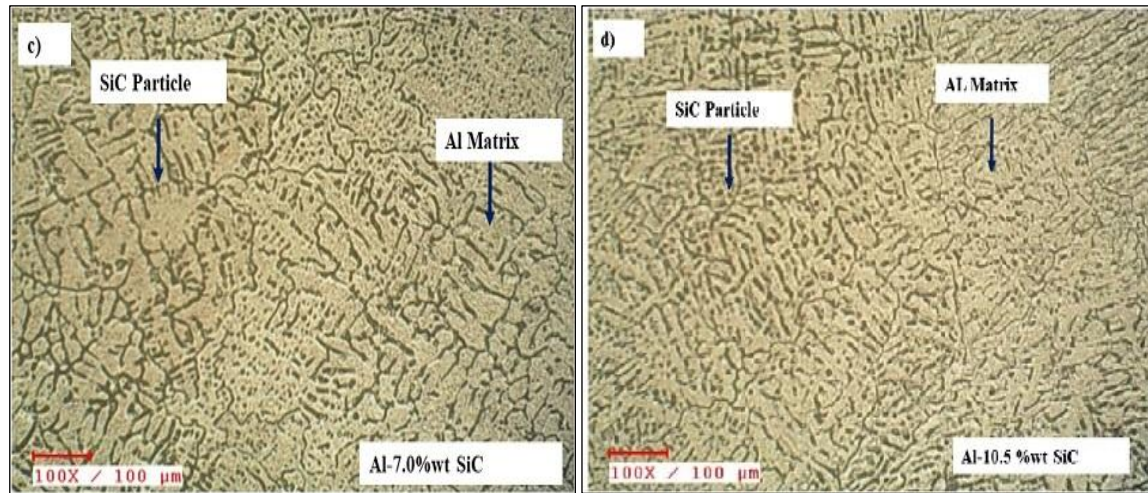


Figure 2: AMMCs Microstructures.

Source: Authors, (2026).

The microstructure of the AL6061–7.0 wt% SiC composite, shown in Figure 2 (c), was captured at 100× magnification with a scale of 100 µm. The matrix phase (highlighted with a black circle) consists predominantly of α -Aluminum (AL6061), while the red-circled regions indicate the presence of silicon carbide (SiC) reinforcement particles. Within the aluminum matrix, the SiC particles are dispersed somewhat evenly, but there is some minor clumping in some areas. This distribution is critical for improving the composite's mechanical performance, as the hard SiC particles act as barriers to dislocation movement, thereby enhancing the hardness and tensile strength of the material. The dendritic structure of the aluminum matrix remains visible, though the dendrites appear finer compared to unreinforced AL6061 alloy. The presence of SiC particles during solidification restricts grain growth by pinning the grain boundaries, leading to a refined microstructure. Grain refinement typically contributes to increased strength according to the Hall-Petch relationship.

No major porosity or defects were observed at this magnification, suggesting that the processing parameters were effective in achieving a sound microstructure. The good interfacial bonding between the AL6061 matrix and SiC particles indicates effective load transfer capability, which is essential for improving both tensile and impact properties. The analysis confirms that increasing the SiC content to 7.0 wt% leads to a more pronounced reinforcement effect compared to lower weight percentages, which is consistent with the mechanical test results showing increased hardness and strength. Figure 2 (d) shows the microstructure of the AL6061–10.5 weight percent SiC composite was examined at 100× magnification with a 100 µm scale. The α -Aluminum matrix (highlighted with yellow labeling and circled in red) retains its dendritic morphology, although it appears more refined compared to composites with lower SiC content. The red-circled areas clearly display the dispersion of SiC reinforcement particles within the matrix. As the SiC content increases to 10.5 wt%, the number density of SiC particles is visibly higher.

This dense distribution of hard SiC particulates effectively impedes dendrite growth during solidification, promoting a finer and more uniform microstructure. Finer dendritic structures contribute to increased strength and hardness due to restricted grain boundary movement. The relationship between the AL6061 matrix and the SiC particles appears clean with no major visible voids or defects at this magnification, suggesting effective particle-matrix bonding, crucial for efficient stress transfer during mechanical loading. However, at this higher reinforcement level, some localized particle clustering can be observed. While such clustering may enhance localized hardness, it could potentially lead to stress concentrations under dynamic loading conditions, slightly affecting toughness. Overall, the microstructure confirms that increasing the SiC content to 10.5 wt% significantly refines the grain structure and increases the volume fraction of hard phases, correlating with the substantial improvements observed in the hardness, tensile, and impact strength tests.

