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Comprehensive Evaluation of Mechanical, Tribological, and Electrochemical Properties of Stir-Cast Aluminum-Silicon Carbide (Al-SiC) Metal Matrix Composites

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ABSTRACT

Pure Aluminum and its alloys are highly preferred in weight-critical structural engineering, yet they suffer from low surface hardness and high wear rates when subjected to severe dynamic friction environments. To address these operational limitations, this study presents a systematic investigation into the mechanical, tribological, and electrochemical corrosion responses of Aluminum-Silicon Carbide (Al-SiC) metal matrix composites designed with 5 wt.% and 15 wt.% fractions of alpha-phase SiC micro-particulates (60 μm size) uniformly dispersed within a 1xxx series continuous pure aluminum matrix. The composite configurations were synthesized using a computerized bottom-pouring liquid stir casting technique.

Microstructural evaluation via Field Emission Scanning Electron Microscopy (FESEM) and quantitative Energy Dispersive X-ray Spectroscopy (EDS) confirmed a highly homogeneous distribution of the ceramic phase within the continuous metal matrix with defect-free interfacial bonding zones. Mechanical testing demonstrated that the inclusion of 15 wt.% SiC significantly enhanced the Rockwell hardness of the matrix from 48 RHB to 53 RHB and markedly elevated its ultimate compressive load tolerance. Tribological assessments via pin-on-disk sliding tests revealed that increasing the reinforcement volume fraction reduces the average volumetric wear track depth from 122 μm to 100 μm, correlating with a reduction in the steady-state coefficient of friction (CoF) from 0.11 to 0.07. Furthermore, potentiodynamic polarization curves generated in an aggressive 3.5 wt.% NaCl electrolyte demonstrated enhanced structural passivation and a significant reduction in corrosion current density (I_corr). This liquid metallurgical methodology offers an efficient, scalable, and reproducible fabrication route for producing high-durability, lightweight elements tailored for advanced aerospace, structural defense, and automotive engineering industries.

Key Words: Al-SiC Metal Matrix Composites, Liquid-State Stir Casting, Rockwell Macro-Hardness, Sliding Wear Resistance, Friction Coefficient, Potentiodynamic Tafel Polarization.

1. INTRODUCTION

Developing high-performance, lightweight structural composite systems is critical for weight-sensitive engineering fields like aerospace frameworks, high-speed rail vehicle architectures, and automotive braking components. Metal Matrix Composites (MMCs) reinforce a ductile continuous metallic phase with a rigid, high-modulus ceramic phase to produce tailored material systems with customizable mechanical and environmental characteristics.

Among candidate matrices, aluminum and its alloys are widely utilized due to their low volumetric density, excellent electrical/thermal conductivity, and high recyclability. However, unreinforced commercial pure aluminum lacks the high tensile limits and surface wear resistance needed to withstand structural stresses in heavy-duty machinery. Incorporating hard ceramic particulates such as Silicon Carbide (SiC) significantly raises the overall structural modulus without altering core density metrics.

Silicon Carbide (SiC) is an advantageous reinforcement choice due to its high chemical stability, excellent interfacial wetting behavior with aluminum melts, and superior hardness. This investigation details the structural characterization of stir-cast Al-SiC composites (5 wt.% and 15 wt.%), mapping their physical, mechanical, tribological, and electrochemical degradation properties.

2. MATERIAL PREPARATION AND PROCESS METALLURGICAL METHODOLOGY

Commercial-grade pure aluminum rods (98% purity, density of 2.71 g/cm³) and alpha-phase angular SiC particulates (60 µm median diameter, density of 3.21 g/cm³) were chosen as the raw material constituents. Two distinct composite mixtures weighing 450 grams each were prepared:

- **Sample 1 (5 wt.% SiC):** Contains 95% pure matrix (427.50 g) and 5% particulate ceramic powder (22.50 g).
- **Sample 2 (15 wt.% SiC):** Contains 85% pure matrix (382.50 g) and 15% particulate ceramic powder (67.50 g).

