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Fatigue Behaviour, Tribological Performance and Failure Analysis of Al-SiC Metal Matrix Composites Fabricated by Stir Casting for Automotive Structural Applications

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Abstract

Aluminium–Silicon Carbide (Al–SiC) metal matrix composites (MMCs) have attracted considerable industrial interest owing to their superior specific strength, stiffness, and wear resistance relative to unreinforced aluminium alloys, making them particularly attractive for weight-sensitive automotive structural components including suspension arms, brake rotors, and engine mounts. However, the fatigue life and tribological behaviour of Al–SiC MMCs fabricated by stir casting — a commercially scalable and cost-effective processing route — remain insufficiently characterised under multi-axial loading and elevated temperature conditions representative of in-service automotive environments. This study fabricates Al 6061 alloy reinforced with SiC particulates at 5 wt%, 10 wt%, 15 wt%, and 20 wt% via double-pass stir casting at 750°C with electromagnetic stirring and characterises the resulting composites through tensile testing, rotating-bending fatigue testing (R = –1, 10^6 to 10^8 cycle range), pin-on-disc tribological assessment under dry and lubricated conditions, and fractographic analysis by SEM. The effect of SiC reinforcement fraction on S–N fatigue behaviour, wear rate, coefficient of friction, and failure mode is systematically quantified. Results confirm that 15 wt% SiC addition yields the optimal fatigue endurance limit (172 MPa, 38% above unreinforced control at 10^7 cycles) while maintaining acceptable ductility (elongation 4.2%). The 20 wt% SiC composite exhibits the lowest specific wear rate (2.4×10^{-5} mm³/N·m) under dry sliding, representing a 61% reduction versus the matrix alloy. SEM fractography reveals a transition from transgranular fatigue cracking in low-SiC composites to interfacial debonding-dominated fracture at 20 wt% SiC, with implications for optimum reinforcement content selection in fatigue-critical designs.

Keywords: *metal matrix composites, Al-SiC, stir casting, fatigue behaviour, tribology, wear resistance, SEM fractography, automotive materials, S-N curve, Al 6061*

1. Introduction

The automotive industry's twin imperatives of fuel economy and crashworthiness have driven sustained demand for lightweight structural materials capable of sustaining cyclic loading over the vehicle lifetime of 10^8 fatigue cycles or more. Aluminium alloys have addressed the weight reduction objective since the 1970s, reducing body-in-white mass by 30–50% relative to equivalent steel structures, but their fatigue endurance limits — typically 35–50% of tensile strength — and poor tribological performance against ferrous counterfaces constrain their adoption in drivetrain and braking system components where cyclic contact stresses and thermal gradients are severe. Metal matrix composites, in which a metallic matrix is reinforced with ceramic particulates, whiskers, or fibres, were commercialised in the 1990s for aerospace applications and have since diffused into automotive contexts as manufacturing costs have declined through process scaling and material standardisation.

Among MMC systems, Al–SiC particulate composites offer the most favourable combination of property enhancement and processability. Silicon carbide particulates with Mohs hardness 9–9.5 confer significant improvements in elastic modulus (typically from 70 GPa for unreinforced Al to 110–120 GPa at 20 vol% SiC), hardness, and wear resistance through load transfer from the compliant aluminium matrix to the rigid ceramic reinforcement phase. Stir casting, in which SiC particulates are mechanically incorporated into the aluminium melt above its liquidus temperature, is the most commercially widespread fabrication route owing to its low tooling cost, scalability to large components, and compatibility with near-net-shape casting, despite challenges of SiC particle clustering, porosity, and interfacial wetting that require careful process control to mitigate.

The fatigue behaviour of Al–SiC MMCs is substantially more complex than that of monolithic alloys due to the particulate–matrix interface, which acts as a stress concentration site and potential fatigue crack initiation location. The fatigue crack growth rate in Al–SiC MMCs depends critically on SiC particle size, volume fraction, distribution uniformity, and the integrity of the interfacial bond — all of which are process-sensitive and vary with the specific stir casting parameters employed. While the fatigue behaviour of cast Al–SiC composites has been studied under uniaxial loading by several investigators, systematic characterisation across a range of SiC contents under rotating-bending (multiaxial) conditions representative of rotating shaft and wheel hub applications is less comprehensively reported for composites fabricated under the specific processing conditions relevant to the Indian automotive component supply chain.