III.2 SEM OBSERVATION WITH EDAX EVALUATION

The characterization of Al6061-SiC MMCs using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) involves a systematic approach to examine the morphology of the surface and elemental makeup of the composite. All wear experiments were performed following the ASTM E2142 standard. The prepared specimen is positioned inside the SEM chamber and exposed to a focused electron beam to generate detailed surface images. SEM imaging reveals critical information about the shape, distribution, and interfacial bonding of the SiC reinforcement particles within the aluminum matrix, as well as any defects such as voids, cracks, or particle clusters. Elemental composition is determined through EDS, which detects characteristic X-rays emitted from the sample when struck by the electron beam.

This technique enables precise identification and spatial mapping of elements within the composite, confirming the presence of silicon carbide particles and highlighting any elemental segregation or secondary phases. Together, SEM and EDS offer a thorough insight into the microstructural and chemical properties of the Al6061-SiC composite, which is crucial for understanding its material performance. The image shown (Figure 3) is an EDAX spectrum obtained during SEM analysis of an AMMCs reinforced with a specific weight percentage of silicon carbide (SiC). The spectrum illustrates the elemental composition of the analyzed region of the composite by displaying the intensity of characteristic X-rays emitted by elements upon electron beam excitation.

On the x-axis, the energy levels of emitted X-rays are plotted in keV, while the y-axis indicates the count intensity, which correlates to the quantity of each element detected. A strong peak is observed for aluminum (Al) around 1.5 keV, which is expected due to its role as the base matrix material in AL6061. Smaller peaks are also visible for magnesium (Mg) and sodium (Na), which are typical alloying elements or trace impurities in the aluminum alloy. Importantly, this spectrum shows clearly identifiable peaks for silicon (Si) near 1.7 keV and also a minor peak around 0.2 keV, indicating the presence of silicon carbide particles in the analyzed area, consistent with the SiC reinforcement in the composite. Additionally, low-intensity peaks for carbon (C) and oxygen (O) are evident, which may be attributed to the carbon content from SiC, surface oxidation, or environmental contamination. The existence of both silicon and carbon peaks provides confirmation of the distribution of SiC particles within the aluminum matrix. This spectrum, therefore, validates the successful incorporation of SiC reinforcement in the AL6061 matrix and highlights the elemental constituents of the composite in the specific region examined.