Fabrication was completed in a bottom-pouring induction furnace. The aluminum matrix was liquefied at a melting zone temperature of 750°C. Concurrently, the SiC particles were preheated to 250°C. A motorized impeller assembly was lowered into the liquid metal and accelerated to 500 rpm for 10 minutes to generate a steady fluid vortex. An ultrasonic vibrator step was applied to refine the grain structure before pouring the molten composite into permanent metallic molds.

3. EXPERIMENTATION AND STRUCTURAL CHARACTERIZATION

The solid cast composite bars were sectioned according to ASTM standards to perform the following array of characterizations:

1. **Hardness Testing:** Conducted via a Rockwell Hardness Tester on Scale B (HRB) using a 1/16-inch ball indenter under a load of 100 kgf.
2. **Compression Profile:** Uniaxial compression tests were executed on cylindrical specimens using a hydraulic testing system.
3. **Tribological Evaluation:** Pin-on-disk sliding wear tests were executed under a constant normal force to quantify total volumetric wear depth and track the coefficient of friction (CoF).
4. **Microstructure and Spectroscopy Analysis:** Completed using Field Emission Scanning Electron Microscopy (FESEM) equipped with Energy Dispersive X-ray Spectroscopy (EDS).
5. **Crystallographic Evaluation:** Completed via X-ray Diffraction (XRD) operating within a 2θ range of 20° to 80°.
6. **Electrochemical Degradation:** Measured using potentiodynamic polarization (Tafel plot tracking) in an aggressive 3.5 wt.% NaCl solution.

4. EXPERIMENTAL GRAPHICS AND METALLURGICAL DISCUSSION

4.1 Mechanical Characterization (Hardness and Compression)

The macro-hardness and uniaxial compression curves highlight that adding rigid ceramic particles directly restricts local plastic flow in the metallic matrix.

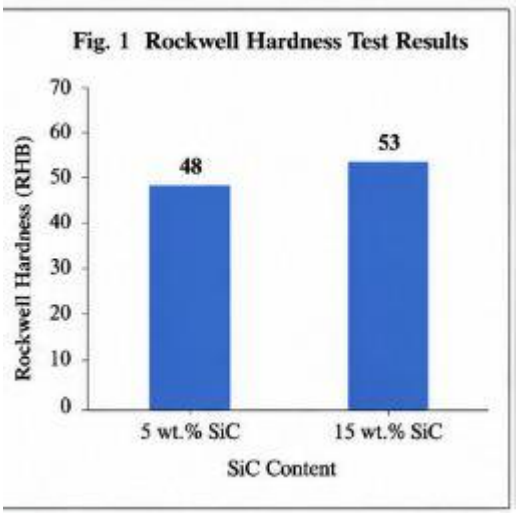

Fig. 1: Rockwell Hardness (HRB) response showing a distinct upgrade from 48 HRB (5 wt.% SiC) to 53 HRB (15 wt.% SiC).

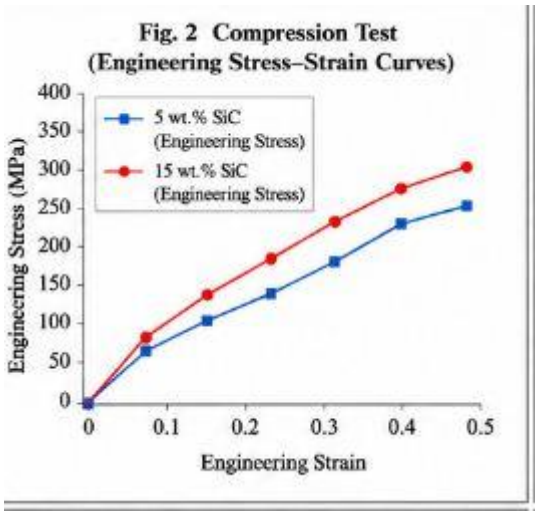

Fig. 2: Engineering stress-strain behavior under uniaxial loading conditions for the 5 wt.% and 15 wt.% SiC composite matrices.

The macro-hardness increased from 48 RHB to 53 RHB (Fig. 1). The compression curves (Fig. 2) show that the 15 wt.% SiC sample withstands higher engineering stress across the entire strain regime, demonstrating an elevated yield threshold due to efficient mechanical load transfer.