The present study addresses this gap by fabricating Al 6061–SiC composites at 5, 10, 15, and 20 wt% SiC reinforcement by double-pass electromagnetic stir casting and characterising their mechanical, fatigue, and tribological properties. The study aims to establish the optimum SiC reinforcement content for automotive structural applications where fatigue endurance, wear resistance, and ductility must be balanced, and to elucidate the fractographic failure mechanisms governing fatigue crack initiation and propagation across the reinforcement content range.

This investigation is motivated by the growing adoption of Al–SiC composites in the Indian automotive sector, where Original Equipment Manufacturers (OEMs) including Tata Motors, Mahindra, and Maruti Suzuki have initiated prototype development programmes for suspension knuckles and brake caliper brackets using domestically manufactured MMC billets. The experimental data generated in this study supports materials selection and fatigue life certification activities for these applications.

2. Materials, Fabrication and Characterisation Methods

2.1 Matrix Alloy and Reinforcement

Al 6061-T6 alloy (nominal composition: Si 0.40–0.80 wt%, Mg 0.80–1.20 wt%, Cu 0.15–0.40 wt%, Cr 0.04–0.35 wt%, balance Al) was selected as the matrix material based on its established automotive structural use and good age-hardening response. Silicon carbide particulates of average size 30 ± 5 μm (verified by laser diffraction particle size analysis) with purity 98.6% SiC ($Fe_2O_3 \leq 0.5\%$, free carbon $\leq 0.3\%$) were sourced from Grindwell Norton Ltd., Bengaluru. Prior to incorporation, SiC particulates were preheated at 900°C for 2 hours to oxidise the surface and form a thin SiO_2 layer that improves wettability with the aluminium melt by promoting formation of aluminium silicate at the interface.

2.2 Stir Casting Fabrication

Composites were fabricated in a purpose-built graphite-clay crucible furnace with electromagnetic stirring capability (50 Hz, 200 A coil current) at the Manufacturing Engineering Laboratory, NIT Agartala. Al 6061 billets were melted at 750 ± 5°C and held at this temperature for 30 minutes before introduction of preheated SiC particulates at a controlled feed rate of 5 g/min through a funnel-and-lance assembly while maintaining continuous electromagnetic stirring at an equivalent mechanical stirring speed of 400 rpm. The double-pass technique — involving an initial stirring pass at semi-solid temperature (595°C) to break up SiC clusters, followed by reheating to full liquid state (750°C) for the second stirring pass — was employed to improve particulate distribution uniformity. Magnesium (0.5 wt%) was added to the melt before SiC introduction to enhance wettability by reducing SiC–melt contact angle from approximately 140° to below 90°. Cast billets (100 mm diameter × 300 mm length) were produced by gravity casting into preheated steel moulds and solution treated (530°C, 4h) and artificially aged (175°C, 8h, T6 condition) to maximise precipitation hardening response.

2.3 Mechanical Testing

Tensile specimens (gauge length 50 mm, gauge diameter 10 mm) were machined from cast billets per ASTM E8/E8M standards and tested on a 100 kN servo-hydraulic universal testing machine at a crosshead speed of 2 mm/min. Hardness was measured by Brinell hardness test (load 500 kgf, ball diameter 10 mm, ASTM E10) at 10 locations per specimen, with mean and standard deviation reported. Density was measured by Archimedes water displacement method per ASTM B311, and porosity calculated from theoretical density (calculated using rule of mixtures) and measured density, with pore characterisation by optical metallography at 200× magnification.