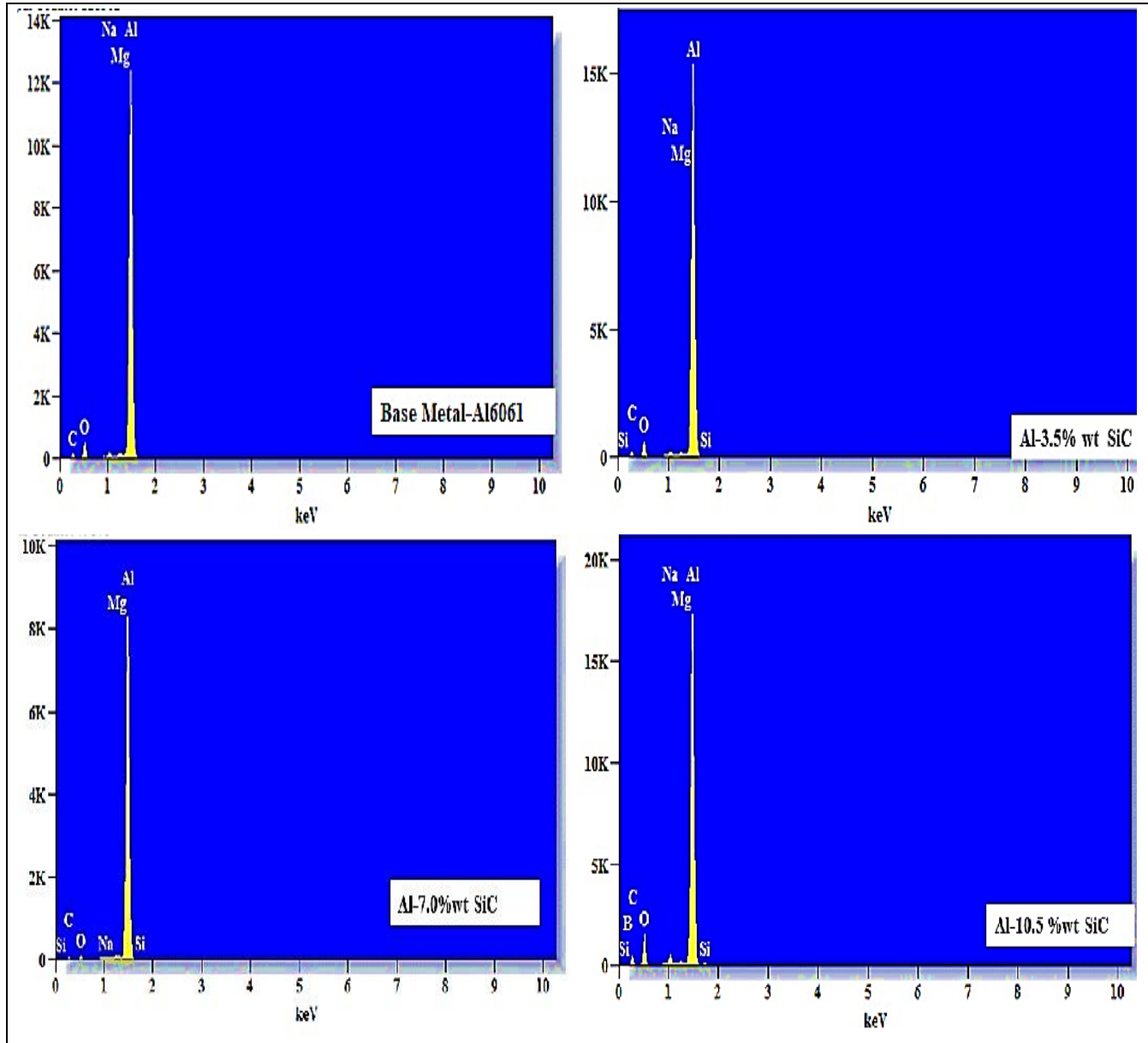


Figure 3: Al6061-SiC Composites EDAX spectrum.

Source: Authors, (2026).

This SEM image (Figure: 4) serves to reveal the microstructural characteristics and surface morphology of the composite at high magnification. In the image, the aluminum matrix forms the continuous phase, while the SiC particles are distinguishable as discrete features distributed within the matrix. At a reinforcement level of 10.5 wt%, the SiC particles appear more numerous and densely distributed compared to lower reinforcement percentages, indicating a higher volume fraction of ceramic reinforcement. The micrograph allows observation of the shape, size, and dispersion of these particles, which are critical in influencing the mechanical behavior of the composite. Uniform dispersion of SiC particles, as suggested in the image, enhances properties such as hardness, wear resistance, and tensile strength by improving load transfer between the matrix and reinforcement. Any visible clustering or agglomeration could potentially lead to stress concentrations, but in a well-processed sample, such defects are minimized. The SEM analysis thus confirms the successful integration of SiC into the aluminum matrix and provides valuable insight into the quality and effectiveness of the composite microstructure at 10.5 wt% SiC reinforcement.