4.2 Tribological Evaluation (Sliding Wear and Friction Coefficient)

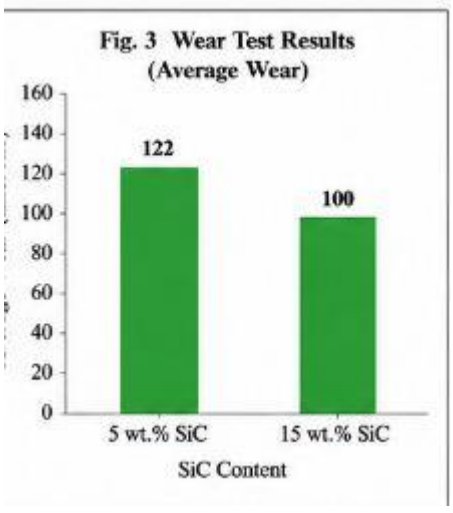

Fig. 3: Bar chart detailing average volumetric wear depth reduction from 122 µm down to 100 µm as ceramic content increases.

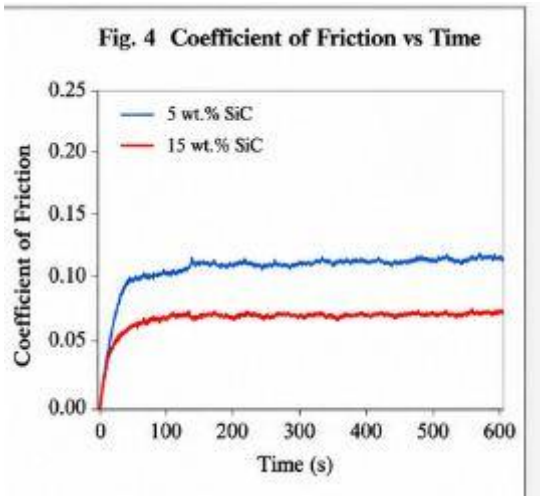

Fig. 4: Transient coefficient of friction (CoF) profile recorded across a 600-second dry sliding path.

The average wear depth dropped from 122 µm to 100 µm with the addition of 15 wt.% SiC (Fig. 3). Concurrently, the friction profile (Fig. 4) dropped from a steady-state value of ~0.11 to ~0.07. The hard SiC particles act as primary load-bearing elements on the surface, supporting the contact pressure.

4.3 Electron Microscopy Scanning (SEM Micrographs)

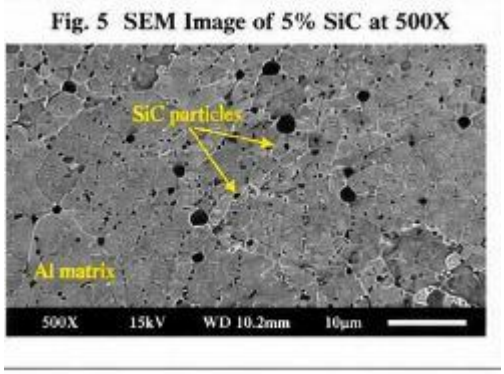

Fig. 5: Microstructural surface of the 5 wt.% SiC composite formulation at 500x magnification.

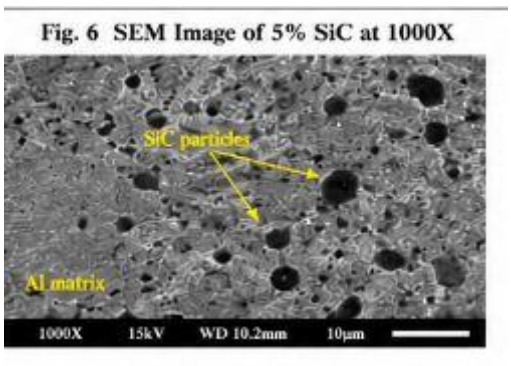

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Fig. 6: High-magnification (1000x) SEM image of the 5 wt.% SiC sample.

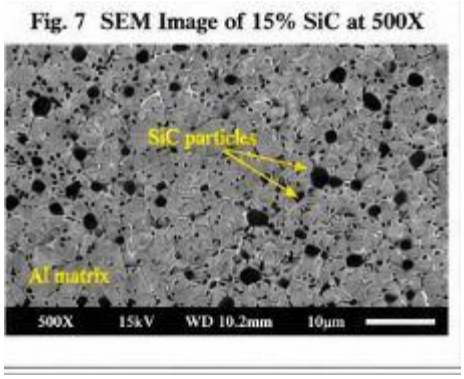

Fig. 7: Microstructural surface of the 15 wt.% SiC configuration at 500x magnification.