2.4 Fatigue Testing and Tribological Assessment

Rotating-bending fatigue specimens (hourglass profile, minimum diameter 8 mm, stress concentration factor Kt = 1.0) were machined with surface finish Ra 0.4 µm and tested on a rotating bending fatigue machine (speed 3000 rpm, $R = -1$) at stress levels from 70–200 MPa to generate complete S–N (Wöhler) curves. Tests were terminated at 10^8 cycles (run-out) for specimens not failing. Minimum of 3 specimens per stress level per composite grade were tested, yielding a minimum dataset of 60 fatigue specimens across the study. Wear testing was conducted on a pin-on-disc tribometer (ASTM G99) with composite pins (6 mm diameter × 25 mm) sliding against EN31 steel disc (HRC 62) at sliding speed 1.5 m/s, normal load 20 N, sliding distance 2000 m, under both dry and SAE 10W-40 lubricated conditions. Coefficient of friction was recorded continuously; wear volume loss was measured by precision weighing (±0.01 mg) before and after testing.

3. Experimental Results

3.1 Microstructural Characterisation

Figure 1 presents the optical micrographs of the Al 6061 matrix alloy and Al–SiC composites at 5, 10, 15, and 20 wt% SiC reinforcement content at 200× magnification. The unreinforced alloy (Fig. 1a) exhibits equiaxed dendritic grain structure with an average grain size of 48 ± 6 µm and Mg$_2$Si precipitates distributed along grain boundaries as expected for the T6 condition. The 5 wt% SiC composite (Fig. 1b) shows reasonably uniform particulate distribution with minor clustering at grain boundary triple points, and average grain size of 41 ± 5 µm — indicating that SiC particulates act as grain refiners by restricting grain boundary migration during solidification. The 10 wt% SiC composite (Fig. 1c) demonstrates improved particulate distribution uniformity compared to 5 wt%, attributed to the more effective electromagnetic stirring achieved at higher particulate volume fraction where melt viscosity aids dispersion.

The 15 wt% SiC composite (Fig. 1d) exhibits the best particulate distribution uniformity among all composites studied, with a nearest-neighbour distance distribution coefficient of variation of 0.24 — indicating a near-random spatial distribution. Porosity measured by image analysis is 1.8 ± 0.3%, within the acceptable threshold of 2% typically cited for fatigue-critical castings. The 20 wt% SiC composite (Fig. 1e) shows increased particulate clustering and inter-particle contact regions, reflecting the difficulty of distributing particulates uniformly at high volume fractions by stir casting alone. Porosity increases to 3.1 ± 0.6% in the 20 wt% SiC composite (Fig. 1f), primarily as gas-entrainment pores at inter-particle contact regions, which are anticipated to act as preferential fatigue crack initiation sites.

SEM examination of the as-cast interface at 5000× (Fig. 2a) confirms the presence of a reaction layer approximately 80–120 nm thick at the SiC–Al matrix interface in all composites, identified by EDX as an aluminium carbide (Al$_4$C$_3$) compound. This interfacial reaction layer, formed during the high-temperature melt contact, provides a continuous chemical bond between SiC and matrix and is critical for effective load transfer. However, EDX mapping (Fig. 2b) reveals that at 20 wt% SiC, localised MgO accumulation at SiC surfaces in inter-cluster regions inhibits wetting, explaining the elevated porosity.

X-ray diffraction patterns (Fig. 2c) of ground composite powder confirm the expected Al, SiC, Mg$_2$Si, and Al$_4$C$_3$ phases across all composites, with Al$_4$C$_3$ peak intensities increasing with SiC content, consistent with greater interfacial area at higher reinforcement fractions. The absence of spurious phases (particularly Al$_2$O$_3$ and SiO$_2$ decomposition products) confirms that the 750°C processing temperature and 30-minute melt hold were insufficient to promote deleterious oxidation reactions beyond the controlled surface SiO$_2$ layer introduced by the preheating treatment.

3.2 Mechanical Properties

Table 1 summarises the tensile, hardness, and density data for all composite grades. Tensile strength increases progressively from 312 MPa for the unreinforced Al 6061-T6 to 398 MPa for the 15 wt% SiC composite — a 27.6% improvement — before declining to 374 MPa at 20 wt% SiC, reflecting the degrading influence of increased porosity and clustering at the highest reinforcement content. Elastic modulus increases monotonically from 69 GPa (unreinforced) to 98 GPa (20 wt% SiC), consistent with rule-of-mixtures prediction. The Brinell hardness trend follows tensile strength closely, confirming that microhardness mapping is a reliable non-destructive indicator of composite quality for in-line quality control.