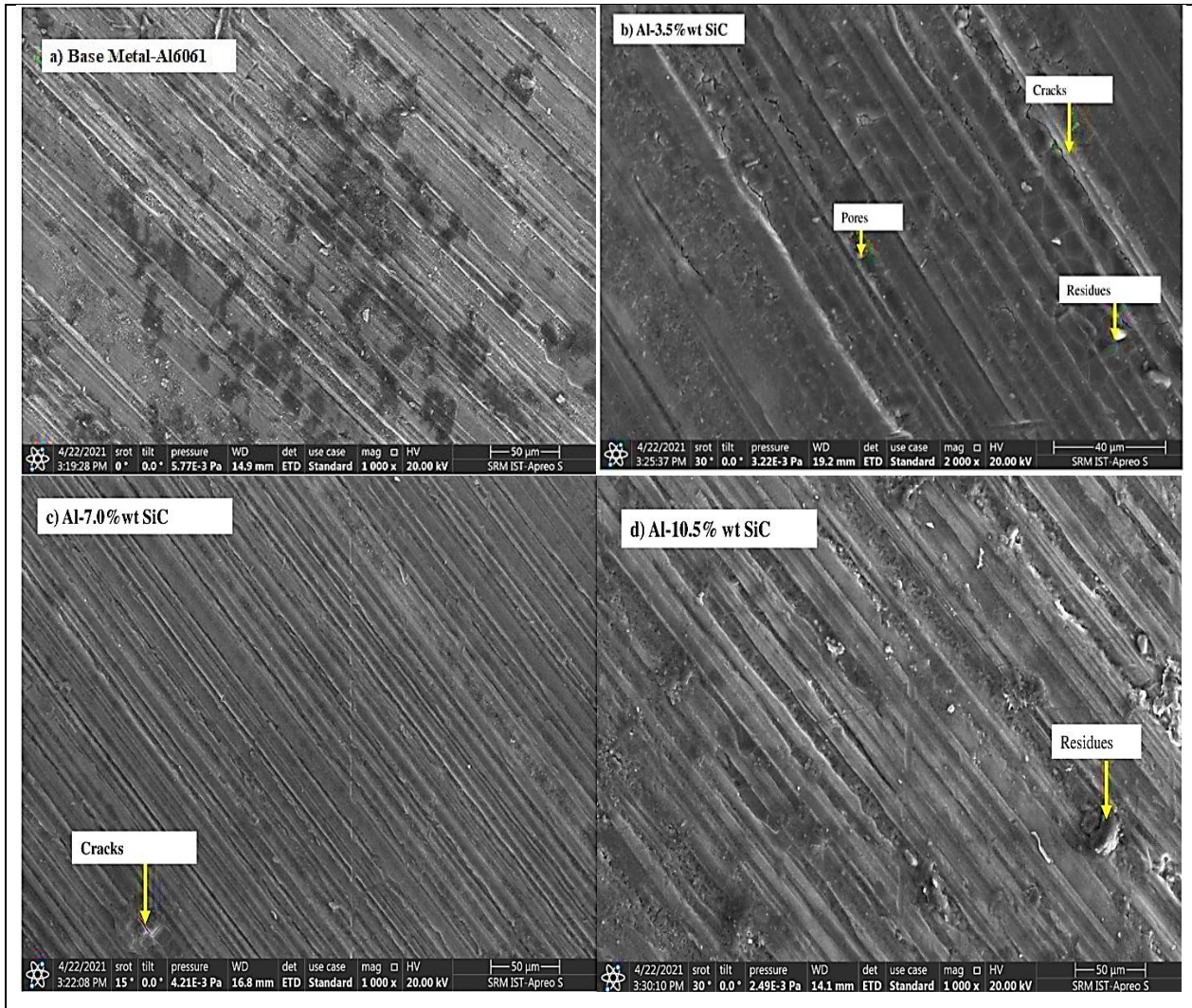


Figure 4: Al6061- SiC Composites SEM image.

Source: Authors, (2026).

IV. CONCLUSIONS

The Al6061–SiC metal matrix composites were successfully fabricated using the stir casting technique, and the process parameters were systematically optimized using the Box–Behnken Design (BBD) within the Response Surface Methodology (RSM) framework. The microstructural analysis revealed that increasing the SiC reinforcement content up to 10.5 wt% significantly refined the grain structure and enhanced the volume fraction of hard phases within the aluminum matrix. A relatively uniform distribution of SiC particles was observed under optimized processing conditions, which minimized particle agglomeration and improved the overall microstructural integrity of the composite. The presence of hard ceramic SiC particles restricted grain boundary movement during solidification and contributed to improved interfacial bonding between the reinforcement and the matrix. As a result, the composite exhibited enhanced mechanical properties, particularly increased hardness and improved wear resistance compared to the base Al6061 alloy. The statistical optimization approach effectively identified the optimal combination of parameters, and validation experiments confirmed the reliability of the developed model. Overall, the results demonstrate that the integration of stir casting with BBD-based RSM optimization is an effective approach for producing high-performance Al6061–SiC composites suitable for lightweight structural and engineering applications.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Sathiyaraj.S,

Methodology: Sathiyaraj.S,

Investigation: Sathiyaraj.S, P.Kumaran

Discussion of results: Sathiyaraj.S,

Writing – Original Draft: Sathiyaraj.S,

Writing – Review and Editing: P.Kumaran.,

Resources: Sathiyaraj.S,

Supervision: S.Sathiyaraj

Approval of the final text: S.Sathiyaraj

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