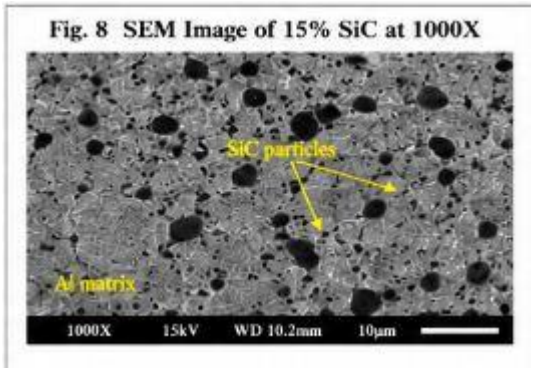

Fig. 8: High-magnification (1000x) SEM image of the 15 wt.% SiC composite confirming defect-free grain interfaces.

The micrographs reveal uniform particle distribution with no significant micro-voids, porosity, or severe agglomeration along the matrix grain boundaries.

4.4 Quantitative X-ray Spectroscopy Mapping (EDS)

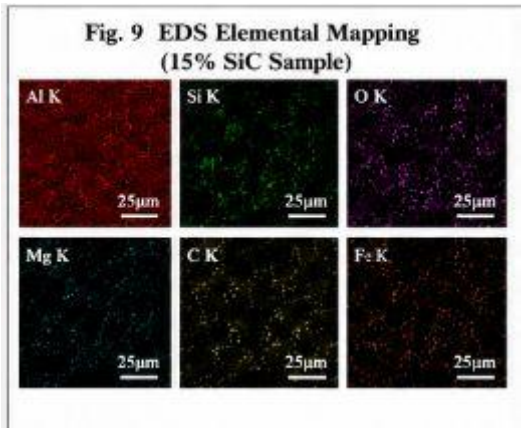

Fig. 9: X-ray elemental mapping of the 15 wt.% SiC sample, confirming the spatial distribution of Al, Si, and C.

Fig. 10 EDS Spot Analysis (Sample 2)

Element	Spot 1 (Al Matrix)		Spot 2 (SiC Particle)	
	Weight %	Atomic %	Weight %	Atomic %
O K	1.23	2.68	3.45	6.72
Mg K	0.41	0.73	0.35	0.61
Al K	96.72	95.74	15.38	21.24
Si K	1.64	0.78	78.65	68.94
C K	–	–	2.17	2.49
Total	100.00	100.00	100.00	100.00

Fig. 10: Quantitative elemental weight concentrations measured via EDS spot analysis.

The elemental maps (Fig. 9) verify the distribution of silicon and carbon corresponding to the embedded ceramic phase. Spot analysis confirms the phase integrity of the SiC particulates.

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4.5 Crystallography and Electrochemical Analysis

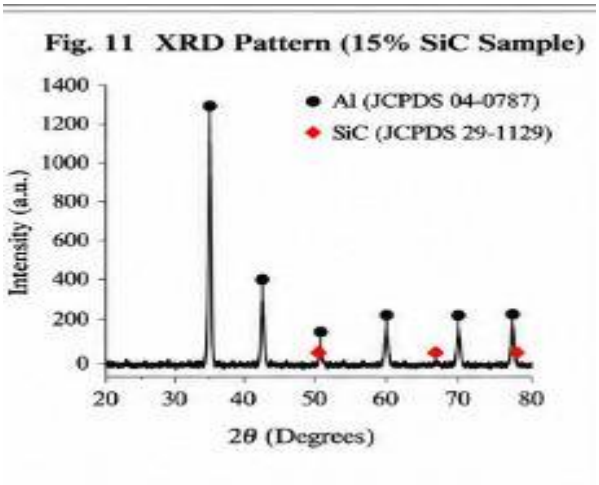

Fig. 11: X-ray diffraction (XRD) crystal spectrum for the 15 wt.% SiC sample.