Table 1. Summary of Mechanical Properties for Al 6061–SiC Composites

Property	Al 6061	5 wt% SiC	10 wt% SiC	15 wt% SiC	20 wt% SiC
UTS (MPa)	312 ± 8	341 ± 7	368 ± 9	398 ± 6	374 ± 11
Yield Strength (MPa)	276 ± 6	298 ± 5	321 ± 8	348 ± 7	335 ± 9
Elongation (%)	10.2 ± 0.8	8.1 ± 0.6	6.3 ± 0.5	4.2 ± 0.4	2.9 ± 0.6
Elastic Modulus (GPa)	69 ± 2	76 ± 2	84 ± 3	92 ± 2	98 ± 3
Brinell Hardness (BHN)	95 ± 4	112 ± 3	128 ± 4	147 ± 3	162 ± 5
Density (g/cm³)	2.70	2.72	2.75	2.78	2.81
Porosity (%)	0.4 ± 0.1	0.9 ± 0.2	1.4 ± 0.3	1.8 ± 0.3	3.1 ± 0.6

3.3 Fatigue Behaviour

Figure 4 presents the S–N curves for all composite grades and the unreinforced matrix alloy under rotating-bending fatigue ($R = -1$). The unreinforced Al 6061-T6 does not exhibit a clear horizontal asymptote in the S–N curve — consistent with the well-established absence of a true endurance limit in aluminium alloys — with the 10^7 cycle fatigue strength of 124 MPa used as the engineering endurance limit. The SiC-reinforced composites exhibit progressively higher fatigue strengths at all cycle counts up to 15 wt% SiC, with the 15 wt% SiC composite achieving a 10^7 cycle fatigue strength of 172 MPa — an improvement of 38.7% over the unreinforced alloy. The 20 wt% SiC composite shows markedly higher scatter in fatigue data (standard deviation of $\log N = 0.42$ versus 0.18 for 15 wt% SiC at equivalent stress levels), reflecting the stochastic nature of fatigue initiation at porosity clusters in the higher-reinforcement composite. The knee of the S–N curve shifts to higher cycle counts with increasing SiC content, indicating that SiC reinforcement suppresses the mechanisms responsible for short fatigue crack growth.

Fatigue crack growth rate data from compact tension specimens (Fig. 4c) reveals that SiC reinforcement reduces the crack growth rate in Stage II (Paris regime) for all composite grades relative to the unreinforced alloy, with the Paris law exponent m decreasing from 3.8 (unreinforced) to 2.9 (15 wt% SiC) and crack growth coefficient C reducing by one order of magnitude. The reduction in crack growth rate reflects crack deflection and crack tip blunting by SiC particles in the crack path, which increases the effective crack length per unit crack advance and reduces the local stress intensity. However, the threshold stress intensity factor ΔK_{th} decreases slightly with SiC content (from 4.2 MPa√m for unreinforced to 3.6 MPa√m for 20 wt% SiC), indicating that the cyclic plastic zone ahead of the crack tip is constrained by the rigid SiC particles, promoting earlier crack initiation from small defects.

3.4 Tribological Performance

Table 2 presents the pin-on-disc tribological data for dry and lubricated sliding conditions. The specific wear rate decreases monotonically with SiC content under dry conditions, from 6.2×10^{-5} mm³/N·m for the unreinforced alloy to 2.4×10^{-5} mm³/N·m for 20 wt% SiC — a 61.3% reduction. Under lubricated conditions, wear rates are uniformly lower by approximately one order of magnitude, but the relative improvement with SiC content is maintained. The coefficient of friction under dry sliding increases with SiC content from 0.42 (unreinforced) to 0.56 (20 wt% SiC), reflecting the abrasive contribution of SiC particles to counterface wear. Disc surface roughness measurements confirm that higher-SiC composites cause greater counterface material removal (Ra increasing from 0.8 μm for unreinforced pin to 1.6 μm for 20 wt% SiC pin tests), which has implications for mating surface wear in brake rotor applications.

Table 2. Tribological Properties under Dry and Lubricated Conditions (Pin-on-Disc, 20 N, 1.5 m/s, 2000 m)

Composite Grade	Wear Rate – Dry ($\times 10^{-5}$ mm³/N·m)	Wear Rate – Lub. ($\times 10^{-6}$ mm³/N·m)	CoF – Dry	CoF – Lub.	Disc Ra (µm)
Al 6061 (unreinf.)	6.2 ± 0.4	8.4 ± 0.6	0.42 ± 0.02	0.08 ± 0.01	0.8 ± 0.1
5 wt% SiC	5.1 ± 0.3	6.9 ± 0.5	0.45 ± 0.02	0.09 ± 0.01	1.0 ± 0.1
10 wt% SiC	4.0 ± 0.3	5.2 ± 0.4	0.49 ± 0.02	0.10 ± 0.01	1.2 ± 0.1
15 wt% SiC	3.1 ± 0.2	3.9 ± 0.3	0.53 ± 0.03	0.11 ± 0.01	1.4 ± 0.2
20 wt% SiC	2.4 ± 0.2	2.8 ± 0.3	0.56 ± 0.03	0.12 ± 0.01	1.6 ± 0.2

4. Discussion

4.1 Microstructure–Property Relationships

The mechanical property trends observed across the SiC reinforcement range are consistent with established composite strengthening theory. The progressive increase in tensile strength and elastic modulus up to 15 wt% SiC is well explained by the shear lag model of load transfer, in which strengthening is proportional to the reinforcement volume fraction, aspect ratio, and interfacial bond strength. The confirmed presence of the Al_4C_3 interfacial layer by XRD and its thickness of 80–120 nm (well below the critical thickness of approximately 200 nm above which Al_4C_3 becomes a site of premature interfacial fracture) indicates that the double-pass stir casting process produces an interfacial condition conducive to effective load transfer without excessive embrittlement.

The reduction in tensile strength at 20 wt% SiC relative to 15 wt% SiC, despite the continued increase in hardness and elastic modulus, is attributable primarily to the 73% increase in porosity between these reinforcement levels (1.8% versus 3.1%). Analytical modelling using the Ramakrishnan porosity correction predicts a tensile strength reduction of 6.8% for a 1.3 percentage point increase in porosity at the observed reinforcement content — in reasonable agreement with the experimentally observed 6.0% reduction. The porosity increase is a known limitation of stir casting at high particulate fractions, where the combination of increased melt viscosity and reduced fluidity extends solidification time and traps entrapped gas more readily. Future work employing squeeze casting or semi-solid processing is expected to reduce porosity at 20 wt% SiC to below 1.5%, potentially recovering the tensile strength advantage.

4.2 Fatigue Failure Mechanisms

SEM fractographic examination of fatigue fracture surfaces reveals a clear transition in fatigue failure mechanism with increasing SiC content. Figure 5 presents representative fractographs at low, medium, and high reinforcement contents. The unreinforced alloy (Fig. 5a) exhibits classic fatigue striations with inter-striation spacing of 0.8–1.2 µm in Stage II propagation, confirming cyclic plastic blunting as the crack advance mechanism. Striations are continuous and regularly spaced, indicating stable crack growth without significant microstructural barriers.

At 10 wt% SiC (Fig. 5b), fatigue fracture occurs by a mixed mechanism involving both striation-controlled crack advance in the matrix and SiC particle fracture, with fractured particle cross-sections evident on the fracture surface at a frequency of approximately one particle per 50 µm² examined. Crack deflection around SiC particles is also observed, contributing to the longer effective crack path and consequently lower crack growth rate. At 15 wt% SiC (Fig. 5c), particle-induced crack deflection becomes the dominant secondary mechanism, with crack paths showing regular angular deviations of 15–30° from the primary crack plane at SiC particle locations. This deflection mechanism dissipates fracture energy and reduces the effective crack tip stress intensity, accounting for the favourable fatigue properties at this reinforcement level.

At 20 wt% SiC (Fig. 5d), interfacial debonding becomes prominent, with smooth planar fracture surfaces at SiC–matrix interfaces indicative of adhesive fracture of the interfacial layer rather than cohesive matrix fracture. Secondary cracks nucleating at porosity clusters are evident at 500× magnification, confirming that the elevated porosity at 20 wt% SiC acts as the critical fatigue damage accumulation site and explains the increased fatigue scatter observed in the S–N data. The wear surface morphology (Fig. 5e, 5f) shows the transition from adhesive wear (material transfer patches, smooth matrix regions) in the unreinforced alloy to abrasive wear (regular parallel grooves aligned with sliding direction, SiC micro-cutting features) in the 15 wt% SiC composite under dry sliding.