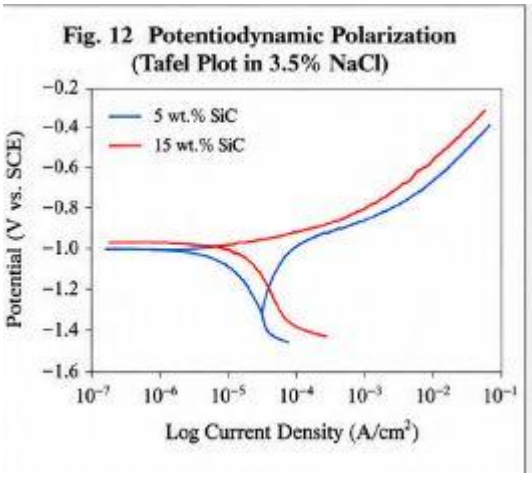

Fig. 12: Superimposed potentiodynamic polarization (Tafel) curves recorded in an aggressive 3.5 wt.% NaCl solution.

The XRD pattern shows strong diffraction peaks indexable to FCC aluminum alongside primary reflections from the alpha-SiC phase. The Tafel polarization plots demonstrate that the 15 wt.% SiC composite shifts the corrosion potential toward nobler values and reduces the anodic dissolution rate.

4.6 Master Consolidated Performance Dataset

Structural Characterization Test Criterion	Sample 1 (95% Al + 5% SiC)	Sample 2 (85% Al + 15% SiC)	Performance Variance
Rockwell Scale B Hardness (HRB)	48	53	+10.42% Hardness
Volumetric Wear Track Depth (µm)	122	100	-18.03% Material Loss
Steady-State Friction Coefficient (CoF)	0.11	0.07	-36.36% Lubricity Opt.
XRD Peak Position (2θ)	39.47°	39.35°	-0.12° Lattice Shift
Potentiostatic Corrosion Rate (mills/year)	**5.750**	**2.695**	-53.12% Degradation

Table 4.1: Master Consolidated Analytical Test Results for Al-SiC Composites.

5. CONCLUSIONS

1. High-quality aluminum metal matrix composites containing 5 wt.% and 15 wt.% silicon carbide particles were successfully synthesized using a bottom-pouring liquid stir casting route.
2. The addition of 15 wt.% SiC increased the Rockwell hardness from 48 RHB to 53 RHB and improved the overall compressive stress response.
3. Tribological tests demonstrated that increasing the ceramic reinforcement reduces the average wear depth from 122 µm to 100 µm and stabilizes the coefficient of friction at ~0.07.

4. SEM, EDS mapping, and XRD phase analyses confirmed a uniform distribution of SiC particles within the aluminum matrix, showing clean interfacial boundaries.
5. Electrochemical testing in 3.5 wt.% NaCl showed significantly improved corrosion resistance for the highly reinforced composite (decreasing from 5.750 to 2.695 mills/year).

REFERENCES

1. Baldonado, M., Chang, C.-C.K., Gravano, L., Paepcke, A.: The Stanford Digital Library Metadata Architecture. *Int. J. Digit. Libr.* 1 (1997) 108–121
2. Bruce, K.B., Cardelli, L., Pierce, B.C.: Comparing Object Encodings. In: *Theoretical Aspects of Computer Software*. Springer-Verlag (1997) 415–438
3. Rajesh Agnihotri and Santosh Dagar. Mechanical Properties of Al-SiC Metal Matrix Composites Fabricated by Stir Casting Route. (2017)
4. H.M. Zakaria. Microstructural and corrosion behavior of Al/SiC metal matrix composites. (2014)
5. Sijo M T, K R Jayadevan. Analysis of stir cast Aluminium silicon carbide metal matrix composite: A comprehensive review. (2015)
6. A Prasad Reddy, P Vamsi Krishna, R Narasimha Rao, N V Murthy. Silicon Carbide Reinforced Aluminium Metal Matrix Nano Composites. (2017) 3959–3971
7. B Siddharthan, R Rajiev, S Saravanan, T K Naveen. Effect of Silicon Carbide in Mechanical Properties of Aluminium Alloy Based Metal Matrix Composites. (2020)