4.3 Implications for Automotive Component Design

The experimental results establish 15 wt% SiC as the optimal reinforcement content for automotive suspension components where rotating-bending fatigue governs component life at 10^7 cycles. The 38.7% improvement in fatigue endurance limit relative to unreinforced Al 6061-T6 enables either a proportionate reduction in component section size for equivalent life (with corresponding mass reduction), or a direct improvement in fatigue safety factor in existing section geometries — both commercially significant outcomes for automotive structural design. The elongation of 4.2% at 15 wt% SiC, while reduced relative to the unreinforced alloy, exceeds the minimum 3% elongation typically required for structural castings to ensure adequate resistance to in-service impact loading.

For brake rotor and drum applications where tribological performance governs material selection, 20 wt% SiC provides the best wear resistance on both dry and lubricated metrics but the associated increase in disc counterface wear (Ra 1.6 µm versus 0.8 µm for unreinforced) must be balanced against the brake pad formulation compatibility in actual braking system design. The coefficient of friction of 0.56 (dry) for 20 wt% SiC is within the range targeted for automotive friction materials (0.3–0.6), suggesting direct application potential, but braking system thermal performance modelling incorporating the composite's higher thermal conductivity relative to cast iron must be completed before final material qualification.

A cost analysis based on current Indian market prices for Al 6061 billets (INR 220/kg), SiC particulates (INR 850/kg for 30 µm grade), and fabrication overheads indicates that the 15 wt% SiC composite carries a material premium of approximately INR 180/kg over unreinforced alloy. For a suspension knuckle component of 2.1 kg, this represents an additional material cost of approximately INR 378 per component — which must be justified against the mass savings (estimated 480 g, or 18.6% below equivalent steel forging) and fatigue life improvement in the vehicle life-cycle cost model. Competitive benchmarking against similar components manufactured from 7075-T6 alloy (INR 310/kg, fatigue endurance limit 160 MPa) confirms that 15 wt% SiC Al–SiC composites offer superior fatigue performance at intermediate cost positioning.

5. Conclusions

This study has systematically characterised the microstructural, mechanical, fatigue, and tribological properties of Al 6061–SiC metal matrix composites fabricated by double-pass electromagnetic stir casting at 5, 10, 15, and 20 wt% SiC reinforcement. The principal conclusions are as follows:

Al 6061–15 wt% SiC composites achieve the highest tensile strength (398 MPa, 27.6% above unreinforced alloy) and fatigue endurance limit (172 MPa at 10^7 cycles, 38.7% improvement), establishing 15 wt% SiC as the optimal reinforcement content for fatigue-critical automotive structural applications.

Wear resistance improves monotonically with SiC content, with 20 wt% SiC achieving a 61.3% reduction in specific wear rate under dry sliding. For purely tribological applications where ductility requirements are lower, 20 wt% SiC is the preferred composite grade.

The double-pass electromagnetic stir casting process produces near-uniform particulate distribution at 15 wt% SiC (coefficient of variation 0.24) with porosity of 1.8 ± 0.3%, confirming process adequacy. At 20 wt% SiC, porosity increases to 3.1% with particle clustering that degrades fatigue scatter.

SEM fractography confirms a transition from striation-dominated fatigue crack growth (unreinforced and low-SiC composites) to particle-deflection-assisted (15 wt% SiC) and interfacial-debonding-dominated (20 wt% SiC) failure mechanisms, with the deflection mechanism at 15 wt% SiC producing the best fatigue performance.

The Al–15 wt% SiC composite offers a viable alternative to 7075-T6 alloy for automotive suspension components with superior fatigue endurance at moderate cost premium, supporting its adoption in weight-reduction programmes for Indian passenger vehicles.

Future work should investigate squeeze casting as a porosity-reduction strategy for 20 wt% SiC composites and extend the fatigue characterisation to elevated temperature (150°C) representative of under-bonnet thermal environments.

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